Symposium on CLIMATE ACTION 2025

"Food, water, and climate security through Integrated water management lessons learned"

EXTENDED ABSTRACTS

Ministry of Agriculture, Livestock, Land and Irrigation
Climate Resilient Integrated Water Management Project(CRIWMP)

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30 September to 1 October, 2025. Colombo, Sri Lanka.

Cost Benefits Analysis of Adopting New Technologies in Mushroom Cultivation - A case study in Madawachchiya Divisional Secretariat Division of Sri Lanka

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Introduction

Agriculture remains the foundation of the rural economy of Sri Lanka. Technology evolution over the past few years has been reshaping conventional modes of agriculture with the capability of enhancing productivity, quality, and cost reduction (FAO 2017). However, technology use, particularly among small-scale farmers, is likely to be based on a strong sense of its economic feasibility (Rogers 2003).

Mushroom cultivation provides a good opportunity for creating income, achieving food security, and implementing eco-friendly cultivation methods (DOA 2020). Growing mushroom encompasses a critical science involving environmental monitoring and control and resource management to generate uniform high yields and quality (Karunarathne et al. 2017). New technologies such as automated humidifiers, climate-controlled grow rooms, and digital monitoring systems can potentially increase these levels. However, the expense of initial investment and changes to operations raise scepticism about their overall cost-effectiveness to local producers (Fernando et al. 2022).

While cultivation of mushrooms has gained momentum among rural groups in Sri Lanka as a profitable means of livelihood, many small- and medium-scale farmers still rely on traditional, labour-intensive practices. While novel technologies such as computerized climate management systems, sophisticated substrate preparation machinery, and state-of-the-art packaging machinery are gaining ground, they have not made significant inroads among rural sectors. This low rate of adoption may be a result of uncertainty regarding the economic payback, lack of awareness, limited technical skills, and perceived high upfront capital expenses.

There is little region-specific information and empirical data to date on the actual cost-benefit outcomes of integrating such technologies within mushroom production. Farmers and policymakers are therefore left without evidence to guide their decisions. Without an honest evaluation of the implications and future rewards, the potential for mushroom modernization and increases in productivity remains untapped.

Conducting an area-specific cost-benefit analysis is significant for several reasons. First, the region has been showing an increasing interest in mushroom cultivation as a means of livelihood, and thus it is a suitable candidate to study the impact of technological interventions. Second, actualizing the economic viability of introducing new technologies can offer immediate benefits to local farmers by allowing them to increase productivity, reduce losses, and maximize profitability. Third, such research can guide agricultural extension services and development programs in designing more targeted interventions, training programs, and subsidy programs.

Furthermore, this research addresses an important knowledge gap in the Sri Lankan context of agricultural research where region-level economic analysis is typically absent. By providing concrete data on the cost and benefits of technology adoption, the research can guide sustainable agricultural development, rural entrepreneurship, and evidence-based policy-making.

This study focused on a cost-benefit analysis of adopting new technologies in mushroom cultivation within the Madawachchiya Divisional Secretariat Division in the Anuradhapura District of North Central Province of Sri Lanka. In this region, mushroom farming is gaining popularity among rural households. The objectives of the study were to assess the financial feasibility of adopting four different technologies in mushroom cultivation, and conduct a sensitivity analysis to investigate the robustness of assumptions. By examining both the financial costs and the measurable benefits associated with technology adoption, this research aims to provide empirical insights that can guide farmers, policymakers, and agricultural extension officers in making informed decisions about modernization in the mushroom sector.

Methodology

This study employed a quantitative research approach to evaluate the cost-benefit outcomes of adopting new technologies in mushroom cultivation within the Madawachchiya Divisional Secretariat Division (MDSD) of Sri Lanka. Both primary and secondary data were collected and analyzed to assess the economic viability of technological adoption in the local context. It was conducted within the MDSD in Anuradhapura District, focusing on areas with a concentration of mushroom farmers. Data collection took place over a five-day period, from 17th to 21st January 2025.

Primary data were gathered through a structured survey administered to 21 mushroom farmers operating in the MDSD. Among these, seven farmers were identified as having adopted advanced mushroom farming technologies such as automated humidifiers, improved substrate sterilization techniques, and controlled environment systems focusing on cultivation practices, technology use, cost of production, and profitability. The collected data were analyzed using Microsoft Excel, applying three standard financial evaluation techniques.

Results and Discussion

The key findings of the study that surveyed seven mushroom farmers in the Madawachchiya DS Division are summarized in Table 1.

Table 1. Summary of the results (n=7).

Parameter	Result
Income Generation	A significant majority (85%) of farmers earned more than Rs. 5,000 monthly from mushroom cultivation
Technology Adoption	Most respondents had adopted a mixed mushroom unit, integrating both modern and traditional methods. Only a minority used fully modern systems
Cultivated Varieties	The Americano Oyster mushroom was the most widely cultivated variety (71.43%), with Abalone or a combination of Abalone and Americano cultivated by the rest
Production Volume	The majority of farmers produced between 500–2,500 mushroom bags per month
Irrigation Methods	About 57% used hand-sprayers and 14% used micro-irrigation. About 28% relied on flood irrigation resulting in higher water losses
Cost of Production	About 57% of the farmers incurred production costs in the range of Rs. 25,000–40,000
Marketing Channels	About 43% marketed their products both in towns and villages. Other channels included village stalls (14%), town markets (14%), and collectors/others (28%)
Selling Price per Bag	About 43% priced at Rs. 100–115 per bag, 28% sold at Rs. 115–130 per bag, and 28% sold above Rs. 130 per bag
Mixture Preparation Methods	About 57% used pots, 28% used machines and 14% practiced hand mixing
Sterilization & Housing Techniques	Most growers used pot and barrel methods for sterilization. The hanging method was the most common racking system. Farmers largely preferred traditional huts and climate control methods like shade nets, clay walls, wetting techniques, and coconut leaf roofs
Pest Control	Farmers commonly used insect-proof nets instead of chemical pesticides, ensuring better health safety
Water Usage	Water usage ranged between 8–50 L per day, depending on irrigation method and unit size. Pot systems required less water, averaging 6–25 L per day
Income/Profit Allocation	Profits were mainly reinvested in infrastructure, followed by spending on education, health, household needs, and food security

The results indicated that mushroom cultivation is a viable income-generating activity in the Madawachchiya DS Division (MDSD). Adoption of a mixed-method approach, blending traditional and modern practices demonstrates a transitional phase in technological integration among the rural farmers. Full modernization was limited, however, technology has helped increase yield and reduce post-harvest losses.

The economic returns reported over Rs. 5,000 per month (approx. US$ 16.6) for 85% of the farmers suggesting that mushroom farming can meaningfully contribute to household income, even when operating on a small scale. However, cost of production remains a challenge, especially for those investing in new equipment or improved infrastructure, which underscore the importance of conducting a cost-benefit analysis.

Water management emerged as a critical issue. While modern irrigation methods like micro-spraying were more efficient, a large proportion of mushroom farmers still relied on flooding, leading to high wastage of water. This highlights the need for farmer training and support programs to encourage adoption of low-cost, water-saving technologies.

The preference for traditional housing and pest control methods reflects both cultural familiarity and a desire to reduce chemical use. However, the gradual introduction of insect nets and improved environmental controls suggests that health-conscious and sustainable practices are being adopted.

From a marketing perspective, the diversification of sales channels (towns, villages, collectors) showed resilience and adaptability. The variation in selling prices indicates that farmers who adopted improved packaging, variety selection, and partial automation likely achieved better profitability.

Acknowledgment

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Collective Actions for Agricultural Activities in Cascade Communities: A case study of selected cascades of the Dry zone in Sri Lanka

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Introduction

The cascade system—an indigenous, interconnected water management infrastructure unique to Sri Lanka's Dry zone—has long supported local agriculture and rural livelihoods (Ariyawanshe et al. 2023). Comprising intricate networks of village tanks within micro-catchments, these systems ensure equitable water distribution and long-term resilience. However, their sustainability is increasingly threatened by climate variability, inadequate maintenance, and fragmented governance (Sakalasooriya et al. 2021). To address these challenges, the Climate Resilient Integrated Water Management Project (CRIWMP) introduced interventions aimed at strengthening collective agricultural practices and promoting climate-smart agriculture (CSA). This study assesses the impact of these interventions across three representative cascades.

Methodology

A pre-tested structured questionnaire survey was conducted in three cascade systems—Kadawala, Chettikkulam, and Ethabediwewa—across four districts (Kurunegala, Puttalam, Vavuniya and Trincomalee) of Sri Lanka. A purposive sampling approach was used to select 54 households, ensuring demographic and socio-economic diversity within three cascades. Data were gathered through structured questionnaires, focus group discussions (FGDs), and field observations. Key aspects of the questionnaire included demographics, institutional participation, collective farming activities, CSA practices, and perceived benefits gained through the implementation of collective decisions.

Results and Discussion

Most participants were aged between 40 and 65 years and had more than 20 years of farming experience. A significant proportion came from economically-vulnerable households, many of whom were *Samurdhi* beneficiaries (Sri Lankans who received financial incentives from the government aimed at poverty reduction by ensuring participation of the poor in the production process). Institutional engagement was strong, with over 80% active participation in farmer organizations and water user groups. Notably, women-led households often demonstrated leadership in adopting climate0smart

agricultural (CSA) practices. Collective action was especially evident in tank rehabilitation, labour sharing, land sharing (*Bethma*), bund maintenance, and synchronized planting schedules. This collaboration enhanced agricultural efficiency and climate resilience. The most widely adopted CSA technologies included parachute planting of seed paddy, irrigation using alternate wetting and drying (AWD) technology, using improved seed varieties, and organic amendments. Use of agro-met tools was widespread in Trincomalee, while organic farming practices were especially common in Vavuniya. These findings are consistent with studies that emphasize the role of Village Tank Cascade Systems (VTCS) in promoting resilience through shared knowledge, pooled resources, and adaptive farming strategies *(*Ariyawanshe et al. 2023*).*

District-level analysis revealed notable differences. Cascades in Kurunegala and Puttalam outperformed others in coordination and seasonal planning, while Vavuniya showed the highest level of gender-inclusive participation. Compared with previous studies, these cascades showed better outcomes due to structured interventions, indicating the CRIWMP model's potential for replication in similar dryland contexts (Ratnayake et al. 2021*;* Sakalasooriya 2021*)*.

The bar chart displays acceptance rates of various organizational decisions by farmers. Decisions tied to shared infrastructure and climate coordination, such as weather advisory (87%) and tank renovations (82%), receive strong support (Figure 1). Conversely, decisions involving personal autonomy—such as pricing and cultivation extent—receive limited acceptance, highlighting the value placed on individual economic control. This pattern suggests that interventions are more effective when aligned with community-prioritized actions that benefit the entire cascade system.

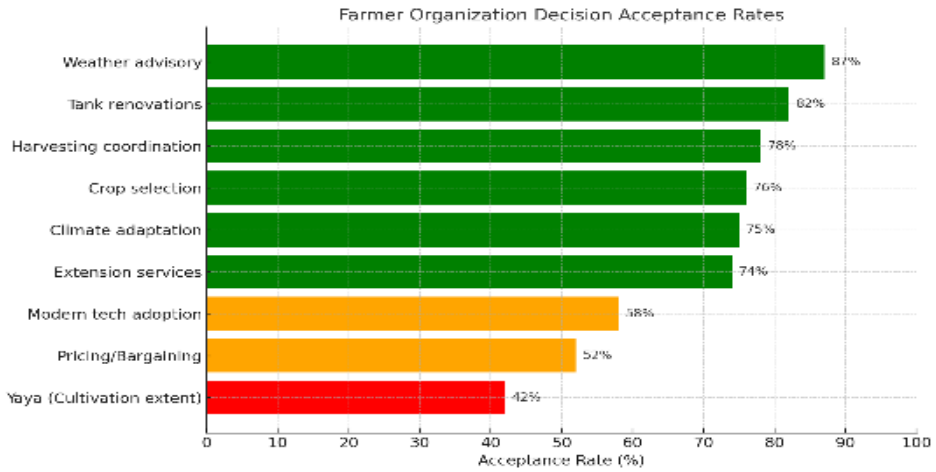

Figure 1. Farmer Organization Decision Acceptance Rates

Figure 2 illustrates the technology adoption rates across six major farming activities. High rates of participation are seen in collective actions such as harvesting coordination (90%),

seasonal planning (85%), and fertilizer application (81%). These indicate that farmers appreciate the efficiency and effectiveness of synchronized efforts. On the other hand, activities like land preparation (31%) and seed establishment (28%) are kept individual, likely due to variability in resource availability and crop preference. The *Bethma* system (30%) also shows low participation, indicating socio-economic and cultural shifts away from traditional labour-sharing.

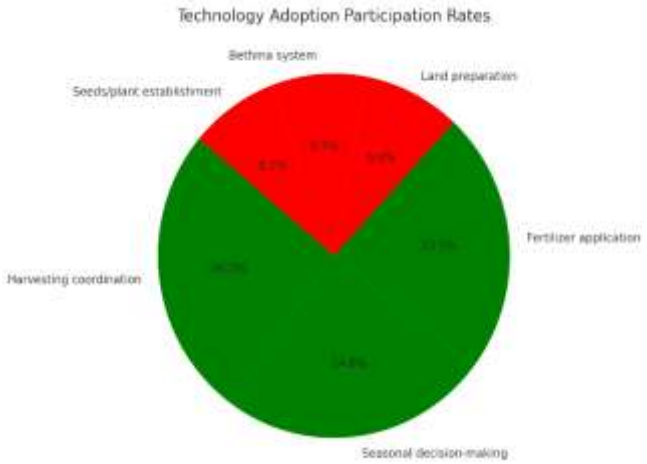

Figure 1. Technology Adoption Participation

Figure 3 illustrates the benefits farmers most strongly associated with collective action. Immediate operational gains such as weather advisory (87%), reduced losses (78%), and water efficiency (76%) dominate recognition, demonstrating a focus on visible short-term benefits. Longer-term or less tangible outcomes like increased income (~50%) and pest control (33%) received much lower recognition, suggesting these areas need better demonstration or support to build trust. It reflects a hierarchy in how benefits are perceived—tangible, urgent outcomes drive engagement more than abstract or future returns.

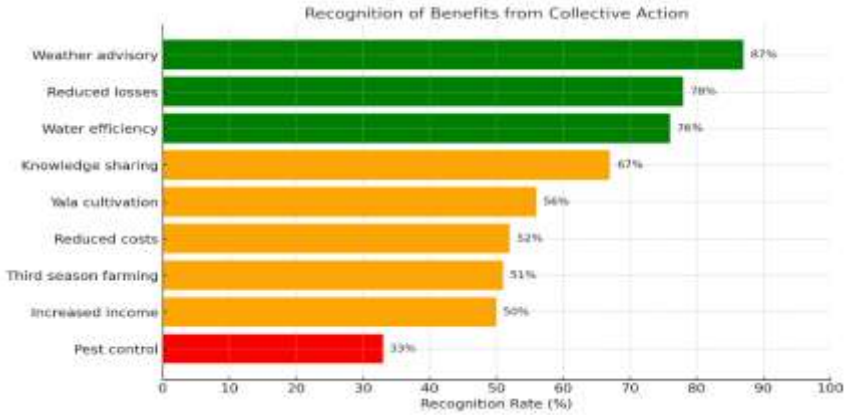

Figure 2. Recognition of Benefits from Collective Action

Conclusion

The results revealed a strategic pattern of 'selective collectivism' among cascade farmers. They engage enthusiastically in community-driven efforts that offer clear, synchronized advantages and maintain autonomy over decisions affecting their personal risk and household outcomes. Policy makers and practitioners should align interventions with this behavioural pattern: strengthen institutions for coordination-required activities and support autonomy for individual plot-level decisions. Addressing under-recognized benefits—especially pest control and income generation—through practical demonstrations and targeted training could foster wider participation and improve agricultural resilience.

Acknowledgment

We express our gratitude to the CRIWMP project team, local authorities, and particularly the farming communities of Kadawala, Chettikkulam, and Ethabediwewa for their valuable cooperation and contributions.

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Contribution of Agrobiodiversity of Home Gardens for Household Food Security and Dietary Diversity in Selected Cascade Systems of Sri Lanka

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Introduction

A home garden (HG) is a diverse and sustainable land-use arrangement that integrates various agricultural elements, including both seasonal and annual crops, livestock, and occasionally even fish, within the household premises. It serves the dual purpose of fulfilling environmental roles and meeting household requirements while creating avenues for employment and income generation for the household members (Mattsson et al. 2013). The HGs are not pure agricultural systems but, represents a multi objective framework. Such systems should consider, multi-dimensional (spatial and temporal), multi-use (forestry and agriculture) and multi-disciplinary (economic, social, environmental) complexities (Pushpakumara et al. 2012).

In particular, such systems with high species diversity are considered resilient to climate change. The HGs are more adaptable to significant climatic impacts because of the trees that enhance the microclimate and act as a buffer between it and the outside world. Climate change is expected to impact food production in different ecosystems to differing extents (Rao et al. 2007). However, it is important to better clarify and measure how tree diversity, and the contribution of other homestead resources such as the contribution of livestock, affect food security and supply domestic food needs (Mellisse et al. 2018). There is a gap in the literature that analyzes the actual role of HGs in adapting to climate change, and household food security, especially in light of the differing compositions, adaptation practices, and in different regions of Sri Lanka.

The present study was conducted to investigate the role of agrobiodiversity in homes gardens to climate change adaptation and it is impact for increase the resilience of vulnerable communities. The study also aimed to assess the contribution of HGs in satisfying household food demand and dietary diversity in four selected cascade systems, to examine existing household food consumption patterns, and to explore the capacity of diverse HG components to mitigate household food insecurity.

Methodology

Study sites

The study sites were selected based on different climatic and topographical zones in island focusing three main river basins, namely, Malwathu oya, Mee oya and Yanoya in the Dry zone of Sri Lanka. The chosen districts and cascades were Sinnakunchikulam cascade in Mannar and Mathavuvaithakulam cascade Vavuniya (Northern Province), Sivalakulama cascade in Anuradhapura (North Central Province) and Madderambewa cascade in Puttalam (North Western Province), known for their varying biodiversity and agricultural practices. A thorough selection process was used to ensure that the HGs in each district have represented the greatest possible diversity.

Selection of Home gardens

In each cascade, an approximate transect was established. The transect was constructed along an elevation gradient to account for ecological and environmental variations. Along the transect, 20 HGs were selected form each cascade. In total, 80 households were included in the survey.

Data collection

Household surveys were carried out in the four selected cascades from January to April in 2025. A structured questionnaire was used to collect primary data including information on general household characteristics, structure and composition of the HG adaptation practices with reasons, animals reared in the HGs and their production, and the contribution of home-grown food items to household consumption.

In order to assess the agrobiodiversity within home gardens, a 20 m × 20 m plot was demarcated in each selected HG. Within this plot, both woody and non-woody plant species, including annuals and perennials, were identified, counted and recorded. Preliminary Investigation reports (PRI) were used as sources of secondary data.

Data analysis

The analysis was conducted using the Shannon-Wiener Index (SWI) to measure the diversity of HGs. Several biodiversity and food consumption indices and scores were calculated according to the standard equations and methods found in the literature, which are based on previous studies in Sri Lanka and other countries in the South Asian region, to interpret the data.

Results and Discussion

Small-scale HGs (<0.2) dominated the sample, followed by medium scale HGs. Only 1% of large-scale HGs were observed in the entire sample, especially in Mannar and Vavuniya. The results indicated that home gardening in Sri Lanka is primarily undertaken on small to medium-sized plots (generally less than 0.8 ha), enabling households to efficiently manage and sustain domestic production at a subsistence level. A considerable proportion of HGs had livestock and poultry incorporated as integral

components of their homestead resources. Compared to the districts of Mannar, Puttalam, and Anuradhapura, the people in Vavuniya showed a high level of interest in rearing domesticated animals both for subsistence and additional income. Approximately 50% of the HGs evaluated in Jaffna had livestock animals, with chicken (*Gallus gallus domesticus*) being the most common animal component, followed by cattle (*Bos spp.*).

The results of the present study indicated that Sri Lankan households primarily depend on market-sourced food items as their main source of nutrition. However, coconuts, jackfruit, and a variety of fruits from HGs play a significant role in supplementing household food requirements. With the exception of Vavuniya site, majority of households relied on market-sourced animal protein to meet their needs for meat, eggs, and milk.

The HGs were mainly used by households to obtain plant-based food products, with the exception of Jaffna site, where livestock and poultry contributed significantly to HGs. Producing at least one food category within the HG has the potential to enhance household food security by contributing to the fulfillment of their domestic food demand. Consequently, there is significant potential for leveraging home garden resources through suitable interventions to satisfy household food requirements and improve dietary diversity.

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I authors like to express sincere gratitude to the CRIWMP Project, Green Climate Fund, and UNDP for their invaluable support. Heartfelt thanks are also extended to the academia of the Faculty of Agriculture, University of Peradeniya, for their academic guidance. The cooperation of all home garden farmers and every individual who contributed to the success of this study is deeply appreciated.

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Azolla and Black Soldier Fly (BSF): Nutritionally-rich non-conventional feed for backyard poultry farming

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Introduction

The global demand for animal protein rises, and backyard poultry farming plays a key role in food security and rural income. However, high feed costs—making up about 70% of production expenses—threaten the sustainability and profitability of these systems. In countries like Sri Lanka, small-scale farmers with limited resources face serious challenges in accessing and affording commercial poultry feed, limiting productivity and growth. To address rising feed costs, interest is growing in non-conventional, locally available, and eco-friendly alternatives. Azolla and Black Soldier Fly (BSF) larvae (*Hermetia illucens*) stand out for their high nutritional value, fast biomass production, and low input needs.

Azolla and BSF larvae are promising non-conventional poultry feeds. Azolla is a fast-growing, protein-rich fern requiring minimal inputs, while BSF larvae offer high protein and fat content through organic waste conversion. Both provide nutritional value and environmental benefits like waste reduction and lower carbon footprint. BSF larvae convert organic waste into nutrient-rich biomass, rich in protein and fat, making them a sustainable alternative feed for livestock and poultry (Dörper and Dicke 2021). Azolla is a nutrient-rich, low-cost poultry feed that enhances yolk color and supports growth. It can be used at 5–10% in diets without affecting performance, though high fiber limits overuse (Swain et al. 2022). Backyard poultry farmers face high feed costs and limited access to commercial feed, reducing productivity. Though Azolla and BSF larvae are rich in nutrients and locally available, their use is limited by low awareness. These affordable, sustainable options offer promising solutions for rural poultry systems.

The study evaluated Azolla and BSF larvae as nutrient-rich, non-conventional feed options for backyard poultry. It focuses on analyzing the cost-benefit of incorporating them into poultry diets, assessing their potential to reduce feed expenses, and examining their impact on growth performance, productivity, and profitability.

Methodology

This research was conducted across five key agricultural districts in Sri Lanka—Anuradhapura, Vavuniya, Puttalam, Trincomalee, and Polonnaruwa—which represent

diverse agro-ecological regions and have a strong presence of backyard poultry farming. These locations were selected to capture a variety of environmental conditions and farming practices, ensuring that the findings are broadly applicable and regionally relevant.

Procedure of Azolla poultry feed production

Azolla was cultivated in 2m x 1m x 0.3m soil pits, cement tanks, or similar containers. Clean soil, cow dung, water, and super phosphate were added to prepare the pond, which was left for 2–3 days. About 1 kg of Azolla was inoculated, broken into smaller parts, and fresh water was sprayed to support growth. The pond was covered with a net for protection and shade. Under optimal conditions, 1–1.5 kg of Azolla was harvested daily after 10–15 days. It was washed thoroughly and fed directly to backyard poultry, either fresh or mixed with other feed.

Procedure of Black Soldier Fly (BSF) Feed Production

Organic substrate was prepared using chopped biodegradable waste like vegetable peels, fruit scraps, stale bread, and poultry manure. BSF eggs were placed on dry leaves or cardboard above the substrate; hatched larvae dropped in and began feeding. They were reared under ideal conditions (27–30 °C, 60–70% humidity), with fresh waste added every 2–3 days. After 12–15 days, mature larvae were harvested and directly fed to backyard poultry as a protein-rich, natural feed, enhancing their health, growth, and egg production.

Data Analysis

The study used field surveys and lab analysis to assess Azolla and BSF as alternative poultry feeds. Data from 50 farmers across five districts covered feed practices. Nutritional content was analyzed, and SPSS software was used for statistical comparison with commercial feed, applying descriptive statistics, and mean comparisons (P=0.05).

Results and Discussion

Egg York Colour

The butritional composition of the test samples are presented in Table 1. Eggs from hens fed with Azolla and BSF (Figure 1A) showed deeper yellow yolk coloration due to its high β-carotene content, especially in Azolla. This was visually distinguishable compared to the lighter yolks from hens fed only on commercial feed (Figure 1B).

Feed Cost and Income

The data showed clear differences in monthly feed cost and income between farmers using only commercial feed and those using a mix of commercial feed with Azolla and BSF.

Most of the commercial feed users (64%) have spent LKR 8,000–10,000 (approx. US$ 26-33) as the feed cost, with about 20% spending more than LKR 10,000. None in the sample have spent below LKR 3,000 highlighting the high cost of animal feed. However, 68% of Azolla + BSF users have spent LKR 3,000–8,000 (approx. US$ 10-26), and 24% spent as low as LKR 1,000–3,000 (approx. US$ 3-10), showing significant savings.

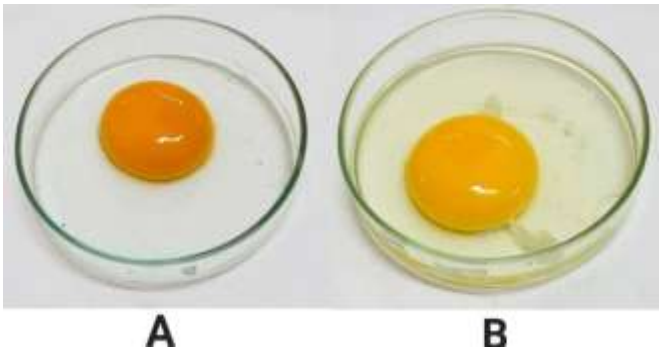

Figure 1. Azolla + BSF (A) and Commercail feed egg yolk (B) samples

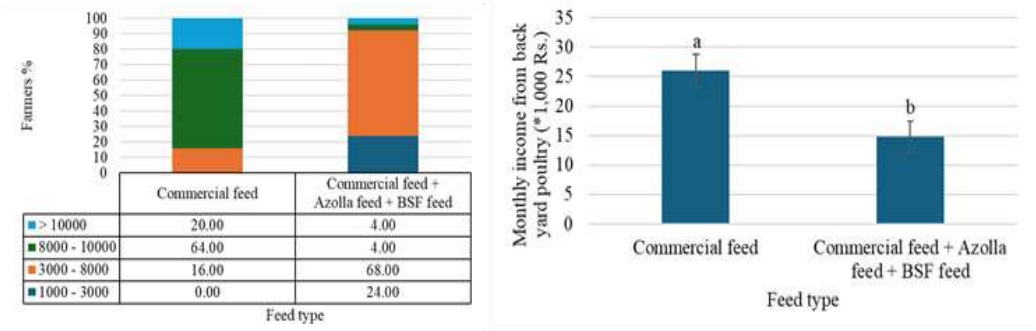

Figure 2. Monthly feed cost and income

Commercial feed users also earned higher monthly income of about LKR 25,000 (approx. US$ 83), while Azolla + BSF users earned around LKR 15,000 (approx.. US$ 50). This gap may be due to the initial transition challenges or limited scale of alternative feed use. Despite lower income, the reduced feed cost with Azolla and BSF improves cost-efficiency and long-term profitability. Being low-cost, local, and sustainable, these feed options offer a practical solution for smallholder poultry farmers. Their wider adoption could lower production costs, support food security, and promote eco-friendly farming.

Egg Production and Performance

Hens fed exclusively with commercial feed produced a significantly higher number of eggs per month (approximately 750 eggs), compared to those fed with the Azolla + BSF + commercial feed combination, which produced around 500 eggs. This indicates a statistically significant difference in egg production between the two feeding groups.

The lower egg production in the Azolla + BSF group may be due to initial feed adaptation, nutrient imbalances, or inconsistent feed quality. Despite this, reduced feed costs and environmental benefits suggest better long-term profitability. Optimizing feed ratios and consistency could improve productivity while maintaining sustainability.

Egg laying Percentage

The data show a slight difference in egg laying performance between the two feeding systems. Hens fed only commercial feed recorded a higher average egg laying percentage of 81.24%, while those receiving a combination of Azolla + BSF + commercial feed had a marginally lower rate (Table 2). The slight drop may be a result of the adaptation period or nutrient variability with Azolla and BSF. However, the impact on productivity is minimal, and the significant feed cost savings make them a viable, sustainable option for smallholder poultry farmers.

Table 2: Egg laying percentage

Type of Feed	Egg laying percentage
Commercial feed only	81.24%
Azolla + BSF + Commercial feed	79.76%

Farmer Perception, Acceptance and Sustainability

The results showed a strong farmer support for using Azolla and BSF as alternative poultry feeds. All respondents (100%) cited reduced feed costs, improved poultry health, and higher production as key benefits. Additionally, 72% recognized environmental advantages like waste reduction and sustainability, though economic factors remained the main motivator.

All farmers expressed their willingness to continue using and recommend Azolla and BSF, highlighting high satisfaction and strong potential for wider adoption. Azolla and BSF are cost-effective, space-efficient, and eco-friendly. Azolla grows easily in small pits, and BSF larvae thrive on organic waste, both requiring minimal labor. Environmentally, Azolla enriches soil, and BSF reduces waste—together offering practical, sustainable feed solutions for backyard poultry farming.

Conclusion

This study highlights the significant potential of Azolla and Black Soldier Fly (BSF) larvae as cost-effective, nutrient-rich, and sustainable alternatives to commercial poultry feed. Integrating these non-conventional feeds in backyard poultry systems reduced feed costs, improved egg quality (especially yolk color), and increased overall profitability for small-scale farmers. Their ease of production, environmental benefits, and positive farmer acceptance make Azolla and BSF practical solutions to address feed challenges in rural poultry farming. Promoting their wider adoption could enhance food security, support rural incomes, and contribute to environmentally friendly livestock production in Sri Lanka.

Acknowledgement

I would like to extend my heartfelt gratitude to the CRIWMP Project, Green Climate Fund, and UNDP for their valuable support. My sincere thanks also go to the Faculty of Agriculture, University of Peradeniya, for academic guidance. I deeply appreciate the cooperation of all backyard poultry farmers and every individual who contributed to the success of this study.

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Home Garden Biodiversity in Cascade Systems: A comparative analysis across two agro-ecological regions in Sri Lanka

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Introduction

Village Tank Cascade Systems (VTCSs) have long-played a crucial role in sustaining agriculture and livelihoods in the Dry zone in Sri Lanka. Despite facing numerous challenges over the years including shifts in climate, rising population, changing land use patterns, and increased agricultural demands, these systems have continued to provide reliable irrigation and vital ecosystem services for generations (Wickramasinghe et al. 2023). A key component of these landscapes is the traditional home-garden (HG), a multifunctional perennial cropping system that supports a wide array of plants such as timber, vegetables, fruits, yams, medicinal herbs, spices and flowers. These home-gardens are typically characterized by multistoried vegetation layers comprising trees, shrubs, vines and herbs (Marambe et al. 2012). The VTCSs are based on the principle of water conservation and reuse through a network of small to large tanks, originally developed to manage seasonal flooding and drought conditions. Their primary function has been to ensure continuous paddy cultivation during both rainy and dry seasons, while also supplying water for domestic and livestock use, especially during dry seasons when water is less available (Brohier et al. 1935; Geekiyanage et al. 2013).

The selected cascades were located in the DL1b and DL3 agro-ecological regions (AERs). Within the Dry zone, DL1b receives bimodal rainfall, enabling dual cropping cycles, whereas DL3 has only a single rainy season (typically in the *Maha* season – the main cultivating season from October to February), supporting one cropping cycle annually. The soils in DL3 are primarily regosols and red-yellow latosols, with terrain that is relatively flat to gently undulating. In contrast, DL1b soils are mainly reddish-brown earths and low-humic gley soils, found on undulating terrain with sandy loam to sandy clay loam surface textures and moderate sub-angular blocky structure, often over gravelly subsoils.

Given the diversity of environmental conditions in four different cascades, this study aimed to assess the agrobiodiversity of home-gardens among the four selected VTCSs by quantifying the diversity and abundance of plant species.

Methodology

The study was conducted in four Dry zone Village Tank Cascade Systems (VTCSs) located in the Anuradhapura, Puttalam, Mannar, and Vavuniya districts of Sri Lanka. The selected cascades were: Mathavuvaithakulam Cascade in the Vavuniya District (1,332 ha of catchment and 269 ha of command area), Sinnakunchukkulam Cascade in the Mannar District (1,715 ha of catchment and 152 ha of command area), Medderambewa Cascade in the Puttalam District (2,170 ha of catchment and 203 ha of command area), and Sivalakulama Cascade in the Anuradhapura District (1,723 ha of catchment and 451 ha of command area). Three of the selected cascades at Sivalakulama, Medderambewa and Mathavuvaithakulam are situated within the DL1b AER, which receives bimodal rainfall. The Sinnakunchukkulam cascade in the Mannar district represents the DL3 AER, characterized by an unimodal rainfall pattern. The study population consisted of households with home gardens (HGs) in the Climate Resilience Integrated Water Management Project (CRIWMP) area. A total of 80 HGs were selected for the study across the four cascades using a purposive sampling technique to ensure adequate spatial representation. The sample distribution among the four cascades were 20 in Sivalakulama Cascade, 21 in Sinnakunchukkulam Cascade, 19 in Mathavuvaithakulam Cascade, and 20 in Medderambewa Cascade. Field surveys were conducted to assess the floral diversity. A transect sampling approach was applied within each selected HG, where transects were established along elevation gradients to capture vegetation from the lowest to the highest points. Within each transect, all tree and plant species were identified, and the number of individuals per species were recorded. For each plant observed, the data collected were the common name, scientific name and number of individuals. To evaluate plant species diversity across the selected cascade systems, the Shannon-Wiener Diversity Index (H'; Equation 1), which accounts for both species richness and evenness, was employed, providing a holistic measure of biodiversity within a community.

$$H' = -\sum_{i=1}^{S} Pi \ln Pi \qquad \text{---------- (Eq. 1)}$$

where, H' = Shannon-Wiener Diversity Index, S = the total number of species (species richness), Pi = the proportion of individuals belonging to the i^{th} species (Equation 2), ln = Natural Logarithm, and ln (Pi)= the natural logarithm of the proportion

$$Pi = \frac{ni}{N} \qquad \text{---------- (Eq. 2)}$$

where, ni = No. of individuals of species I, and N = Total Number of individuals of all species

The diversity indices were compared across the four cascades and between the two AERs (DL1b and DL3) to assess variations in agrobiodiversity by employing t-test, one-way ANOVA and Post-hoc Tukey's HSD test.

Results and Discussion

Shannon Wiener Diversity Index (SWDI) values from the four cascades Sinnakunchukkulam, Sivalakulama, Mathavuvaithakulam, and Medderambewa ranged from 0.77 to 2.20, indicating moderate to high levels of biodiversity across HGs. The mean SWDI values are presented in Table 1.

Table 1. The mean Shannon Weiner Index values of the Home Gardens in four selected cascade systems

Cascade	Mean Shannon Wiener Index
Sinnakunchukkulam (DL3)*	1.55 (±0.25)**
Sivalakulama (DL1b)	1.58 (±0.19)
Mathavuvaithakulam (DL1b)	1.75 (±0.27)
Medderambawa (DL1b)	1.48 (±0.26),

*Values within parenthesis indicate the agroecological region; **standard error of the means are presented within parenthesis.

The results indicated a significant difference in mean diversity among cascades ($P<0.01$). Mathavuvaithakulam had a significantly higher SWDI values than Medderambewa ($P<0.01$), while differences with Sinnakunchukkulam and Sivalakulam were not significant. This suggested that HGs in Mathavuvaithakulam, located in the DL1b AER with Reddish Brown Earth and low-humic gley soils, together with alluvial soils in the flatter or valley portions, had greater biodiversity than those in Medderambewa. Among the four cascades examined, Mathavuvaithakulam and Sivalakulam were situated within the same AER and shared the same soil group. However, HGs in Mathavuvaithakulam exhibited a comparatively higher biodiversity. This observation underscore that the biodiversity in HGs is likely to be driven by socio-ecological factors such as household socio-economic status, cultural and traditional plant-use practices, management intensity, and differential access to resources, rather than by the AER.

The within cascade variation widely differed in the four cascades, where Sinnakunchukkulam and Medderambewa showed a high within cascade variation while Sivalakulama showed a lower variation. This observation revealed the area specific heterogeneity of home-garden biodiversity. The results to evaluate the influence of AER on HG biodiversity revealed that there was no significant difference ($p>0.05$) in mean biodiversity between DL1b and DL3. The results demonstrated that though there is a statistically significant variation of HG-biodiversity among the four cascades, those differences do not strictly attributable to variation exists among AERs. Mathavuvaithakulam in DL1b exhibited significantly greater biodiversity while the two other cascades in DL1b showed lower biodiversity. Thus, the diversity that exists in HGs is likely due to local management practices and community preferences which may highly influence the faunal composition in the HG.

The within cascade variability in Sinnakunchukkulam and Medderambewa suggests a more diverse set of home-gardening practices among households, possibly influenced by socio-

economic or cultural heterogeneity. In contrast, a relatively narrow range of diversity in Sivalakulama may indicate standardized garden structures maintained by the community probable reflecting the access to resources. It was interesting to note that biodiversity of HGs in Sinnakunchukkulam (DL3) did not differ significantly from those in DL1b cascades. This implies that micro climatic, cultural, or socio-economic factors play a stronger role in biodiversity exists in home-gardens than the macro-zonal classification.

Conclusion

Among the four dry zone VTCSs, Mathavuvaithakulam exhibited the highest HG-biodiversity compared to Sivalakulama, Medderambewa and Sinnakunchukkulam cascades. The AERs DL3 and DL1b did not have a significant influence on HG-biodiversity. Thus, the HG-biodiversity is a locally defined characteristic which is governed by land use practices, household preferences, and socio-economic conditions rather than broader ecological zoning. Therefore, recognizing the household-level diversity within localized landscapes is important. The findings underscore the value of implementation of site- specific biodiversity conservation strategies rather relying on macro-zonal classifications. Future research may focus on qualitative data on specific management drivers at local level that determine biodiversity of HGs.

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Cloud Forest Restoration for Climate Resilience: A corporate responsibility case study from Bopaththalawa in Sri Lanka

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Introduction

Sri Lanka's Central Highlands are home to rare and ecologically significant cloud forests, which act as natural water towers for the island by regulating stream flow of over 103 river systems (IUCN 2021). These ecosystems support not only endemic biodiversity but also downstream communities dependent on clean and reliable water supply. Due to increasing anthropogenic pressures (such as agricultural expansion, forest fires, spread of invasive species and unsustainable land use) many of these forested landscapes are rapidly degrading. These changes threaten the core source of Sri Lankan water source and increase the potential of future water scarcity.

The Bopaththalawa region (Agarapathana) in the Nuwara Eliya District of Sri Lanka represents one such upper catchment site that has undergone significant ecological transformation over decades. The area lies at an elevation of approximately 1,820-1,940 m above sea level, with annual mean rainfall ranging from 2,500 mm to 3,800 mm. The southern inter-monsoon season (May–July) plays a key role in regulating the ecosystem's hydrological patterns. Formerly covered in montane forest, large strips of the landscape are now dominated by shrub mix grasslands. The ecological shift of these diverse habitats into grasslands has entirely changed the local vegetation patterns. The spread of Invasive Alien Species (IAS) in disturbed habitats (Fernando et al. 2018) creates highly flammable conditions during the dry season (December to April). Seasonal dryness, often worsened by human-induced forest fires (Sellamuttu et al. 2013), further reduces the sites biodiversity. Following such fires, invasive species are typically the first to recolonize, rapidly expanding and outcompeting native vegetation. In 2022, the Bopaththalawa Cloud Forest Restoration Project (at site 6°80'95.06"N, 80°69'58.25"E) was initiated as a collaborative effort between Rockland Distilleries (Olu Tropical Water), and its partnering volunteering organization: Earthlanka Youth Network.

The overall goal is to rehabilitate a degraded montane forest within this critical water catchment site (Perera et al. 2024). By applying a nature-based solution (NbS) framework, the project looks at ecosystem restoration, community engagement and private sector corporate responsibility. These efforts aim to re-establish the ecological integrity of the forest while helping ecosystem services such as water catchment replenishment, carbon sequestration, and microclimate regulation (Chazdon 2017). By engaging marginalized rural communities, the project aims to improve the local livelihoods in a way that supports, rather than burdens, the surrounding social and ecological systems. The initiative also directly

addresses the threats posed by ecological degradation to water security, aiming to restore natural forest cover, improve soil moisture retention (Fernando et al. 2018) and enhance perennial stream flows; thus, ensuring long-term water availability.

The project contributes to Sri Lanka's Nationally Determined Contributions (NDCs), the National Adaptation Plan (NAP) and the Sustainable Development Goals (SDGs); particularly in relation to water access (SDG 6), climate action (SDG 13) and ecosystem conservation (SDG 15) (Ministry of Environment Sri Lanka, 2021). As a replicable model, it looks at emphasizing how local-scale restoration initiatives can deliver measurable water resilience outcomes through corporate-environmental partnerships.

Methodology

To address the interlinked challenges of ecological degradation and to prevent future water scarcity in Sri Lanka's upper montane regions, the Bopaththalawa Cloud Forest Restoration Project began with a detailed understanding of the local ecosystem. A comprehensive biodiversity assessment was conducted over a 3-year period (March 2022–April 2025) across the 23-acre (approx. 9.3 ha) restoration site and an adjacent twofold buffer zone. Floral diversity assessments were carried out using random sampling. The site was further divided into degraded grassland, regenerating forest edge, invasive outgrown area and intact remnant forest patches. Within each habitat type, circular plots of average 5 m radius were randomly established (n = 20). In each plot, all naturally regenerating plant species were recorded. Species richness and presence-absence data were compiled for each plot.

Day and night field surveys were conducted by a team of ecologists and restoration specialists using a combination of visual encounter surveys (VES), random transects. A specific set of species (including Amphibians, butterflies, dragonflies, reptiles, freshwater fish, mammals, birds and plants) were assessed within the study that represents a wider range of taxa. These taxa were categorized under IUCN threatened categories. Species identifications were cross-referenced with flora and fauna field guides. Where field identification was uncertain, they were cross checked with field experts and via identification groups.

With the floral assessment findings, the team commenced sourcing for plants for the restoration initiative. From the identified plant list, the project selected the pioneer plant varieties (that were originally found in the area, which helps formation of cloud forest biome, climatic suitable and ecologically functional) and commenced community-based home garden nursery establishment. Rather than employing artificial planting systems, the project followed the principle of Assisted Natural Regeneration (ANR) emphasizing ecological integrity over manmade rapid canopy recovery (Perera et al. 2024). Species selection focused primarily on ecological functionality and native status of the plants including a mix of canopy-forming trees, sub-canopy species and understory vegetation. The restoration aimed to establish a biodiversity corridor linking Horton Plains buffer zone with adjacent forest patches that are isolated. The initial focus contributed to the restoration of 3 acres of degraded habitat using a combination of ANR, native species planting and the management of invasive species spread. This methodology was targeted to enhance

perennial stream flows through ecological restoration and thereby strengthening long-term downstream water availability (IPCC 2022).

Taking rural marginalized community members in the program was a project priority to enhance ecological restoration benefitting local communities. The project therefore conducted several community meetings to understand local land-use needs, perceptions of the forest and willingness to participate in restoration efforts. Community-based home garden nurseries were then established, allowing locals to propagate native saplings, which were later purchased for project use. Empowering women to support climate smart rural livelihoods (WWF 2022) and youth in building environment stewardship was projects focusses arising from these discussions. The project engaged 11 local families to establish home garden plant nurseries, providing economic opportunities particularly for women within these households. The community-centered model was identified to be fairly cost-effective and providing direct financial benefits to the locals. The environmental education and cloud forest capacity development workshops were also conducted focusing students and local youth groups covered biodiversity monitoring, restoration techniques and ecological importance of cloud forests.

Strengthened Corporate Responsibility action positioned by the supporting partners could be taken as a model for private sector involvement in cloud forest restoration and climate adaptation, through CSR funding, technical support and biodiversity offset contributions. Funds were allocated for biodiversity survey across eight taxonomic groups, purchasing of community grown saplings, locally sourced labour for planting initiative and also establishing fire prevention belt. Additionally, partners supported a community health camp at the local school, contributing to broader community welfare and trust-building (Perera et al. 2024).

In celebration of International Women's Day 2025, the team donated field gear and needy rations to the local community women as a goodwill gesture for supporting the restoration initiative. This participatory, ecosystem-based methodology not only supported the ecological rehabilitation of the water catchments in Bopaththalawa, but also aligned with Sri Lanka's national climate and policy frameworks, including National Adaptation Plan (NAP), Nationally Determined Contributions (NDCs) and global commitments under the UN SDGs and the UN Decade on Ecosystem Restoration (Ministry of Environment Sri Lanka 2021).

Results and Discussion

The Bopaththalawa Cloud Forest Restoration Project delivered tangible ecological and social outcomes within its first three years of implementation. Project has restored 3 acres of degraded montane habitat using ANR techniques and is showing early signs of hydrological stabilization in the upper catchment area. Selective removal of some expanding invasive species was also beneficial in maintaining habitat health. Although the total restored area covers only 3 acres, the restoration was carried out in various scattered locations, potentially enhancing its overall ecological value by increasing habitat connectivity together with micro-refugia. Restoration belts planted along the slopes have visibly reduced surface runoff based

on the observations from the past year. However, continuous monitoring is necessary to accurately assess the long-term benefits of these interventions.

Biodiversity assessments conducted during the project time documented over 250 species across multiple taxa, including 15 amphibians, 12 butterflies, 12 dragonflies, 9 reptiles, 3 freshwater fish, 10 mammals, 63 birds, and 128 plants. 34.7% of the recorded species were classified under IUCN threatened categories, indicating both the ecological vulnerability and conservation importance of the site (Perera et al. 2024). *Rusa unicolor* (sambar deer) were visually recorded in newly restored forest edges from the observations of edge effect analysis. The diversity suggests that the establishment of the future biodiversity corridor might support wildlife movement and foraging as soon as they are created. Evidence such as scat and footprints suggested that the reconnecting forest edge is already supporting increased animal movement.

Among native flora, several species were dominant across regenerating plots and fire-cleared edges. These included *Neolitsea fuscata, Calophyllum walkeri, Alpinia abundiflora, Utricularia uliginosa*, and *Drosera burmanii*. Many of these particularly. Early successional and pioneer species such as *Alpinia abundiflora* and *Drosera burmanii* were frequently observed in degraded zones, especially those recently exposed by fire or grazing. These species were selected for propagation due to their moisture retention capabilities and role in early ecological succession.

One of the most severe threats to the restoration efforts and local biodiversity comes from anthropogenic activities, particularly the practice of deliberately setting fires to clear pathways. These human-induced forest fires destroy already degraded landscapes (Wijesinghe et al. 2012; Sellamuttu et al. 2013) dominated by dry grasses and invasive species. While invasive plants such as *Cymbopogon nardus* and *Austroeupatorium inulifolium* were found dominating within sloped habitats, some regenerated rapidly from underground rhizomes that remain unaffected by fire, native saplings especially those newly planted were often unable to survive such extreme conditions. 5 plots having *Austroeupatorium inulifolium* and *Solanum mauritianum* was found invading over 7 hectares in general. The largest single plot of invasive spread within the site was recorded to be 19 hectares of land (mix species).

Fires also have severe impacts on native fauna, many of which become trapped and killed, further increasing ecosystem degradation. Illegal tree felling for fuelwood remains a persistent challenge within the forest area. Despite the legal restrictions, some local residents continue to harvest forest trees for fuelwood, often looking into convenience over sustainability. This practice weakens restoration outcomes, contributes to creating degraded forest gaps, and accelerates habitat loss. While regular patrolling has proven effective in preventing some of these illegal activities, community engagement and awareness-raising initiatives have also played a role in forest protection. From the community discussions conducted, the project suggests innovative approaches such as utilizing invasive tree biomass as a substitute for fuelwood and long-term behavioral change.

To address this risk, a 1-meter-wide fire prevention belt was established during the project implementation phase, which successfully prevented wildfires from encroaching into the active restoration area. Periodic maintenance and coordination with local Forest Department community members officers helped reduce fire incidences during the intervention period. However, ongoing maintenance of firebreaks and continuous community awareness programs are essential to ensure the long-term recovery and resilience of the ecosystem. During the replanting phase, survival rates of vegetation exceeded 60% in most zones. Notably, shorter saplings (under two feet) demonstrated greater resilience to environmental stressors, including exposure to fire, highlighting the importance of species selection and planting techniques in restoration success. From a social perspective, the project successfully engaged 11 women-lead local families in sapling propagation, with over 1,000 native plants grown in decentralized home garden nurseries. The income generated through plant purchases contributed directly to household livelihoods. Youth and school children participated in biodiversity monitoring and field-based conservation learning, nurturing early environmental awareness. By including school children in cloud forest field visits and awareness programs, the project raised a growing interest in conservation among the younger generation. The adapted home garden plant nursery model, incentivized locals creating a small but impactful income stream for 11 families in the area.

The Bopaththalawa Cloud Forest Restoration Project demonstrates that locally driven, nature-based solutions can effectively address the twin challenges of ecological degradation and water insecurity (Seddon et al. 2020) in Sri Lanka's highland regions. Through the restoration of 3 acres of upper montane habitat, the project contributed to the re-establishment of water-regulating forest functions, improved soil retention, and the gradual recovery of biodiversity corridors essential for ecosystem resilience. These environmental outcomes directly support climate adaptation by improving the availability and quality of water for downstream communities, particularly during dry seasons.

Beyond its ecological achievements, the project also offers a replicable model of community-centered restoration. The decentralized home garden nursery system empowered local families especially women with income-generating opportunities, while youth engagement in biodiversity monitoring and conservation education laid a foundation for long-term stewardship. Importantly, the project succeeded in reducing costs and increasing impact through hybrid funding and participatory design.

A defining feature of this initiative is its integration of corporate environmental responsibility. Olu Tropical Water, which sources its product from a deep spring well fed by the Bopaththalawa cloud forest, adopted a sustainable water extraction strategy—limiting sourcing to only twice a week to maintain aquifer recharge and ecological balance. In return, the company directly funded restoration, biodiversity research, and fire management interventions in the very ecosystem that sustains its operations. This reciprocal model exemplifies how the private sector can meaningfully contribute to national climate adaptation efforts and ecosystem service protection.

To scale the impact of similar interventions, the recommendations proposed are (1) Institutionalize Nature-Based Solutions within national climate policy frameworks and integrate them into catchment-level water security planning, (2) Establish mechanisms for Payments for Ecosystem Services (PES) and voluntary biodiversity offsetting, enabling upstream community restoration efforts to be financed by downstream beneficiaries and corporate actors, (3) Provide fiscal incentives for private sector investment in ecological restoration through tax benefits, co-financing mechanisms, and recognition schemes, (4) Integrate environmental education and restoration programs into rural school curricula and national youth development initiatives to foster future conservation leadership, (5) Expand fire prevention infrastructure and enhance invasive species control across degraded hill country areas to reduce the risk of catastrophic ecosystem loss, and (6) The project's early success underscores that effective water adaptation strategies do not always require expensive infrastructure. Instead, empowering communities, restoring natural systems, and engaging the private sector can together build resilient landscapes and safeguard drinking water resources for future generations.

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Community Perspectives on Flooding in Siththandy in Batticaloa of Sri Lanka: Causes and solutions

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Introduction

Flooding is one of the most frequent and destructive natural disasters in the world, affecting millions of people annually and creating large economic, environmental, and social impacts. The severity and frequency of floods have increased over the last few decades, mainly due to climate change, land degradation, and uncontrolled urbanization. Sri Lanka, a tropical island, frequently experiences both riverine and flash floods, particularly during the two monsoon periods: the Southwest Monsoon (May to September) and the Northeast Monsoon (December to February) (Alahacoon et al. 2018). Flooding is one of the most common and expensive natural disasters in Sri Lanka, according to Sri Lanka's Disaster Management Centre (DMC). Agriculture, an important livelihood for rural residents, is significantly affected when crops are flooded, resulting in food shortages and loss of earnings. Flooding also contaminates drinking water sources, resulting in an increased risk of waterborne disease.

The Eastern part of the country is categorized as a region that is severely affected by flood impacts. Recent flooding threats in this part are triggered by temporal riverine flooding that primarily follows heavy rainfall, which increases the water level in the river to surge and overflow beyond its natural path, causing flooding of usually dry land (Amarnath et al. 2015). Siththandy possesses several water sources like small canals, ponds, and drain channels, which overflow during heavy rains.

Most studies of floods in Sri Lanka aim at highly populated districts; therefore, there is very little evidence, community-based assessment, and adaptation planning in communities like Siththandy. This leaves an important research gap: inadequate information regarding local understanding, issues, and potential solutions of flooding in the vulnerable. It not only analyzes the environmental aspects of flood vulnerability but also the social aspects. The objective of this study was to identify the root causes of flooding in Siththandy in Sri Lanka and propose community- driven solutions.

Methodology

Siththandy is in the Eastern Province of Sri Lanka, within the Batticaloa district. This area is flood-prone, experiencing frequent and severe flooding. It is situated at a very low elevation (approximately 7 to 10 m above sea level) and receives heavy rainfall during the Northeast

monsoon. Siththandy is also near the ocean, where cyclones form or pass through, bringing additional rainfall and strong winds.

Data Collection

Data were collected using questionnaires to gather insights from residents regarding the causes of and solutions to flooding in Siththandy. Additionally, interviews were conducted with Government officers knowledgeable about the flood situation. Both the survey and the interviews were conducted in Tamil, the local language. In addition to interviews and the questionnaire survey, a community-based session was conducted for this research to develop the capacity of local youth in Siththandy to respond well during flood incidents. The workshop included practical sessions and group discussions on learning about flood hazards, identification of early warning signs, individual and community preparedness, and mechanisms for recovery from floods.

Results and Discussion

Survey Results from Local Residents' Questionnaire

Eighty four (84) resident in Siththandy were involved in the questionnaire survey. 91.7% replied they had lived here for more than 20 years, while 1.2% responded they had been residents for fewer than five years. In the frequency of flooding, 70.2% reported that flooding occurs every year, and 25% reported that it occurs every half-year. Most extreme cases of flood events occur during the Northeast monsoon period. Siththandy typically experiences heavy rainfall from October to February, and there were extreme flooding events that occurred in November to December 2024 and January 2025. When queried regarding flood pattern changes, 82.1% of respondents concurred that flooding within the region has increased over the years (Figure 1).

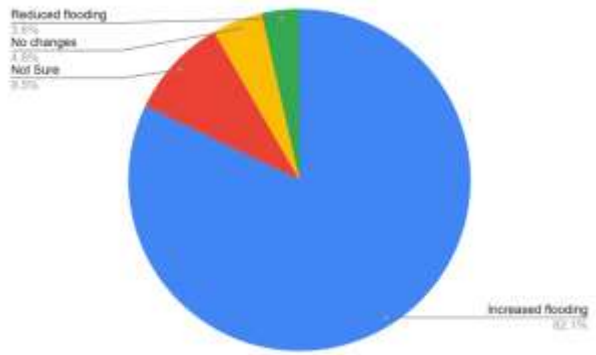

Figure 1. Community perspective on Changes in flooding patterns over the years in Siththandy

Causes of Flooding in Siththandy collected from Surveys

The respondents indicated various major causes of flooding in their community. The most common reason was heavy rainfall (77%), as Siththandy is found in a tropical monsoon region, where heavy rainfall during the Northeast monsoon readily exacerbates surface runoff. Rivers and tanks that are flooded were cited by 72% of the responders as the other primary issue, often because continuous rain fell beyond the capacity of the water bodies.

Compromised drainage facilities and blocked drains were mentioned by 56%, the issues varying from sedimentation, inappropriate disposal of waste, and poor infrastructure resulting in recurrent flooding. Besides this, 39% indicated human encroachment, such as unregulated development along rivers and settlements in floodplains, as a significant concern. Other variables were urbanization, which reduced vegetation cover and increased runoff, and unauthorized spillages from nearby dams, which caused flash flooding.

Proposed Solutions by the Locals

The locals proposed some solutions that would assist in halting flooding in Siththandy. Some of the most noted were the facilitation of drainage facilities in areas like Murugan Kovil Back Road, where bad infrastructure causes frequent blockage and overflow. Most of the respondents (24%) stressed the need to rebuild and elevate the series of bridges in the Kiran area, to enhance flow and prevent stagnation. Sandhanamadu Bridge development was suggested as a channelling measure to channel floodwaters into the sea. A flood barrier or wall was suggested for protection in low-lying areas like Sinnaveli. Enhancing the network of canals by adding new ones and strengthening the old was seen as an effective method of diverting surplus water in wet seasons. Further, people called for expanding the openings of rivers and lakes into the sea to cut back on stagnation of water. People further called for tightening up controls against illegal sand mining from nearby lakes and rivers, which worsens floods. Regulation of dam water discharges and construction of flood-resistant houses in high-risk zones were other suggestions. Finally, promoting environmental sustainability by maintaining and developing local water bodies was proposed to improve stormwater management.

Interview Findings with Government Officers

Interviews with government officers (Figure 2) identified some of the major problems that were leading to flooding in Siththandy.

Figure 2. Interview with government officers

One of the most important problems was the insufficient heightening of the Kiran bridge series, which are presently too low to allow for the free flow of water, leading to extensive flooding in the surrounding areas. Another issue was water discharge from various sources, including Rabukkana Oya, Mundinayar, Mavadiottam, Orugaman, and Madura Oya, which all drain excess water towards Siththandy and increase the risk of flooding. Infrastructure

issues were the collapsed condition of the Vandaramulla dam gate, which cannot regulate water effectively, and the continuous overflowing of the Sandanamulla River due to the lack of a protective fence.

Different solutions were proposed by government officers to reduce the identified challenges. Lifting the Kiran bridge was deemed to be the topmost priority since the estimates suggested raising it would contribute to addressing 75% of the flooding issues. This would require immediate action and sufficient financing. They also proposed a comprehensive review of existing water release policies through scientific evaluation to ensure equilibrium between agricultural water needs and flood control. Immediate refurbishment of the Vandaramulla gate dam was crucial to make water discharge control possible. Constructing floodgates on the Sandanamulla River, as well as in flood-susceptible locations elsewhere, was suggested to facilitate water-level control. Finally, it was suggested that the drainage infrastructure be strengthened to alleviate water stagnation in Siththandy and its border villages.

Youth Awareness Session Outcomes

The awareness session yielded several significant outcomes. Participants reported higher levels of understanding the causes and local factors for flooding in Siththandy, such as blocked drainage and improper waste disposal. Further, most of the respondents mentioned the value of learning simple but effective readiness measures like preparing go-bags, evacuation paths, and staying informed about weather warnings. Others recommended measures like conducting regular community cleaning activities and forming youth-awareness squads in schools and places of worship.

Community Roles in Flood Management

Survey and workshop participants highlighted that the community can actively reduce flood risks. They suggested forming local committees to monitor and maintain drainage channels. They also recommended organizing regular clean-up campaigns to prevent blockages, working with authorities on timely dam-release alerts, and joining discussions about infrastructure upgrades. These community efforts support government-led improvements and build resilience against flooding.

Conclusion

Flooding in Siththandy is caused by a combination of natural and human-induced factors, including heavy rainfall, poor drainage systems, human encroachment, and uncontrolled water releases from dams. Community members have proposed solutions such as improving drainage systems, rebuilding Kiran Bridge, and enforcing regulations on sand mining. Government officers have identified infrastructure deficiencies as a major issue, particularly the low elevation of Kiran Bridge and inadequate dam management. Urgent structural improvements are required to mitigate future flooding. A comprehensive and integrated flood management approach is essential to safeguard the community from future flood-related disasters.

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Seasonal Rainfall Variability and their Changes in the Colombo, Kurunegala, and Anuradhapura Districts in Sri Lanka

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Introduction

In Sri Lanka, rainfall is the most important climatic factor that plays a major role in the agricultural sector. However, marked variabilities of rainfall lead to the vulnerability of floods and droughts. Researchers have found that most of the flood events were related to extreme wet events and the heavy precipitation has likely increased on the continental scale over three continents: North America, Europe, and Asia (IPCC 2023).

Previous studies on long-term rainfall trends have also shown significant spatial and temporal variability across different climatic zones of Sri Lanka (Wikramage 2015; Ampitiyawatta and Guo 2009; Madduma and Wickrmage 2004; Malmgren et al. 2003; Senevirathna et al. 1997; Ampitiyawatta and Wijeratne 2015). Therefore, as an agriculture-based country, it is necessary to understand the patterns and the characteristics of the rainfall in the country.

This study focuses on the Colombo, Kurunegala, and Anuradhapura Districts in Sri Lanka considering the main three climatic zones of the country. The Colombo District is in the Wet zone (WZ) of the country and it is the most populated and highest-density area in the country. The Kurunegala District is situated in the Intermediate zone (IZ) of the country and it is famous for coconut. Coconut yield is strictly affected by changing rainfall and temperature as coconut palm is a continuous bearer and heavy water consumer (Ferdnando et al. 2007; Ekanayake et al. 2016). Anuradhapura District is in the Dry zone (DZ) of Sri Lanka and the zone has constructed 'tanks' to store wet season water for dry season cultivation (Imbulana et al. 2006).

Sri Lanka is an Island nation of Asia and it has heterogeneous topography. This topography creates a unique rainfall pattern (Mendis 2018). The rainfall of Sri Lanka is the main form of precipitation and is mainly influenced by the Asian monsoon system (Zubair *et al*. 2008). Based on the rainfall patterns, Domros (1971) identified four rainfall seasons in Sri Lanka, namely, the First Inter-monsoon season (FIM – convectional) rainy season from March to Mid-May, Southwest monsoon season (SWM) from Mid-May to September, Second Inter monsoon (SIM – convectional) rainy season from October to November, and Northeast Monsoon season (NEM) from December to February. This zonal representation is vital for understanding the spatial variations in climate-related impacts and vulnerabilities across

the country. By selecting one district from each zone, this aimed at gaining a general and basic understanding of the behaviours of rainfall and its effects in three districts in Sri Lanka.

Methodology

This study is entirely based on secondary data. Monthly rainfall data of Colombo, Kurunegala and Anuradhapura District for the period 1961-2022 was purchased from the Department of Meteorology, Sri Lanka. Then the obtained data were segregated into the four rainy seasons that are privileged in Sri Lanka: First Inter-Monsoon season (FIMS), Southwest Monsoon season (SWMS), Second Inter-Monsoon season (SIMS), and Northeast Monsoon season (NEMS). The least square method of time series analysis has been used to identify the long-term variability of the seasonal rainfall in each study area for the two 30-year periods: 1961-1990 and 1991-2020. Moving averages (MA) were used to analyze the marked fluctuations of the variability of the seasonal rainfall with time. The MA method is a widely used technique to identify the variations of a variable. The regression formula used is shown in Equation 1 (source: www.csulb.edu)

$$Y = a + bx \quad \text{..... (Eq. 1)}$$

where, Y = Rainfall (Dependent Variable), a = Intersect, b = Slope, x = Value worked out (Independent Variable)

The Man-Kendall Test is a non-parametric statistical test used to analyse trends in time series data and The Mann-Kendall Test was performed using the Mann-Kendall and Sen's Slope data analysis tool, as demonstrated in Sen's Slope.

Results and Discussion

Changes in seasonal rainfall patterns in the Colombo, Kurunegala and Anuradhapura Districts

This section discusses the changes in seasonal rainfall patterns of the three study locations: Colombo, Kurunegala, and Anuradhapura using a parametric regression method of OLS in time series analysis comparing the standard two 30-year periods 1961-1990 and 1991-2020 (Hereafter, the period 1961-1990 is referred to as the 1st 30-year period and 1991-2020 as the 2nd 30-year period).

Rainfall Trends of the First-Inter Monsoon (FIM) Season in the Colombo, Kurunegala, and Anuradhapura Districts during the Periods 1961-1990 and 1991-2020

A decreasing trend of the FIM seasonal rainfall was observed in the Colombo District during the 1st 30-year period (P=0.24). An opposite feature of the FIM seasonal rainfall trend could be seen during the 2nd 30-year period showing an increasing trend of the FIM seasonal rainfall in the Colombo District. However, the identified positive trend is no statistically significant (P=0.291). Kurunegala also followed a non-significant decreasing trend (P>0.05) of the FIM rains during the 1st and 2nd 30-year periods. The Anuradhapura District showed a

decrease in FIM rains in the 1st 30-year period and an increase in the 2nd 30-year period. However, both situations were not statistically significant (P>0.05).

The Mann-Kendall test reveals a statistically significant increasing trend in annual rainfall over both the 1961–1990 and 1991–2020 periods in Colombo District. During the first thirty years (1961–1990), the trend is moderate, and during second thirty-year period (1991–2020), the upward trend continues with greater intensity, showing an average annual increase of about 5.2 mm (P<0.05).

In the Kurunegla District the Sen's slope estimate indicated an annual increase of about 5.65 mm from 1961 to 1990, suggesting a notable rise in rainfall during this period. In contrast, from 1991 to 2020, the test showed a weak increasing trend with (P= 0.31). The Sen's slope suggested a 3.82 mm annual increase. The Mann-Kendall test showed a significant increasing trend (P=0.025) in rainfall from 1961 to 1990 in the Anuradhapura District. However, there was no significant trend observed for the period 1991 to 2020 (P=0.68).

Rainfall trends of the Southwest Monsoon (SWM) season in the Colombo, Kurunegala, and Anuradhapura Districts during the periods 1961-1990 and 1991-2020

The SWM seasonal rainfall showed decreasing trends in the Colombo District for the two 30-year periods (P=0.008). The 2nd 30-year period showed only an apparent decreasing trend (P=0.394). There was no statistically significant trend (P>0.05) of the SWM rains during the 1st and 2nd 30-year periods in the Kurunegala District. The Anuradhapura District showed increasing trends in SWM rains for both the 30-year periods (P=0.02).

The Man Kendall analysis showed a statistically significant decreasing trend in rainfall from 1961 to 1990 (P<0.05 and a negative Z-value) in Colombo District. The rainfall data from 1991 to 2020 showed no statistically significant trend (P>0.05), with a Z-value close to zero, suggesting rainfall remained relatively stable during this later period.

From 1961 to 1990 in the Kurunegala District, the Mann-Kendall test showed an apparent decrease of 1.97 mm per year (P=0.68). It shoes a strong and statistically significant increasing trend (P<0.001) was observed during the 2nd 30-year period (1991-2020), with a notable rise of approximately 18.24 mm per year, reflecting a clear upward shift in annual rainfall in the Kurunegala District. The Mann-Kendall test revealed a statistically significant increasing trend in rainfall for both 1961–1990 and 1991–2020 in Anuradhapura District. During 1961–1990, the p-value (~0.016) and Sen's slope of 5.35 mm/year indicate a clear upward trend. This trend strengthens from 1991 to 2020, with a highly significant p-value (~0.0007) and a steeper increase of about 8.42 mm/year, highlighting a consistent and accelerating rise in rainfall over the six decades.

Rainfall Trends of the Second-Inter Monsoon (SIM) Season in the Colombo, Kurunegala, and Anuradhapura Districts during the Periods 1961-1990 and 1991-2020

The regression model analysis showed an increasing trend of the SIM seasonal rainfall in the Colombo and Kurunegala Districts than in the past (P<0.05). The Anuradhapura District showed apparent decreasing trend in SIM rains during the 1st 30 years (P=0.12) and an apparent increasing trend for the 2nd 30 years (P=0.47). The Mann-Kendall test indicated an

apparent increasing trend in annual rainfall for both 1961–1990 and 1991–2020 in Colombo District. For 1961–1990 (P=0.62). Similarly, from 1991 to 2020, the Sen's slope showed a marginal increase of 2.45 mm/year (P=0.43).

In the Kurunegala District, the Mann-Kendall test indicated an apparent increasing trend in rainfall during 1961–1990 (P=0.18) and 1991–2020 (P=0.45). For the period 1961–1990, the Sen's slope (4.32 mm/year) suggested a variability without a confirmed trend. Similarly, from 1991–2020, the Sen's slope (~3 mm/year) reflected only a weak increasing trend. The Mann-Kendall test showed an apparent decrease of -0.94 mm/year (P=0.74) from 1961 to 1990 indicating a natural variability in the Anuradhapura district. In contrast, the period from 1991 to 2020 demonstrated a significant increasing trend (P=0.016) in Anuradhapura with a Sen's slope of 7.77 mm/year, reflecting a steady increase in rainfall over these three decades.

Rainfall Trends of the Northeast Monsoon (NEM) Season in the Colombo, Kurunegala, and Anuradhapura Districts during the Periods 1961-1990 and 1991-2020

The NEM seasonal rainfall showed an apparent decreasing in the Colombo District during the 1st 30-year period (P=0.18). An apparent increasing trend of the NEM seasonal rainfall was observed in the 2nd 30-year period in the Colombo District (P =0.08). An apparent decreasing trend could be identified in the 1st 30-year period (P=0.58) _and an increasing trend in the 2nd 30-year period in Kurunegala District (P=0.4). In the Anuradhapura District, the NEM also showed only an apparent decrease in NEM rains for the 1st 30 years (P=0.14) and an apparent increase in the NEM for the 2nd 30 years (P=0.49).

The Mann-Kendall test indicates weak increasing trends in rainfall for both 1961–1990 at 1.98 mm/year (P=0.74) and 1991–2020 a strong increase at 13.2 mm/year (P=0.001) highlighting a clear and substantial increase in rainfall over these three decades in Kurunegala District. The Mann-Kendall test also revealed a statistically significant decreasing trend in rainfall from 1961 to 1990 (P=0.018) and a Sen's slope indicating a decline of 4.96 mm per year in the Anuradhapura District. However, there was a weak increasing trend in rainfall from 1991 to 2020 (P>0.05) at 3.44 mm/year, which is likely due to natural variability rather than a consistent trend.

Overall, the study revealed limited statistically-significant long-term trends in seasonal rainfall during the considered period of 1961-2020 and both the regression and Mann-Kendall tests showed similar results. However, all three study locations were accompanied by marked fluctuations or deviations in seasonal rainfall.

The rainfall variability of the Colombo District showed a marginal decreasing trend during the 2nd 30 year period. Previous reports show a downward trend in SWM rainfall (Karunathilaka *et al*. 2017). Although the decrease was not statistically significant for the 1st 30-year period, rainfall amounts were relatively high in recent years compared to the past decades. Therefore, it can be assumed that rainfall in the Colombo District may increase, especially during the SWM season.

In the Kurunegala District the SIM rainfall decreased during the study period, which could pose a significant problem for the area. The SIM season typically contributes with a substantial rainfall to the Intermediate Zone of the country, but it appears to be weakening. Anuradhapura District has shown an increasing rainfall trend, especially during the NEM season. Therefore, it can be assumed that rainfall in the district may continue to increase in the future, as reported by Jayawardene et al. (2005).

In Sri Lanka, the variability of seasonal rainfall has increased making the predictability of rainfall difficult (Punyawardena 2008). However, this research has revealed future trends in rainfall variability by comparing past data, and therefore, it will be useful for all relevant stakeholders in planning the country's future development.

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Application of Automated Floating Chamber to Quantify CO_2 and CH_4 Fluxes from Inland Freshwater Systems in Sri Lanka

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Introduction

Tropical freshwater systems are significant sources of greenhouse gases, particularly carbon dioxide (CO_2) and methane (CH_4). however, estimation of their contributions to global carbon budgets remain uncertain (Canadell et al. 2021). Further, these systems are characterized by their unique climatic and ecological conditions. In Sri Lanka, where numerous tropical freshwater systems exist, data on CO_2 and CH_4 emissions are lacking. Accurate and cost-effective monitoring and estimations of these fluxes are important for better understanding of the emission dynamics and introducing climate-related policies.

Floating chamber methods are widely adopted globally for measuring gas fluxes, and recent advancements in low-cost sensor technologies offer new opportunities for real-time, high resolution monitoring in resource-limited settings (Bastviken et al. 2020). There is no published literature on application of floating chamber method to quantify carbon flux from freshwater systems of Sri Lanka. This study aimed to build an automated floating chamber from locally available materials and quantify carbon flux from Inland freshwater systems.

Methodology

An automated floating chamber was developed and deployed to quantify CO_2 and CH_4 emissions from three permanently flooded, man-made freshwater systems in Sri Lanka: Thalangama Lake, Kandy Lake, and Hurulu Wewa. Field deployments were conducted at Thalangama Lake on 5th March 2025, Kandy Lake on 11th March 2025, and Hurulu Wewa on 25th March 2025.

The chamber, having dimensions of 0.30 m in width, height, and length, was constructed using transparent acrylic sheets and mounted on a Styrofoam base with dimensions of 0.91 m in length, 0.60 m in width, and 0.0635 m in height to ensure buoyancy. To minimize the influence of external temperature, the chamber was insulated using aluminum double bubble wrap. The bottom opening of the chamber, which was in contact with the water surface, had an area of 0.0625 m^2.

For measurements of gas concentration, an MQ4 semiconductor sensor (Winson Electronics) was used for CH_4 detection, and a Non-Dispersive Infrared (NDIR) sensor (SCD30, Sensirion Holding) was used for CO_2. These sensors tested for field application without further improvement. (Furuta et al. 2022; Mitchell et al. 2024) Both sensors were calibrated in well aerated ambient air, assuming baseline concentrations of 1.9 ppm for CH_4 and 421 ppm for CO_2 (Bastviken et al. 2020).

A DHT22 sensor was used to measure air temperature and relative humidity, while an RTC3231 module provided accurate timekeeping. All sensors were strategically mounted at the 0.05 m below from top panel of the chamber to ensure uniform exposure and minimize potential measurement biases. No active mixing was incorporated inside the chamber to avoid disturbing the natural water-air interface, following standard practice in passive flux measurements where gas accumulation is driven by natural convection and diffusion. An Arduino Uno microcontroller processed the sensor outputs and logged the data onto an SD card in every 2 seconds. Gas accumulation and flushing were controlled using an R365 diaphragm-based air pump, operated via a Delay Trigger Module (JZ-801).

Fluxes were measured at hourly intervals. Each cycle included a 40-minute gas accumulation period inside the sealed chamber, followed by a 20-minute flushing period to reset the internal air. This automated process allowed for continuous, unattended data collection in the field. Five-hour fluxes were quantified in each lake during March 2025. The total dissolved solids (TDS), pH, Electric conductivity (EC), Dissolved oxygen, Temperature, oxidation-reduction potential (ORP), Atmospheric pressure and Salinity were recorded using Hanna HI9829 Multiparameter. Incoming solar power was logged with TES1333R solar power meter.

Then gas fluxes were calculated using the Equation 1,

$$F = \frac{V}{RTA} \times \frac{dC}{dt} \times 3600 \quad \text{..... (Eq 1)}$$

Where F = Flux of the specific gas (µmol m^{-2} h^{-1}), $\frac{dC}{dt}$ = Concentration changes over the time (µmol m^{-3} s^{-1}), T = ambient temperature (K), R = Universal gas constant (m^3 atm K^{-1} mol^{-1}), A = Chamber area in contact with water (m^2), V = Chamber volume (m^3)

Results and Discussion

Table 1 shows the diffusive fluxes of CO_2 and CH_4 with time in all 3 locations studied. These measurements demonstrated that the automated floating chamber was capable of quantifying both diffusive fluxes of CO_2 and CH_4, as well as ebullitive fluxes of CH_4 from freshwater systems. The results revealed considerable spatial variability in flux rates across the three study sites. Among the quantified hourly diffusive CH_4 fluxes, the highest and lowest values were recorded at Kandy Lake, with rates of 62.43 µmol·m^{-2}·h^{-1}

and 11.10 µmol·m^{-2}·h^{-1}, respectively. Notably, ebullitive CH_4 events were observed only at Kandy Lake, with fluxes of 1455.83 µmol·m^{-2}·h^{-1} and 634.33 µmol·m^{-2}·h^{-1}.

Table 1. Diffusive CO_2 and CH_4 fluxes

Time	Kandy Lake µmol/m²/hr	Thalangama Lake µmol/m²/hr	Hurulu wewa µmol/m²/hr
Diffusive CO_2 fluxes			
10:00 AM	1,716.97	5,860.43	N/A
11:00 AM	506.9	1,772.13	554.9
12:00 PM	1,230.21	1,524.85	114.78
13:00 PM	676.94	2,285.46	139.51
14:00 PM	139.27	371.20	594.15
15:00 PM	N/A	N/A	569.21
Diffusive CH_4 fluxes			
10:00 AM	13.43	36.51	N/A
11:00 AM	11.1	24.64	58.22
12:00 PM	62.43	25.05	43.92
13:00 PM	20.4	22.29	31.75
14:00 PM	40.14	36.29	22.17
15:00 PM	N/A	N/A	25.12

N/A=Not available

The highest CO_2 flux recoded at Thalangama Lake (5860.43 µmol/m²/hr) while lowest value showed by the Hurulu wewa (114.78 µmol/m²/hr). The variation of carbon fluxes may depend environmental and anthropogenic factors. Figure 1 illustrates the CH_4 flux with solar energy at Kandy Lake. Water quality parameters in each lake were shown in Table 2.

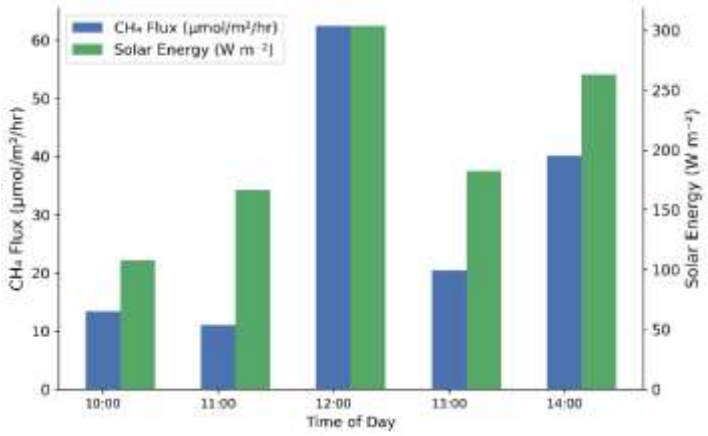

Figure 1. CH_4 flux and Solar energy variation of Kandy Lake

Table 2. Water quality parameters of each lake

Parameter	Kandy Lake	Thalangama Lake	Huruluwewa
pH	7.60	7.36	8.36
Total dissolved solids (TDS) (mg/L)	155	102	156
EC (µS)	311	204	312
Mean Water Temperature (°C)	27.43	30.85	32.39
Oxidation-reduction potential (ORP) (mV)	-22.0	-26.5	-16.8
Salinity (PSU)	0.15	0.09	0.15

The CH_4 fluxes show a positive correlation with Solar Energy, Air temperature, Water temperature and wind speed. Extensive field measurements are needed to identify exact influencing factors on CH_4 and CO_2 fluxes that specific to the Sri Lankan Environment.

These results identify significant spatial variability in greenhouse gas emissions, potentially influenced by environmental and anthropogenic factors.

Conclusion

The successful deployment of this automated floating chamber demonstrates its feasibility for long-term, high-resolution flux monitoring in tropical freshwater systems in Sri Lanka. This system could play an important role in freshwater ecosystem carbon assessments, contributing to climate change mitigation strategies and greenhouse gas reporting.

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Contribution of Home Garden for Household Economy – Case study of Dry zone in Sri Lanka

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Introduction

Home garden (HG) is the oldest land use practice that has played a significant role in ensuring food security and economy at the household, village, and national levels. The home garden is a complex and sustainable land use system that integrates annual and perennial crops, livestock, and sometimes fish. It provides essential resources such as foods, employment, an income generation for household, and environmental services (Weerahewa et al. 2012). In the Sri Lankan context, there are several types of home gardens including forest gardening, kitchen gardening, and dry zone home gardening. Dry zone home gardens, in particular, consist of a diverse plant community that may include trees, shrubs, vines, and herbaceous plants, growing in or near homesteads. Dharmasena (1994) classified Dry zone (DZ) HGs into three categories includes traditional village home gardens (Gangoda), recently evolved HGs and colony home gardens. Further, Mattsson et al. (2015) classified HGs according to the land size. It includes small, medium and large-scale home garden. The average size of a DZ HG ranges from 0.05 to 2.5 ha, with a mean size of 0.4 ha and DZ HGs account for 46% of the country's total HG (Lowe et al. 2023).

The DZ is a major agricultural region of the country, covering about 70% of the land area. It has experienced climate change and related extreme events. Climate change and the continuous rise in population impact households regarding food insecurity, livelihood opportunities, and the economy (Lowe et al. 2023). Furthermore, multidimensional vulnerability also impacts household economies. It includes three dimensions and twelve indicators (UNDP 2024). However, sustainable management of HG resource is one of the opportunities for increase the household economy and food security (Yapa 2018). The HGs provide household more food security, social context and environmental sustainability (Afreen et al. 2021).

This study attempted to assess the effectiveness of contributing to the household economy, enhancing food security and improving household living conditions in the context of changing socio economic and climate conditions.

Methodology

The study was conducted across seven Dry zone (DZ) districts in Sri Lanka, Anuradhapura, Kurunegala, Puttalam, Polonnaruwa, Mannar, Vavuniya, and Trincomalee. A random sample of 1,968 HGs was selected from the project implementation sites of the Climate Resilience Integrated Water Management Project (CRIWMP). The CRIWMP funded by the Green Climate Fund (GCF) and implemented by the United Nations Development Programme (UNDP) in collaboration with the Ministry of Irrigation, operated for a period of seven years from 2017 to 2024. The project support to established HGs from 2017 to 2020, conducting various capacity building programs and providing essential inputs to enhance their resilience and productivity.

The pre-tested structured questionnaire was developed, encompassing demographic details, food consumption, production status, and income and expenditure. Data were collected through interviews with respondents and direct observations by enumerators from the project. Descriptive analysis was used to analyze the survey data, allowing for the description and comparison of various components.

Results and Discussion

Of the total of 1,968 home gardens were surveyed, 27% (the highest) was located in the Anuradhapura district, while the Mannar district had the fewest (3%). The HGs were categorized based on land size following the classification by Mattsson et al. (2015) into small-scale (<0.2 ha), medium-scale (0.2–0.8 ha), and large-scale (>0.8 ha). The majority (52%) of HGs of small-scale while 10% of medium-scale, and 38% of large-scale. Most large-scale HGs were located in the Kurunegala district, while Anuradhapura had the highest number of small-scale HGs. Medium-scale HGs were predominantly found in the Puttalam district. These findings highlighted a trend toward small-scale HG practices in the study area.

The number of family members significantly influenced household economy and food security. According to survey results, the majority (32%) of households consisted of four family members across the seven districts, while only 1% had more than seven family members. District wise, Polonnaruwa and Anuradhapura had higher family sizes, whereas Kurunegala had smaller household sizes. The age of household heads ranged between 35 and 50 years across all districts. Male-headed households were predominant across the seven districts. Regarding socio-economic status, 64% of the surveyed households were *Samurdhi* beneficiaries (A programme implemented entirely by the government of Sri Lanka focusing on poverty reduction by ensuring participation of the poor in the production process), while 14% fell under other categories, including chronic kidney disease (CKDu) patients, individuals with disabilities, and widows. About 7.34% of the sample suffered from CKDu with the highest number of patients reported from the Vavuniya district (30.1%) followed by Polonnaruwa district (25.7%). The incidence of CKDu and tube-well usage showed a significant relationship (P=0.006) and with rarely used chemicals (P=0.007). The variations in household characteristics, such as family size, age of the household head, and socio-economic status, suggest the need for tailored interventions to support home garden sustainability and improve household well-being.

Availability of a reliable water source was one of the factor that affects the sustainability of the HG. The survey results revealed that the majority of the HG farmers tends to utilize dug well (37.7%). The highest percentage of HG farmers using dug-well water was reported from the Anuradhapura district (52.8%) followed by about 32.5% of those in the in the Kurunegala district. Among the HG farmers, 29.4% in the Anuradhapura district and 24.9% in Puttalam district did not have water reservoirs for their HGs.

Further, 67% of farmers used micro-irrigation systems such as sprinkler and drip irrigation for their crop cultivation with the majority reported in the Anuradhapura and Vavuniya districts while it was less in the Mannar district. Year round cultivation is a critical factor that affects the household income and food security. About 55% of the surveyed HGs were managed year-round, with Anuradhapura district recording the highest number of year-round HGs, while Mannar district had the least. Water availability was identified as critical influencing year-round cultivation. The distinct dry periods in the Mannar district have led to significant challenges for the sustainability of HGs, limiting their practice during such periods.

Year-round home gardens were observed to provide consistent supplies of vegetables and fruits, contributing to household food availability across all districts. Commercial-type HGs provide the income and livelihood opportunities for household. The survey data revealed that 67% of farmers practiced HGs at the subsistence level, while 33% managed HGs for commercial purposes. Subsistence HGs were predominantly practiced in Mannar (61%) and Kurunegala (57%) districts, whereas commercially-oriented HGs were high in Anuradhapura (65%) and Vavuniya (60%) districts. It was observed that the commercially-oriented HGs had cash crops cultivated during the *Yala* and *Maha* seasons and perennial crops were maintained for year-round production.

Animal husbandry is one of activity that affect the sustainability of HGs. It provides a protein source, income for household, and fertilizer/manure for the HG. About 21% of HGs surveyed had an animal component embedded, with majority of such HGs reported from Mannar and Vavuniya districts. Poultry, goat and cattle farming were the most popular. Further 18% HGs were engaged with other livelihood activities, especially with women participation in Anuradhapura and Vavuniya districts. These also enhanced income generation and protein security of the household.

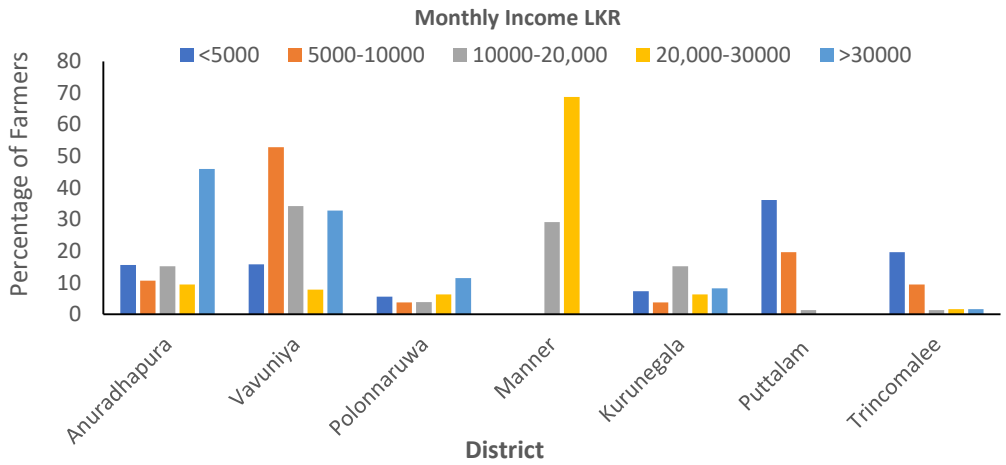
These systematically-planned HGs played a critical role in ensuring food security, particularly in rural areas. The findings emphasized the importance of promoting year-round cultivation and maintenance of HGs as a strategy to enhance household food security and resilience. Special attention should be given to addressing water scarcity and water management in the Mannar district to support the sustainability of these HG systems. Additionally, animal husbandry and other livelihoods provide economic benefits to households in suitable districts should be targeted for interventions to support such efforts.

Majority of home gardens (67%) practiced HGs for own consumption while 33 % at commercial level. Nearly, 94.8% farmers used HG products for their family consumption, out

of which 41.86%, 33.71%, and 16.97% of the farmers consumed vegetables, fruits and cereals, respectively, from the HG. The highest commercial level practice was reported in HGs in the Vavuniya district (76%) while farmers in the Mannar district (28%) showed a less commercial level practices in HGs. Puttalam HG-farmers had the highest fruits and vegetable consumption in the category <5 kg. Those in the Vavuniya district showed the highest vegetable consumption in the category <5-10 kg and the highest cereal consumption, while those in the Kurunegala district showed the highest fruit consumption in categories 5-10 kg and >10 kg.

Conversely, the highest income gain from cereals as opposed to the lowest gain from honey. About 26.7% of the HG-farmers earned more than LKR 20,000 (approx. US$ 67) from cereals while 2.93%, 1.82% of the farmers earned from vegetables and fruits respectively. Furthermore, Anuradhapura district HG-farmers gained high income from vegetables and fruits while Mannar HG-farmers earned the highest income from cereals.

Based on the income categories majority of the sample farmers (47.%) were categorised under below LKR 5000 (approx. US$ 16,7) and LKR 5,000-10,000 (approx. US$ 16.7-33) was the second highest income category of the HG-farmers (28.84%) while 7.21% of famers earned above LKR 30,000 (Approx. US$ 100). HG-farmers in Vavuniya district had the highest income gain compared to the other district (Figure 1) where about 32.8% HG-farmers gained more than LKR 30,000. About 36.2% of Puttalam HG-farmers gained below LKR 5,000.



Conclusion

The study highlights the significant potential of systematic home gardening in rural DZ as a viable strategy to enhance household level food security and income generation. The HGs play a pivotal role in providing a diverse range of food items, including staple foods, vegetables, fruits, cereals, and, to a lesser extent, animal products. While most households meet their requirements for animal products from external sources, HGs remain integral to

fulfilling dietary needs through year round cultivation. The findings underscore the critical role of home gardens in ensuring consistent food availability and income generation. Promoting sustainable and well-planned home gardening practices can contribute substantially to improving food security and overall well-being in rural communities.

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Tendency of Using Modern Agricultural Inputs for Transforming Lives of Smallholder Farmers in the Dry Zone of Sri Lanka

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Introduction

Agriculture has been the backbone of the rural existence in Sri Lanka's Dry zone (DZ; annual rainfall <1,750 mm). Dry zone farmers are now essential to both national food security and local economic resilience. However, farmers today face a mix of environmental and economic challenges that endanger their productivity and well-being. Unpredictable rains, extended dry spells, and rising temperatures have made traditional rain-fed agriculture uncertain and unsustainable. Meanwhile, soil erosion and poor soil fertility, expensive inputs, and poor access to irrigation and support services have undermined the resilience of the farming household. The majority of farmers have failed to maintain stable yields. They are forced to make a compromise between using funds on agricultural inputs or fulfilling basic household requirements. This puts into sharp perspective, the need for climate-resilient agricultural technologies in the DZ.

In response, the Climate Resilient Integrated Watershed Management Project (CRIWMP) was initiated as a partnership project supported by the Green Climate Fund. It aims to build resilience in climate exposed agricultural lands by formulating sustainable land and water management systems and introducing new agricultural technology based on local needs. The CRIWMP technology interventions include sprinkler and drip irrigation in order to optimize water use, insect-proof nets for reducing insect damage and chemical application (Amarasinghe et al. 1999; Aheeyar et al. 2005 Udagedara and Sugirtharan 2017; Sugirtharan et al. 2021), and plastic mulch for soil moisture conservation and weed control. The interventions are a shift from short-term reactive coping strategies to long-term proactive intervention strategies. They focus not just on enhancing farm productivity but also reducing environmental degradation and improving household livelihoods.

The successful adoption of this type of innovation is based on more than their technical effectiveness, though. Affordability, simpleness, access to training, institutional support, and cultural acceptability all bear upon how and whether technologies are adopted in agricultural systems. Understanding about these factors is required to determine the real impact of CRIWMP interventions.

This study examined the environmental, economic, and livelihood impacts of modern farm inputs imported through CRIWMP in Sri Lanka's DZ. Specifically, it considers how farmers have changed in response to these technologies, the way in which their productivity and earnings have been affected, how satisfied the users are and how their attitudes have changed, and the limitations to broader adoption. By a focus on the everyday lives of farmers, the research provides rich accounts of everyday reality in agricultural modernization under climate risk and evaluates how far such technology can contribute to long-term resilience and sustainable development.

Methodology

A mixed-methods research approach was employed to gain both quantitative and qualitative insights into the adoption and impact of modern agricultural inputs. A pre-tested structured questionnaire was administered to 55 smallholder farmers (n=55) across four districts Anuradhapura, Kurunegala, Puttalam, and Trincomalee representing CRIWMP intervention zones in the DZ.

Participants were purposively selected to represent diversity in gender, age, education, and landholding size. The questionnaire covered seven thematic areas: demographic characteristics; awareness and usage of technologies; productivity and income changes; water use and labour efficiency; training effectiveness; satisfaction levels; and barriers and future preferences.

Results and Discussion

Socio-Demographic Profile

The demographic profile of the sample aligns closely with the typical smallholder farming community targeted by CRIWMP (Table 1). These characteristics highlight a relatively experienced and moderately educated population capable of engaging with new technologies when adequately supported.

Table 1. Demographic profile of the study sample

Parameter	Description
Gender	58% females – indicating active involvement of women in farming
Age	73% between 30-50 years
Education	58% completed G.C.E. Ordinary Level education
Farming experience	40% had over 10 years of experience; 38% between 5–10 years
Farm size	58% cultivated 1 - 5 acres (approx. 0.4 – 2 ha), and the rest <0.4 ha

Adaptation Process Before and After CRIWMP

Prior to CRIWMP interventions, the majority of farmers relied on traditional surface irrigation methods (e.g., canal and rain-fed systems), with little awareness of modern input technologies. The adaptation process significantly accelerated following targeted training and demonstrations by CRIWMP field officers. The key changes observed are listed in Table

2. This transformation highlights the project's ability to overcome traditional resistance and encourage a mind-set change, motivating farmers to explore and adopt innovative agricultural technologies.

Table 2. Key changes observed after project interventions

- A notable increase in awareness, especially of sprinkler and drip irrigation systems
- A notable increase in awareness, especially of sprinkler and drip irrigation systems.
- Adoption was highest among farmers who received hands-on training and peer exposure visits

Technology Awareness and Adoption Patterns

Adoption of sprinkler and drip irrigation systems was relatively high, driven by the immediate and visible benefits in water savings and crop health (Table 3). However, insect-proof nets and mulch remained underutilized, reflecting either lack of awareness or cost constraints.

Table 3. Technology Awareness and Adoption Patterns

Technology	Aware Only (%)	Aware & Used (%)	Used Only (%)	Not Aware (%)
Sprinkler System	69	24	3.6	3.6
Drip Irrigation	51	18	14.5	16.3
Insect-Proof Nets	38	3.6	1.8	56.4
Plastic Mulch	23.6	1.8	1.8	72.7

Economic Impact and Productivity Outcomes

Significant improvements were reported by adopters in multiple aspects of farm operations (Table 4). Farmers who had adopted CRIWMP-introduced technologies reported significant changes in various farm operations.

Table 4. Economic Impact and Productivity Outcomes

Technology	%	Observation/Outcome
Water Use Efficiency	70	Improved irrigation efficiency
Labour Requirements	65	Reduction in labour, especially for watering and weeding
Input Use	60	Reduced use of chemical fertilizers and pesticides
Yield Increases	68	Yield increases ranging from 15% to 40%
Income Levels	35	Moved to a higher income bracket (> Rs. 60,000 per season)

Irrigation efficiency was enhanced by approximately 70% of the respondents, and 65% reported reduction in labour needs, particularly for weeding and watering. Reduced use of chemical fertilizers and pesticides, primarily by drip irrigation and insect-proof net adopters, was reported by 60%. Increases in yield were high, with 68% of the farmers reporting 15% to 40% increase in yields. In addition, 35% of farmers shifted to the upper income strata,

with over Rs. 60,000 (approx. US$ 200) in a cropping season, illustrating the economic benefit from these new farming inputs.

Farmer Satisfaction and Perceived Effectiveness

The majority of respondents expressed high satisfaction with the CRIWMP-introduced technologies (Table 5). Nearly 85% of respondents claimed to be highly or fairly satisfied with sprinkler irrigation systems, and 75% of respondents were similarly satisfied with the drip irrigation system. Training sessions were also received well by 78% of farmers, who considered it useful especially preferring field training over seminar training. Interestingly, 72% of the farmers indicated willingness to reinvest in the technologies, provided that financial or institutional support arrangements still prevail. The findings indicated significant farmer confidence regarding the viability and benefits of the introduced interventions.

Table 3. Farmer Satisfaction and Perceived Effectiveness

Technology	%	Farmer Feedback
Sprinkler Irrigation	85	Satisfied
Drip Irrigation	75	Satisfied
Training Programs	78	Found the training effective
Re-investment Potential	72	Willing to reinvest

Challenges and Barriers to Adoption

Despite evident benefits, several barriers persist, limiting broader uptake (Figure 1). There have been multiple barriers to their uptake among smallholder farmers. The single most significant drawback is high initial cost, and 53% of the respondents cited unaffordability even for the subsidy recipients. Restricted availability of spare parts and service outlets, particularly in rural settings, further constrains actual use. Besides the advanced technology, 37% of adopters reported knowledge gaps in maintenance, calibration, and seasonal adjustments and hence needed continuing technical support. Cultural vulnerability also come into play as 10% of farmers were not willing to abandon traditional irrigation practices for unfamiliar new technologies.

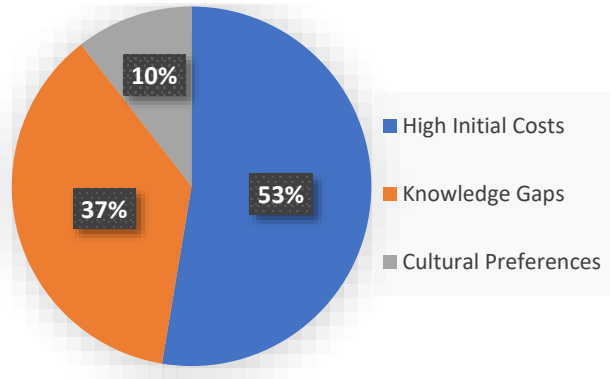

Figure 1. Challenges and Barriers to Adoption

Conclusion

This study demonstrated that the new agricultural innovations included under the Climate Resilient Integrated Watershed Management Project (CRIWMP) have indeed had a revolutionary impact on small-scale farmers in Sri Lanka's DZ. Farming households who integrated new technologies such as sprinkler and drip irrigation systems, insect-proof nets, and plastic mulch saw significantly higher efficiency in water use, lower labour requirements, decreased input costs, and greater crop yields. These gains were reflected in tangible economic benefits, as many farmers entered higher income levels and expressed very high satisfaction with the technology and training received.

In addition, the project has succeeded in bringing about change in behaviour and encouraging interest in better farming practices among traditionally vulnerable societies. High satisfaction, willingness to reinvest, and positive evaluation of field-based training modules confirm the usefulness and relevance of the CRIWMP interventions.

The CRIWMP has performed admirably in advancing climate-smart agriculture, however, an integrated support system that ensures long-term adoption and resilience is needed. To sustain and scale these benefits, continued support through training, subsidies, accessible inputs, and localized technical assistance is essential. Strengthening these areas will ensure long-term resilience and lasting transformation in climate-vulnerable farming communities.

Acknowledgement

The authors would like to express sincere thanks to the involved farmers whose lives and experiences formed the foundation of this study. Gratitude is also due to the CRIWMP field team, and local Agricultural Instructors for their prompt contributions made during data collection. Special gratitude is offered to the Sri Lanka Red Cross Society, Janthakshan Gte Ltd, PLAM Foundation, and South Asian Partnership Sri Lanka for their help, field-level facilitation, and encouragement during the research process for the successful accomplishment of the study.

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Integrated Technological Interventions for Enhancing Cropping Intensity and Income under Small Tank Systems in the Dry zone of Sri Lanka

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Introduction

The Dry zone (DZ) of Sri Lanka covers nearly two-thirds of the island and plays a crucial role in the country agricultural production, particularly in paddy cultivation. This region is characterized by low and erratic rainfall, high rates of evapotranspiration, and prolonged dry periods, especially between May and September. It is home to an ancient hydraulic civilization that features a complex network of small/village tank systems, which have served as the backbone of rural agricultural livelihoods (Abesekara 2015).

However, the impacts of climate change are becoming increasingly evident across Sri Lanka, highlighted by rising air temperatures and shifting rainfall patterns. These climatic changes have led to water scarcity, extended growing seasons, and additional stress on agricultural activities (Costa 2008). Consequently, farmers are finding it increasingly challenging to maintain crop productivity. The unpredictability of rainfall, combined with longer dry spells, higher temperatures, and elevated levels of atmospheric CO_2, is resulting in reduced crop yields and, in some cases, complete crop failures. These changes pose significant threats to food security and the livelihoods of farming communities in the DZ (Dharmasena 2020).

Agriculture is the backbone of the DZ economy, with paddy farming being the predominant activity. As rice is the staple food of Sri Lanka, it provides about half of the daily caloric requirement. Every government has prioritized self-sufficiency in paddy production in terms of national food security. Paddy is best suited for cultivation in aquatic environments, where water availability is a key factor (Kumar and Ranjitha 2019). The main cultivation seasons are *Maha* (October to February) and *Yala* (March to September) encompassing both irrigated and rainfed systems. Irrigated paddy cultivation relies on irrigation for water supply, while rainfed cultivation depends on rainfall (Rathnayaka et al. 2019). In the 2023/2024 *Maha* season, the total cultivated paddy lands in Sri Lanka was 806,673 ha, and in the 2024 *Yala* season it was 481,316 ha. The irrigated areas accounted for 71.95% and 90.35% of the total cultivation areas during the *Maha* and *Yala* seasons, respectively (DCS 2024).

However, cropping intensity (CI) under the small/village tank remains low, typically limited to cultivation during the *Maha* season, with minimal or no cultivation during the *Yala* season. Several factors contribute to this low cropping intensity in small tank systems,

including climate change induced shifts in rainfall patterns, frequent and prolonged dry spells, and the limited water storage capacity of village tanks (Dharmasena 2020). Additionally, inadequate maintenance, high siltation rates, and a lack of efficient water management practices reduce the availability and reliability of irrigation water. Socio-economic and institutional barriers, such as weak extension services, limited access to credit and technology, and insufficient farmer awareness, further affect cropping intensity, restricting cultivation to a limited extent each year.

Therefore, various strategies and models have been explored to increase cropping intensity within small tank command areas to enhance paddy production in the country. The objective of this study was to assess and evaluate models that can increase cropping intensity and productivity applicable to small tank systems in the DZ of Sri Lanka. The focus will be on identifying effective water management practices, agronomic innovations, and institutional strategies that enhance productivity of paddy land. The study aims to analyze the feasibility, sustainability, and productivity impacts of these models.

Methodology

The Climate Resilience Integrated Water Management Project (CRIWMP) is implemented across seven DZ districts in Sri Lanka, including Anuradhapura, Kurunegala, Puttalam, Polonnaruwa, Mannar, Vavuniya, and Trincomalee in Sri Lanka. The project established water management demonstration sites in the paddy lands. Five programs were implemented during the 2024 *Yala* season in five districts, and seven programs in the 2024/25 *Maha* season across all seven districts.

Bund removal was carried out to support land or plot consolidation, laser levelling to improve uniformity of land surface and efficient irrigation water management throughout the cropping season. Uneven land surfaces also tend to retain more water and leading to inefficient water usage. Seed broadcasting, row seeding and parachute method for seedling broadcasting were the crop establishment techniques used. Alternate wetting and drying technique (AWD) was adopted for efficient water management, agro-meteorological advisories and weather forecasts were used for better planning of cropping season and irrigation schedules. In addition, initial rainfall was strategically used for land preparation and to initiate cultivation across the entire command area simultaneously, reducing the excess demand for irrigation water throughout the season. The use of rainfall and depth gauge data further supported decision making in irrigation scheduling and water allocation. Irrigation duty was recorded.

The cropping intensity (CI) was calculated, cost-benefit analysis of the production systems was done, and paddy yields were assessed through crop cut surveys under the guidance of the Provincial Department of Agriculture. The yield data were analyzed and compared across various components including crop establishment method and district average yield.

Results and Discussion

According to the data collected from seven districts, land consolidation led to an average bund reduction of 24.1%, contributing to more uniform and accessible fields. Paddy fields in the Kurunegala and Puttalam districts had a higher reduction in the number of internal bunds by 21.5% and 20.1%, respectively. The reduction of bunds directly increased the net cultivable area, allowing farmers to utilize more of their land for productive purposes. Land consolidation has emerged as a key strategy for improving agricultural efficiency, particularly in smallholder-paddy cultivation systems in the DZ of Sri Lanka, mainly by reducing unnecessary internal bunds that often fragment paddy fields, limit cultivable area, and hinder the use of machinery.

Irrigation duty is a critical metric that reflects the efficiency of water use in agriculture, particularly in paddy cultivation, which is highly water-intensive. The recorded values were 3.45 acre-feet per acre in the *Yala* season and 2.45 acre-feet per acre in the *Maha* season. Lower irrigation duties can be beneficial in terms of water conservation, especially in regions where water is scarce or during dry seasons. It may indicate better water management practices, such as uniformity in water levels, improved irrigation techniques, effective scheduling of water releases, and maintenance of irrigation infrastructure to minimize losses.

The efforts of the CRIWMP has led to the maximum utilization of available irrigation water, contributing to more sustainable practices under both *Yala* and *Maha* seasons. The results indicate significant differences in yield among these methods. The mean paddy yields recorded are illustrated in Figure 1. Seed broadcasting recorded the lower yield (4.4 Mt/ha). Row seeding improved yield by 13.9% over broadcasting, while parachute method increased yield by 31.4%. These findings demonstrated that parachute method of seedling broadcasting has performed better than row seeding and seed broadcasting. District wise analysis further reveals that the yield from demonstration plots was consistently higher than the respective district average yields for the corresponding seasons across all seven districts. This clearly reflects the positive impact of improved crop establishment techniques on overall productivity. The parachute method, in particular, not only increased yields but also offered advantages in terms of reduced labor costs, better plant spacing, and more efficient use of irrigation water.

Furthermore, the cropping intensity (CI) of the selected 12 village tanks showed an average value of 2.0 during the years 2024 and 2025, indicating an improvement compared to previous years (Table 1). Traditionally, the *Bethma* system is practiced during the *Yala* season under small tank systems, where only a portion of land is cultivated due to limited water availability. However, the improved water management strategies and interventions such as laser land levelling, AWD, and better irrigation scheduling have enabled farmers to move beyond the limitations of the *Bethma* system. As a result, some paddy fields were even able to go through a third cropping season, leading to the maximum utilization of available land, water and significantly contributing to the overall increase in cropping intensity. These findings underscore the potential of integrated water and land management practices to transform the productivity of village tank systems in DZ of Sri Lanka.

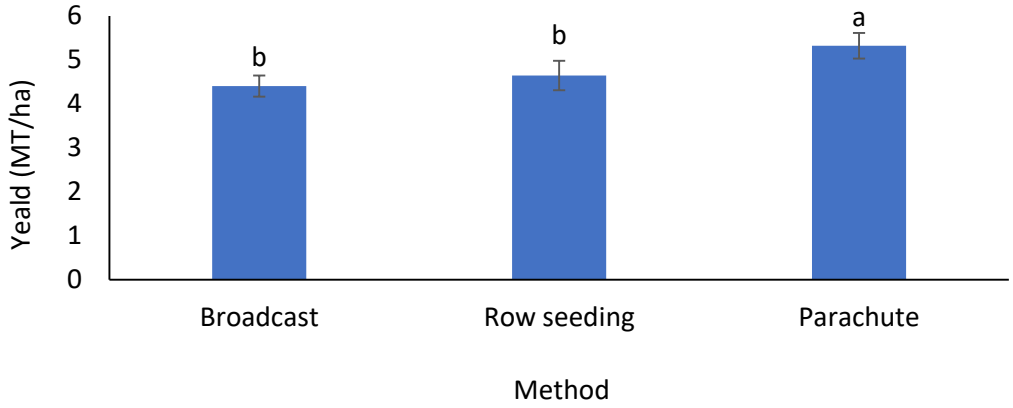

Figure 1. Comparison of paddy yield of different crop establishment methods. The vertical lines indicated the standard error of the means. Bars with the same letter are not significantly different at P=0.05.

Table 1. Average Cropping Intensity of 12 village tanks in different years

Year	Cropping Intensity (%)
2021	1.65
2022	1.92
2023	1.85
2024	2.0

The cost-benefit analysis of the implemented program demonstrated a significant economic advantage for farmers cultivating under village tank systems. The production costs was reduced by an average 25% (Table 2). This reduction is attributed to the adoption of improved agronomic practices, efficient water use strategies, and better input management promoted through the program.

Table 2. Average cost of production of paddy before and CRIWMP intervention

Prior to CRIWMP intervention (LKR/kg of paddy)	After CRIWMP interventions (LKR/kg of paddy)
89.15	66.0

Furthermore to lowering production costs, the program also increased crop yield and farmer income. The average yield improvement per farmer was valued at LKR 35,362.50 (approx. US$ 118), while the combined effect of increased yield and reduced costs led to an average total income increment of LKR 51,922.50 (approx. US$ 173). These findings indicated that the CRIWMP interventions have not only improved the economic efficiency of paddy farming but also the profitability and livelihood resilience of smallholder farmers.

Conclusion

The study concludes that cropping intensity under small/village tank systems in the Dry zone of Sri Lanka can be significantly enhanced through a multi-pronged strategy that integrates appropriate technologies with the socio-economic context of farming communities. Key interventions such as laser levelling of land and efficient irrigation water management techniques have demonstrated a marked reduction in the irrigation duty, resulting in improved water use efficiency. The introduction of the parachute transplanting (seedling broadcasting) method has contributed to yield improvements. Moreover, the adoption of these technologies has not only reduced the cost of production but also increased the net income of farmers, thereby enhancing both productivity and profitability. These outcomes highlight the importance of promoting climate-smart agriculture and resource efficient practices at scale. The study recommends a broader adoption of such technologies as a viable pathway to improve cropping intensity, farm income, and climate resilience in smallholder paddy farming.

Acknowledgment

We extend our sincere thanks to the Climate Resilient Integrated Water Management Project (CRIWMP) for their valuable contribution to conducting this study. We are also grateful to the Provincial Department of Agriculture (North western, Northern, North Central and Eastern) for guidance for conduct the crop cut survey and farmers in the project area for their valuable support.

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Investigation of Carbon Sequestration of Home Gardening Systems in Resettlement Area of Vavuniya District

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Introduction

The dry zone of Sri Lanka is one unique and major agricultural zone accounts for 70% of the land area of Sri Lanka (Abeysekera et al. 2015). Moreover main districts of the dry zone Vavuniya, Anuradhapura and Kurunegala and Hambantota where tank cascade systems are concentrated, are considered as highly vulnerable to climate change (Abeysekara et al. 2015). Priyapulyamkulam and Salahinigama are resettlement villages under the "*Waugampubuduwa*" tank cascade rehabilitation project of climate- resilient integrated water management which was implemented to upgrade the tank cascade system in three river basins. Moreover due to the resettlement process and agricultural and non-agricultural land use activities huge ecosystem damage occurred. The Climate Resilient Integrated Water Management Project (CRIWMP) has introduced climate-resilient and commercial home gardening however, those home gardening systems have not been evaluated as a climate change mitigation strategy.

Furthermore, to face adverse effects of climate change and ensure food security climate change mitigation and adaptation strategies can help local land user through the effective support of the stake holders and policymakers. Analysis of quantitative information and estimates of tropical home gardens in terms of sequestration of carbon need to identify new strategies. According (Kumar 2006) home gardening and it importance for carbon sequestration have been underscore earlier, there is no considerable amount of data on home gardening and its carbon content especially in dry zone home gardening system. Though few study related to the species diversity and ecosystem process was conducted (Pushpakumara et al. 2012). This subject should be further investigation.

As a multifunctional land use system home gardening provides several benefits to the ecosystem. home gardens to maintain species diversity diversification of home garden-derived products as well as facilitate long-term carbon stock (Mattsson et al. 2013). Home gardens also store higher amounts of carbon than other agriculture systems in the above- and below-ground biomass and soils, but usually inferior to mature forests at the same site (Mattsson et al. 2013). Tree-based agroforestry increases the atmospheric Carbon sequestration process, which ultimately reduces the atmospheric CO_2 and assists in moderating climate change implications (Wilson and Lovell 2016). Therefore, it is obvious

that the agroforestry ecosystems stand a great chance to sequester Carbon more than annual cropping and monoculture systems in the long run. Therefore the carbon sequestration process was identified as a sound option to for climate change. Carbon sequestration potential mainly depends on the different characteristics of home gardening systems including plant characteristic, system characteristics, soil characteristics, management aspects and agro-ecological conditions. Further, lack of quantitative data and information including species diversity, carbon content and existing conditions with related to the Dry zone home gardening system. Therefore, is a timely to assess the species diversity, carbon stock of home gardening system in different ecological condition to acclimate change mitigation strategy and it further development. This study was conducted to assess the tree diversity and quantify the carbon sequestration potential of selected dry zone home hardening systems in the CRIWM project in Sri Lanka.

Methodology

Site selection

This study was carried out in 46 home gardens and 11 adjacent forest patches in Salalihinigama and Periyakulama resettlement villages in the Vavuniya District of Sri Lanka.

Data collection

The field survey was conducted 2023 November to 2024 January in 46 randomly selected home gardens in Peryapuliyalamkulam and Salalihimigama resettlement villages under the Climate Resilient Integrated Water Management Project in the Vavuniya district. The survey respondent always will be a household head. A total of 11 sampling plots (20x20m) were established in the natural forest.

Identification of tree plant species diversity

Tree and plant species diversity were identified with in the fixed boundary of selected home gardens and 11plots of natural forest patches by using Shannon wiener index (SWI) (Mattsson et al. 2013) was calculated according to the Ponce-Hermandez (2004) (Equation 1).

$$\text{SWI} = -\sum_{i=1}^{n} pi\text{Ln}(Pi) \quad \text{..... (Eq 1)}$$

Determination of Above ground carbon stock

Above ground carbon was estimated by using non-destructive harvesting method. Plant heights and diameter at breast height (DBH) of ≥ 3 cm were measured using a clinometer and DBH tape, respectively, for all perennial crops. Home gardens were categorized into three size groups according to their land extent including small (<0.2ha) medium (0.2ha to 0.8) large (>0.8ha) for the comparison purpose (Mattsson et al. 2013). Due to the lack of standard equation estimate carbon stock in agroforestry system in Sri Lanka , pan tropical allometric equations developed for dry zone forest under (rain fall 1500 mm yr^{-1}) which has wide geographical and diameter range of vegetation of all types and were used to estimate Above Ground Carbon stock (Chave et al. 2005).

Data Analysis

Field survey data was analyzed using t-tests, correlation analysis and one way ANOVA tests with the version 21 of SPSS software. Additionally descriptive analysis was performed.

Results and Discussion

A survey of 46 home gardens analyzed crop composition, land extent, and irrigation methods. All gardens were subsistence-based. The total land area was 10.2 ha, with small-scale farmers managing 26% and medium-scale farmers 74% (Figure 4.1 a & b). About 63% of the gardens relied on rain-fed water, while 37% used irrigation. Home garden diversity plays a crucial role in food security. The charts show the most commonly grown crops among the farmers.

Field observations from 46 home gardens recorded 5,488 trees and plants, representing 74 species across 33 families. Papaya (*Carica papaya* L.) and banana (*Musa* sp.) were the most common non-woody species. Tree density averaged 170/ha, with a mean species richness of 15 ± 0.7 and Shannon-Wiener Index (SWI) of 1.4 ± 0.05 (range: 0.69–2.28). Interestingly, the highest number of trees and plants was found in small-sized home gardens, with mean tree species per hectare at 146 for small and 43 for medium-sized gardens.

Tree plant diversity was evaluating using Shannon wiener index (SWI). According to our findings the mean SWI of 46 home gardens was 1.402 with a range of 0.69 to 2.28 ,this finding nearly close to the mean SWI value Meegahaula region 1.55 to 1.77 earlier findings of (Senanayake et al. 2010) and lower than to the tree based traditional home garden in Sinharaja area (Martin et al. 2019). According to our estimate mean SWI value is 1.9 with range of 1.49 to 2.19. Further, it was revealed that mean SWI value in the home garden is significantly less ($p<0.05$) less than that of forest patch.(Mattsson et al. 2013) agrees with current study and it revealed the mature forest has high species density compare to the home garden. Weerahewa et al. (2012) studied the vulnerability of home garden system to climate change and the mean SWI recorded in his study in Sri Lanka (2.00) was the highest followed by India (SWI=1.44) and Bangladesh (SWI=1.9). The same study found that the home garden in Keeriyawawe representing dry zone Sri Lanka recorded SWI of 2.13 (N=59). Results of present study is lower than that value but higher than the value of Siwalakulama village home garden (SWI=1.77 n=30, intermediate zone) and Pethiyagoda (SWI=1.99, n=59 wet zone) (Weerahewa et al. 2012).

The Shannon winner index (SWI) for the small, medium, home gardens were 1.35 ±0.06, 1.46 ± 0.10, respectively, but there is no statistically significant difference recorded in tree species diversity of three different home garden groups (Table 1). In total 11 sample plots of forest patch has 330 woody plants and among all of them 26 number of different species were identified from 12 families. Tree diversity described by the SWI was between 0.69 to 2.28, with a mean value of 1.907 for the natural forest patch. The tree diversity of forest patch is statically significant ($P<0.05$) from home gardens

Table 1. Tree and plant diversity characteristics in different categories of home gardens

Land use system	Species ha^{-1}	Trees ha^{-1}	SWI		Mean land extent	Species richness
			Mean	Range		
Small (n=27)	146±7.88	235.53±15.56	1.35±0.06	0.72-1.87	0.1±5.55	17±0.32
Medium (n=19)	43±3.31	82.25±7.39	1.46±0.10	0.69-2.28	0.39±0.005	14±0.81

Tree stand measurements were recorded from approximately 253 individual trees across both forest patches and home gardens, covering land extents of 10.2 ha and 0.44 ha, respectively. In the 46 surveyed home gardens, above-ground carbon (AGC) stocks ranged from 3.48 Mg C ha^{-1} to 64.07 Mg C ha^{-1}, with a mean value of 3 Mg C ha^{-1}. In comparison, the natural forest patch had a significantly higher mean AGC stock of 99.36 Mg C ha^{-1}, ranging from 68.04 Mg C ha^{-1} to 161.75 Mg C ha^{-1} (Table 4.3). No statistically significant difference ($P > 0.05$) was found between small and medium home gardens. The mean AGC stock in small home gardens was 40.33 Mg C ha^{-1}, compared to 21.92 Mg C ha^{-1} in medium home gardens.

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Effect of gypsum and fish tonic application on groundnut (*Arachis hypogea* L.) yield in Mullaitivu District of Sri Lanka

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Introduction

Groundnuts or peanuts (*Arachis hypogaea* L.) are also known as poor man's nuts (Kpienbaareh et al. 2022) and represent an important source of edible oil with a high oil content (45-50%), as well as being the third most significant source of vegetable protein (25-30% protein). Due to their leguminous nature, groundnuts can fix atmospheric nitrogen through symbiotic nitrogen-fixing bacteria in root nodules, thereby enhancing the nitrogen content in the soil (Ramya and Singh 2022). Consequently, groundnuts can be employed in smallholder agricultural systems, including crop rotation and intercropping (Kpienbaareh et al. 2022). In high-intensity cropping programmes, the cultivation of legumes has been shown to improve the physical and chemical qualities of the soil. Furthermore, groundnuts can serve as a cover crop in areas prone to soil erosion (Kumar et al. 2023).

Sri Lanka cultivated groundnut in 16,597 ha and produced about 29,680 MT in 2023, which is 10% of the total worldwide production (FAOSTAT 2024). Groundnut is mainly produced in Mullaitivu, Kilinochchi, Vavuniya, Anuradhapura, Batticaloa, Trincomalee, Ampara, and Kurunagale districts. The total annual production in the Mullaitivu district was 2,208 MT from 1,760 ha, with the average yield of 1.25 Mt/ha (Department of Agriculture 2024).

Climate change, mainly abiotic stress, such as heat, cold, flood, drought, and salinity, hinders plant growth and productivity. To enhance the productivity and resilience to climate change, the Climate Smart Agriculture (CSA) approach, including agronomic practices (crop rotation, irrigation methods, fertilizer application), cultivation of short-age crop varieties, biotic and abiotic stress-resistant varieties, and generating diversity by plant breeding methods, needs to be adopted (Manjaya and Gupta 2023).

Furthermore, excessive usage of chemical fertilizers to improve crop production has negative environmental effects, such as soil degradation, chemical runoff, soil biodiversity losses, and a decline in the availability and quality of water (Litskas 2023; Tripathi et al. 2020). Therefore, moving towards organic fertilizer would be an economical and environmentally beneficial approach.

"Tissa", a mutant variety, has been widely cultivated in Sri Lanka as well as in the Mullaitivu district. Tissa is a short-age crop (90-100 days) with the improved attributes of disease resistance, drought tolerance and high yield. Furthermore, the average potential pod yield of the Tissa variety is 2.0–2.5 MT/ha (Parasuraman and Weerasinghe 2021). However,

according to the DOA statistics 2023 (Department of Agriculture 2024), the actual yield (1.25 MT/ha) reported in the Mullaitivu district is lower than the potential yield. Poor agronomic management, including fertilizer management, is the main hindrance to bridging the gap between potential and harvested yields (Bekele et al. 2023).

Calcium is an essential nutrient for groundnuts. Adequate Ca^{2+} in the pegging zone is essential for proper groundnut development. Lack of calcium results in undeveloped pod formation, a decrease in yield and poor-quality seeds (Hamza et al. 2021). Furthermore, calcium application in the form of gypsum significantly improved groundnut production and oil yield compared to foliar calcium application in the form of CaO, under clay soil conditions (Hamza et al. 2023).

Application of gypsum along with NPK significantly increased plant growth parameters and yield in groundnut (Yadav et al. 2015). Fish tonic, a product of fermented fish waste, mainly consists of N, P, K, Ca and essential amino acids, is a potential organic fertilizer, and can be used as an alternative to chemical fertilizer (Hepsibha and Geetha 2019; Ramesh et al. 2020). In addition, application of fermented fish waste resulted in increased soil fertility and proliferation of nitrogen-fixing and phosphate-solubilizing microorganisms than in chemical fertilizer (Maquén-Perleche et al. 2023).

The World Bank-funded Climate Smart Irrigated Agriculture Project (CSIAP) supports smallholder farmers in Sri Lanka and promotes groundnut cultivation with stress-tolerant variety Tissa to improve their resilience and increase productivity by adopting various climate-smart agriculture practices. This study was designed to find out the effect of application of Gypsum and Fish tonic on the yield performance and oil content of the groundnut variety “Tissa”.

Methodology

This research was conducted at the District Agriculture Training Center (DATC), Mullaitivu of Sri Lanka (9.16 °N latitude, 80.66 °E longitude) located 29 m altitude above the mean sea level (MSL). The soil type was sandy loam soil/ Reddish Brown Earths.

The experimental design was a Randomized Complete Block (RCB) with two replications. The effect of gypsum and fish tonic was studied under three treatments: T1, Control or no gypsum application; T2, Application of gypsum alone (100 kg/ha) in split dose at the time of sowing and flowering; T3, Application of gypsum in split dose together with fish tonic (50 mL/10 L at the rate of 240 L per ha). Certified groundnut seeds were procured from the DoA. Unshelled seeds were soaked in fungicide captan (3 g/kg seeds/5 L water) and dried in the shade. Seeding was done manually at the recommended spacing of 45 cm × 15 cm with a rate of one seed per hill. Urea (35 kg/ha at the basal stage and 30 kg/ha at the flowering stage) and Muriate of Potash (MoP at 75 kg/ha) were applied at the recommended levels for all three treatments. Earthing-up was done 37 days after planting, reaching 5 cm from the collar region. Weeding was done one time, i.e., in the 3rd week after sowing. Groundnuts were harvested 95 days after planting, then the pods were separated from the plant and allowed to sun dry for 5 days.

The yield parameters, fresh weight of pods per plant (g), dry weight of pods per plant (g), number of mature pods per plant, number of immature pods per plant,100 pods weight (g), 100 kernel weight (g) were recorded with five randomly selected plants from each plot and the total pod yield from each plot was also recorded. Then the total yield (kg/ha) was calculated from the yield obtained from each plot. To determine the shelling percentage (%), dried pods were deshelled and weighed, and calculated using Equation 1.

$$\text{Shelling percentage (\%)} = \frac{\text{weight of kernel (g)}}{\text{weight of pods (g)}} \times 100\% \quad \text{..... (Eq. 1)}$$

Pod yield (kg/ha) was determined by the total weight of groundnuts obtained from the test plots after plugging and adjusting to a moisture content of 12%. The nutritional quality of groundnut was analyzed in terms of fat content according to the AOAC methods (AOAC 2006). Crude fat was determined by Soxhlet apparatus (LabKits-SZF-06A, Hong Kong, China).

The optimum treatment was determined by statistical analysis using one-way ANOVA. The Duncan's Multiple Range Test (DMRT) was used in determining significant differences between means at P=0.05.

Results and discussion

Yield parameters and yield

Yield parameters, including the number of mature and immature pods, which are smaller in size and not fully developed or fully formed, were summarized in the Table 1.

Table 1: The average number of mature pods and immature pods (Mean ± Standard Deviation).

Treatment	Number of mature pods per plant	Number of immature pods per plant
T1	26.33 ± 6.02 [c]	7.33 ± 2.88 [a]
T2	39.50 ± 3.67 [a]	5.83 ± 1.94 [a]
T3	33.33 ± 1.97 [b]	5.33 ± 1.63 [a]

T1: Control or no gypsum application; T2: Application of gypsum alone; T3: Application of gypsum together with Fish tonic. Means followed by the same letter in each column are not significantly different by the Duncan's Multiple Range Test at P=0.05.

Significantly, the highest number of mature pods (39.50 ± 3.67/plant) was recorded with gypsum application (T2), whereas the lowest number (26.33 ± 6.02/plant) was recorded in the control plot (T1). This may be due to the calcium and sulphur availability in the pegging zone, with the application of gypsum, as their deficiency in the soil can inhibit the swelling of peg and pod formation (Kumar et al. 2019). A similar observation was made by Kabir et al. (2023) who reported a significant increase in the total pods per plant with a higher level of P and Ca. The results for the other yield parameters, including kernel weight, shell weight, pod weights and shelling percentages were tabulated below (Table 2).

Table 2. The yield parameters and fat content of groundnut samples (Mean ± Standard Deviation).

Treatment	Mean 100 pod weight (g)	Mean 100 kernel weight (g)	Mean shell weight (g)	Shelling percentage (%)	Yield (MT/ha)	Fat (%)
T1	146.69 ± 0.86 [b]	54.94 ± 0.09 [b]	36.80 ± 0.68 [a]	74.9% [b]	1.61 ± 0.37 [c]	37.93 ± 2.34 [a]
T2	165.03 ± 4.21 [a]	63.52 ± 1.60 [a]	37.99 ± 1.02 [a]	77.0% [a]	2.71 ± 0.25 [a]	41.23 ± 0.88 [a,b]
T3	167.82 ± 4.69 [a]	64.97 ± 1.23 [a]	37.87 ± 2.44 [a]	77.5% [a]	2.33 ± 0.14 [b]	44.60 ± 1.84 [b]

T1: Control or no gypsum application; T2: Application of gypsum alone; T3: Application of gypsum together with Fish tonic. Means followed by the same letter in each column are not significantly different by the Duncan's Multiple Range Test at P=0.05.

Despite no significant difference was observed in mean 100 kernel weight and 100 pod weight observed in treatments T_2 and T_3, the highest 100 pods dry weight (167.82 ± 4.69 g) and 100 kernel weight (64.97 ± 1.23 g) were reported under T_3 treatment and the lowest (146.69 ± 0.86 g and 54.94 ± 0.09 g, respectively) under T_1 treatment. A slight increase in the kernel and pod weight may be attributed to the Ca and S content in gypsum, as well as the higher content of macronutrients like N, P, and K, and other micronutrients found in fish tonic (Balkhande 2021). Application of gypsum (T_2) and gypsum together with fish tonic (T_3) showed a positive effect on shelling percentage (77.5% and 77.0%, respectively). It is higher than the value reported with zinc and gypsum application (Aruna et al. 2022).

According to the current findings, application of gypsum alone (T_2) significantly increased the groundnut yield (2.71 ± 0.25 MT/ha). This result is in agreement with the findings of Thivakaran et al. (2021) and Thilakarathna et al. (2015). Mandal et al. (2005) also indicated that gypsum at 100 kg/ha was found to be more productive. When gypsum and fish tonic were applied together, groundnut pod yield was recorded as 2.33 ± 0.14 MT/ha, which was higher than the control but lower than the T_2. This may be due to substances, such as ammonia, amino acids and organic acids, etc., released during fermentation may be toxic to plants and native soil microorganisms (Ramesh et al. 2020).

Gypsum may have a positive impact on yield and its parameters by lowering soil pH through sulfuric acid oxidation and increasing the availability of soil nutrients. Sulfur also enhances soil water relations, promotes root growth, and aids in urea transformation, supporting better plant growth and productivity (Abd Alla et al. 2009). Further, Ca and S content in gypsum favorably influence on uptake of N, P, K by groundnut and help increase the pods/plant, kernels/pod, shelling (%) and 100 kernel weight as well as oil content (Dutta and Yadav 2022). The soil profile is important for pegging and pod development.

Fat content

The significantly highest fat content was reported with the treatment T_3 (44.60 ± 1.84%), which is 17.5% higher than that of the control. This may be associated with the influence of sulphur, being an essential component of enzymes, and is involved in the conversion of starch to oil and protein, leaving behind less starch in the grain (Elakiya et al. 2020; Kumar et al. 2024).

Groundnut is a legume-oilseed crop, and increasing yield and oil content would increase the farmer's income and be beneficial for the edible peanut oil and other value-added product sectors.

Conclusion

In conclusion, as per the results obtained, gypsum (100 kg/ha) and fish tonic (50 mL/10 L) applied together improved the yield parameters like number of mature pods/plants, 100 pods weight, 100 kernel weight, and shelling percentage, which in turn enhanced the groundnut pod yield (2.33 ± 0.14 MT/ha). Furthermore, based on nutritional analysis, the fat content increased by 17.5% when gypsum and fish tonic were applied together compared to control (T_1) and gypsum alone (T_2).

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Foliar Supplement of Calcium Improves the Growth, Yield and Fruit Quality of Gherkins (*Cucumis sativus* sub sp. Anguria) Affected due to Moisture Stress

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Introduction

Gherkins (*Cucumis sativus* sub spp. Anguria); a commercially important export-oriented vegetable is valued based on the crispness or crunchy mouth-feel of its young fruits under pickled or salted storage. Production reports support the fact that the crops grown under sub-optimal soil moisture regimes during climate change based prolonged droughts are more prone to loss of fruit firmness, leading to loss of crispness. Further to this, as a constituent of the cell wall of plant tissues calcium hardens the tissues, especially increasing the fruit firmness (Siddique 2017). Meanwhile, calcium uptake and translocation in plants occur through the transpiration stream, making soil moisture availability a critical factor.

The implications of this study extended beyond finding the effects of Calcium (Ca) foliar application concentration on the growth, development and fruit quality of gherkin. The study aimed to provide an understanding of how these changes influence the structural and nutritional properties of gherkin fruits. The results revealed the mechanisms behind textural and compositional changes of gherkin fruits, supporting the development of improved agricultural practices to enhance fruit quality under adverse climate changers. Furthermore, the findings will contribute to ensure that gherkins could reach consumers in optimal condition, thereby potentially reducing the post-harvest losses.

Methodology

A replicated pot experiment was conducted to investigate the effect of foliar application of Ca on the growth, yield and fruit quality of gherkins, under two soil moisture regimes; adequate and deficit (moisture stress). The stress was imposed by maintaining the moisture content of the pot at 30-40% of the field capacity (F.C.) in comparison with its well-watered counterpart (70-80 % of F.C.). Foliar application of Ca (Ca $(No_3)_2$) was applied, flowering onwards at two concentrations (25g and 35g per 16L) in five-day intervals, keeping no-calcium as the control. The effects of the Ca foliar application under adequate soil moisture and under severe moisture stress were investigated in terms of growth, yield, and fruit quality of fresh and pickled gherkins.

Results and Discussion

Vegetative Growth

Plant height was significantly different ($P<0.05$) between well-watered (70–80% F.C.) and drought-stressed (30–40% FC) conditions, with drought markedly reducing height regardless of foliar Ca application (Figure 1). This aligns with the findings by Arshad (2017), who attributed reduced shoot growth in cucumbers under water stress to diminished turgor pressure, limiting cell expansion, more than cell division. Similarly, Luvaha et al. (2008) observed reduced stem elongation in seedlings under severe drought. These results are consistent with prior studies (Arshad 2017; Odhiambo and Aguyoh 2022) reporting suppressed plant growth under limited soil moisture.

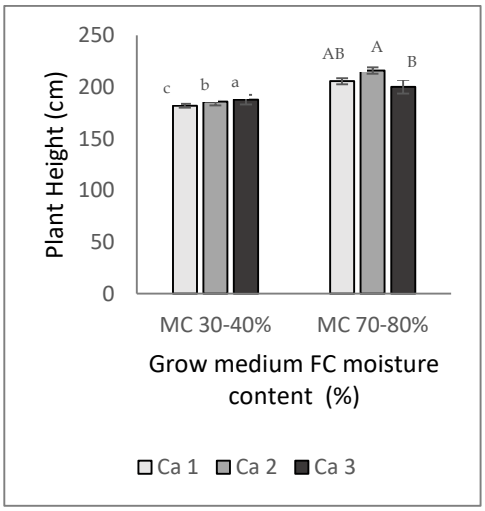

Figure 1. Plant height of gherkin grown under different levels of soil moisture (MC 70-80%: Well-watered condition where soil moisture was maintained at 70-80% of the field capacity.) and foliar application of Ca (Ca 1, Ca 2 and Ca 3: Foliar application of Ca at the rate of 0g, 25g and 35g per 16L, respectively.) at 40 days after transplanting (Reproductive Stage) Error bars represent the standard error. (S.E.; n=6) Different data labels indicate significantly different treatment means with respect to foliar Ca concentration.

Under drought-stressed conditions, foliar application of Ca exhibited a pronounced influence on plant height, with the highest growth observed at a concentration of 35 g/16L and the lowest at 0 g/16L. The intermediate concentration of 25 g/16L resulted in moderate height, suggesting a dose-dependent response under water-limited conditions. Notably, this effect was absent under well-watered conditions, indicating that calcium's role in promoting plant height is more prominent under abiotic stress. The present results on Ca foliar application agrees with previous literature on papaya, indicating a significant effect on plant height. Additionally, foliar Ca applications have increased the plant height of tomato (Rab and Haq 2012). Other than that, scientific studies have demonstrated that Ca

foliar application enhances stress tolerance in plants by supporting drought resistance mechanisms (Shao et al. 2008).

Reproductive Growth

Early fruit yield during the first week of harvest (35 DAP) was significantly influenced by both soil moisture levels and foliar Ca concentrations. Well-watered conditions (70–80% F.C.) resulted in markedly higher yields ($p < 0.001$) compared to drought-stressed conditions (30–40% FC), underscoring the critical role of adequate soil moisture in early reproductive success (Figure 2).

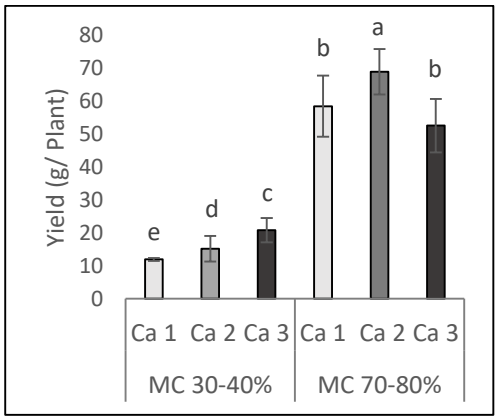

Figure 2. Fruit yield of gherkin grown under different levels of soil moisture (MC 70-80%: Well-watered condition where soil moisture was maintained at 70-80% of the field capacity.) and foliar application of Ca (Ca 1, Ca 2 and Ca 3: Foliar application of Ca at the rate of 0g, 25g and 35g per 16L, respectively.) at 40 days after transplanting (Reproductive Stage) Error bars represent the standard error. (S.E.; n=6) Different data labels indicate significantly different treatment means with respect to interaction of moisture content and foliar Ca application.

This outcome reflects the enhanced dry matter partitioning toward reproductive organs under optimal water availability, as efficient translocation of assimilates from the source (leaves) to sink (fruits) is facilitated (Amanullah et al. 2021). In contrast, moisture stress restricts assimilate flow and biomass accumulation, leading to reduced early yield.

There was a significant interaction ($p=0.0402$) between Ca application and moisture availability in the growth medium. It indicates that the effect of calcium supplementation on fruit yield is influenced by soil moisture conditions. Under drought-imposed conditions, increasing the calcium concentration in foliar applications led to a positive yield response while the same was not significant under well-watered conditions (Figure 2). Hence, foliar application of Ca plays a significant role in improving yield under water stress rather than the well-watered (near field capacity) conditions. This suggests that calcium supplementation may play a crucial role in enhancing the plant's ability to withstand water stress.

According to Naeem et al. (2018), foliar application of Ca^{2+} can be an effective strategy to strengthen plant resilience and promote growth under limited water availability. This phenomenon appears to be applicable to gherkin plants as well, as the observed yield increase under drought conditions indicates a positive response to calcium application.

Fruit Quality

Fruit firmness and pericarp thickness, key quality traits, were not significantly affected by either soil moisture levels or foliar Ca application, indicating that while yield was responsive to treatments, these structural quality parameters remained stable. These results contrast with Takayoshi (2013), who reported improved fruit firmness in tomatoes following Ca foliar application, suggesting crop-specific responses likely influenced by environmental context and calcium uptake efficiency. Similarly, pericarp thickness showed no significant variation across treatments ($P = 0.3022$).

Gherkins grown under moisture-limited conditions showed a significant reduction in leaf Ca in the vegetative stage of plant growth. When considering the reproductive stage, the leaf Ca content was higher in well-watered conditions, irrespective of the foliar application of Ca. Approximately similar Ca content was observed in leaf tissues of the well-watered plants and drought-imposed plants, indicating non-significance of the effect foliar application of Ca on leaf Ca content in the present study.

Conclusion

In this context, foliar application of Ca emerges as a promising climate-resilient strategy to mitigate the adverse effects of moisture stress that may occur under climate change affected seasonal shifts in the dry zone of Sri Lanka. Direct supply of calcium to the plant (in the form of foliar application) can help compensate the reduced water uptake under drought conditions, ensuring better growth, development and fruit quality. Further research under varying moisture levels with and without foliar calcium will help validate this method as a sustainable climate resilience for loss of crispness of pickled or salted gherkin fruits in storage.

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Carbon Footprint Assessment of Intensive Dairy Systems in the Upcountry of Sri Lanka: A quantitative approach

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Introduction

Climate change remains one of the most pressing global issues, with greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) playing a major role. Among anthropogenic sources, the livestock sector contributes significantly, responsible for about 8.1 gigatonnes of CO_2-equivalent (CO_2e) emissions annually. Dairy farming, in particular, emits CH_4 through enteric fermentation, N_2O via manure management, and CO_2 through feed production and energy use.

In Sri Lanka, dairy farming is one of the main livestock subsectors, contributing both to national food security and rural livelihoods. The Central Province stands out, hosting nearly 42% of intensively managed dairy farms, aided by its cooler climate, which supports temperate cattle breeds. However, despite its importance, there is a critical lack of localized data on greenhouse gas emissions from these systems. Most current estimates rely on global default values, which often fail to capture the unique environmental, nutritional, and management factors specific to Sri Lankan dairy farming conditions.

The scope of this study focuses on real time quantification and validation of methane emissions from enteric fermentation and manure management within an intensively managed upcountry dairy system. Specifically, the study aims to develop a low-cost, Arduino-based portable methane analyser for field use, quantify emissions using both direct measurement and IPCC Tier 2 estimation methods, validate sensor derived data against established methodologies, and produce a user-friendly Microsoft Excel tool that enables farm-level emission calculations. Through this integrated approach, the study supports the generation of accurate, localized emission factors and promotes the adoption of data-driven practices in sustainable dairy management.

Methodology

The study was conducted from January to April 2025 at a large-scale intensive dairy farm located in the upcountry region of Sri Lanka where the moderate climate supports high-yielding dairy systems. Field data collection and laboratory analyses were performed at the Department of Animal Science, Faculty of Agriculture, University of Peradeniya, Sri Lanka.

Based on farm records, animals were categorized into four physiological groups: heifers, early lactating cows, peak lactating cows, and dry cows. Five animals from each group (n = 20) were selected for data collection related to live weight, feed intake, milk yield & composition, and assessing manure characteristics. Milk samples were analysed using an ultrasonic milk analyser, while feed and manure samples were analysed for gross energy (GE) using the bomb calorimetric method.

Methane emissions from manure and slurry pits were quantified using a custom-built, low-cost Arduino-based sensor unit incorporating an MQ-4 sensor along with environmental sensors for temperature and humidity. This setup was suitable for manure related measurements due to relatively stable environmental conditions. However, it was not appropriate for enteric methane quantification, as the MQ-4 sensor's accuracy is significantly compromised in high-humidity environments typically found in animal sheds. Therefore, enteric methane emissions were measured using a real-time sensing system developed by the National Building Research Organization (NBRO), which features a calibrated non-dispersive infrared (NDIR) methane sensor designed for higher precision in humid and dynamic environments. Spot sampling was conducted during feeding by positioning a sensor funnel approximately 50 cm above the cows' heads, with data logged every 30 seconds over a 10-minute interval at four locations per shed.

To enhance the accuracy and completeness of the emission assessment, the study employed both direct CH4 measurements and Tier 2 emission estimations. Direct sensor data provided real-time, empirical values for methane emissions, while the Tier 2 methodology enabled the incorporation of broader farm-level variables.

Farm-level data such as herd size, feed intake, energy use, milk production, and manure handling practices were obtained from the farm's digital record systems to ensure consistency and traceability across all calculations.

All calculations were performed using a custom-designed Microsoft Excel tool developed as part of the study, incorporating the 2019 refinement of the IPCC Tier 2 methodology (IPCC 2019). This tool integrates empirical data, such as live weight, feed energy, methane measurements, and milk production - into embedded IPCC equations to generate accurate and localized emission factors.

Results and Discussion

The CF of an intensive dairy farm in upcountry Sri Lanka was estimated as 3.36 kg CO_2e/kg FPCM, which is notably lower than the default value of 4.80 kg CO_2e/kg FPCM reported by the FAO and NZAGGRS (2017) for the same region. This discrepancy underscores the importance of using farm-specific, real-time data over default values to enhance the accuracy of national GHG inventories. Methane emissions from enteric fermentation were quantified using the IPCC Tier 2 methodology, supported by a custom Excel-based model developed specifically for this study. The incorporation of sensor-based technologies and

cow-specific input data enhanced the resolution and accuracy of emission estimates, enabling more precise, individualized assessments compared to traditional approaches.

Enteric methane EFs were estimated for four cow categories: heifers, early lactating cows, peak lactating cows, and dry cows. The average EFs ranged from 155 to 325 kg CH_4/head/year, with the highest emissions recorded for early and peak lactating cows. This trend is attributed to the physiological state of these animals, which demands higher feed intake and leads to an elevated metabolic activity. Although energy digestibility was uniformly low across all categories (below 60%; Figure 1), the combination of poor digestibility and higher feed intake in lactating cows likely contributed to increased methane production. The lower emissions observed in heifers and dry cows are likely due to their reduced intake and metabolic requirements.

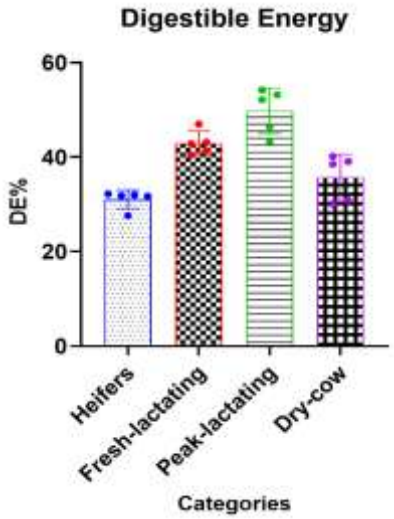

Figure 1. Dry matter energy digestibility of selected cow categories of the upcountry intensive dairy farm in Sri Lanka

The trend of methane emissions across cow categories was consistent between the IPCC Tier 2 estimates and the Arduino-based sensor measurements (Figure 2). Only the relative pattern is comparable, as absolute values differ due to unit differences and the open-environment sensor setup, where dilution and short measurement periods prevent conversion of ppm readings to kg CH_4/head/year. Direct comparison would require chamber-based measurements. The consistency between these methods validates the potential of low-cost sensors as reliable tools for real-time methane monitoring in field settings. This finding is significant in resource-constrained contexts prevailed in Sri Lanka, where high-end GHG quantification systems may be inaccessible. Similar observations were made by Rotz et al. (2010), who emphasized the utility of practical, data-driven tools in farm-level emissions monitoring.

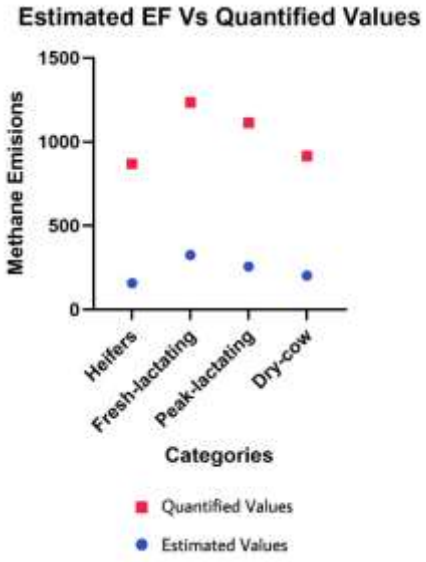

Figure 2. Pattern of estimated average EF and quantified average methane levels of the upcountry intensive dairy farm in Sri Lanka

Although EFs were elevated for individual animals, the overall CF remained lower than default estimates. Several factors are likely to be contributed to this outcome. The dietary inclusion of Yea-Sacc®, a yeast-based additive used at the farm, may have moderated rumen fermentation and reduced methane output, while simultaneously enhancing milk yield, thereby reducing emissions per unit of FPCM.

Manure management emerged as another key emission source, with notable contributions to total CF. The low digestibility of feed likely increased the amount of organic matter excreted, resulting in higher methane emissions from manure pits. This reflects the findings of other studies where manure-related emissions are exacerbated by poor feed utilization. Despite this, the overall CF remained favourable compared to the FAO baseline, emphasizing the value of farm-specific interventions.

The Excel-based tool developed in this study played a critical role in CF estimation by enabling cow-level data entry and real-time calculation of methane EFs based on energy requirements, feed intake, and milk production. This tool not only streamlined data analysis but also provided a platform for exploring mitigation scenarios under different management practices. The model's consistency with Tier-2 outputs enhances its applicability in broader dairy farm assessments and supports its use in policy-oriented emission monitoring frameworks.

The integration of both direct measurement methods and IPCC Tier 2 estimations significantly enhanced the robustness of the study. Real-time sensor data offered empirical insights into methane emission dynamics under local farm conditions, while Tier 2 estimations allowed for the systematic incorporation of key animal-level variables such as

live weight, feed intake, and milk yield. This dual approach enabled effective cross-validation of results, thereby improving the precision of emission factors derived for the upcountry dairy system. Moreover, it underscores the potential for combining empirical field data with established methodologies to support more accurate national GHG inventories and inform targeted mitigation planning in the livestock sector.

Conclusion

The carbon footprint of the upcountry intensive dairy farm was quantified at 3.36 kg CO_2e/kg FPCM. Although higher emission factors were observed in early and peak lactating cows, these results reflect the complex interaction of physiological state, feed intake, and digestibility. The use of real-time data, supported by Arduino-based sensors and an Excel-based Tier-2 estimation tool, proved effective in delivering precise and scalable emission assessments. These findings highlight the importance of adopting context-specific, affordable quantification methods to support national GHG inventories and inform future mitigation strategies within Sri Lanka's dairy sector.

Acknowledgement

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Assessing the Financial Cost-Benefit of Diversified Cropping Systems as an Adaptation Strategy for Climate Change in Selected Cascade Areas of Sri Lanka

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Introduction

The agriculture sector plays an important role in the economy in terms of GDP contribution, Job possibilities, and revenue production. Despite a significant fall in its share of the GDP over the last three decades from 30% in 1970 to 7.3% in 2020, it remains the primary source of employment for the majority of Sri Lankan workers (Thanigaseelan 2021). Paddy farming and Sri Lankan life are so intertwined that it affects every facet of the country's history and culture. The Paddy sector plays a vital role in the economy of Sri Lanka by providing livelihood to nearly 0.9 million farmer families island-wide. While 26 percent of the labour force in the country is engaged in agriculture-related activities, and about half of it is involved in the paddy/rice industry (Wijesooriya et al. 2020). Since the agriculture sector in Sri Lanka directly depends on rainfall and other climatic factors, it is greatly impacted by climate change factors (Yohannes 2015). Sri Lanka is experiencing protracted droughts, high-intensity rainfalls, high temperatures, and other changes as a result of climate change. Farmers residing close to Malwathu Oya, Mi Oya, and Yan Oya were forced to give up four consecutive seasons of seasonal cropping due to the severe drought that struck between 2015 and 2018 (Juhkam 2021). It is crucial to learn the detrimental consequences of climate change on agricultural ecosystems and the social and economic well-being of Sri Lankans, particularly smallholder farmers, as Sri Lanka is a climate-sensitive country in Asia.

Therefore, the Sri Lankan Agriculture sector identified the need for the Climate Smart Agriculture (CSA) concept. The Climate Resilient Integrated Water Management Project (CRIWMP) was initiated in 2017 in the selected village irrigation systems of Anuradhapura, Kurunegala, Vavuniya, Puttalam, and Trincomalee by the government of Sri Lanka collaboratively with UNDP, which is funded by the Green Climate Fund. The main focus of this project is to introduce the concept of Climate Smart Agriculture (CSA), which is regarded as an agricultural approach to transform the country's systems, effectively support farmers in their livelihoods, and ensure food security, while reducing greenhouse gas emissions (Juhkam 2021). Introducing other field crops to paddy cultivation is one of the CSA methods implemented by the project to increase cropping intensity and crop diversification. According to Humphreys et al. 2015, the promotion of viable cropping system intensification could be one of the suitable options for increasing the livelihood

conditions of small-holder farmers. Agricultural intensification is the process of increasing crop productivity per unit area, which can either include higher yields for a single crop or higher system productivity by growing multiple crops per year on the same land (i.e., higher cropping intensity. The project has introduced three cropping intensities for the paddy farmers in the selected village irrigation system of the above-mentioned districts in order to increase the cropping intensity (CI).

Table 1. Introduced Cropping Intensity (CI) Models by UNDP

Model	Yala	Maha
1	Paddy	Paddy
2	Paddy + Other field crops (OFC)	Paddy
3	OFC	Paddy

(Source: CRIWM Project UNDP)

The project has introduced five different OFC: Green gram, Black gram, Cowpea, Groundnut, and Millet for paddy farmers as a crop diversification option. Cultivating OFCs is a cost-effective option for crop diversification since they produce various benefits, including reducing crop risk, improving soil health and nutrients, increasing profit, and helping to gain high income from less yield. Legumes rank second only to cereals. Legume species are special among all plant species because of their capacity to fix atmospheric nitrogen in soil-crop ecosystems. It is commonly recognized that legumes have a significant role in agricultural development, nutrition, food security, and economic growth.

Though the farmers practice these cropping intensity models in terms of improving cropping intensity and economic well-being, the economic impact of the cropping systems has not been evaluated yet. According to the literature, other field crops have a considerable economic impact. Therefore, it is important to identify the economic importance of incorporating OFC into paddy cropping systems. Hence, evaluating the economic viability of different cropping intensity models and identifying the most suitable and economically effective cropping system will help farmers identify the most suitable and economically effective CI model for higher economic returns while practicing a climate adaptation strategy.

Methodology

Study site

The research was conducted across five districts located within the Dry and Intermediate Zones of Sri Lanka— Anuradhapura, Vavuniya, Trincomalee, Puttalam, and Kurunegala— encompassing five cascade systems and ten associated village irrigation systems. Primary data were collected through a questionnaire survey from 150 randomly selected farmers who practiced diversified cropping systems, including paddy and Other Field Crops (OFC). (Figure 1).

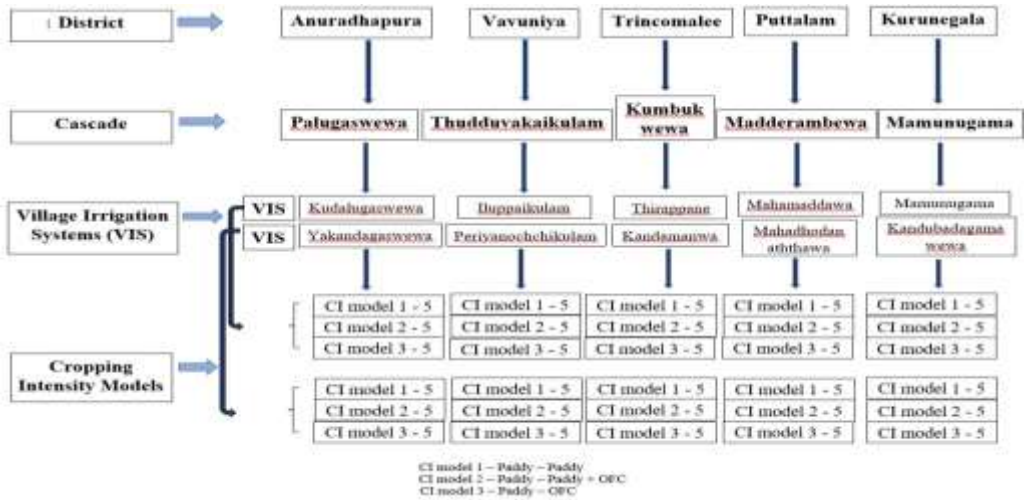

Figure 1. The model of sampling design procedure of the study

Data Collection

The data was collected through a self-administered survey. Data types that were used for assessing economic viability included the Extent of the cultivable land (acres), other earning options rather than agriculture, Family income (Annual), Net income from agriculture (Annual), Input cost for agriculture (Annual), Income distribution, etc. The model for the sampling designing procedure is illustrated in Figure 1. For the research, the main CI models (PP, PO, and PPO) that farmers practiced were selected as mentioned in Table 1.

Statistical method of data analysis

The financial benefit-cost and NPV values were determined for each model in each district. For the NPV value discount rate was selected as 13% (BOC - 2023), and the significance of those results was assessed using the one-way ANOVA and Duncan test.

Results and Discussion

Cropping Intensity of Cropping Intensity Models

According to Table 1, the average cultivated land extent of OFC is lower than that of paddy cultivation in the *Yala* season. When considering the *Maha* season, Paddy cultivation is higher than in the *Yala* season in all the districts. In the PP model, most of the farmers cultivated paddy more than two acres in the *Maha* season, and it will be 0.9 – 2 acres in the Yala season. The average land extent is mostly similar in both paddy and OFC cultivation in the PPO model. The total average land extent for the PPO model is greater than the other two models. However, farmers cultivate paddy to a greater extent than the OFC.

Table 2. Average cultivated land extent (acres) values of each season of each model in district-wise

District	PP Model		PPO Model			PO Model	
	Maha - Paddy	Yala - Paddy	Maha - Paddy	Yala - Paddy	Yala - OFC	Maha - Paddy	Yala - OFC
Anuradhapura	2.45	2.00	2.20	1.58	0.4844	1.30	0.6538
Vavuniya	2.15	1.75	7.05	3.75	1.6765	4.85	2.0000
Trincomalee	1.90	1.85	1.95	1.70	0.5962	1.65	0.7500
Puttalam	2.70	1.85	1.80	1.50	0.8409	1.93	0.9167
Kurunegala	1.60	0.98				1	0.2679

Source: Survey (2023). PP – Paddy + paddy, PPO – paddy + paddy + OFC, PO – Paddy + OFC

Figure 2A depicts that those three out of four districts that practiced the PPO model have the highest income (Anuradhapura ≅ LKR 360,000.00, Vavuniya ≅ LKR 1,105,000.00, Trincomalee ≅ LKR 374,000.00) than other models they practice (Note; IS$ = LKR 300). Further, the PO model of almost all the districts (< Rs 30,000.00) except in Vavuniya (≥ LKR 750,000.00) has the lowest income. According to the survey results, most of the farmers are reluctant to cultivate OFC to a larger extent of the land in the Yala season. Since most of the plants get damaged and they cannot get a considerable yield, they used to cultivate OFC on a smaller land extent.

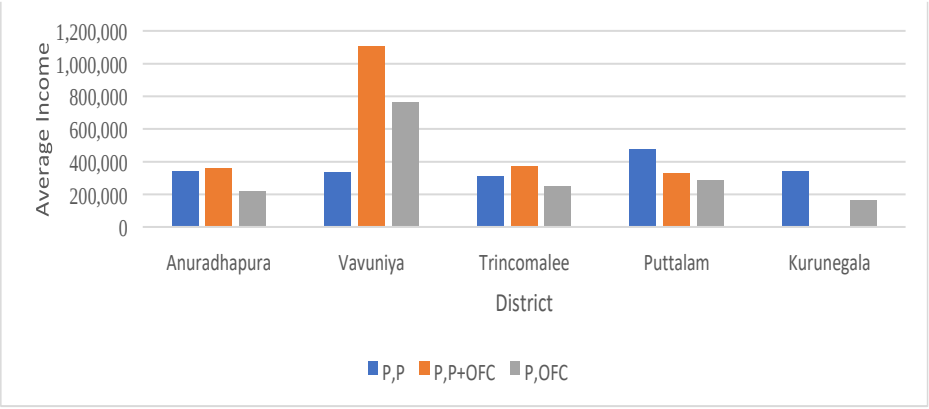

Figure 2A. The average income of each CI model in different districts
Source: Survey (2023)

According to Figure 2B, the annual expenditure for agricultural activities of the PPO model is higher in the Vavuniya district than in other models because the farmers who practice the PPO model have to bear the higher cost of buying seeds (Rs. 20,000 – 40,000/per kg). Since their cultivation extent is comparatively larger, their seed banks are

not sufficient. In addition, they have to expend more than Rs. 10,000/- for fuel due to their larger land extent. Farmers who are practicing PPO models have to spend on both seed paddy and seeds of OFCs. In the Trincomalee district, Farmers who practice the PPO model pay a considerable amount of money.

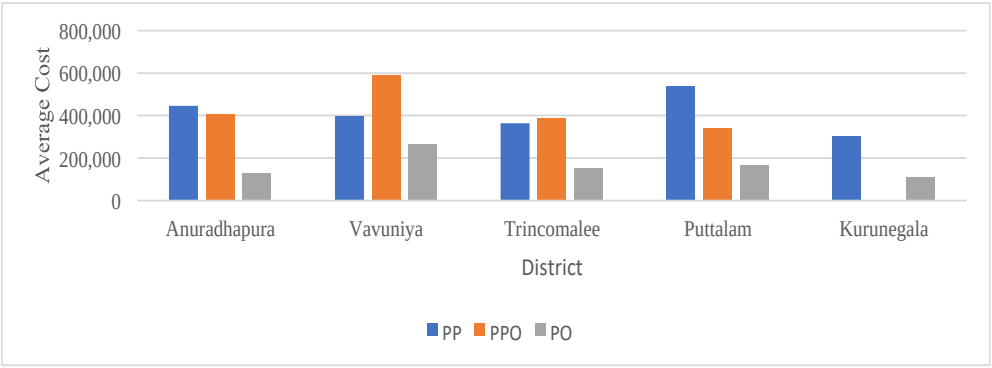

Figure 2B. The Annual expenditure for agricultural activities in different CI models under different districts
Source: Survey (2023)

For Fuel and Transport. Most of the farmers do not have vehicles to transport their harvests/products to market areas, thus having to bear the transport cost for vehicles. In the PO model, all the districts cultivate only paddy in the Maha season and OFC during the Yala season in their small land areas. The requirement for management practices for OFCs is comparatively less than the field practices in paddy. Due to this reason, the cost for agriculture activities of farmers who practice the PO model is less than the other two models.

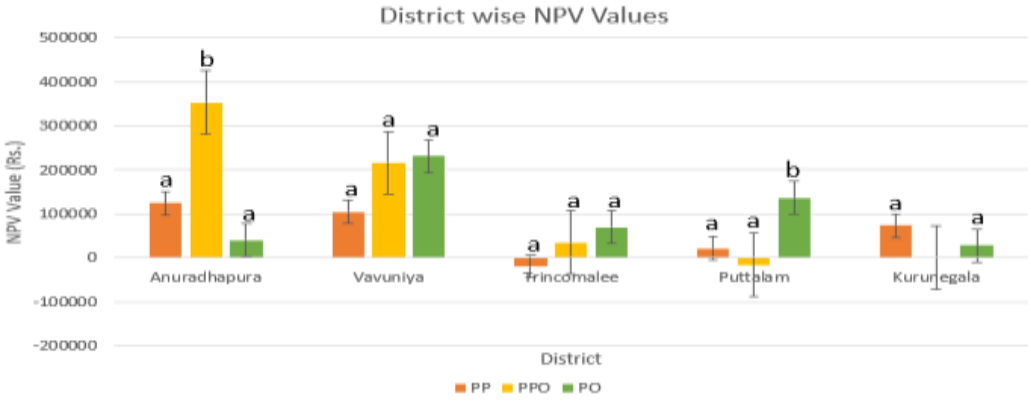

Figure 3. The NPV values (13% - discount rate) of the cropping intensity models under each district. Source: Survey (2023)

According to the results of Figure 3, Vavuniya (P=0.093), Trincomalee (P=0.242), and Kurunegala (P=0.274) did not show a significant contrast among the three CI models, as there were no statistically notable differences. Also, the significant value of the variance of the NPV values among the CI models in Anuradhapura (P=0.001) was less than in the other

districts. However, in the Anuradhapura district (Average NPV value = Rs. 352,856.64), the PPO model showed a considerable deviation in the NPV value from the other two CI models. Puttalam district showed a significant difference (P=0.021) among the CI models, where the PO model showed the highest NPV value. When considering all the PPO models, the highest NPV value (Rs 35,2856.64) was shown in the Anuradhapura district. For the PO model, Vavuniya district (Rs. 231,338.50) showed the highest NPV value among the other districts (Anuradhapura – Rs. 40,729.20, Trincomalee - Rs. 69,300.88, Puttalam - Rs. 135,955.87, and Kurunegala- Rs. 28,585.84). Overall, as stated in Figure 3, PO models of most districts depicted a higher NPV value than the other two models. The management practices and input costs for OFC were lower than those for paddy. According to Dharmasena et al (2001), generally, OFCs are cultivated by resource-poor farmers, hence input use is very low. There are no institutional arrangements to provide input materials such as seed, fertilizer, chemicals, machinery, etc., in time for legume cultivation.

Conclusion

Almost all the districts gain higher profit by cultivating other field crops as the establishment and management costs for them are considerably lower than cultivating paddy, and they provide considerably higher yields even from a small land extent. Hence, the cost of management practices for OFCs is much lower than paddy cultivation. Diversification of paddy-based cropping patterns with the integration of OFC offers various advantages, such as income diversification and risk reduction, leading toward low-input agriculture, which will act as a climate-adapted strategy.

Acknowledgment

Thanks go to all those who helped me complete the research successfully.

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Real-Time Weather Data, Soil Type, and Root Depth-Based Crop Water Requirement Assessment to Minimize Methane Emissions in Rice Fields: A Case Study of the Huruluwewa Scheme

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Introduction

Rice cultivation in the Dry zone of Sri Lanka faces the dual challenge of water scarcity and greenhouse gas emissions, particularly methane. This staple food crop is critical for rural livelihoods, yet the region suffers from limited rainfall and high evapotranspiration, necessitating efficient water use. Traditional paddy irrigation practices, characterized by continuous flooding, promote prolonged soil saturation, encouraging anaerobic microbial activity that produces methane (CH4) through anaerobic decomposition in saturated soils. As methane is a potent greenhouse gas with a global warming potential significantly higher than carbon dioxide (CO2), it is crucial to address these emissions.

This study evaluates the use of real-time weather data, spatial soil parameters, and root depth variations to estimate crop water requirements specifically for the Huruluwewa irrigation scheme in Sri Lanka. The objective is to enhance water management efficiency, reduce methane emissions, and improve yield. A data-driven method that incorporates weekly crop coefficients, root depth, and real-time climatic data is proposed to achieve this. Python-based scripting is utilized to handle the spatiotemporal variability of climatic and soil parameters, enhancing processing and interpretation efficiency. The findings promote sustainable rice cultivation practices that ensure water availability and reduce environmental impacts.

Methodology

The study focuses on the Huruluwewa Irrigation Scheme in the Yan Oya River Basin, Anuradhapura District, Sri Lanka, characterized by Dry zone climate and variable soil types. Data collection included four major soil series classified by the Irrigation Department, each with saturated hydraulic conductivity (Ks) and available water capacity (AWC) (Table 1). Real-time weather data obtained from the Hydrometeorological Information System (HMIS). Weekly crop coefficient (Kc) values and root depth data for paddy were adapted from Gu et al. (2017) and Choudhury and Singh (2016), respectively.

Table 1. Weekly Root Depth and Kc Values

Week	Kc	Root Depth (mm)
1	1.03	25.4
2	1.07	50.8
3	1.12	114.3
4	1.14	153.6
5	1.2	201.4
6	1.32	216
7	1.35	241.3
8	1.48	264.1
9	1.5	281.4
10	1.42	290.5
11	1.23	307
12	0.94	318.6
13	0.86	318.6

Calculations

Crop evapotranspiration (ETc) was calculated by Equation 1 using reference crop evapotranspiration (ETo) and Crop factor (Kc).

$$ETc = Kc \times ETo \quad \text{..... (Eq. 1)}$$

The ETo ws calculated using the FAO Penman-Monteith equation:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \text{---------- (Eq. 2)}$$

where, Eo = the reference evapotranspiration, Rn = the net radiation on the crop surface, G = soil heat flux density = mean air temperature at 2 m for the day, u2 = wind speed at 2 m, es = saturation, vapour pressure, ea = actual vapor pressure, es - ea = vapor pressure deficit, Δ = slope of the saturation vapor pressure curve, and γ = psychrometric constant.

Field Capacity Deficit (FCD)

FCD is the additional water required to bring the soil moisture back to field capacity. It was calculated weekly based on root zone depth and current moisture levels. Different soil types have different water retention abilities, impacting the deficit.

Time to saturate

The time to saturate varied depending on the available moisture at the beginning of each weekly irrigation schedule. For ease of calculation, it was assumed that 80% of the moisture loss from the field capacity level occurred at the start of each irrigation

week. This loss is attributed to root uptake during the irrigation interval (delivery gaps). The amount of moisture lost is considered as the Field Capacity Deficit (FCD), as discussed in Section 3.2. The time to saturate was calculated by dividing the moisture deficit by the unsaturated hydraulic conductivity. The unsaturated hydraulic conductivity was assessed using the Van Genuchten–Mualem model (Equation 3).

$$K(\theta) = K_s S_e^{l} \left[1 - (1 - S_e^{1/m})^{m}\right]^{2} \quad \text{..... (Eq. 3)}$$

where: K(θ) = Unsaturated hydraulic conductivity, Ks = Saturated hydraulic conductivity, Se = Effective saturation, m and n = Empirical parameters (m=1−1/n), τ = Pore connectivity parameter (often assumed as 0.5)

Infiltration Loss (IL)

Infiltration loss was estimated based on the time to saturate and the Saturated Hydraulic conductivity (Ks), using Equation 3 (Deficit time after time to saturate-t) * Ks

$$t = \frac{(\theta_{sat} - \theta_{fc}) \times Z_r}{K_s} \quad \text{..... (Eq. 3)}$$

where, t = time to drain to FC (in days), θsat = volumetric water content at saturation, θfc = volumetric water content at field capacity, Zr = root zone depth (in mm), Ks=saturated hydraulic conductivity (mm/day).

Total irrigation Requirement

The Crop water requirement for each scheduling interval (7 days) was calculated using Equation 4.

Irrigation water requirement = Etc*7 + FCD + IL ..... (Eq. 4)

Results and Discussion

Figure 1 illustrates that the crop water requirement of The CWR differs significantly with the weather, weekly assessment of root depth, and spatial distribution of soil properties. Among the four series of soils investigated, Huruluwewa and Dikwewa possess higher CWR than the other two series. This can be attributed to their higher hydraulic conductivity (Ksat) values, which lead to increased infiltration rates throughout the week. Consequently, maintaining ET demand and ensuring soil moisture at FC and WP necessitates a higher water supply for these fields than other soil series in the scheme.

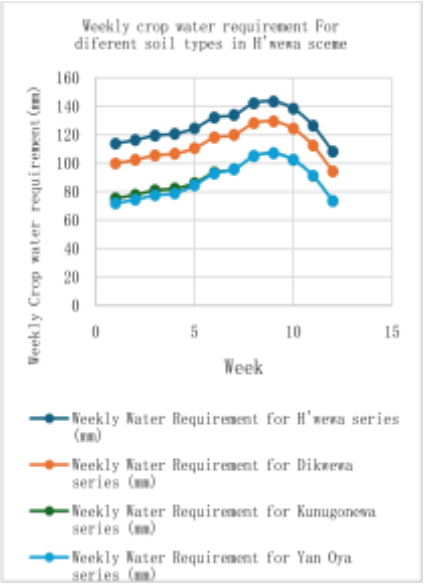

Figure 1. Weekly crop water requirement for different soil types

These findings highlight the importance of real-time parameters, root depth, and soil type-based CWR analysis in optimizing water content while maintaining soil moisture at field capacity (FC) and the wilting point (WP). This balance ensures aerobic conditions in the subsoil, which is crucial for minimizing methane emissions that typically occur under saturated and anaerobic conditions.

Figure 2 further illustrates how the Kunugonawa and Yanoya soil series remain unsaturated after the fourth week of the schedule while maintaining aerobic conditions. This prevents methane emissions by allowing air to enter the subsurface. The real-time assessment of crop water requirements, based on root depth and soil properties, ensures an optimal water supply for evapotranspiration while maintaining soil moisture within the range of field capacity (FC) and wilting point (WP). This balance supports efficient water management while maintaining favourable soil aeration.

Excessive percolation in the Huruluwewa and Dikwewa series requires more water to meet crop water demand. However, due to high hydraulic conductivity, the soil quickly becomes saturated, leading to anaerobic conditions that limit oxygen availability and hinder photosynthesis in rice plants.

Reducing rotational time can help manage high-conductivity soils like Huruluwewa and Dikwewa by ensuring frequent water supply without prolonged saturation, preventing anaerobic conditions, and supporting maximum yield from these soil types.

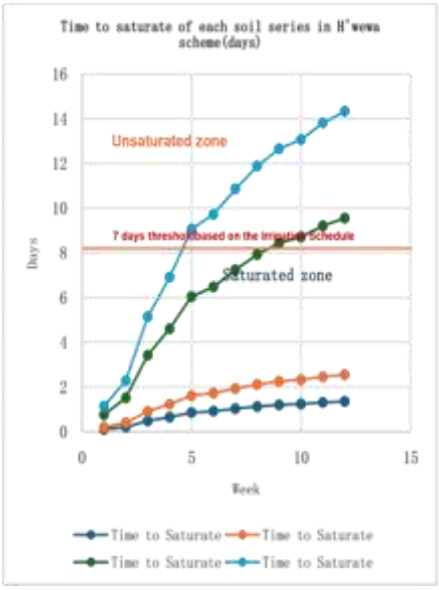

Figure 2. Time to saturate different soil types in Huruluwewa scheme

Conclusion

This study demonstrates the value of integrating real-time weather data, soil characteristics, and crop parameters to assess crop water requirements. Through Python scripting and precise weekly evaluation, water can be supplied efficiently, reducing methane emissions and ensuring sustainable rice production. The proposed methodology is scalable to other irrigation schemes and adaptable to real-time monitoring systems. It aligns with sustainable development goals by enhancing climate resilience, conserving water, and reducing greenhouse gases in agriculture.

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Longitudinal and Temporal Variations in Water Quality of rehabilitated Cascade Systems in Sri Lanka: A comparative study of Mathawaiththkulam and Thudduwahikulam

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Introduction

Tank cascade systems are interconnected tanks, especially in the dry zone, which are essential for sustaining agricultural productivity and livelihoods. However, decades of neglect, poor land-use practices, and climate-induced stress have degraded their ecological balance and water quality (Karaouzas et al. 2017). The Climate Resilient Integrated Water Management Project (CRIWMP), implemented in the Vavuniya District of Sri Lanka, has rehabilitated Mathawaiththkulam and Thudduwahikulam cascades to restore their functionality prior to 2021. Yet, systematic studies evaluating post-rehabilitation water quality changes are limited.

Cascade tank systems are a vital component of Sri Lanka's traditional water resource management, especially in the dry zone, where seasonal rainfall patterns require efficient storage and distribution mechanisms (Ratnayake et al. 2024). The ecological and hydrological functioning of these systems has been studied in multiple contexts, but limited literature explores their post-rehabilitation performance from a water quality perspective. This study examined the longitudinal, temporal, vertical, and seasonal variations in water quality within two cascade systems—Mathawaiththkulam and Thudduwahikulam—located in the Dry zone (DZ) of Sri Lanka.

Methodology

The rehabilitation works carried out by the CRIWMP in cascades included tank head works and infrastructure improvements, de-silting, upper and lower catchment improvements and protections, ecosystem restoration and community mobilization for best practices.

A total of 56 samples were collected from 10 tanks within the Mathawaiththkulam (35.7%) and Thudduwahikulam (64.3%) cascades in Vavuniya District in Sri Lanka. Distribution of tanks in the two cascades are presented in Figure 1. Samples were distributed across upper (42.9%), middle (35.7%), and lower (21.4%) cascade locations. Surface (51.8%) and 1-meter below depth (48.2%) samples were analysed to evaluate vertical variation

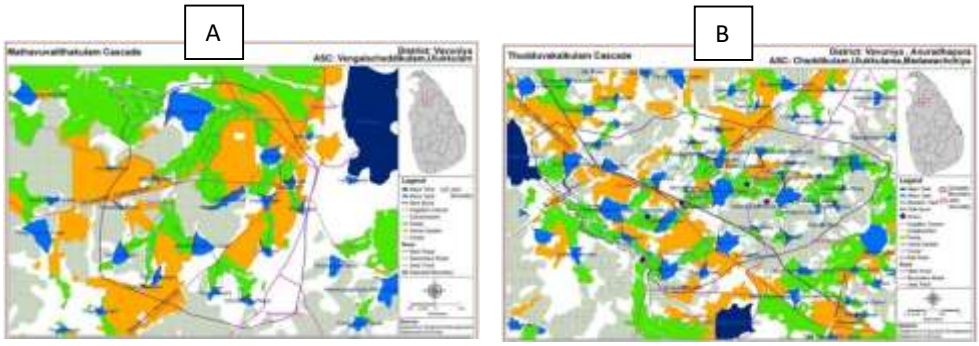

Figure 1.Distribution of tanks in the Mathawaithikulam cascade (A) and Thuduwakkaikulam cascade (B)

Water samples were collected from tanks in both cascades during 2022, 2023, and 2024, from various cascade positions (upper, middle, lower), depths; surface and sub-surface (1-meter below), and during both wet and dry seasons. Tests covered physical parameters (colour, turbidity), chemical parameters (pH, EC, chloride, alkalinity, nitrate, phosphate, hardness, TDS, sulphate, fluoride, iron, calcium, manganese), and bacteriological parameters (coliform count). Data were statistically analysed using ANOVA and mean comparisons to identify significance levels. The National Water Supply and Drainage Board (NWSDB) conducted all laboratory tests

Results and Discussion

Temporal Trends

Despite some seasonal and catchment-related fluctuations, the overall trajectory suggested improvements in several water quality indicators (Table 1), particularly in Mathawaiththkulam. In Mathawaiththkulam, mean turbidity significantly declined from 17.26 NTU in 2023 to 2.75 NTU in 2024 ($P<0.05$), indicating enhanced sediment control likely due to installed soil filtration traps and upper catchment improvements.

Table 1. Summary of Key Water Quality Parameters (2023–2024)

Parameter	MK* (2023)	MK (2024)	TK (2023)	TK (2024)
Turbidity (NTU)	17.26	2.75	21.13	8.60
pH	7.89	7.60	7.36	7.73
Chloride (mg/L)	45.31	70.00	61.42	129.20
Nitrate (mg/L)	7.04	2.00	7.71	4.10
Coliform (CFU/100mL)	344.42	106.00	604.60	217.33

*MK = Mathawaiththkulam; TK = Thudduwahikulam

In contrast, Thudduwahikulam exhibited greater variation; turbidity increased from 6.46 NTU (2022) to 21.13 NTU (2023) before falling to 8.60 NTU in 2024 (Table 1). This pattern suggests episodic sediment inflow possibly linked rainfall. pH levels in both cascades remained within acceptable ranges (6.5–8.5), though a minor decline was noted in Mathawaiththkulam (7.89 to 7.60) and a slight increase in Thudduwahikulam (7.36 to 7.73) from 2023 to 2024.

Chloride and nitrate levels, sensitive indicators of agricultural runoff, displayed divergent trends. Mathawaiththkulam saw a gradual increase in chloride (45.31 to 70.00 mg/L) and a reduction in nitrate (7.04 to 2.00 mg/L). This suggests effective nutrient control at post-rehabilitation. Conversely, Thudduwahikulam's nitrate levels remained comparatively elevated (7.71 in 2023, 4.10 in 2024), corroborating earlier findings by Jeyaruba and Thushyanthy (2009) that poor land-use in upstream areas contributes to high nutrient loading.

Coliform counts showed notable reductions in both cascades (Table 2). Mathawaiththkulam dropped from 344.42 to 106.00 CFU/100mL between 2023 and 2024, a significant improvement attributed to improved sanitation awareness and catchment protection.

Table 2. Summary of Key Water Quality Parameters Across Cascades

Parameter	MK* - Middle	MK - Lower	TK - Upper	TK - Middle	TK - Lower
Turbidity (NTU)	6.51	3.78	59.26	2.39	10.67
pH	8.04	7.57	7.49	7.64	7.63
EC (µS/cm)	48.5	232.0	102.5	252.17	199.33
Chloride (mg/L)	12.5	91.17	38.25	131.66	77.5
Total Alkalinity (mg/L)	15.25	259.83	72.45	344.5	219.5
Nitrate (mg/L)	4.0	2.52	12.15	1.75	4.33
Fluoride (mg/L)	0.22	0.91	0.2	1.21	0.84
TDS (mg/L)	47.0	406.57	107.25	611.0	401.0
Total Hardness (mg/L)	46.25	224.67	77.0	302.83	187.33
Iron (mg/L)	0.82	0.13	2.16	0.09	0.16
Coliform (CFU/100ml)	413.0	320.75	485.0	405.25	668.0

*MK = Mathawaiththkulam; TK = Thudduwahikulam

Thudduwahikulam also demonstrated a reduction (604.60 to 217.33 CFU/100mL), though absolute values remained higher, echoing concerns from Rajasooriyar and Suriyakumari (2014) on persistent microbial contamination in agricultural zones. The improved parameters in Mathawaiththkulam align with sustainable management strategies including perennial cropping, CSO facilitation, and land-use zoning. In contrast, Thudduwahikulam's mixed results highlight the continued impact of unregulated upstream activities.

Longitudinal Variation

The analysis of longitudinal water quality across the two cascade systems revealed significant spatial variability in physical, chemical, and bacteriological parameters. Turbidity levels were significantly lower in the Mathawaiththikulam cascade compared to Thudduwahikulam. For example, turbidity reduced from 6.51 NTU in the middle section to 3.78 NTU at the lower end in Mathawaiththikulam (Table 2), suggesting effective sediment control, soil filtration traps and/or since higher water capacity in the lower tanks, has tendency for dilution. Conversely, Thudduwahikulam's turbidity (Table 2) showed erratic distribution, ranging from 59.26 NTU (upper) to 10.67 NTU (lower), reflecting upstream erosion and inadequate sediment trapping. This supports past findings by Abeysinghe et al. (2015), who highlighted that unprotected upper catchments significantly affect downstream water clarity.

The pH levels across both cascades remained within acceptable ranges (7.4–8.1). However, a marked increase in Electrical Conductivity (EC) and Total Dissolved Solids (TDS) was observed downstream, particularly in Mathawaiththikulam (from 48.5 to 232 µS/cm EC; 47 to 406.6 mg/L TDS) (Table 2), aligning with studies by Pathirana et al. (2020) which reported that evaporation and solute concentration amplify with downstream flow.

Chloride levels followed similar trends (Table 2), surging from 12.5 mg/L to 91.2 mg/L in Mathawaiththikulam and 38.2 mg/L to 77.5 mg/L in Thudduwahikulam. Total Alkalinity and Hardness showed substantial increases downstream in both systems, especially in Mathawaiththikulam (15.3 to 259.8 mg/L Alkalinity and 46.3 to 224.7 mg/L Hardness), which may be linked to geochemical interactions intensified by agricultural runoff, as also indicated by Jayasekara et al. (2018).

Notably, Nitrate (NO_3^-) levels (Table 2) were higher in the upper Thudduwahikulam (12.15 mg/L) compared to downstream tanks (4.33 mg/L), indicating the possible influence of localized fertilizer application. In contrast, Mathawaiththikulam exhibited lower and more stable nitrate levels across its reach, suggesting better adoption of perennial cropping systems.

Fluoride levels increased along the flow path in both cascades (Table 2). The highest concentration (1.21 mg/L) was recorded in the middle Thudduwahikulam segment. Iron was highest at the upper section of Thudduwahikulam (2.16 mg/L), possibly due to lateritic soil leaching, a phenomenon also observed by Fernando et al. (2013). Coliform counts exceeded 300 CFU/100ml across most tanks, peaking at 668 CFU/100ml in Thudduwahikulam's lower section. Though Mathawaiththikulam recorded lower averages (320.75 CFU/100ml), all values surpassed the acceptable limit for human consumption, emphasizing the need for continued community awareness and hygiene interventions.

Vertical Variation

The analysis of water quality parameters revealed significant spatial and vertical variations after post-rehabilitation. Surface and subsurface (1-meter below) depth samples were

assessed for all tanks and in Mathawaiththkulam, tanks such as Iyankankulam and Sinnathambanyikulam showed marked improvements in chemical and bacteriological parameters.

Surface water colour ranged between 71.33 and 125.5 PCU, whereas sub-surface values were more stable (Table 3), indicating sedimentation and improved catchment filtration. The pH values across both depths remained within neutral to slightly alkaline ranges (7.57–8.08), aligning with Herath and Ratnayake (2010), who noted similar stratification in Kurunegala.

Table 3. Key Water Quality Parameters

Parameter	**Cascade***	**Surface Mean**	**1m Depth Mean**	**Notable Observation**
Colour (PCU)	MK	71.33–125.5	87.5–289.5	Higher sedimentation
pH	TK	7.56–7.69	7.34–7.80	Stable pH
EC (µS/cm)	MK	233	231	Low variability
Chloride(mg/L)	TK	130.33	133	Higher in tanks
Coliform (CFU/ 100ml)	MK	220.25–554.5	271.5–404	Lower levels

*MK = Mathawaiththkulam; TK = Thudduwahikulam

Electrical conductivity (EC) values in Mathawaiththkulam averaged 233 µS/cm at the surface and 231 µS/cm at depth (Table 3), showing stable ion concentration after rehabilitation. These values, though lower than those in Thudduwahikulam's (254–250 µS/cm), reflect better upper catchment management and reduced fertilizer runoff. Fonseka et al. (2024) emphasized such patterns, attributing lower EC to improved land use practices.

Chloride concentrations (Table 3) were significantly elevated in Mathawaiththkulam's lower tanks, with means rising from 87.67 to 94.67 mg/L, particularly at sub surface. Conversely, Thudduwahikulam showed high variability, reporting 130.33–133 mg/L, likely due to intensified agriculture upstream (Jeyaruba and Thushyanthy 2009). Notably, total alkalinity in both cascades displayed vertical variation. Mathawaiththkulam recorded values between 127.5–262.67 mg/L (surface to sub surface), while Thudduwahikulam's tanks ranged from 94.5–344.67 mg/L. These values are within expected ranges post-monsoon, reinforcing the dilution theory of Rajasooriyar and Suriyakumari (2014).

Bacteriological analysis (Table 3) showed that Mathawaiththkulam had comparatively lower coliform counts (220.25–554.5 CFU/100ml) than Thudduwahikulam (up to 902 CFU/100ml). This suggests that CSO-led awareness and catchment protections were more effective in Mathawaiththkulam. TDS and hardness were notably higher in the Thudduwahikulam cascade. For instance, TDS in Oddaisalanbakulam exceeded 600 mg/L, while Mathawaiththkulam peaked at 475 mg/L. These findings align with observed groundwater and subsurface interactions.

As such, Mathawaiththkulam cascade benefited more from integrated catchment improvements, sustainable land use changes, and community engagement, which collectively led to sustained improvements in water quality. Thudduwahikulam, while improved, exhibited higher variability, suggesting partial success of interventions and the need for enhanced management practices.

Seasonal Variation

This comparative analysis of the water quality variation results reflected substantial shifts in physical, chemical, and bacteriological parameters between dry and wet seasons. In Mathawaiththkulam cascade, turbidity and color levels (Table 4) showed lower variability in both seasons, with mean turbidity values remaining under 5 NTU at most sampling points, except Puliyankulam during the dry season (mean = 50.75 NTU), suggesting episodic erosion or sediment inflow. In contrast, Thudduwahikulam experienced higher seasonal disparity. For example, Damenawawa reported dry season turbidity at 108 NTU, sharply dropping to 10.52 NTU in the wet season, indicating sedimentation stabilization through upper catchment control.

Table 4. Summary of Seasonal Water Quality Variation in the Two Cascades

Parameter	Cascade	Dry Season Mean	Wet Season Mean
Turbidity (NTU)	Thudduwahikulam	108 (Damenawawa)	10.52(Damenawawa)
Turbidity (NTU)	Mathawaiththkulam	3.12–50.75	3.17–11.43
Nitrate (mg/L)	Thudduwahikulam	19.95 (Damenawawa)	4.35(Damenawawa)
Nitrate (mg/L)	Mathawaiththkulam	2.5–4.5	2–4.1
Coliform (CFU/100mL)	Thudduwahikulam	668 (Muthliyarkulam)	NA
Coliform (CFU/100mL)	Mathawaiththkulam	690.5 (Iyankankulam)	135.5(Iyankankulam)

Chemical parameters such as pH, EC, chloride, and total alkalinity exhibited better stability in Mathawaiththkulam across both seasons (Table 4). The pH range, EC values were indicating suitable and stable conditions for aquatic life and irrigation. Nitrate concentrations highlighted a clear divergence. Thudduwahikulam exhibited elevated nitrate values during the dry season (e.g., Damenawawa mean = 19.95 mg/L), while in Mathawaiththkulam, nitrate levels remained relatively low throughout (mean < 5 mg/L), signifying more effective nutrient runoff control—likely a result of perennial crop transitions and soil filtration traps. These findings support earlier conclusions by Rajasooriyar and Suriyakumari (2014) regarding the benefits of catchment regulation on nitrate retention.

Coliform contamination (Table 4) posed significant concerns in both cascades. While Mathawaiththkulam showed seasonal decline in coliform counts, Thudduwahikulam maintained high levels across most tanks, particularly in dry seasons (e.g., Muthliyarkulam mean = 668 CFU/100mL). Such persistence suggests unresolved sanitation linkages or livestock access, in line with observations by Fonseka et al. (2024).

Seasonal variations were statistically significant in most parameters including nitrate, iron, and total alkalinity (ANOVA, $P < 0.05$), reflecting the influence of rainfall and flow regulation. Comparatively, Mathawaiththkulam demonstrated a more consistent post-rehabilitation water quality trend, likely due to comprehensive upstream interventions.

These results affirm the effectiveness of integrated rehabilitation in enhancing water quality, particularly where upstream agricultural reforms and community participation are strong. Expansion of such interventions must consider localized hydrological behavior and catchment characteristics, as supported by Herath and Ratnayake (2010), to ensure sustainable outcomes across different tank cascades.

Comparative results across four scenarios confirm Mathawaiththkulam's superior water quality improvements post-rehabilitation. Temporal trends from 2022–2024 show significant turbidity and nitrate reduction. Longitudinal data indicates better sediment and nutrient control downstream, unlike Thudduwahikulam, which showed erratic turbidity and elevated nitrate in upper sections. Vertical comparisons reveal consistent chemical stability in Mathawaiththkulam at both surface and sub surface; 1-meter depth, contrasting with Thudduwahikulam's higher subsurface contaminants. Seasonal variation highlights dry season vulnerability in Thudduwahikulam (e.g., turbidity = 108 NTU), while Mathawaiththkulam remained stable due to soil filtration and land-use changes. These outcomes demonstrate the positive impact of integrated catchment and community interventions, affirming the need for localized strategies in cascade rehabilitation.

Conversely, Thudduwahikulam, while structurally rehabilitated, showed slower improvement. Continued use of agrochemicals, lack of vegetative cover, and limited CSO engagement were likely contributors. The disparity is evident in trends of EC and nitrate: while Mathawaiththkulam's EC drastically reduced in 2024, Thudduwahikulam's increased. Moreover, community-led land use practices proved crucial in sustaining water quality gains beyond physical infrastructure

Conclusion

This study comprehensively examined the longitudinal, temporal, vertical, and seasonal variations in water quality along the rehabilitated Mathawaiththkulam and Thudduwahikulam cascades. The results revealed distinct spatial variation along the cascade flow direction, with significant reductions in turbidity, nitrate, and coliform counts from upper to lower tanks, particularly in Mathawaiththkulam. This pattern demonstrates the effectiveness of sedimentation, natural filtration, and increased retention time within cascade sequences. Downstream improvements in parameters such as EC, alkalinity, and TDS reflect cumulative geochemical interactions and dilution effects. Vertical analyses confirmed stability at 1-meter depths, while seasonal data highlighted peak contamination during dry periods, emphasizing the role of flow dynamics. These findings validate the hypothesis that integrated rehabilitation, when combined with catchment interventions and controlled land use, yields sustained water quality improvements throughout the

cascade. Future programs must focus on maintaining upstream controls, enhancing sediment and nutrient retention in upper tanks, and institutionalizing regular monitoring to optimize cascade-wide water quality performance and long-term resilience.

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Study on Water Quality Changes and Behavioral Variations in Roof Rainwater Harvesting Systems Installed in the Dry Zone of Sri Lanka

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Introduction

The Dry zone (DZ) of Sri Lanka is marked by arid and semi-arid climatic conditions, receiving limited and irregular rainfall, primarily during the second inter-monsoon and Northeast Monsoon (October–February) with the remainder of the year, is characterized by dry periods, high evaporation rates, and declining surface water availability. Communities in this region face recurring water scarcity and rely heavily on seasonal water bodies, shallow wells, and groundwater sources, many of which dry up during droughts. This situation is worsened by unsustainable agricultural practices, over-extraction of groundwater, and contamination from excessive use of agrochemicals, leading to nitrate, phosphate, and heavy metal pollution. The resulting health crisis includes widespread cases of Chronic Kidney Disease of Unknown Etiology (CKDu), with regional prevalence rates as high as 22.9% in districts like Anuradhapura, Polonnaruwa, and Badulla.

To mitigate these challenges, Roof Rainwater Harvesting Systems (RWHS) have been introduced as decentralized, climate-resilient water solutions. In 2017, the Climate Resilient Integrated Water Management Project (CRIWMP) was launched by the Ministry of Irrigation with support from the United Nations Development Programme (UNDP) and other national stakeholders under the GCF fund. Under Output 2 of the project, more than 4,000 RWHS units were installed across seven districts of the Dry Zone to enhance access to safe drinking water, strengthen resilience to climate-induced water stress, and support rural health, livelihoods, and education.

Although RWHS offers clear potential, its long-term success is dependent on both technical reliability and community engagement. Studies have shown that the effectiveness of RWHS is compromised when key components such as gutters, first-flush systems, filters, and sealed tank covers are absent or poorly maintained. For example, Kandasamy and Nilmini (2014) observed that nearly 50% of RWHS lacked basic filtration systems, and only 15% were equipped with first-flush devices, contributing to water contamination and system abandonment. Goonewardene (2012) pointed out that small tank capacities lead to

underutilization of rainfall and emphasized the potential of combining rooftop harvesting with dug well recharge for greater sustainability.

Furthermore, behavioral factors such as cleaning routines, perceptions of water safety, and lack of technical knowledge are key contributors to system underperformance. According to Balasuriya and Arachchige (2021), only around 10% of households use rainwater for drinking, despite its low chemical content, largely due to distrust and lack of awareness. This concern is echoed in school settings, where operational and maintenance challenges often lead to system disuse due to unclear responsibilities and inadequate follow-up (NWSDB 2015).

This paper evaluates spatial and temporal water quality changes and the impact of user behavior on RWHS performance in CRIWMP districts, and the effectiveness of our interventions in addressing these challenges. The study analyzes physical (turbidity, color), chemical (pH, EC, TDS), and bacteriological (coliforms, E. coli) parameters across diverse settings, while also examining environmental and operational variables, including tank design, first-flush usage, cleaning frequency, and user awareness. By integrating these insights, the study aims to offer evidence-based recommendations for improving RWHS design, user training, and policy development, enhancing the long-term effectiveness of rainwater harvesting as a climate-resilient water supply solution.

Methodology

Study Area and Sample Selection

The study was conducted in Sri Lanka's Dry zone across seven districts, namely, Anuradhapura, Polonnaruwa, Kurunegala, Trincomalee, Vavuniya, Puttalam, and Mannar, where over 4,000 Roof Rainwater Harvesting Systems (RWHS) were installed under the Climate Resilient Integrated Water Management Project (CRIWMP) from 2017 to 2024. A stratified random sample of 1041 RWHS was selected to ensure representation across geographic regions.

Table 1. Number of samples obtained from different districts

District(s)	Number of Samples
Trincomalee	65
Vavuniya and Mannar	291
Anuradhapura	342
Polonnaruwa	41
Kurunegala	302

Water Quality Sampling and Testing

Water samples were collected directly from RWHS tanks at three intervals per year, covering both dry and wet seasons between 2021 and 2024. Following APHA (2017) standard methods, samples were tested for (a) Physical parameters: Colour, turbidity, (b) Chemical parameters: pH, electrical conductivity (EC), total dissolved solids (TDS), and (c)

Bacteriological parameters: Total coliforms and *E. coli.* Samples were analysed at certified laboratories with field validation using portable kits, ensuring reliability through proper handling and a 6-hour testing window for bacteriological samples. Table 2 provides water quanlity parameters measured and their standard values.

Table 2. Water Quality Sampling tested Parameters and its standard values.

Parameter	**Standard Limit**	**SI Unit**
Colour	≤ 15	Hazen units
Turbidity	≤ 2.0	NTU
Electrical Conductivity	≤ 500	µS/cm
Total Dissolved Solids (TDS)	≤ 500	mg/L
pH	6.5 – 8.5	–
Coliform	≤ 3 per 100 mL	Count/100 mL
E. coli	0 per 100 mL (should be absent)	Count/100 mL

Intervention and Training Monitoring

All RWHS users in the sample group participated in training sessions conducted by CRIWMP with the Department of National Community Water Supply (DNCWS) between 2018 and 2023. They received a color-coded, bilingual maintenance guidebook (Sinhala/Tamil) and participated in hands-on sessions on tank cleaning, filter maintenance, and safe water handling.

Data Analysis and Visualization

All quantitative data were analyzed using Microsoft Excel. Descriptive statistics and cross-tabulations were employed to examine variations in water quality and user practices. Additionally, a combination of MATLAB and Microsoft Excel was used for further quantitative analysis and data visualization. Bar graphs and scatter plots were used to visualize behavioral trends and quality comparisons. Qualitative data were transcribed and analyzed using thematic coding techniques to identify recurring behavioural patterns, attitudes, and knowledge gaps among users.

Results and Discussion

Overview of Water Quality Failures

A total of 1,041 water samples collected from RWHS tanks across five districts were analysed for compliance with national drinking water standards specified by SLS 614: 2013 and the Ambient Water Quality Standards Gazette by CEA. The results (Table 3) revealed that overall failure rates varied significantly across parameters, with the highest number of failures recorded in bacteriological and chemical parameters.

As indicated in Table 4, (a) Coliform contamination was observed in 698 samples (67.05%)**,** making it the most critical issue across all locations, (b) *E. coli***,** an indicator of fecal contamination, failed in 542 samples (52.07%) confirming the widespread presence of pathogens and pointing to serious public health risks, (c) pH non-compliance was found in 279 samples (26.8%)**,** indicating either acidic or alkaline water conditions that may affect

taste and chemical stability, (d) Turbidity failures were detected in 198 samples (19.02%), exceeding the acceptable limit for visual clarity and microbial safety, (e) Failures in TDS (1.15%) and electrical conductivity (1.34%) were comparatively low, suggesting that chemical contamination from dissolved solids is less of a concern, and (g) Colour deviations were minimal (4.42%), likely influenced by organic matter or storage conditions.

Table 3. The percentages and total number of failures with Parameters and districts.

District	No. of samples	Colour	Turbidity	Electricity Conductivity	TDS*	pH	Coliform	*E. coli*
		Numbers failing						
Trincomalee	65	0	0	0	0	6	38	21
Vauniya & Mannar	291	17	9	3	7	57	134	117
Anuradhapura	342	0	61	3	1	100	328	229
Polonnaruwa	41	2	1	0	2	2	29	8
Kurunegala	302	27	127	8	2	114	169	167
Sub Total	1041	46	198	14	12	279	698	542

*TDS = total dissolved solids

Table 4. The percentage of failing samples

District	Colour	Turbidity	Electricity Conductivity	TDS*	pH	Coliform	*E. coli*
	Percentage of Samples failed						
Trincomalee	0.00	0.00	0.00	0.00	9.23	58.46	32.31
Vauniya & Mannar	5.84	3.09	1.03	2.41	19.59	46.05	40.21
Anuradhapura	0.00	17.84	0.88	0.29	29.24	95.91	66.96
Polonnaruwa	4.88	2.44	0.00	4.88	4.88	70.73	19.51
Kurunegala	8.94	42.05	2.65	0.66	37.75	55.96	55.30

*TDS = total dissolved solids

Coliforms and *E. coli* accounted for more than 50% and 67% of total failures, respectively, followed by pH and turbidity. This emphasizes that biological contamination is the primary water quality challenge in RWHS tanks.

District-Wise Variation

There were notable differences in parameter compliance across districts (Figure 1). Anuradhapura reported the highest bacteriological failure rates, with 95.91% for coliforms and 66.96% for *E. coli*, alongside 29.24% of samples failing pH standards. Vavuniya and Mannar had significant microbial contamination (46.05% for coliforms and 40.21% for *E. coli*), indicating moderate system vulnerability. Kurunegala had the highest rate of turbidity failures (42.05%), and also recorded 114 pH failures (37.7%). Polonnaruwa and Trincomalee had lower failure rates overall, though localized issues with pH and microbial indicators were still present. These spatial differences reflect the influence of environmental factors

(dust, organic matter, animal activity) and user behavior, such as irregular cleaning, open tank lids, and absence of first-flush systems.

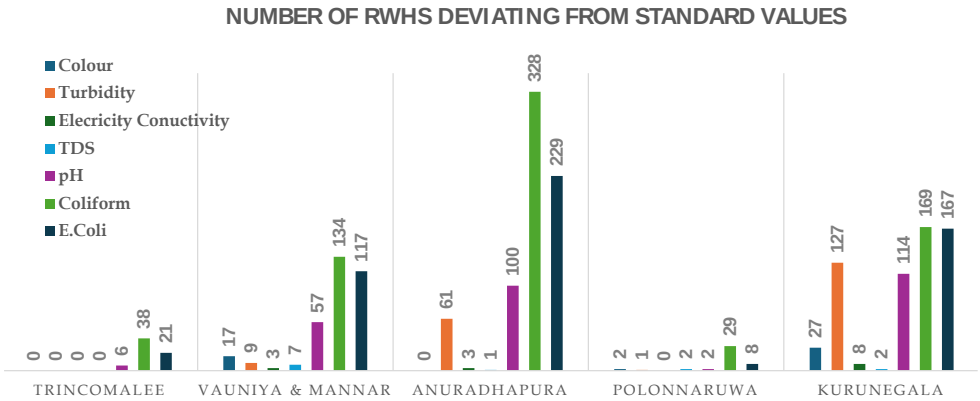

Figure 1. Number of RWHs deviating from standard values with selected regions

Implications for RWHS Design and Use

The predominance of microbial contamination suggests that while rainwater itself is generally safe, the collection and storage process is highly susceptible to external contamination. Open or poorly sealed tanks, lack of pre-filtration, and infrequent maintenance contribute to bacterial growth. Observations confirmed that many households did not use first-flush diverters or clean their tanks regularly key contributors to water quality deterioration. Interestingly, districts with higher training engagement under the CRIWMP program showed slightly better compliance in physical and chemical parameters, supporting the value of capacity building and district-level Resource Pools. Additionally, the use of specially designed PVC tanks and the distribution of guidebooks in Sinhala and Tamil improved maintenance routines in several communities, though behavior adoption varied.

These findings are consistent with previous studies by Kandasamy and Nilmini (2014) and Balasuriya & Arachchige (2021), which reported microbial contamination as the main limitation of RWHS in Sri Lanka. The current study confirms this at a larger scale and links it directly with observable behavior and system design gaps. Moreover, the results validate those of Goonewardene (2012) about the limitations of small tanks and the importance of proper pre-treatment. The relatively low rate of chemical failures aligns with literature that considers harvested rainwater less prone to heavy metal or chemical pollution compared to groundwater.

Conclusion

Through comprehensive water sampling and user behaviour analysis in five districts and over 1,041 systems, the research identified significant spatial and operational disparities in RWHS effectiveness. The results revealed that 67.05% of samples failed coliform tests, and

52.07% failed for *E. coli*, highlighting serious microbiological contamination. pH imbalances were present in nearly 27% of samples, while turbidity failures accounted for 19%. In contrast, chemical indicators like TDS and electrical conductivity showed low failure rates (<2%).

These results confirm that the primary threats to harvested rainwater safety are biological, rather than chemical, and are largely linked to maintenance behavior and infrastructure completeness. Districts with higher system use, poorer maintenance, or lack of first-flush and filter mechanisms recorded elevated failure rates. The variation in user practices and awareness had a direct influence on water safety outcomes. While RWHS offers a promising solution to water scarcity in drought-prone areas, the study reveals that hardware alone is insufficient. Sustained system effectiveness depends on continuous user engagement, accessible guidance, and clear operation protocols. Encouragingly, the introduction of PVC tanks and bilingual guidebooks through CRIWMP contributed positively to system upkeep in some districts, but behavioral change remains inconsistent.

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Assessing Water Quality Risks across Tank Cascade Levels in Sri Lanka's Dry Zone: A Multi-Depth and Multi-District Study

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Introduction

Water quality is a critical factor influencing human health and agricultural productivity, especially in semi-arid regions such as Sri Lanka's dry zone. This study evaluated water quality dynamics in thirteen (13) major cascades—within the Vavuniya, Trincomalee and Anuradhapura Districts, where traditional water management systems are increasingly pressured by climate variability, population growth, and agricultural demands. Given the reliance of local communities on surface water bodies for drinking, irrigation, and livestock use, periodic assessments are vital to ensure water safety and sustainability.

Methodology

The study employed a cascade-based cross-sectional water quality assessment across 60 tanks within 13 cascade systems in the Vavuniya, Anuradhapura and Trincomalee Districts (Figure 1).

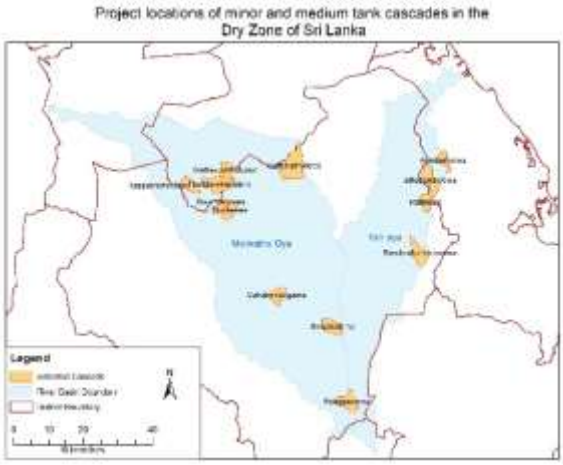

Figure 1. Distribution of cascades selected for surface and subsurface water quality evaluation across study districts

Water samples were collected at both surface and 1-meter depths during wet (n=16) and dry (n=44) seasons from end 2021 to 2024. Parameters analysed included physical (colour, turbidity), chemical (pH, EC, chloride, nitrate, fluoride, phosphate, iron, hardness), and bacteriological (total coliforms, E. coli) indicators, tested using standard methods. Results were compared to previous studies in particular region, WHO and Sri Lanka Standards (SLS). A stratified sampling method was employed to ensure representation across cascade levels (upper, middle, lower) and tank sizes. Sample points were geo-referenced using GPS and each was analysed for surface and sub-surface water (1-meter depth) to assess vertical variation. Water quality testing adhered to laboratory techniques at the National Water Supply and Drainage Board (NWSDB) laboratories.

Descriptive statistics, one-way ANOVA (P=0.05) were used to determine spatial and seasonal variation across parameters. ANOVA was used to test inter-cascade and seasonal differences with 95% confidence intervals. The SPSS v25.0 was used for statistical analysis

Results and Discussion

Table 1 shows that a majority of sampling sites were located in Vavuniya (51.3%) and Anuradhapura (42.7%), with limited representation from Trincomalee (6%), indicating focused cascade-based assessments in three major dry zone districts. The majority of samples (38.5%) were collected from the middle level of the cascade, with 34.2% from the top and 27.4% from the lower level. Most of the sampling occurred during the dry season (82.9%) and predominantly from the surface water layer (75.2%).

Table 1. Distribution of Demographic Data

Variable	Charachteristics	Total (n=117)		Vavuniya (n= 60)		Anuradhapura (n=50)		Trincomalee (n=7)	
		No.	%	No.	%	No.	%	No.	%
Level	Lower	32	27.4	14	23.3	16	32.0	2	28.6
	Meddle	45	38.5	26	43.3	16	32.0	3	42.9
	Top	40	34.2	20	33.3	18	36.0	2	28.6
Season	Wet Season	20	17.1	16	26.7	4	8.0	7	100.0
	Dry Season	97	82.9	44	73.3	46	92.0	0	0.0
Depth	1m Depth	29	24.8	29	48.3	0	0.0	0	0.0
	Top	88	75.2	31	51.7	50	100.0	7	100.0

The colour values of water in 13 cascades (Table 2) showed statistically significant variation (P=0.001) with a wide range from 18 Pt-Co units (Rathmale) to 454 Pt-Co units (Mathavaiththakulam), indicating localized differences in water quality. Several cascades—such as Kappachchikulam (mean 208.25) and Mathavaiththakulam (mean 122.45)—exceeded the SLS/CEA guideline of 100 Pt-Co units.

Turbidity levels across the cascades varied significantly (P=0.021), with Karambawewa showing the highest mean (151.9 NTU) and Sivalakulama the lowest (4.74 NTU). This wide variation suggests differences in sediment input, catchment erosion, or tank management.

Compared to Fonseka et al. (2024) who reported turbidity around 7 NTU in major irrigation tanks, several cascades—particularly Karambawewa and Diwulwewa—exhibited alarmingly higher levels, indicating greater vulnerability to sedimentation. In terms of physical quality, coloor and turbidity were notably higher in the dry season. Such elevated values are attributed to reduced inflows, tank desiccation, and accumulated organic matter during dry periods. These values significantly differ (ANOVA $p<0.05$), indicating strong seasonal influence.

Table 2. Surface Water Quality - Colour and Turbidity across 13 Cascades

Cascade Name	Mean Colour (Pt-Co)	Max Colour (Pt-Co)	Mean Turbidity (NTU)	Max Turbidity (NTU)
Mathavaiththakulam	122.45	454.0	14.36	190.00
Kappachchikulam	208.25	382.0	13.13	35.00
Thuduwakkaikulam	121.71	440.0	12.76	129.00
Diwulwewa	82.17	165.0	63.25	243.00
Karambawewa	79.67	131.0	151.90	570.00
Rathmale	31.00	51.0	10.60	23.50
Mahakirindegama	57.63	176.0	20.35	85.40
Palugaswewa	43.00	76.0	24.31	129.00
Bandarakumbukwewa	59.83	95.0	34.11	78.20
Sivalakulama	39.25	81.0	4.74	9.00
Aluthhalmilewawewa	34.67	52.0	13.20	27.90
Kumbukwewa	65.00	116.0	32.33	58.20
Ethabendiwewa	61.33	92.0	49.38	99.50

The pH values across the studied cascades ranged from 6.6 to 8.7, with no significant variation observed ($P=0.999$), indicating relatively stable chemical conditions among tanks. The overall mean pH values were within the acceptable range for irrigation and aquatic life (6.5–8.5), aligning closely with findings by Rajasooriyar and Suriyakumari (2014) in Vavuniya and Jeyaruba and Thushyanthy (2009) in Batticaloa.

Electrical conductivity (EC) values (Table 3) among cascades showed significant variation ($P=0.000$), with Diwulwewa (647.25 µS/cm) and Karambawewa (628.75 µS/cm) recording the highest means, while Mathavaiththakulam had the lowest (119.75 µS/cm). Several cascades, including Sivalakulama and Mahakirindegama, approached or exceeded 600 µS/cm, indicating moderate to high salinity levels. Compared to Kumudumali and Nirmanee (2019) who noted EC <1000 µS/cm across most Sri Lankan reservoirs, the results align with typical irrigation standards but after upper catchment improvement and changes of agricultural practices with ecosystem development it has observed significant improvement of EC.

Chloride concentrations among cascades displayed a significant variation ($P=0.001$), with Sivalakulama (126.5 mg/L), Karambawewa (123.0 mg/L), and Diwulwewa (116.1 mg/L) recording the highest means, whereas Bandarakumbukwewa (32.1 mg/L) and

Kappachchikulam (30.0 mg/L) showed lower levels. Compared to Kumari et al. (2019), who reported a wide chloride range (20–2,120 mg/L) in Ulagalla Cascade, these findings suggest localized salinity risks in certain tanks, possibly due to evaporation, runoff, or geochemical influences.

Table 3. Surface Water Quality - pH, EC, Chloride, Total Alkalinity, Nitrate across 13 Cascades

Parameter	**Range (Min–Max)**	**ANOVA**	**Notable Observations**
pH	6.60 – 8.70	F=0.173, P=0.999	No significant variation. All values within acceptable range (6.5–8.5) for irrigation and aquatic life.
Electrical Conductivity (µS/cm)	0 – 1248	F=6.051, P=0.000	Diwulwewa (647.3), Karambawewa (628.8) high; Mathavaiththakulam lowest (119.8). Moderate salinity observed.
Chloride (mg/L)	3.0 – 239.0	F=3.259, P=0.001	Sivalakulama (126.5), Karambawewa (123.0), Diwulwewa (116.1) high; localized salinity risks present.
Total Alkalinity (mg/L as $CaCO_3$)	3.0 – 412.0	F=3.307, P=0.001	Karambawewa (237.3), Aluthhalmilewawewa (229.0) exceeded SLS (200 mg/L); linked to bicarbonate and retention time.
Nitrate (mg/L as NO_3^-)	0.1 – 49.0	F=1.444, P=0.160	Not statistically significant; Mathavaiththakulam (6.25), Kappachchikulam (8.33) exceeded SLS (5 mg/L).

Total alkalinity levels (as $CaCO_3$) across 13 cascades (Table 3) showed a significant variation (P=0.001), with the highest mean values reported in Karambawewa (237.3 mg/L) and Aluthhalmilewawewa (229.0 mg/L), exceeding the SLS guideline of 200 mg/L. In contrast, Kappachchikulam and Bandarakumbukwewa recorded considerably lower means (53.0 mg/L and 74.9 mg/L). These findings align with Abeysingha et al. (2021), who also noted elevated alkalinity in dry zone tank cascades, likely due to high bicarbonate presence and prolonged retention in weathered regolith aquifers.

Nitrate levels (as NO_3^-) across cascades exhibited no statistically significant variation (P=0.160), though some localized elevations were observed. Mathavaiththakulam (mean: 6.25 mg/L) and Kappachchikulam (8.33 mg/L) exceeded the Sri Lanka Standards (SLSI) threshold of 5 mg/L, indicating possible agricultural runoff influences. In contrast, Karambawewa and Rathmale recorded the lowest levels (<1 mg/L). These trends are consistent with Abeysingha et al. (2021) and Herath (2021) who reported low-to-moderate nitrate levels in dry zone tanks, with higher values often linked to intensified farming activities.

Fluoride concentrations in the studied cascades varied significantly (P=0.000), with Thuduwakkaikulam exhibiting the highest mean (0.91 mg/L) and Bandarakumbukwewa the lowest (0.26 mg/L), indicating localized influences such as geology or seasonal variation. Phosphate levels were highest in Thuduwakkaikulam (0.78 mg/L), while many cascades remained below 0.3 mg/L. These values exceed those reported by Edirisinghe et al. (2020) who recorded an average of 0.16 mg/L, suggesting increased nutrient loading possibly due to agricultural runoff. Consistent with Fonseka et al. (2024), both parameters were likely influenced by dry-season concentration effects in minor tank systems of the Dry zone.

During the dry season, the TDS levels (Table 4) across the studied tank cascades exhibited significant spatial variability (p=0.001), with Karambawewa recording the highest mean (463.67 mg/L) and Bandarakumbukwewa the lowest (128.86 mg/L). Thuduwakkaikulam, Diwulwewa, and Mahakirindegama also showed elevated TDS concentrations, often exceeding 350 mg/L, suggesting possible salinity intrusion or evaporative concentration. Compared to earlier findings from the Northern Province by Dissanayake and Weerasooriya (1985), which reported much higher TDS levels (1,200–1,900 mg/L), the current values remain within acceptable freshwater limits. However, trends mirror those in Kumari et al. (2019), indicating moderate irrigation suitability in areas like Ulagalla, shaped by seasonal and anthropogenic factors.

Total Hardness (as $CaCO_3$) values varied significantly across cascades (ANOVA, p=0.000), with Karambawewa (mean=237.33 mg/L) and Diwulwewa (mean=214.00 mg/L) reporting the highest mean concentrations, exceeding levels in Mathavaiththakulam (mean=119.05 mg/L) and Kappachchikulam (mean=30.25 mg/L). These findings correspond with Chandrajith et al. (2012) and Rajasooriyar et al. (2003), who attributed high hardness in NCP tanks to regolith composition and seasonal evaporation. Weerasinghe et al. (2011) also noted similar moderate-to-hard water levels ranging from 60–240 mg/L. The present study reinforces earlier evidence, highlighting both geogenic and seasonal drivers of hardness variability in Sri Lanka's tank ecosystems.

The sulphate concentration (as SO_4^{2-}) in cascade samples showed broad variability, with mean values ranging from 1.3 mg/L in Mathavaiththakulam to 19.0 mg/L in Ethabendiwewa. The highest individual measurement reached 49.0 mg/L, while many cascades, including Kumbukwewa and Sivalakulama, showed moderate values. Although Mahakirindegama (14.75 mg/L) and Diwulwewa (11.44 mg/L) indicated elevated sulphate levels, the ANOVA test (p=0.102, F=1.620) suggested no statistically significant difference across cascades. These levels consistent with findings from Weerasinghe et al. (2016), who noted low sulphate concentrations in dry zone tanks due to limited industrial discharge and reduced sulphate-bearing mineral exposure.

The analysis of total iron concentrations revealed substantial spatial variation, with the highest mean observed in Kappachchikulam (3.13 mg/L) and Mathavaiththakulam (2.04 mg/L), whereas most other cascades, including Diwulwewa and Sivalakulama, remained below 0.2 mg/L. Despite elevated values in a few locations, the ANOVA test (p=0.840, F=0.580) indicated no statistically significant differences among cascades. These

findings corroborate Fonseka (2024), who reported iron concentrations of 2.38 ± 0.95 mg/L in Anuradhapura tanks during the wet season, exceeding WHO's 0.3 mg/L guideline water.

Table 4. Other Chemical Water Quality Parameters across Cascades

Parameter	ANOVA (P-value)	Highest Mean Value (mg/L)	Lowest Mean Value (mg/L)
Fluoride	0.000	0.91 (Thuduwakkaikulam)	0.26 (Bandarakumbukwewa)
Phosphate	0.128	0.78 (Thuduwakkaikulam)	<0.3 in most cascades
TDS	0.001	463.67 (Karambawewa)	128.86 (Bandarakumbukwewa)
Total Hardness	0.000	237.33 (Karambawewa)	30.25 (Kappachchikulam)
Sulphate	0.102	19.0 (Ethabendiwewa)	1.3 (Mathavaiththakulam)
Iron	0.840	3.13 (Kappachchikulam)	<0.2 in most cascades
Calcium	0.098	94+(Thuduwakkaikulam / Mahakirindegama)	Varied - no lowest specified
Manganese	0.002	0.24 (Diwulwewa)	Varied
Free ammonia	0.000	2.0 (Kumbukwewa)	Varied - most <0.3

Calcium concentrations varied widely, with Thuduwakkaikulam and Mahakirindegama showing elevated means above 94 mg/L, yet indicated no significant cascade-level differences (P=0.098). In contrast, manganese levels showed significant variation (p=0.002), particularly in Diwulwewa (0.24 mg/L) and Ethabendiwewa (0.23 mg/L), nearing WHO limits (0.4 mg/L). Free ammonia (n=51) also displayed significant differences (P=0.000), with Kumbukwewa recording an extreme value (2.0 mg/L), suggesting localized contamination. These trends align with Jayasundara et al. (2020), who attributed elevated calcium and manganese in dry zone tanks to mineral-rich catchments and the build-up of organic waste influencing ammonia levels in stagnant tank systems.

Bacteriological analysis

The analysis of total coliform levels across 13 cascades in the DZ (Tables 5 and 6) indicates, with mean values ranging from 310.36 MPN/100 mL in Mathavaiththakulam to an alarming 14,825 MPN/100 mL in Sivalakulama. These findings align with Bandara et al. (2021), who reported values between 500–2,400 MPN/100 mL in Vavuniya cascades, and Fernando et al. (2017), whose studies in Kurunegala and Puttalam recorded means near 1,100 MPN/100 mL. Similarly, Jayasinghe et al. (2019) and the CRIWMP Baseline Study (2020) confirm persistent contamination across the region, primarily driven by organic pollution, animal intrusion, and poor sanitation practices.

The bacteriological assessment of total E. coli in revealed considerable spatial variation, with mean values ranging from 7 CFU/100 mL in Aluthhalmilewawewa to 361 CFU/100 mL in Sivalakulama. Despite the observed variability, the ANOVA results (p=0.407) indicated no statistically significant differences among cascades. Comparatively, these findings align with the study by Mahagamage and Manage (2019), which reported widespread E. coli contamination in village tanks across Madawachchiya, Padaviya, and Kebithigollewa in

Anuradhapura, with levels consistently exceeding WHO and SLS thresholds, underscoring persistent microbial risks in rural irrigation water sources.

Table 5. Total Coliform Levels across Cascades

Cascade Name	Mean (MPN/100mL)	SD*	Min	Max
Mathavaiththakulam	310.36	260.63	78	920
Kappachchikulam	649.33	184.72	470	839
Thuduwakkaikulam	466.41	240.62	112	902
Palugaswewa	1720.0	nan	1720	1720
Bandarakumbukwewa	580.0	170.88	420	760
Sivalakulama	14825.0	4970.83	9200	21000
Aluthhalmilewawewa	1325.0	106.07	1250	1400

*SD = standard deviation

Table 6. Total *E. coli* Levels across Cascades

Cascade Name	Mean (CFU/100mL)	SD*	Min	Max
Palugaswewa	158.25	294.56	6.0	600.0
Bandarakumbukwewa	194.71	200.42	8.0	480.0
Sivalakulama	360.75	371.76	20.0	1000.0
Aluthhalmilewawewa	7.0	1.41	6.0	8.0

*SD = standard deviation

Surface water quality vs sub surface water quality (in 1 meter depth)

The comparative analysis of surface and subsurface water quality within cascades in the Vavuniya District highlights distinct spatial and vertical variations in physical parameters such as colour and turbidity. Notably, the subsurface (1m depth) water in Kappachchikulam cascade recorded the highest colour intensity (mean = 284.5), followed by Mathavaiththakulam (mean = 141.67) and Thuduwakkaikulam (mean = 108.6). However, surface water colour values showed less contrast, with Thuduwakkaikulam (mean = 134.0) slightly exceeding Kappachchikulam (mean = 132.0) and Mathavaiththakulam (mean = 106.73). These variations suggest the presence of suspended solids and organic loading in lower depths, especially in Kappachchikulam, which may be influenced by catchment runoff and tank sedimentation. This finding aligns with prior observations by Jeyaruba and Thushyanthy (2009), who reported similar vertical differences in colour intensity within Eastern Province tank cascades.

Turbidity levels demonstrated inconsistent stratification patterns across cascades. In Mathavaiththakulam, subsurface turbidity was substantially higher (mean = 25.23) than the surface (mean = 5.47), indicating sediment re-suspension or accumulation at depth. Conversely, Thuduwakkaikulam exhibited higher turbidity at the surface (mean = 15.15), possibly due to surface runoff, algal blooms, or human activity near the tank periphery. These results support the findings of Herath and Ratnayake (2010), who observed that physical disturbances and sediment transport mechanisms strongly affect turbidity in

shallow irrigation tanks. Kappachchikulam maintained relatively low turbidity across both layers, reflecting more stable sediment conditions or effective upstream catchment protection.

Chemical quality analysis showed minimal variation in pH between surface and subsurface layers across most cascades. Mathavaiththakulam and Kappachchikulam maintained slightly alkaline conditions (mean pH ~7.8–8.0), whereas Thuduwakkaikulam presented lower surface pH (mean = 7.62).

Electrical conductivity (EC) displayed pronounced spatial differences, especially in Kappachchikulam, where surface EC (mean = 432.5) was markedly elevated compared to subsurface levels (mean = 95.5), implying surface salinity inputs likely from agricultural runoff or shallow saline seepage. In contrast, EC values in Thuduwakkaikulam remained relatively stable across depths, while Mathavaiththakulam showed low EC values at both levels. These findings echo the work of Fonseka et al. (2024), who linked EC variability to fertilizer use and catchment inflows in Anuradhapura. Overall, these results underscore the importance of layer-specific monitoring in tank cascade systems, as vertical gradients in quality parameters may inform tailored management strategies. It is recommended that tank rehabilitation and water quality improvement programs prioritize sediment control in deeper zones and regulate catchment activities to limit surface-level contamination.

Thuduwakkaikulam showed the highest chloride concentrations at both 1m depth (95.22 mg/L) and surface (74.83 mg/L), with significant variation across cascades at 1m depth ($p=0.035$). In contrast, Kappachchikulam reported minimal chloride levels, possibly due to its smaller catchment area or effective dilution capacity. Total alkalinity also peaked in Thuduwakkaikulam, recording 198.54 mg/L at depth and 218.17 mg/L at the surface, suggesting high buffering capacity likely associated with catchment soil properties or organic content. These findings are aligned with earlier observations made by Herath and Ratnayake (2010), where tanks in mineral-rich catchments demonstrated elevated alkalinity levels.

Nitrate (NO_3^-) concentrations varied mildly between depths, with Mathavaiththakulam showing the highest mean concentration at depth (8.67 mg/L), indicating potential leaching of agricultural inputs through vertical percolation. However, the difference was statistically insignificant ($p=0.618$). Surface concentrations remained below 5 mg/L across all cascades. Nitrite (NO_2^-) values were generally low, with slightly elevated concentrations in subsurface samples from Mathavaiththakulam (2.42 mg/L) as compared to the top layer (0.03 mg/L), implying possible anaerobic conversion at depth. These results corroborate the study by Rajasooriyar and Suriyakumari (2014), which documented seasonal and spatial variations in nitrogen compounds, particularly in tanks influenced by fertilizer runoff and organic matter accumulation.

Fluoride concentrations remained within permissible limits across all locations, with Thuduwakkaikulam recording higher concentrations both at 1m depth (0.87 mg/L) and surface (0.95 mg/L). In contrast, Mathavaiththakulam exhibited lower fluoride content (approximately 0.55 mg/L at both depths), reinforcing the idea that geological composition

significantly governs fluoride mobility, as supported by Jeyaruba and Thushyanthy (2009). Similarly, phosphate levels ranged moderately, with slightly higher levels in Thuduwakkaikulam, but no significant statistical variation was observed, suggesting limited influence of external phosphate sources.

The TDS and total hardness values were considerably higher in Thuduwakkaikulam at both depths (TDS: ~375–385 mg/L; hardness: ~177–185 mg/L), indicating greater solute accumulation due to longer water retention, reduced flushing, or geological solubility. Conversely, Mathavaiththakulam and Kappachchikulam had relatively lower values, implying lower mineralization or better dilution. This pattern is consistent with Fonseka et al. (2024), who reported higher TDS levels in tanks with longer residence time and downstream position within the cascade system.

Iron and sulphate concentrations displayed noticeable differences between depths and across cascades. Thuduwakkaikulam showed elevated sulphate levels (7.44 mg/L at depth and 6.67 mg/L at surface) and moderate iron concentrations. Mathavaiththakulam had lower sulphate (1.44 mg/L at 1m depth) but a notably high iron level at depth (3.91 mg/L), possibly linked to reducing conditions in the subsurface. These parameters highlight the importance of depth-wise chemical stratification. Similar patterns of redox-sensitive element variation were noted by Herath and Ratnayake (2010), particularly in older or eutrophic tanks.

Bacteriological analysis revealed that total coliform levels were high at both depths, often exceeding 300 CFU/100mL, with no statistically significant difference between depths ($p>0.05$). Notably, Kappachchikulam displayed the highest surface coliform levels (739 CFU/100mL), suggesting localized faecal contamination likely from livestock or human activity near tank peripheries. These findings echo those of Rajasooriyar and Suriyakumari (2014), who emphasized the need for buffer zones and community sanitation measures to mitigate microbial contamination in minor tank systems.

In conclusion, the study highlights considerable intra-cascade and vertical (depth-wise) variation in water quality parameters. While surface water is often assumed to be more vulnerable, several parameters such as TDS, nitrate, and iron were higher at subsurface levels, challenging conventional assumptions. Thuduwakkaikulam exhibited the most mineral-rich and chemically loaded profile, whereas Mathavaiththakulam showed relatively stable and moderate water quality. These findings emphasize the necessity for depth-integrated monitoring and site-specific management, especially for cascades in the dry zone where water quality is critical for domestic and agricultural use. Future interventions should integrate cascade morphology, land use, and community behavior to ensure sustainable water quality management.

Policy implications include promoting buffer zones, restricting agrochemical use in tank upstreams, introducing phytoremediation strategies such as aquatic macrophytes, and community-based tank protection schemes. The results strongly advocate for localized water safety planning and awareness among communities using these tanks as their primary drinking and irrigation source.

Conclusion

Cascades such as Thuduwakkaikulam demonstrated elevated levels of total dissolved solids, hardness, chloride, and fluoride, indicating mineral accumulation due to prolonged retention and reduced flushing. Subsurface layers in tanks like Mathavaiththakulam and Kappachchikulam showed unexpectedly higher levels of iron, nitrates, and turbidity, suggesting sediment interactions and possible vertical leaching of agricultural inputs. Bacteriological contamination was prevalent across all cascades, with total coliform levels exceeding national and WHO standards—most critically in Sivalakulama. These findings challenge conventional assumptions and underscore the complexity of tank hydrology influenced by catchment use, sedimentation, and water stagnation during dry periods. Spatial comparison across districts revealed that water quality is strongly governed by catchment characteristics, tank morphology, and human activities. Cascades in Vavuniya recorded the highest frequency of microbial contamination, likely due to livestock intrusion and inadequate sanitation.

Based on these findings, several targeted recommendations are proposed. Regular water quality monitoring should be conducted at multiple depths to capture vertical differences, particularly for chemical and microbial indicators. Further, strengthening catchment protection through vegetative buffers and regulated agrochemical usage is recommended to minimize runoff contamination. Establishing buffer zones and restricting livestock access around tanks can reduce fecal contamination. Integrated catchment management practices, such as minimizing agrochemical use and improving soil conservation, are essential to control nutrient loading Prioritizing sediment control and de-silting interventions in tanks showing high turbidity and organic accumulation. The upcoming tank rehabilitation and improvement projects should pay special attention of tailor district-specific management strategies focusing on microbial risk in Vavuniya and chemical risks in Anuradhapura and Trincomalee. These actions should be embedded within broader policy frameworks targeting sustainable rural water security under SDG 6.

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Post-Implementation Sustainability of Roof Rainwater Harvesting Systems in Schools: A Study on Operation, Maintenance, and Usage in Sri Lanka's Dry Zone

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Introduction

Rainwater harvesting (RWH) has emerged as a vital climate adaptation strategy for water-scarce regions, offering an alternative and decentralized source of potable water. In Sri Lanka's dry zone—plagued by chronic kidney disease of unknown etiology (CKDu) and seasonal droughts—the integration of Roof Rainwater Harvesting Systems (RWHSs) into schools through the Climate Resilience Integrated Water Management Project (CRIWMP) initiative has offered renewed promise (Rahman et al. 2014). However, the long-term success of such infrastructure is predicated not only on installation but also on post-installation operation, maintenance, and sustainability (NBRO 2024).

This research investigates the post-implementation performance of Roof RWHSs installed in schools across seven districts in Sri Lanka under the CRIWMP. The study evaluates consumption practices, maintenance effectiveness, user satisfaction, and sustainability strategies. Indeed, this research examines the level of usage, operational condition, maintenance practices, and stakeholder commitment to ensure sustained system performance across 43 selected schools.

As such, access to safe and sustainable drinking water remains a persistent challenge in Sri Lanka's dry zone, particularly in rural schools where students face heightened risks of waterborne illnesses and chronic conditions such as CKDu (Indika et al. 2022). In response, the CRIWMP facilitated the installation of RWHSs in over 100 schools to provide a decentralized, climate-resilient water source. While the initial installation phase was successful and positively received, concerns have emerged regarding the systems' long-term performance and sustainability. Preliminary observations and limited follow-up studies suggest that many systems face operational disruptions, irregular maintenance, inadequate institutional ownership, and inconsistent water quality monitoring. Moreover, gaps in formal service agreements, stakeholder engagement, and post-project support raise

critical questions about the durability and impact of these interventions (NBRO 2024). Without comprehensive evaluations, it is unclear whether these systems continue to serve their intended purpose or whether they are at risk of degradation and disuse.

This research addresses the need for empirical evidence on the operational condition, maintenance practices, usage patterns, user satisfaction, and sustainability mechanisms of RWHSs in schools. It seeks to identify the institutional, technical, and social factors influencing system performance, with the goal of informing policy and implementation strategies for enhancing long-term functionality and resilience of school-based rainwater harvesting infrastructure in water-scarce regions.

Methodology

The study employed a cross-sectional survey design targeting 43 schools across the Mannar, Kurunegala, and Puttalam Districts, where RWHSs were installed under the CRIWMP. Data was collected using a structured feedback tool translated into Sinhala, Tamil, and English to ensure inclusivity. Respondents included school principals, teachers, students, and parents. Key indicators measured include water consumption, system condition, maintenance records, stakeholder satisfaction, and post-installation sustainability practices. Statistical tests, including Chi-square and Fisher's Exact Test, were applied to assess associations between operation/sustainability levels and demographic/system variables.

Results and Discussion

Operational Condition and System Functionality

Findings show that 95.3% of schools reported that their RWHSs were operational (Table 1). The functional status of effluent units and water outlets was similarly high at 93.0%. Tank and tap structure cleaning arrangements were confirmed in 90.7% of schools, indicating consistent adherence to basic upkeep protocols. However, disparities emerged across districts—Mannar showed relatively low performance with only 58.3% of schools meeting all four functional indicators, compared to 100% in Kurunegala and Puttalam. This variation highlights the importance of region-specific capacity building. These results align with Gunawardena et al. (2018), who noted that user commitment and local context significantly impact RWHSs upkeep.

Table 1. System Functionality and User Satisfaction

Indicator	Yes (%)	No (%)
Proper Functioning RWHS	95.3	4.7
Proper Effluent Unit	93.0	7.0
Tap Structures Functional	93.0	7.0
Storage Cleaning Arranged	90.7	9.3

Consumption Patterns and Water Quality Perception

Rainwater is used exclusively for drinking in 95.3% of the schools (Table 2), and an equal percentage expressed satisfaction with its sensory quality. Yet, only 32.6% had conducted formal water quality testing—entirely from Puttalam. In Mannar and Kurunegala dsitricts, no water quality tests had ever been conducted. Even more critical, schools with tested water reported a 100% satisfaction and sustainability rate, highlighting the importance of routine quality checks. According to Fisher's Exact Test (p=0.000), water quality testing showed significant association with both operational (χ^2=8.653) and sustainability outcomes. This mirrors findings by Rajeswaran et al. (2020), which stressed the breakdown of RWHSs in schools where water testing was not institutionalized.

Table 2. Water Consumption and Quality Monitoring

Indicator	Yes (%)	No (%)
Used Solely for Drinking	95.3	4.7
Satisfied with sensory Water Quality	95.3	4.7
Water Quality Tested	32.6	67.4
Frequent Water Testing (6 months)	32.6	67.4

Maintenance Practices and Institutional Agreements

All schools (100%) reported receiving O&M training, and 76.7% kept maintenance logbooks (Table 3). However, only 41.9% had a service agreement with a technical provider, and this was entirely absent in Kurunegala District. In contrast, Puttalam district showed 100% adherence across institutional linkage indicators. A statistically significant relationship was found between good maintenance and the presence of larger 10,000L RWHS units (Fisher's P=0.000). Schools with fewer than 10 teachers were more likely to maintain the systems well (χ^2=4.036, P=0.045), reinforcing the operational burden in large schools without proportionate technical support.

Table 3. Maintenance and Support Structures

Indicator	Yes (%)	No (%)
Agreement with DNCWS	72.1	27.9
Agreement with Maintenance Provider	41.9	58.1
Trained on O&M	100.0	0.0
Logbook Maintained	76.7	23.3

Post-Sustainability Measures

Despite strong initial adoption, only 14.0% of schools demonstrated any self-led fundraising efforts. Over 81.4% lacked adequate funds to maintain RWHSs post-project (Table 4). While 53.5% developed sustainability mechanisms, this was concentrated in Mannar and Kurunegala Districts. Puttalam District relied heavily on external agreements (100%), but these may be unsustainable without local engagement. Sustainability was significantly associated with system size (P=0.020), water quality monitoring (P=0.020), and installation year (2023 installations had 100% sustainability, P=0.017). The literature confirms that early

adoption and community integration are central to lasting impact (Gunawardena et al. 2018).

Table 4. Sustainability and Institutional engagement

Indicator	Positive Response (%)	Negative Response (%)
Adequate Funds for Maintenance	18.6	81.4
Developed Own Mechanism	53.5	46.5
Fundraising Efforts	14.0	86.0
Legal Agreement Useful	37.2	62.8

Stakeholder Engagement and Monitoring

Monitoring visits from Zonal Education Officers and DNCWS varied widely across districts. In Mannar District, 83.3% of schools reported no DNCWS visits post-handover. Similarly, School CBOs were inactive in over 50% of locations. Statistical analysis revealed that strong stakeholder engagement, especially through SDS and CBOs, correlated positively with good maintenance and sustainability (Fisher's P=0.000). These findings confirm that formal agreements are necessary but insufficient without active oversight. The survey results indicate high initial adoption and acceptance of RWHSs, with 95.3% of schools using the filtered water for drinking. The quality of maintenance practices also correlated strongly with whether water quality testing had occurred (P=0.000). The study also finds that poor sustainability is often linked with inadequate stakeholder visits, poor financial allocations, and absence of legal backup agreements. Table 5 shows the summary of key associations between variables.

Table 5. Summary of key associations

Variable	Significance with O&M	Significance with Sustainability
RWHS Capacity (10,000L)	Significant (p=0.000)	Significant (P=0.020)
Water Quality Tested	Significant (p=0.000)	Significant (P=0.020)
Year of Installation (2023)	Better Performance	100% Sustainability
Overall System Condition	Significant (p=0.003)	Strong Association

Conclusion

This study critically evaluated the post-installation performance of RWHSs installed in schools across Sri Lanka's dry zone under the CRIWMP. The findings reveal high user satisfaction and operational functionality, with 95.3% of schools utilizing RWHSs for drinking purposes and expressing satisfaction with water quality. However, the performance varied significantly by district and was influenced by installation year, system capacity, and stakeholder involvement.

Statistical analysis confirmed that systems with a 10,000L capacity, those installed in 2023, and those subjected to regular water quality testing demonstrated superior maintenance

and sustainability outcomes. Schools with formal agreements, particularly in Puttalam District, consistently reported 100% functionality and sustained usage. Conversely, Mannar District faces challenges in system upkeep, financial planning, and stakeholder support.

Based on these findings, the recommendations proposed are (a) Mandate water quality testing at least twice annually, supported by regional health departments, (b) Allocate dedicated budgets within school development plans for RWHSs maintenance, (c) Strengthen legal agreements and monitoring responsibilities of DNCWS and SDS, (d) Scale up the use of 10,000L systems, which performed better under operational stress, (e) Encourage school-led sustainability mechanisms, including recordkeeping, fundraising, and technical training refreshers, and (f) Overall, the research reaffirms the potential of RWHSs to offer climate-resilient solutions in water-stressed areas but underscores the necessity of aligning technical systems with institutional and community-based practices for enduring sustainability.

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Barriers to Implementing the Ambatale Salinity Barrier: A case study on delays, design gaps, and stakeholder influence

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Introduction

Climate change is exerting an increasing influence on water resources in Colombo, presenting significant challenges to the provision of a sustainable and reliable drinking water supply. The combined effects of rapid urbanization, population growth, sea level rise, escalating pollution, and environmental degradation are placing considerable pressure on existing water infrastructure. These evolving conditions underscore the urgent need for robust and adaptive water management strategies to enhance climate resilience and ensure long-term water security.

Colombo, the commercial capital of Sri Lanka and its primary water source, the Kelani River, faces severe pollution from industrial and domestic waste while the Seethawakka tributary contributes high turbidity levels, particularly during rainfall season, compounded by ongoing gem mining activities. The confluence of these issues has driven up treatment costs and exceeded the capacities of existing water treatment infrastructure, exacerbating water scarcity in the city.

Sea water level rise of Climate change, salinity intrusion at the Ambatale Intake further complicates water treatment processes. This climate-induced issues have escalated existing treatment plants challenges its treatment efficiencies.

To address these challenges, a multi-faceted approach is essential as construction of salinity barrier, upper-level reservoir, reducing Non-Revenue Water (NRW) through improved pipeline management and leak detection can significantly mitigate water demand deficits. Furthermore, adopting advanced water treatment technologies such as membrane filtration, desalination, and smart water quality monitoring systems can enhance water availability, production efficiency and ensure a resilient water supply.

The extraction of fresh water from Kelani River for water treatment plants has also increasing with time, meanwhile the water purification process has complicated due to impact of salinity intrusion of Kelani River particularly during dry period. Hence, it is important to understand the salinity distribution in the Kelani River to take mitigation action to prevent salinity intrusion into the water treatment process.

Despite its critical importance, the Ambatale Salinity Barrier has remained incomplete for over three decades, constrained by technical shortcomings, prolonged delays, and complex

stakeholder dynamics. This case study seeks to examine the underlying barriers that have hindered its implementation, with particular attention to design gaps, institutional challenges, and stakeholder influence. By analysing these factors, the study aims to highlight lessons learned and provide insights that can inform the successful realization of this nationally significant project and guide similar water infrastructure initiatives in the future.

Salinity intrusion in river can has significant implications for water treatment plants. As a result, reduce the quality of drinking water, increasing operational costs, environmental impacts, higher energy consumption, and corrosive effects due to saline water.

The Ambatale Salinity Barrier Project, first proposed in 1992, is critical for protecting the Colombo District's drinking water supply from salinity intrusion. Although the barrier base only constructed in 2011, subsequent phases have not progressed due to design gaps, technical objections, and stakeholder disagreements. As a result, reliance on temporary sandbag barriers, costing LKR 40–50 million annually, continues to pose financial and operational risks. With future demand projected at 1.9 million cubic meters per day by 2030, the prolonged delays highlight the urgent need to address planning inefficiencies, structural shortcomings, and institutional challenges that hinder the project's execution.

Implementation of Salinity barrier at Ambatale is vital and urgent requirement. The objective of this study is to critically examine the barriers that have hindered the timely implementation of the Ambatale Salinity Barrier, a project of national significance for securing Colombo District's drinking water supply. Specifically, the study seeks to identify the underlying causes of prolonged delays, highlight structural and operational design gaps, and assess the influence of multiple stakeholders on project decision-making. By doing so, the research aims to provide insights that can guide more effective planning, coordination, and policy interventions for the successful realization of this vital water infrastructure.

Methodology

This study adopted a qualitative case study approach to examine the barriers to implementing the Ambatale Salinity Barrier, focusing on delays, design gaps, and stakeholder influence. The methodology involved, (a) Document review – Analysis of project proposals, feasibility studies, design reports, environmental assessments, and government planning documents to establish the historical context and identify technical and institutional gaps, (b) Technical Assessment – Evaluation of structural and operational design shortcomings, including hydraulic, stability, and constructability issues, as well as gate, sediment management, and ancillary structures, (c) Delay and Timeline Analysis – Chronological review of project milestones to identify causes and duration of planning and implementation delays, and (d) Stakeholder Analysis – Examination of the roles, influence, and interactions of key stakeholders, including government agencies, consultants, and funding partners, using reports, meeting records, and documented correspondence.

This integrated approach enables a systematic understanding of the barriers and provides insights for improving the planning and implementation of this nationally significant water infrastructure project.

Historical Timeline

The issue of salinity intrusion (Figure 1) at the Ambatale intake initially identified in 1992, prompting the implementation of a temporary sandbag barrier (Figure 2) as an immediate mitigation measure. In 1993, a mathematical modelling study undertaken to explore the feasibility of an inflatable salinity barrier. This study followed by a basic feasibility study conducted by an international consultant in 1998. In 2003, further investigations continued, including geotechnical assessments, and the first Environmental Impact Assessment (EIA) was prepared to evaluate potential environmental implications. In 2005, parallel studies were conducted to assess the feasibility of a Kelani Conservation Barrage, and in 2008, the Irrigation Department explored the possibility of developing an upstream reservoir as a long-term solution.

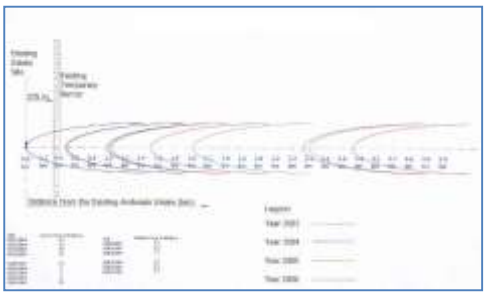

Figure 1. Salinity wave records

The design of the inflatable salinity barrier was completed in 2010, and in 2011, the construction of the barrier base was finalized. The sill level of the base was established at -0.5 m MSL. However, due to concerns over unacceptable flood level increases, the construction of the remaining components—specifically, the inflatable rubber dams atop the base—was halted. In 2018, under the Climate Resilience Improvement Project (CRIP), further hydrological modelling and flood mitigation studies were conducted for the Kelani River Basin by an independent consultant. Subsequently, in 2021, a new gated salinity barrier was proposed, located approximately 35 meters downstream of the existing, partially completed inflatable barrier base. The detailed design for this proposed barrier was subsequently developed.

Currently, under the Climate Resilience Multi-Phase Approach (CResMPA) project, the detailed design of the gated salinity barrier, prepared by LHI in 2021, is being reviewed by international consultants. This review has identified critical design issues and gaps, necessitating further refinement and technical reassessment.

Details of Existing Salinity Barrier

The existing barrier (Figures 3 and 4), built across the river, consists of a thick reinforced slab supported on a series of bored piles and sitting on an infill of compacted sand retained

by two rows of sheet piles along the edges of the concrete slab. There are Rockfill access ramps upstream and downstream of the sheet piles to allow smooth river flow over the concrete base. This structure was built with the intention of installing a retractable rubber dam.

Figure 2. Temporary Sandbags salinity barrier

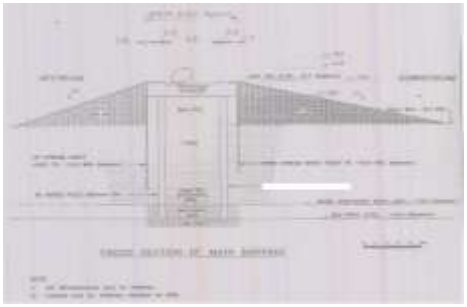

Figure 3. Existing barrier base cross section

Figure 4. Existing Salinity barrier base

New Proposed Salinity Barrier

New Salinity structure (Figures 5 and 6) is proposed at downstream of the existing partially completed salinity barrier built in 2011. The new gated structure will consist of a submerged concrete base up to -3m msl with 6 hydraulically operated flap (collapsible) gates installed on top of the concrete, together with necessary features. The existing structure will be demolished, and all obstructions will be cleared.

Figure 5. Plan view of new proposed barrier

Figure 6. Proposed gate for barrier

Evaluation of the Design Gaps of Proposed new Salinity Barrier

The newly proposed gated salinity barrier (Figure 7), although conceptually sound, has revealed few structural gaps and operational concerns during the design review process. Key issues include insufficient consideration of flood level impacts, inadequate sediment management provisions, and limited adaptability to future sea level rise and extreme hydrological events. Additionally, operational complexity during high-flow conditions, especially in synchronizing gate operations with upstream water supply needs and downstream flood management, poses significant risks. These gaps highlight the need for refined hydraulic modelling, improved structural detailing, and a comprehensive operations and maintenance strategy to ensure long-term functionality and resilience of the barrier.

There are significant issues in the electromechanical design, particularly with the gates, which are overdesigned by 200% in weight, making them difficult to operate and maintain. Key elements like the boat pass, fish pass, and stoplogs either lack proper design or need full reassessment due to operational and constructability issues.

The design of the proposed salinity barrier has number of critical shortcomings that require major revisions. The foundation design lacks detailed analysis, including missing finite element modelling and stability checks, and the design for key structures such as the HEC building is absent, and essential components like bank protection, access roads, and cofferdams are not intelligently designe

Figure 7: Existing & new proposed locations

Results and Discussion

The Ambatale Salinity Barrier project illustrates the complexities of implementing critical water infrastructure in developing contexts, where technical, institutional, and governance challenges intersect. Despite the project's national significance, it has been delayed for over three decades, compelling reliance on costly and temporary sandbag barriers.
A key finding from this case is the misalignment between stakeholder perceptions and project urgency. Evidence suggests that some agencies do not fully recognize the strategic importance of the barrier, leading to fragmented decision-making and inconsistent support. Similar institutional challenges have been documented in water management projects globally, where stakeholder misalignment has delayed climate adaptation interventions. Strengthening institutional awareness and accountability is therefore critical.

The study also highlights design-related shortcomings that have undermined project confidence and slowed approvals. The absence of advanced engineering analyses such as finite element modelling, stability checks, and sediment assessments are raises significant concerns about structural reliability. Furthermore, conceptual gaps, including inappropriate gate design, insufficient sediment management, and unresolved provisions for navigation and fish migration, suggest that the project has not adequately integrated long-term operational realities. Literature on hydraulic infrastructure underscores that overlooking operational adaptability often leads to costly redesigns and reduced effectiveness.

Another barrier lies in the institutional capacity of the implementing agency has shown hesitation in taking responsibility for design approvals due to limited in-house expertise and lack of confidence in external consultants. This institutional gap is compounded by inadequate documentation of past studies and decisions, resulting in repeated re-studies and inefficiencies. Such patterns reflect broader challenges in developing countries, where weak institutional memory and capacity deficits often impede water sector resilience.

Stakeholder influence and preferences have further complicated progress. Individual biases, and inter-agency disputes have contributed to delays and frequent scope changes. At the same time, restrictions imposed by funding agencies and rigid procurement conditions have slowed adaptation to evolving technical requirements. Studies on

international donor-funded projects indicate that overly stringent conditions, when not balanced with contextual realities, often create friction and prolong implementation.

Taken together, these findings reveal that the Ambatale Salinity Barrier is not merely a technical challenge but a multi-dimensional governance issue. The convergence of technical design gaps, weak institutional ownership, fragmented stakeholder engagement, and donor-imposed restrictions has created a cycle of delays. Addressing these barriers requires a coordinated governance framework that ensures technical rigor, strengthens institutional accountability, and fosters transparent stakeholder collaboration.

Ultimately, overcoming the barriers to implementing the Ambatale Salinity Barrier demands both technical refinement and institutional reform. Evidence from this study reinforces the urgency of adopting a systems-based approach that links engineering solutions with governance mechanisms, thereby ensuring timely, resilient, and sustainable water infrastructure for Colombo's growing urban demand.

Conclusions

The proposed Ambatale Salinity Barrier, conceived to mitigate salinity intrusion in the Kelani River under rising sea levels, has remained stalled since 1992. Despite its national significance in securing Colombo's drinking water supply, progress has been hindered by design deficiencies, institutional weaknesses, and fragmented stakeholder engagement. Overcoming these barriers will require urgent technical refinement, strengthen institutional accountability, and coordinate stakeholder collaboration to transition from costly temporary measures to a permanent and sustainable solution.

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Drinking Water Solutions of a Community Managed Rural Water Supply Scheme for Climate Adaptation: A case study of Parape Integrated Rural Water Supply Project in Kegalle, Sri Lanka

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Introduction

Safe drinking water is a fundamental human need and a key stone of public health. Even though, millions of people around the world still lack access to safe drinking water sources which may lead to negative impacts for their health, livelihoods and overall well-being. It is very essential to understand the gravity of this issue and it is urgent to address it effectively. Developing countries are more vulnerable to water and sanitation inadequacy (Gadgil 1998). As per the 2016 records, all districts in Sri Lanka have reported having more than 50% safe drinking water in the meantime, 87% population possess on site sanitation (https://data.sdg.lk/dashboard/6).

Climate change has significant implications for water security in Sri Lanka in order to availability, accessibility and quality of water across the country. On the Global Climate Risk Index (CRI), Sri Lanka is positioned high especially due to climate change-induced risks to water (UNEP 2023). Climate change affects the environment in different ways such as sea level rise, rising temperature, flooding, drought and many more. It affects negatively for energy, water, transportation, wild life, agriculture, human health and eco systems. Rural water supply schemes reduce vulnerability of women and children from the difficulties happening due to climate impacts. They save time and energy of women spending hours to fetch water. And they cause to increase of the number of school attendance of children. In addition to that, rural water supply schemes help to empower women economically and socially during climate related issues.

This study attempted to reveal the strategies and initiatives taken to design a sustainable water supply system for managing the issues related to climate change. Designing a rural water supply scheme which is resilient to climate change related issues requires integrated adaptive approach to ensure sustainability, reliability and community participation.

Methodology

Study area

The study was conducted in the Kegalle district of the Sabaragamuwa Province of Sri Lanka, with a land area of 1692.8 km^2. The district is composed of 11 divisional secretariat divisions

(DSD). Approximately 69.1% of households in Kegalle district had access to safe drinking water while 30.9% relied on unsafe sources in 2012. Challenges exist particularly in rural and estate sectors where reliance of unprotected dug wells or surface water. However, investments are to be continued in infrastructure improvement and community-based water management is essential to improve access to safe drinking water within the Kegalle district. The location map is given as Figure 1.

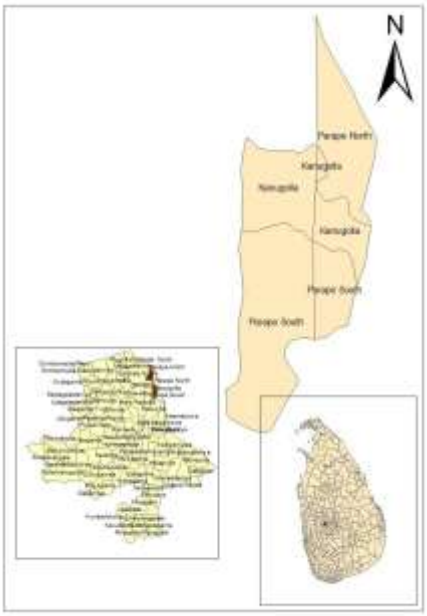

Figure 1. Location Map

Primary Data Collection

Primary data for socio-economic survey was collected through a semi structured questionnaire survey using tablets, direct and indirect observations, public consultations through focus group discussions, gender consultation through focus group discussions.

In addition to the above consultations, key informant interviews were conducted to obtain a thorough understanding in various socio-economic aspects of Rambukkana DS area. Three key government officers attached to the DS area such as Divisional Secretary, Public Health Officer, Economic Development Officer and Grama Niladhari were interviewed.

Secondary Data Collection

Prior to field work, available literature both published and unpublished and which are applicable to the Rambukkana DS area were reviewed. The maps related to study area and some related websites and office files are some of the sources used to collect secondary data. In addition, Resource Profile of Rambukkana, census data, and data related to education, income level, water supply and sanitation were also reviewed.

Selection of the Sample

The study was supposed to represent all the beneficiary families in the selected GNDs. In addition, Applicable key informants were selected based on purposive sampling method in relation to collect data to obtain a thorough knowledge of the study.

Results and Discussion

Existing Socioeconomic Background

Though Rambukkana DSD consists of 89 GNDs, the subproject covered only 04 GNDs. According to the Resource Profile of Rambukkana Divisional Secretariat, the total population of the selected GNDs in 2016 is 4571 and 1055 households. The majority (82%) of the households used water from sources which were located outside their homesteads. Therefore men, women and children have to go out of their homesteads for bathing and washing to the nearby stream or to the neighbouring houses. In addition, they happened to carry water for their other household requirements such as drinking, cooking and for sanitation.

During the survey, several households did not reveal their actual income. Looking at the expenditure patterns of the households, it has been observed that around 86% of the households can afford to pay an average monthly water bill of LKR. above 500.00.

Existing Water consumption and Sanitation Facilities

A survey was carried out by collecting four water samples from four wells in each of the selected GNDs and test results showed that water in all selected wells had faecal contamination (Figure 1). Very often it may happen due to pollution from the septic tanks and toilet pits especially due to poor sanitation practices of the rural villagers. More than 92% of the respondents mentioned that water is not sufficient during dry seasons, which may cause to reduce the water quality as well.

Majority of the respondents (83%) mentioned that they are not satisfied with their present water supply. Therefore, they expect an improvement of the existing water supply facilities.

Since currently used water for drinking was not undergone with any treatment method 98% people used domestic purification methods such as domestic filters and boiling, chlorination and other methods whereas 2% were using other & traditional purification methods**.** As the current water supply was not sufficient to cover their demand, majority of the people were willing to acquire new water connection. Thus, 94% people were willing to pay a monthly water bill (Figure 2).

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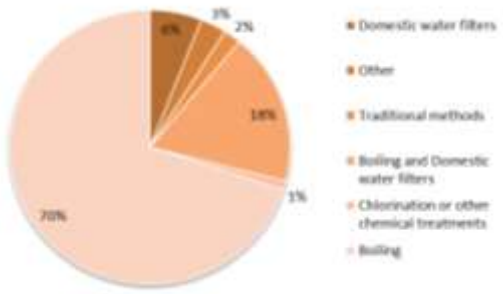

Figure 1. Purification of Drinking Water

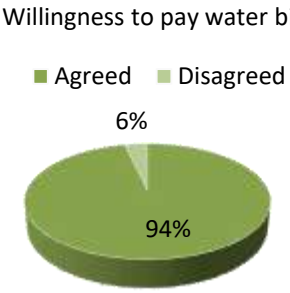

Figure 2. Willingness to Pay Water Bill

In addition to the household survey, public and gender consultations were carried out to analyse the safe drinking water demand of the area. Four Public consultations were carried out consecutively representing each selected GNDs. Every consultation consists of 5 to 10 male and female participants who were in between the age range of 20 to 70 years.

Apart from the public consultations, gender consultations were conducted to get a thorough knowledge on water related issues in the sub project area. The majority of the women participated in the gender consultations were not satisfied with the quality and the adequacy of the current water supply. A key issue that they highlighted was safeguarding of infant/kids' health from this contaminated water.

All women agreed that they have the decision-making power during community meetings. They were willingly and actively engaged in social and welfare activities through these special community gatherings. All women expressed their support for implementation of the proposed water supply scheme.

Key informant interviews were conducted to obtain a thorough understanding of various socio-economic aspects of Rambukkana DS area. Three government officers attached to respective DS area namely Assistant Director (Planning), Supervising Public Health Inspector, Economic Development Officer were interviewed during the period of socio-economic survey. According to the Supervising Public Health Inspector, there is no

considerable number of cases/patients during past four years identified for water related problems.

Divisional Secretary of the Divisional Secretariat, Rambukkana provided socio economic data of people living in the sub project area. According to him, traditional livelihood practices like farming have been replaced with various other forms of modern livelihoods and the economy is largely mixed and younger generation pursuing higher education, which keep them away from their traditional agricultural activities.

Conclusion

This study attempts to provide analytical explanation of Parape-Kanugolla Integrated Rural Water Supply Scheme in Kegalle district of Sri Lanka as a good case study for climate adaptation and sustainable water management. The area was characterised by hilly terrain, abundant natural springs and it faces increasing climate variability with erratic rainfall, frequent droughts and occasional flooding.

The villagers relied heavily on local water sources for drinking, cooking, washing and small-scale agriculture before implementation of this water supply project. Therefore, this water supply scheme was especially launched to address water scarcity and improve resilience to climate impacts.

Parape-Kanugolla Integrated Rural Water Supply Scheme was especially designed based on specific climate adaptation features such as water source diversification to reduce dependency on a single source, having multiple storage tanks to retain water during periods of droughts, conducting routine water quality testing during the monsoons when contamination risk is high and carrying out periodical awareness campaigns on water conservation, sanitation and climate change.

Further, it exemplifies how community managed rural water supply systems can effectively respond to climate challenges. And this model can be replicated in other vulnerable rural areas in Sri Lanka and beyond. In addition to that, it is recommended to enhance institutional support and linkages with government agencies, integrate early warning systems and climate data in to planning, ensure periodic system evaluations based on climatic trends and promote sharing of best practices across similar communities.

Acknowledgement

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Agro-climatic Information Service for Farmers – Enhancing Resilience and Productivity in a Changing and Variable Climate

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Introduction

Agriculture remains a vital part of Sri Lanka's economy, providing employment to 25 percent of the workforce in 2020, which translates to approximately 8.1 million jobs (FAO 2022). Agriculture is the mainstay of Sri Lanka's rural economy. Given the country's diverse agro-ecological conditions and landscapes, smallholder farmers, who make up the overwhelming majority of the country's 1.7 million farmers, have long sought ways to build the resilience of the food system under increased change and variability in climate (World Bank 2015).

Furthermore, agriculture is a cornerstone of Sri Lanka's economy, contributing significantly to the Gross Domestic Product (GDP) and providing livelihoods to a large portion of the population, particularly in rural areas. Despite its economic importance, the agricultural sector faces numerous challenges, including climate change and variability, extreme weather events, and inefficient dissemination of critical agro-climate information to the last mile.

The most important food product systems in Sri Lanka are rice, maize, pulses, and vegetables, which are produced at varying scales and intensities (World Bank, 2015) and intensities across different agro-ecological environments of the country. Sri Lanka's staple food crop, rice, is produced both by small-scale farmers (using intensive and extensive practices), and by large-scale farmers (using intensive, irrigation, and input-dependent practices) (World Bank 2015). Paddy cultivation dominates in the Dry and Intermediate zones, where both irrigated and rain-fed systems are practiced.

In the backdrop of increasing uncertainty in seasonal weather patterns under a changing and variable climate, weather forecasts play a crucial role in enhancing the productivity and sustainability of these agricultural systems. Timely and accurate weather and climate information is critical for optimizing agricultural practices, improving productivity, and mitigating risks associated weather aberrations arising due to climate change. However, rural farmers in Sri Lanka often do not fully utilize such information due to multiple reasons, including, limited access to reliable climate information, particularly in remote areas, communication gaps in delivering forecasts to the last mile, preventing effective use at the

farm level and scientific complexity in climate information, making it difficult for farmers to interpret and apply the information in real world situation.

Under the Climate Resilient Integrated Water Management Project (CRIWMP), extensive awareness programs were conducted in seven districts of Sri Lanka (Anuradhapura, Kurunegala, Puttlam, Vavuniya, Mannar, Trincomalee and Polonnaruwa) to bridge the gap between climate information generators and users at the last-mile, including farmers and agricultural extension and agrarian officers. The initiative focused on, training programs for farmers and extension and agrarian officers on using climate information for decision-making, simplification of weather forecasts to ensure better comprehension and usability at the local level and development of localized or customized agro-meteorological advisories to provide location specific guidance for strategic and tactical decision making in a given growing season.

During recent times, the Department of Agriculture (DoA) generates and disseminate national agro-met advisories based on seasonal climate forecasts issued by the Department of Meteorology (DoM). However, these advisories often did not reach farmers or local agricultural and agrarian officers with a reasonable lead-time before the growing season starts. Even when received, the technical language made it difficult for farmers and grass-root level officers to understand, interpret and apply the information to their specific farming needs as it is not customized for the local context.

This study reveals the outcomes from interventions undertaken by the CRIWMP to improve the accessibility and usability of agro-meteorological information, issued jointly by the DoA/DoM.

Methodology

Provision of climate and agro-climatic information to farmers and grass-root level extension and agrarian officers as a last-mile climate service is a key component of the Climate Resilient Integrated Water Management Project (CRIWMP) under the Green Climate Fund (GCF). The initiative aims to bridge the gap between climate data and information availability and their practical application in agriculture and irrigation water management.

During the preliminary survey, it was found that many farmers neither utilize climate information nor have a clear understanding of the type of climate information needed for different agricultural operations and other value chain actions. Recognizing this gap, the program was launched in 2019, starting with an awareness campaign targeting leaders of farmer organizations and agricultural instructors, and agrarian officers. The initial training sessions helped identify the importance of seamless weather forecasting for informed decision-making at various crop growth stages in a given cultivation season. This includes using seasonal climate forecasts for strategic decision making and incorporating sub-seasonal, medium-range, and short-range forecasts for tactical adjustments as the season progresses.

To support effective decision-making, a Standard Operating Procedure (SOP) was developed for stakeholders involved at different stages of crop production. Based on this framework, farmers and agricultural instructors and agrarian officers were trained to develop localized agro-meteorological (agromet) advisories, ensuring that climate information is directly applicable to their specific farming needs. A sample advisory is included in the results section.

Additionally, actionable climate information services were introduced, guiding farmers on key agricultural activities such as land preparation, variety selection, cropping pattern, water management, input application and harvesting. To enhance communication and accessibility, agricultural instructors and divisional agrarian officers were trained to create and disseminate localized agro-met advisories. These advisories were effectively shared through a WhatsApp-based communication network, enabling real-time updates and farmer engagement.

Seasonal weather prediction plays a crucial role in developing agrometeorological advisories, as it informs farmers from land preparation through to harvest. Before the start of the cultivation season, the DOM issues a seasonal weather forecast, which serves as the primary input for developing agro-meteorological advisories. The accuracy of these advisories depends heavily on the quality of the seasonal weather prediction, and thus, it is essential to assess the reliability of the seasonal forecasts. Forecast verification is the process of assessing the accuracy and skill of a forecasting system. The forecast is verified against a corresponding observation of what actually occurred. Stanski et al. (1989), Harolds (1996), Jerome (2003) have described some of the standard verification methods and scores in use. These include scores derived from contingency tables for dichotomous forecasts.

Monthly rainfall forecast has been done comparing with long term average (climatology) such as below normal, near normal and above normal by the Department of Meteorology. Rainfall observations and forecasts for twenty-five districts for a period of three year were collected from 2020 January to 2022 December. The event is forecasted to occur when a continuous, scalar forecast variable “X” comparing with threshold “U” (Table 1). Suppose that we have “n” pairs of forecast and observation variables, and have the criteria, namely, X = observed category, Y = forecasted category, and Normal = long term average (1981-2010, 30-year average)

Table 1. Categories of monthly rainfall forecast

Category	**Threshold (u)**
Below normal	U< 90% of Normal
Near normal	90% of Normal < U < 110% of Normal
Above normal	U > 110% of Normal

The resulting Monthly rainfall forecasts and observations are usually summarized in a contingency table shown in the Table 2. Summaries of Table 1 that describe the correspondence between the forecasts and observations are measures of forecast

performance. Suppose that we have "n" pairs of forecast and observation variables, and have chosen thresholds "U". The resulting "n" binary forecasts and observations are usually summarized in a contingency table such as Table 2.

Table 2. Contingency Table

Parameter	Observed	Not observed	
forecasted	a	b	a+b
Not forecasted	c	d	c+d
	a+c	b+d	

Three such measures are the hit rate 'a/a+c'. The Hit rate or Probability of Detection (POD) = a/(a+c), which ranges 0-1 and the perfect score is 1. Hit rate gives a simple measure of proportion of rain events successfully forecast by the DOM, comparing forecasted data with observed outcomes. This process helps to validate and refine the forecasts, leading to better-informed agricultural decision-making and improved resilience to climate variability. Results of the POD values for the seven districts under the project CRIWMP are shown in Table 3,

Table 3. Probability of Detection (POD) or Hit Rate across project's districts

District	Hit rate (POD)
Vavuniya	0.7
Anuradhapura	0.5
Mannar	0.7
Puttalam	0.6
Kurunegala	0.6
Trincomalee	0.5
Polonnaruwa	0.5

By integrating climate services into local farming practices, the project strengthens climate resilience, enhances productivity, and promotes informed agricultural decision-making to ensure sustainability agricultural operations.

A post evaluation has been conducted through questionnaire survey on the completion of the project. Dissemination modes of climate information services, availability of climate information at different time scales, the use of traditional knowledge for weather prediction, the use of science-based agro-met advisories, and other ways to access information are some of the areas included in the questionnaire. In addition, questions cover water management, understanding of agro-met advisories with existing scientific knowledge, and language barriers. Sample sizes used for the survey district-wise is shown in Table 4.

Table 4. Survey sample size across project's districts

District	Sample size
Anuradhapura	150
Kurunegala	70
Trincomalee	50
Vavuniya	30
Puttalam	50
Polonnaruwa	10
Mannar	8

Results and Discussion

The Department of Meteorology issues weather forecasts at various time intervals such as one day, 3-day, 9-day, weekly and seasonal, which are highly valuable for agricultural planning, especially at different crop stages. These forecasts help farmers protect their crops from adverse weather conditions, thereby reducing potential losses.

Under the Climate Resilient Integrated Water Management Project (CRIWMP), use of seasonal weather forecasts by farmers has significantly increased. It has been observed that, on average, around 86% of farmers across the seven districts covered by the CRIWMP now utilize these forecasts in their farm-level decision making process (Figure 1). Prior to the implementation of the project, the use of weather forecasts by farmers, as well as by agricultural officers, was minimal - almost non-existent.

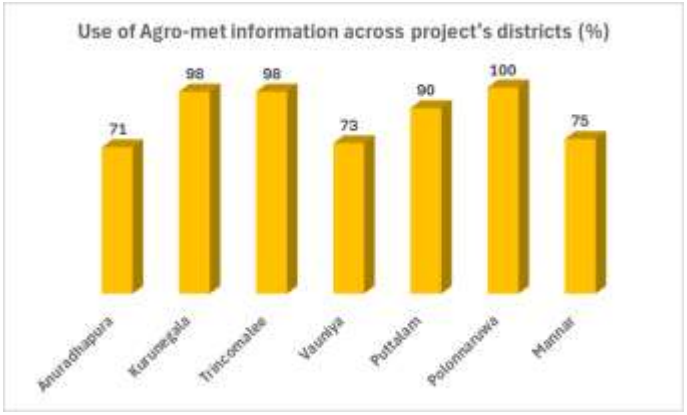

Figure 1. Use of Agro-met information across project's districts

Through the CRIWMP, extensive efforts were made to educate and train farmers and agricultural stakeholders on the practical use of climate information service. While some farmers have begun to access seasonal forecasts directly, the majority still rely on agro-meteorological advisories, which translate complex weather data into actionable rule-based farming guidance. These advisories have proven to be an effective channel for disseminating climate information to farming communities, thereby enhancing their resilience to climate variability.

Previously, there was no established platform at the local level for the effective dissemination of agro-meteorological (agro-met) advisories to farmers. A study by Dissanayake et al. (2021) highlighted that while agro-met advisories were shared with farmers via Agriculture Research and Production Assistants (ARPAs), these efforts lacked a co-production approach, which limited their relevance and effectiveness in terms of local context.

However, through the interventions of the CRIWMP project, the knowledge and capacity of Agriculture Instructors (AIs), Divisional Agrarian Officers and Development Officers (DOs) have been significantly enhanced. As a result, Agricultural Instructors (AIs) in each district have initiated the creation of WhatsApp groups to share timely agro-meteorological advisories with farmers. This initiative has proven effective, with analysis indicating that approximately 50% of farmers in the project areas now receive agro-met information via social media platforms, a communication channel that was virtually non-existent in the past. In addition to social media dissemination, the ARPA, who work closely with farmers at the field level, continue to play a key role in sharing weather-related information. This represents a notable achievement in reaching the “last mile” of climate services and ensuring that critical advisories reach those who need them most.

Furthermore, farmer leaders who participate in Divisional Agriculture Committee meetings are expected to relay information to the farmers in their respective areas. However, the effectiveness of this mechanism remains limited, and efforts to enhance awareness and engagement among farmer leaders are needed. It is recommended to strengthen the role of farmer leaders in disseminating agro-met advisories and related agricultural information.

To support this, a Training of Trainers (ToT) program was conducted under the project, equipping field officers with the necessary skills to train farmer leaders. To ensure sustainability and continuity beyond the project’s lifespan, it is proposed that these training programs be institutionalized and continued, enabling ongoing capacity building at the community level and enhancing the resilience of farming systems to climate variability.

Ultimately, agrometeorological advisories are being utilized by farmers at various stages of crop cultivation, contributing to improved decision-making and risk reduction. On average, a significant majority of farmers (approximately 81%) use agro-met advisories to determine optimal harvesting times. However, the level of usage varies notably across district. For example, the use of agro-met information for harvesting is considerably lower in Polonnaruwa (0%), Puttalam (30%), and Trincomalee (14%).

During earlier stages of cultivation, such as land preparation, planting/seeding, and irrigation scheduling, the use of agro-met advisories is relatively more consistent, with over 60% of farmers incorporating this information into their practices. This suggests growing awareness of the value of weather forecasts in enhancing agricultural planning and productivity.

However, significant variability in the use of advisories is observed between districts, particularly in Kurunegala and Polonnaruwa Districts. This discrepancy may be attributed to the differences in local irrigation systems. Polonnaruwa relies almost entirely on major irrigation schemes, which means farmers tend to delay cultivation until reservoirs (tanks) have accumulated sufficient water storage and their sensitivity for seasonal weather changes is thus, minimal at the early stage of the crop. n contrast, agriculture in Kurunegala is predominantly dependent on rainfed systems and minor irrigation schemes. Farmers typically initiate cultivation based on the onset of seasonal rains and the adequacy of carry-over water storage in village tanks. As a result, they are often less responsive to weather predictions, preferring instead to minimize risk by waiting until tanks are sufficiently filled and phreatic water in paddy fields are adequate to support a rainfed rice crop. This distinction highlights the need for tailored dissemination strategies that consider local agricultural contexts and water management systems. Enhancing the relevance and timing of agro-met advisories to match district-specific conditions can further improve their adoption and impact.

Table 5 illustrates the usage of agro-met advisories by crop stage across project's district, providing a clearer picture of the advisory integration across the cultivation cycle.

Table 5. Usage of agro-met advisories by crop stage across project's districts,

District	Land preparation	Planting/ Seeding	Irrigation scheduling	Fertilizer application	Pest and disease management	Harvesting
Anuradhapura	75	83	65	72	65	81
Kurunegala	27	24	10	4	80	57
Trincomalee	80	84	52	36	98	30
Vavuniya	83	87	80	77	90	60
Puttalam	40	54	26	38	44	14
Polonnaruwa	100	100	0	0	100	0
Mannar	88	100	88	75	100	63

Conclusion

This study highlights the importance of timely and accessible agro-meteorological information for farmers in the Dry zone of Sri Lanka. The Climate Resilient Integrated Water Management Project (CRIWMP) demonstrated that, provision of proper training and localized agro-met advisories, farmers are better equipped to manage climate risks, make informed decisions, and enhance land and water productivity. While a substantial progress has been made, particularly with the use of WhatsApp groups and local advisory systems, challenges remain, especially in areas with different irrigation systems and low adoption rates. Continued efforts to simplify climate information, tailor advisories to local contexts, and strengthen communication networks are essential to fully integrate agrometeorological services into Sri Lanka's agricultural practices, supporting climate resilience and sustainable development.

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A Digitalized Advisory System for Climate Resilient Smart Agriculture in Sri Lanka

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Introduction

Extreme weather conditions are increasingly prevalent worldwide resulting in catastrophic damages to farmlands and crops. Data driven smart management of agricultural activities is one of the most promising solutions to confront the irregular weather patterns. Smart agricultural decisions require weather forecasts, analysis of past weather data, current water availability data, and expertise on agricultural methods and technologies are suitable for prevailing weather conditions and irrigation methods, assume fertilization is due in two days according to the crop calendar of a cultivation. If the latest weather forecast for the next three days shows heavy rain, then the fertilization date can be adjusted accordingly if the right actionable advisory is provided to farmers beforehand. Timely, comprehensive and reliable agro-met advisories will help farmers to make prudent decisions saving their crops from significant damages.

The availability of experienced people with heuristic and traditional knowledge are not adequate in generating such agro-met advisories due to high variability in present day weather compared to the past when the weather was much more stable with predictable seasons and patterns. To ensure accountability, different authorities are mandated to provide the services of weather data collection, analysis and forecast, monitoring and management of water resources, and preparation of agro-met advisories. Key challenges in these tasks include (1) Preparation of advisories based on most up-to-date data with customization for the location, and (2) Dissemination of customized actionable advisories to the final beneficiary, the farmer.

For this purpose, agro-met advisories should be co-produced in a multidisciplinary working group at appropriate regional levels to capture local knowledge and experience and to customize the advisory with location specific information. This work presents a digital system developed for automatically generating agromet advisories based on data uploaded by mandated agencies with a particular focus on minor tank based paddy and other field crops cultivation.

Interview-based detailed review of stakeholder requirements with key personnel across the information supply chain, field observation of district-level agro-met

advisory co-production process followed by designated officials and review of best practices regionally and internationally through document reviews were used for requirement gathering and for reviewing available digital systems.

Current Practice in Agro-met Advisory Generation and Dissemination

The review results revealed that there are multiple systems controlled and operated by different agencies that receive and process data relevant to generation and co-production of agro-met advisories. The key agencies are the Department of Meteorology (DOM), Irrigation Department (DOI), Department of Agriculture (DOA), and Department of Agrarian Development (DAD) with respect to the minor tank based paddy and other field crops (OFC) cultivation scenario. The review showed that all relevant departments and organizations have made significant efforts to digitize their processes (Table 1).

Table 1: Key information products of stakeholder agencies

Agency	Application	Characteristics
Department of Meteorology (DOM)	Anaweki	Mobile app, complex computational models and manual processing to generate content internally at the agency
	meteo.gov.lk	Web app, pdf files, complex computational models and manual processing to generate files internally at the agency, own weather stations
	weather.meteo.gov.lk	Web app, interactive and dynamic content, international data feeds including technologically advanced data inputs (satellite data/ remote sensing)
Department of Irrigation (DOI)	Major Reservoir Status	GIS portal-based real-time water level data
Department of Agriculture (DOA)	Krushi Advisor	Mobile app, static content
	National Agromet Advisory	Web app, static, pdf/doc format files
Department of Agrarian Development (DAD)	Geogoviya	Interactive web, large databases to be maintained and updated internally by the agency
	CultivateX	Interactive web, dynamic content, large databases to be maintained and updated internally by the agency

Tangible outcomes are visible in the form of publicly available information products as summarized in Table 1 (Department of Meteorology 2025; Department of Agriculture, 2025; Department of Agrarian Development 2025). It was also noted that these systems

have been designed and implemented for different purposes, often resulting in them operating in silos, with their own data sources and outcome dissemination channels. Consequently, there is no significant procedural or technical mechanism to digitally share the source data or the outcomes of these systems for the purpose of inter-agency working groups to co-produce advisories based on their current setup and policies. Yet, it is noteworthy that, from a technical point of view, sharing this data and/or information for the purpose of generating and co-producing agro-met advisories is a possibility if necessary administrative and other logistic arrangements are made. Further, each agency requires IT professionals to manage IT infrastructure while the core mandate of the agency is not in IT. A common observation in agencies is their digital system development mainly is outsourced to external parties.

As far as agro-met advisory generation and dissemination to the ground level farmer community is concerned, the most complete digital system seems to be the CultivateX system (Figure 1).

Figure 1. CultivateX interface for managing farming activity

CultivateX presents the weather forecast using https://www.windy.com/ when the desired climate zone is selected. Given the start date of the cultivation, it also checks the agricultural activities in the crop calendar and provides an advisory. However, it does not automatically relate the advised agricultural activity and the weather forecast. For example, if heavy rain is forecasted but the activity due is fertilizer application, the advisory does not currently relate the two.

Readiness for Digital Advisory Usage

Based on the information collected during field visits, agricultural decision making requires community participation and negotiation. For example, in case of low water level in the tank and below normal rainfall forecast in the upcoming season, the preseason planning meeting decision may be to cultivate only a portion of the total extent according to the *Bethma* method which imposes high dependency among farmers. There is a legal process known as "*Kanna Rasweema*" which is the Pre-season Cultivation Planning Meeting that brings farmer organizations and agency officials together to make agricultural decisions for the season and thereafter the officers and farmers meet monthly to update the plan and the progress. Currently, computer-aided manual processes are followed by agencies.

Agro-met Advisory Generation System Developed

The digital system presented in this paper mediates the agencies as a facilitator to generate the advisory automatically when relevant agencies upload the data in predefined formats. The system is designed such that the integration is seamless and smooth to the current data generation and uploading processes.

Design of the system

As illustrated in Figure 2, there are three applications developed to facilitate the digital agromet advisory generation process. App1 is to generate the co-produced district level agromet advisory. This advisory is sent to the Agrarian Service Centers (ASCs) to customize according to location specific information such as tank water level and location specific weather forecasts using App3. The customized agro-met advisory is taken to the Pre-Seacon Cultivation Planning meeting to be discussed with farmer organizations. At this point App2 is used to calculate the cultivable land extent based on the observed tank water level and the rainfall forecast available in the advisory generated by App1.

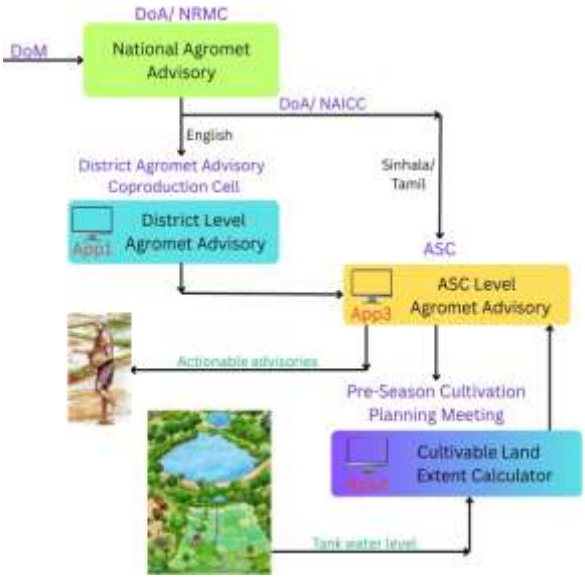

Figure 2. Overall process for digital agro-met advisory dissemination

The App3 also generates actionable advisories throughout the season that will be disseminated to farmers at critical milestones in the crop calendar and at noteworthy weather events. It was observed that certain Agricultural Research & Production Assistants (ARPAs) and ASC officials already communicate to farmer communities of information in pdf and text message formats via social media groups. The generated advisories in App3 will be shared in such existing channels. The experts insist on the importance of actionable advisory generation and local customization. The effectiveness of current information dissemination level and quality depends on the personal dedication and capacity. A digital system will mitigate the subjective nature and other biases of advisory and allow a larger knowledge base to source the information.

Sometimes the local knowledge and circumstances may suggest alternate actions. Feedback loop is required to capture such causes of action unanticipated at the time of advisory generation. Ability to have a closed loop advisory system is an attractive feature and digital systems provide flexibility to achieve such features. We have developed a web application that can run on both desktop computers and mobile phones. It supports all three languages (Sinhala, Tamil and English).

Figure 3 illustrates a set of interfaces captured from App1. The application is for the officials for district level co-production of agromet advisory. When the user input the date and the district the report is generated using the database populated with data provided regularly by the agencies such as DoM and DAD.

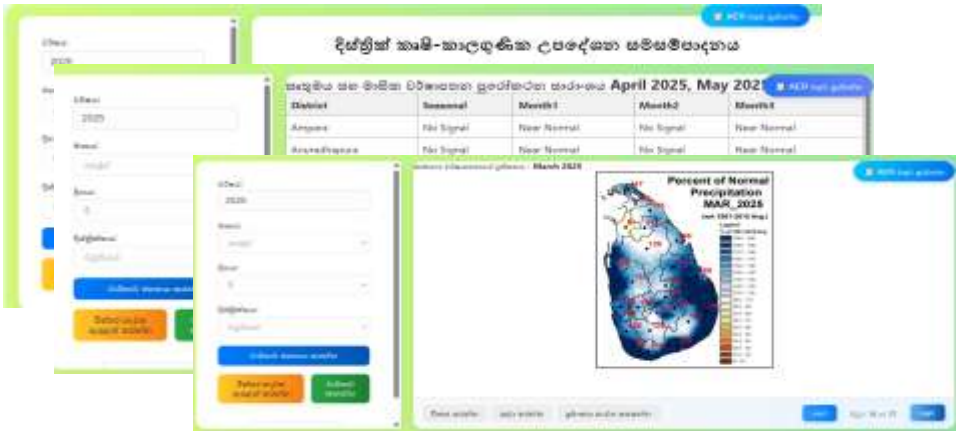

Figure 3. Interfaces of the software

As depicted in Figure 3, the report is organized as easily navigable pages with options for customization. The output carries tables and images in par with the current national level advisory content.

Sustainability of the system

There should be policy level agreement among agencies and systematic information sharing processes set up for sustainability of the digital systems in concern. The interaction with the systems should be embedded into Terms of Reference of designated officer duties for proper maintenance and usage of the digital system. Further, a proper IT service center should be available to maintain the IT infrastructure at a professional level or proper collaboration is required with an IT service company or an agency capable of hosting government cloud services and a data center.

Conclusion

This study reviews digital products available for the endeavor of smart agriculture taking agro-met advisory co-production as the example scenario. A web-based software that we developed for automatic generation of agro-met advisory for district level co-production was presented with the objectives (1) To assist officials to efficiently perform duties, (2) To mitigate person and other biases in information

generation and customization, (3) To generate a digitalized large knowledge base, (4) To allow information sharing, and authorization among agencies, (5) To close the loop by reporting actual decisions taken against the issued advisory, (6) to provide characteristics of the developed system, (7) To provide simpler interfaces to share data or information product outputs among information producer and consumer agencies (e.g. Application Programming Interfaces (API)), and (8) To enhance capability to report actual cause of actions taken by the end farmers.

Acknowledgement

Authors wish to acknowledge the CRIWMP project for facilitating interviews with stakeholder agency officials, participation in agro-met coproduction workshops conducted for ASC officials and for providing consultation of domain experts in agriculture, meteorology, and irrigation for this study.

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Integrating Modern GIS and Participatory Mapping Tools for Flood Exposure and Vulnerability Assessment in Malwathu oya, Yan oya and Mi oya River Basins in Sri Lanka

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Introduction

Accurate spatial mapping is a added advantage in local development planning. Traditional mapping approaches are mostly rely on handheld Global Positioning System (GPS) devices; however, these methods frequently fall short in delivering the level of accuracy needed for fine-scale analysis. With a typical positional accuracy of around 10 - 15 meters due to factors such as Urban Canyons, Dense Tree Cover, Poor Satellite Geometry, Atmospheric Conditions, Receiver Quality. This is specially a problem in densely settled areas where closely located and therefore differentiating individual buildings accurately is a challenge. i. Additionally, recording a single point using a handheld GPS devise (e.g., at the front of a house) rather than delineating its actual location further compromises data reliability.

To address these limitations, this study proposes a more precise and contextually rich approach by integrating modern Geographic Information System (GIS) tools with participatory mapping techniques. This combined methodology enhances spatial resolution and data reliability while embedding local knowledge into the mapping process, thereby improving both the technical accuracy and social relevance of the outputs.

The primary objective of the study was to develop a robust, household-level flood vulnerability assessment across flood inundation areas within the Malwathu Oya, Yan Oya, and Mi Oya river basins to strengthen the flood monitoring, preparedness and early warning and preparation of standard operating procedures . By utilizing high-resolution satellite imagery, local level data collection, and advanced GIS analysis, the study aimed to produce a comprehensive spatial database that supports evidence-based flood vulnerability assessment that supports flood risk management. This approach not only strengthens the foundation for an effective flood emergency preparedness and response, but also development planning that promotes community engagement in building long-term resilience.

Methodology

The flood hazard mapping exercise was conducted at household level using a structured questionnaire and participatory geospatial mapping aimed at improving spatial

understanding and supporting informed decision-making at the community level. The methodology comprised the following:

Identification of the Study Area

The first step involved the selection and delineation of the study area, which consisted of specific flood affected Grama Niladhari (GN) Divisions in 3 river basins using available historical flood records Identified GNDs were also validated by the respective district and divisional officers in flood affected areas.

Boundary Demarcation and Landmark Mapping in flood affected GN divisions

Using high-resolution satellite imagery available through Google Maps, the boundaries of the selected GN Divisions were demarcated. Key physical and cultural landmarks—including public places, places of interest such as water bodies, road networks, and other critical infrastructure—were identified and mapped with the full involvement of Grama Niladhari officers and community members. This step ensured an accurate spatial representation of the local geography and built environment.

GN Base Map Development

Based on the demarcated boundaries and mapped features, a GN-level base map was developed. The cartographic specifications included, Scale: Less than 1:3000 to ensure high spatial detail, and Map Size: 3 feet by 4 feet (approx. 0.9-1.2 m) for enhanced readability and field usability. The map was **p**rinted on digital flex for durability and portability in field settings.

Housing level questionnaire survey

A household level survey was conducted to collect details such as demographic and socio-economic status, housing materials and status, hazard and vulnerability information, preparedness levels. Housing ID were assigned to each house for the purpose of integrating into the map and questionnaire data base. This survey was conducted by GN officers with the support of other officials in the GN level.

Map Reading and Data Marking

Prior training was conducted to community representatives and local officers on map reading and identification of geographical features (Figure 1). At this exercise, Housing ID were marked on the base map for the purpose of linking the questionnaire survey and GIS data base. In addition, flood inundation areas, evacuation paths and safe locations were marked on the GN map.

Digitization of Field Maps

The annotated maps from the field were collected and digitized using Geographic Information System (GIS) software. This process converted physical annotations into spatial data layers for further analysis. These maps were also validated with the flood maps available in the Irrigation Department.

Database Integration

The spatial data layers were linked to non-spatial data derived from a household questionnaire survey. As a result household level data can be retrieved visualized. This relational database enabled the integration of demographic, socio-economic, and environmental variables with spatial features.

Figure 1. GN level Map reading training in Nanattan DS Division in Mannar

GIS and Statistical Analysis

Integrated spatial and non-spatial data were analyzed using GIS and statistical methods. The analyses supported the identification of flood vulnerability levels, trends, and spatial relationships

Decision-Making Support

The results of the spatial analyses were utilized for river basin, district and local level flood risk management planning purposes. This include flood early warning, emergency preparedness and response planning and flood management by taking to account upstream and downstream integration as the study taking to account river basin flood affected area. Therefore, spatial database and visual outputs facilitated evidence-based planning, resource allocation, and Standard Operating Procedures (SOP's) formulation by local authorities and community stakeholders.

Results and discussion

The development of a comprehensive and spatially specific GIS database represents a significant advancement in flood vulnerability and risk management. The main outputs of this initiative include a housing-level flood exposure GIS database, which details the extent and frequency of flood events affecting individual houses across 3 river basins.

Using the data base and vulnerability maps, highly flood inundated households, most vulnerable households such as impermanent houses, areas where early warning not received, vulnerable families with special illnesses, women headed household, elderly, etc can be identified (Figure 2).

This assessment identified that 25 DS divisions and 191 GN divisions in 3 river basins (6 districts) are vulnerable to floods. 9018 households are directly inundated by floods and 66,368 houses are indirectly affected. Anuradhapura, Trincomalee and Puttalam are the 3

districts that most of the houses are affected in Malwathu Oya, Yan Oya and Mi Oya basins (Table 1).

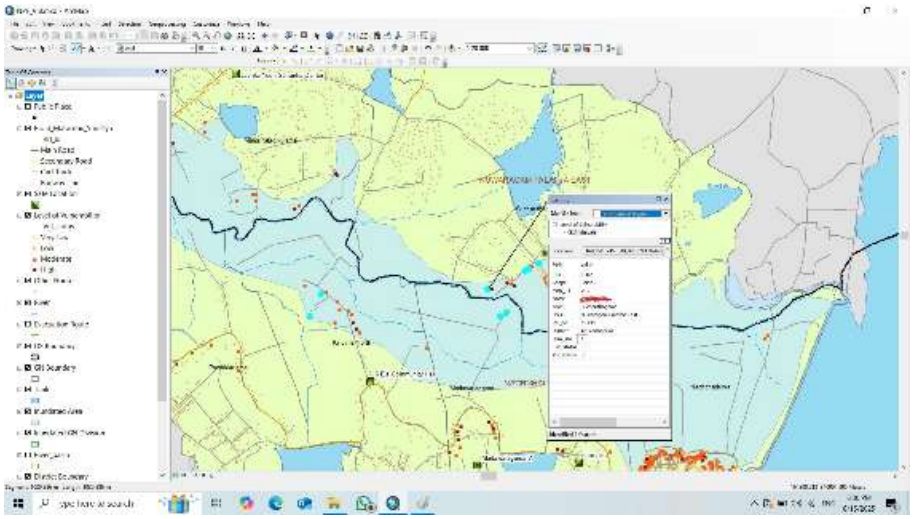

Figure 2. Flood vulnerability map (details shown are a household with disable person)

Table 1. Flood inundation housing statistics by river basin and districts

River basin	District	Affected DSDs	Affected GNDs	Total Number of houses	Number of Inundated houses (2010 - 2018)
Malwathu oya	Anuradhapura	8	71	27444	3285
	Mannar	2	14	2860	1493
	Vavuniya	2	14	5185	1353
	Sub total	12	99	35489	6131
Mi oya	Anuradhapura	4	37	10595	667
	Trincomalee	3	8	3282	1049
	Sub total	7	45	13877	1716
Yan oya	Kurunegala	2	15	3859	173
	Puttalam	5	32	13136	998
	Sub total	7	47	16995	1171
	Grand total	26	191	66361	9018

Complementing this is the housing-level flood vulnerability GIS database (Table 2), which integrates social, economic, and structural attributes to assess the vulnerability of each household to flood impacts. This shows that out of the total flood affected people in Malwathu Oya basin nearly 53% are in Anuradhapura. Similarly In Yan Oya basin 61% of the flood inundated houses Trincomalee and in Mi Oya basin 85% of the flood inundated houses are in Puttalam districts. Table 2 also shows that 25% flood affected people in Mannar district are highly vulnerable and 53% households are moderately vulnerable where as 50

% of the households in Vavunia are low vulnerable to floods. Also in Mi Oya basin, majority of the flood affected households (56%) in Anuradhapura and 63% in Trincomalee are flood inundated. In Mi Oya majority (69%) are low vuunerable and in Puttalam majority of the households are moderately vulnerable (46%).

Table 2. Housing level vulnerability statistics inundated houses by river basins and districts.

River basin	District	Very low	Low	Moderate	High	Grand total
				Number		
Malwathu oya	Anuradhapura	81	1080	1783	341	3285
	Mannar	23	254	822	394	1493
	Vavuniya	47	679	494	133	1353
	Sub total	**151**	2013	3099	868	6131
Mi oya	Anuradhapura	22	161	372	112	667
	Trincomalee	40	251	661	97	1049
	Sub total	**62**	412	1033	209	1716
Yan oya	Kurunegala	38	120	15	0	173
	Puttalam	133	193	467	205	998
	Sub total	**171**	313	482	205	1171

The inclusion of precise locational data—such as household level geographic coordinates, point elevation relative to the riverbank, and distance from the river—enables accurate spatial analysis and flood modeling. Furthermore, information on early warning systems (availability, sources, etc.) allows authorities to assess the effectiveness of existing alert mechanisms. As such, this comprehensive database can be utilized for multiple purposes including risk assessment and emergency operations, development of flood Standard Operating Procedures (SOPs) at the river basin level, preparation of local-level flood management plans, and long-term development and infrastructure planning.

Conclusion

This study demonstrates the significant potential of integrating modern GIS technologies with participatory mapping approaches to enhance household-level vulnerability assessment and local-level flood risk management planning. By moving beyond conventional GPS-based methods, the project addressed the critical limitations of spatial inaccuracy and contextual gaps often encountered in rural mapping exercises. Through the use of high-resolution satellite imagery, household level data collection and validation and rigorous GIS analysis, the study successfully generated spatially accurate, socially informed, and policy-relevant data products. The outputs—such as the housing-level flood exposure and vulnerability GIS databases, detailed flood inundation maps, and high-precision administrative and infrastructure layers—provide a comprehensive foundation for flood risk analysis across the Malwathu Oya, Yan Oya, and Mi Oya river basins. The integration of physical and socio-economic data enables nuanced vulnerability assessments, facilitating targeted interventions and more effective flood management strategies.

Furthermore, the participatory nature of the mapping process not only improved the accuracy of spatial data but also fostered local ownership and knowledge-sharing, strengthening community engagement in disaster preparedness and response. The resulting database is highly useful, supporting risk assessment, emergency operations, and long-term development planning at both local and river basin levels.

Overall, this study establishes a replicable model for local level hazard mapping that bridges technical precision integrated with local knowledge and experiences. It offers valuable lessons for enhancing disaster resilience and sustainable development in flood-prone areas through data-driven and inclusive planning practices.

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Preparation of Standard Operating Procedures (SOPs) for Flood Management in the Malwathu Oya, Yan Oya, and Mi Oya River Basins of Sri Lanka

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Introduction

Sri Lanka's Dry Zone, especially the Malwathu Oya, Yan Oya, and Mi Oya River basins covering the districts of Anuradhapura, Kurunegala, Puttalam, Trincomalee, and parts of Kandy, is increasingly vulnerable to extreme weather events such as floods, droughts, and temperature extremes, driven by climate change and variability. These basins form the agricultural heartland of the country, supporting diverse agro-ecological systems, traditional Village Tank Cascade Systems (VTCS), and several major and medium irrigation tanks. They are vital for national food security, supporting rice, field crops, vegetables, dairy, inland fisheries, and providing water for agriculture, public supply, and industry. Additionally, they contribute to biodiversity conservation, eco-tourism, and recreation. However, these basins face mounting climate-induced challenges including erratic rainfall, prolonged droughts, and periodic flooding. These issues are worsened by declining VTCS functionality, falling groundwater levels, and soil moisture deficits in uplands. As a result, agricultural productivity, ecosystem services, and rural livelihoods especially for smallholders and marginalized groups are increasingly at risk. In response, the Ministry of Irrigation, through the Climate Resilient Integrated Water Management Project (CRIWMP), is working to enhance the adaptive capacity of smallholder farmers, particularly women, by promoting integrated water management practices. As part of its disaster risk reduction efforts, the project is developing Standard Operating Procedures (SOPs) for flood management in these three critical river basins to help safeguard climate-sensitive livelihoods and improve resilience.

Based on a detailed flood risk assessment in these three river basins, 192 flood-prone Grama Niladhari Divisions (GNDs) across 25 Divisional Secretariat Divisions (DSDs) were identified, comprising a population of approximately 215,000 people. These areas are frequently affected by floods, threatening lives, property, and livelihoods. These SOPs are anticipated to significantly reduce flood-related casualties, property damage, and disruption to livelihoods in these vulnerable communities. The SOPs are being developed to establish a technical coordination mechanism in line with the revised Flood Protection Act, and to enhance institutional capacity and community awareness for effective flood preparedness, response, and recovery.

The objectives of the SOPs are multifaceted, and include (1) To clearly define the roles and responsibilities of government agencies, local authorities, and community stakeholders in flood management, (2) To promote early actions and minimize reactive or ad hoc responses, (3) To strengthen multi-agency coordination, technical operations, disaster response and information sharing upstream and downstream of the basins, (4) To ensure that flood response measures are inclusive, considering gender and disability perspectives, (5) To build community awareness and promote participatory planning at all levels, and (6) To explore technological solutions for efficient forecasting, communication, and operations.

The SOPs cover the full disaster management cycle, including preparedness, early warning, emergency response, and post-flood recovery. They address multiple flood types riverine, reservoir induced, and urban while propose both structural and non-structural measures to reduce impacts in future. Institutional mapping, policy review, and gap analysis are conducted to ensure that the SOPs are grounded in current practices while addressing key deficiencies.

Methodology

The methodology emphasizes participatory and evidence-based approaches, including, river basin-level consultations with government agencies, provincial councils, and local authorities, Focus group discussions with stakeholders and communities affected by previous flood events, Preparation of an inception report, including stakeholder mapping, gap analysis, and a conceptual framework, Development of detailed SOPs aligned with national regulations, the Flood Protection Act, and international best practices, Validation workshops at the river basin level to finalize the SOPs and Translation and dissemination of SOPs in Sinhala, Tamil, and English, along with district-level awareness sessions. To support long-term sustainability, the SOPs will be complemented by agency specific activity plans for actions before, during, and after flood events, an institutional capacity building program, community awareness materials, and recommendations for institutional coordination. A monitoring and incorporate lessons learned from actual flood responses.

Results and Discussion

The development of the SOPs has led to several key outcomes that strengthen institutional preparedness and community resilience to flooding in the three Dry Zone River basins.

Institutional Coordination Framework Established

Through river basin-level consultations and institutional mapping, a multi-tier coordination mechanism was developed. This mechanism defines clear roles and responsibilities among national agencies such as the Irrigation Department, Disaster Management Centre (DMC), Department of Meteorology, District and Divisional Secretaries and local government authorities. SOPs delineate pre-agreed actions and communication flows to be triggered based on early warning thresholds and flood forecasts, significantly reducing response time and confusion during emergencies.

Flood-Prone Areas Clearly Identified and Prioritized:

Using hydrological modeling, historical flood records, and field validation, 192 flood-vulnerable GN Divisions were mapped and categorized by risk level. This granular risk zoning enabled the formulation of tailored preparedness and evacuation protocols that address site-specific challenges, particularly in areas vulnerable to reservoir-induced and flash floods.

Participatory Validation and Local Integration

Three basin-level validation workshops ensured that the SOPs reflect local realities, incorporate lessons from past flood responses, and receive buy-in from local stakeholders. Community- level feedback highlighted issues such as communication breakdowns during night-time floods, inadequate evacuation infrastructure, and limited inclusion of women and persons with disabilities in emergency planning. These insights were directly incorporated into the SOP content and district-specific response matrices.

Integration of Early Warning and Communication Protocols:

The SOPs incorporate basin-specific early warning dissemination pathways using multi-channel approaches, including SMS alerts, sirens, community focal points, and integration with DMC's national alert systems. Provisions for backup communication strategies during power or network failures were also defined, enhancing reliability.

Institutional and Community Capacity Enhanced

Draft agency-specific action plans were prepared for relevant departments, outlining operational responsibilities before, during, and after flood events. Community awareness campaigns, school-level education materials, and training modules were also developed. Pilot awareness sessions demonstrated increased understanding of flood signals, safe evacuation practices, and responsibilities at the household level.

Policy Alignment and Institutional Gap Bridging

The SOPs were aligned with the pending Flood Protection Act and key disaster management frameworks. The gap analysis identified deficiencies in current emergency response systems, including coordination bottlenecks, underutilization of data, and lack of real-time communication platforms. The project proposed strategic interventions, including the establishment of basin-level technical units and regular inter-agency simulation exercises.

Collectively, the results underscore the importance of localized, inclusive, and data-driven approaches to flood risk management. SOPs are not only regulatory tools but also instruments for knowledge transfer, institutional reform, and community empowerment. They are expected to serve as replicable models for other river basins in Sri Lanka facing similar climate-induced challenges.

Institutional Mechanism for River Basin Level Technical Flood Operation

To ensure effective real-time coordination, data-driven decision- making, and synchronized operational response before, during, and after flood events, a Flood Control Technical Unit has been established for the three river basins, including an example unit for the

Malwathu Oya Basin at the Anuradhapura district (Figure 1). This unit functions as a basin-level technical operational structure, aligned with the provisions of the proposed Flood Protection Act. It promotes an integrated approach to flood management at the basin level, facilitating inter-agency coordination, timely information sharing, and improved flood risk mitigation and response.

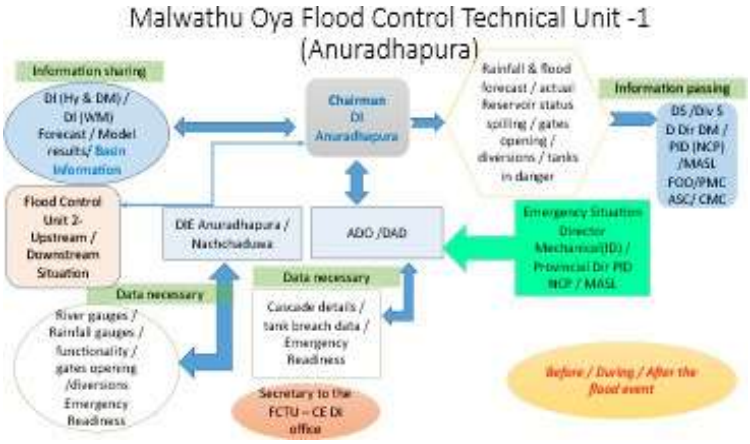

Figure 1. Malwathu Oya flood Control Technical Unit

This mechanism facilitates multi-agency coordination, information sharing, and flood emergency operations, anchored in the river basin context. Key features of the institutional mechanism include, (a) Chairmanship by the Director of Irrigation (DI) at Anuradhapura who oversees basin-wide technical operations and decisions, (b) Coordination between Divisional Irrigation Engineers (DIEs) and Agrarian Development Officers (ADOs/DADs) to consolidate ground-level data and operational updates on tank cascades, reservoir safety, and community readiness, (c) Real-time information flow between DI (Hydrology and Disaster Management) and DI (Water Management)Divisions) forecasting units, and field offices, supported by model outputs and rainfall/flood alerts, (d) A parallel technical link with Flood Control Unit-2, Mannar monitoring upstream and downstream hydrological behavior and infrastructure risks. (e) Direct communication with EmergencyOperations Coordinators – Mechanical Engineers from the Irrigation Department and Provincial Directors from PID/MASL – for activation of flood preparedness and immediate response measures, (f) A structured channel for information dissemination to Divisional Secretaries, District and Provincial-level officials, Field Officers, Agrarian Service Centers (ASCs), and Community-based Mechanisms (CMCs/PMCs), (g) Emphasis on critical data acquisition including rainfall and river gauge readings, tank spill and gate operations, and breach alerts to inform emergency decisions, (h) Secretary to FCTU positioned at CE DI office ensures operational documentation and escalations.

This mechanism enables a technical and institutional backbone for flood operations at the river basin scale and ensures timely coordination across all actors engaged in flood forecasting, community response, and safety infrastructure.

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Impact of Dry and Wet Conditions on Irrigation Water Quality of Basawakkulama Wewa, Nuwara Wewa and Thissa Wewa in Anuradhapura District

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Introduction

The planet earth comprises of geosphere, atmosphere, biosphere and hydrosphere. The hydrosphere is the total amount of water on a planet. The hydrosphere includes water storage areas such as oceans, seas, lakes, ponds, rivers, and streams. Less than 0.5% of the total hydrosphere is present on the continents as lakes and rivers (Gunawardhana 2009). **T**hough the surface of the earth mostly consists of water, the smaller amount of accessible freshwater is being used by human for drinking and many other purposes including transportation, hydroelectric power generation, and industry, which makes this resource limited. Therefore, water must be used with care (Roy 2019).

Historically, humans have used irrigation tanks, lakes for various purposes, such as drinking, washing, and agricultural activities and for fisheries in Sri Lanka. A higher density of tanks is distributed in the dry zone of Sri Lanka, and human dependence on such water bodies is very high (Nilusha et al. 2012) . The largest user of water in Sri Lanka is irrigated agriculture. The irrigation water flows through a system of tunnels, streams, reservoirs (*Wewa*), canals, etc.

The water quality of freshwater systems is controlled by climatic variability, hydrological, biogeochemical, and anthropogenic influences. These influences operate at various temporal and spatial (e.g. global, river basin, local catchment) scales (Mosely 2015). Water quality in rivers and lakes can generally be connected with land use in its own catchment and prevailing dry conditions. Droughts affect more people than any other natural disaster (Burchfield 2016). Droughts are a perturbation in the natural climatic and hydrologic regime which can affect the determinants of water quality in multiple ways. Prevailing dry (drought) Condition often cause subsequent hydrological effects such as water flow and volume decreases during drought typically led to increased salinity due to reduce dilution and concentration of mass (Mosley 2015).

Nuwara wewa and Thissa wewa are major freshwater bodies used for drinking water in the Anuradhapura district (Dissanayaka et al. 2021). Nuwara wewa ,Thissa wewa , Basawakkulama wewa are major reservoirs used for water in the agricultural sector in anuradhapura district .In this study, the impact of the surrounding land uses and prevailing drought on water quality of Basawakkulama wewa, Nuwara wewa and Thissa wewa in

anuradhapura were Investigated. Water in these reservoirs are widely used for many agricultural, drinking, domestic and recreational purposes.

In Sri Lanka as well as in other developing countries, water pollution is a major problem. Deterioration of water quality in surface water is a severe threat to the smooth functioning of ecosystems including the health of human beings. Climatic changes (prevailing dry and wet conditions) and anthropogenic activities such as agriculture, urbanization and industrialization are the main pathways for water pollution. The identification of the relationship between surface water quality and dry and wet conditions is important for decision making regarding the mitigation of water pollution in Basawakkulama wewa, Nuwara wewa, and Thissa wewa which are major reservoirs surrounding Anuradhapura city. The identification of possible point and non-point sources of water pollutions in these reservoirs has become a timely necessity.

This study assessed the major water quality parameters at the selected water sampling locations of each reservoir and the relationship between the water quality parameters of each reservoir and the prevailing dry and wet conditions.

Methodology

Study site

The study was carried out in three major reservoirs located around Anuradhapura city of Sri Lanka, namely, Basawakkulama wewa, Nuwara wewa and Thissa wewa.

Water sampling

Water sampling locations were identified representing the land uses surrounding each reservoir. The coordinates of the sample locations were recorded using the GPS receiver and sample collection was repeated from the same locations. Water samples were collected from the selected locations prior to the onset of rain (dry condition) and after the rain (wet condition). Water samples were collected from five selected points in each reservoir. Water samples were collected into the pre-cleaned polypropylene bottles.

Analysis of water samples

The collected water samples were analyzed for various water quality parameters. The parameters include pH, electrical conductivity (EC), total dissolved solids (TDS), ammonium -nitrogen (NH_4^+-N), nitrate-nitrogen (NO^-_3 -N), dissolved reactive phosphorus (DRP), alkalinity, sodium adsorption ratio (SAR), sodium percentage (Na%), water dissolved Na^+, K^+, Ca^{2+} and heavy metals (Cd^{2+}, Ag^+, Pb^{2+}).

Results and Discussion

Variation of pH in tanks

The temporal variations of water pH of five selected sampling locations of Basawakkulama wewa, Nuwara wewa and Thissa wewa are depicted in Figure 1. The pH value indicates the level of acidity or alkalinity in a particular aqueous solution which ranges from 0 to 14.

Water is generally classified into three main categories such as acidic (pH < 6.5), neutral (pH 6.5-8.5), and hard (pH>8.5) based on pH (Dissanayaka et al. 2021). The pH of dry and wet condition varied from 8.49 to 6.60 in Basawakkulama wewa , 8.72 to 7.29 in Nuwara wewa and 8.15 to 7.43 in Thissa wewa respectively. Water pH slightly fluctuated over the period in a given sampling location of each studied reservoir. Some pH values were within the recommended range (6.5- 8.5) according to FAO standards for irrigation water quality (FAO 1985).

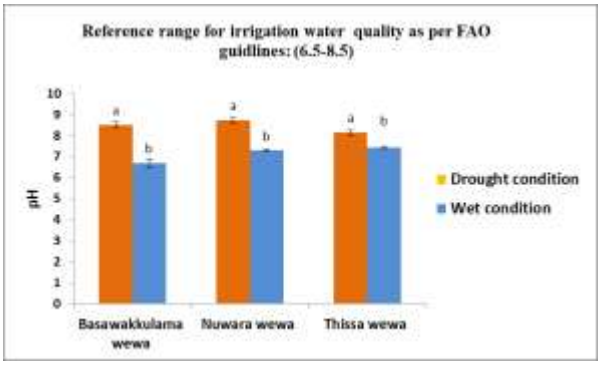

Figure 1. Temporal variation of water pH during dry (drought) and wet conditions of Basawakkulama Wewa, Nuwara Wewa and Thissa wewa. (Values followed by same letter are not significantly different at P=0.05 in each reservoir at dry (drought) and wet conditions).

Variation of Electrical Conductivity (EC) in tanks

The Water EC slightly fluctuated over the study period in a given sampling location of each studied reservoir (Figure 2). The EC of dry (drought) and wet condition varied from 0.73dS/m to 0.31 dS/m in Basawakkulama wewa, 0.72dS/m to 0.43 dS/m in Nuwara wewa and 0.24 ds/m - 0.26 ds/m in Thissa wewa. However, all the EC values were within the recommended range (0-3 dS/m) according to FAO standards for irrigation water quality (FAO 1985). High conductivity in water is directly related to rising temperature because it increases solubility and ionic mobility. However heavy rain can decrease the conductivity of water as it dilutes the current salinity concentration. If heavy rainfall or another major weather event contributes to flooding, the effect on conductivity depends on the water body and surrounding soil. Electrical conductivity usually drops overall during the wet seasons due to the dilution of the water sources.

Variation of Total Dissolved Solids (TDS) in tanks

The total dissolved solids (TDS) of dry (drought) and wet condition varied from 352.20 mg/l to 166.40 mg/l in Basawakkulama wewa, 392.40 mg/l to 232.00 mg/l in Nuwara wewa and 175.33 mg/l to 138.13 mg/l in Thissa wewa (Figure 3). Water TDS slightly fluctuated over the period in a given sampling location of Basawakkulama wewa and Nuwara wewa. During a drought the TDS in a lake can increase for several reasons. These may be due to the water level decreasing in lakes; the concentration of dissolves solids becomes higher since there is less water to dilute them. This means that the same amount of dissolve solids is now present in a smaller volume of water, resulting in an increase in TDS. According to the Figure 3, Thissa wewa showed no significant (p>0.05) difference in TDS value. The TDS of drought

condition in Basawakkulama wewa and Nuwara wewa had significantly greater value ($p<0.005$) compared to the wet condition.

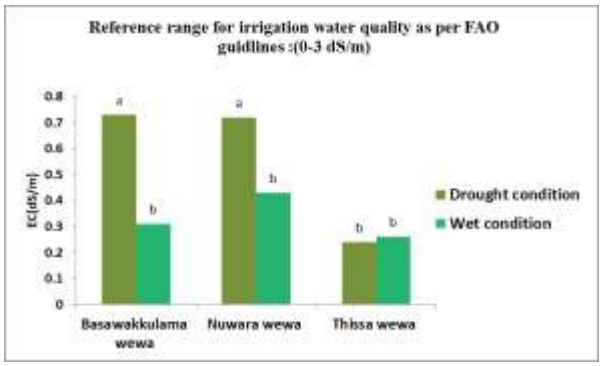

Figure 2. Temporal variation of water EC during dry (drought) and wet conditions of Basawakkulama Wewa, Nuwara Wewa and Thissa wewa (Values followed by same letter are not significantly different at P=0.05 in each reservoir at dry (drought) and wet conditions)

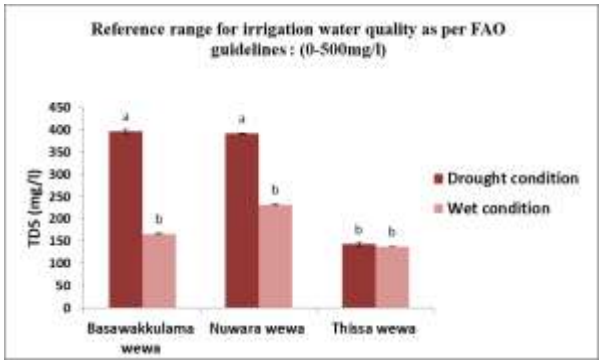

Figure 3. Temporal variation of water total dissolved solid during dry (drought) and wet conditions of Basawakkulama Wewa, Nuwara Wewa and Thissa Wewa. (Values followed by same letter are not significantly different at P=0.05 in each reservoir at dry (drought) and wet conditions)

Variation of Alkalinity in tanks

The concentration of carbonates and bicarbonates should be under the limit in water and if the level of carbonates and bicarbonates is increased, it may be harmful for humans, animals and plants (Arshad and Shakoor 2017). The alkalinity of dry (drought) and wet condition varied from 172.25 mg/l to 122.29 mg/l in Basawakkulama wewa, 169.6 mg/l to 131.03 mg/l in Nuwara wewa and 92.75 mg/l to 101.91 mg/l in Thissa wewa (Figure 4). Permissible range of alkalinity in irrigation water is between 0 and 610 mg/l (FAO 1985). Water alkalinity slightly fluctuated over the study period in a given sampling location of each studied reservoir. All alkalinity values were within the recommended range (0-610 mg/l) according to FAO standards for irrigation water quality. According to the Figure 4, alkalinity is higher in the dry (drought) condition than in the wet condition.

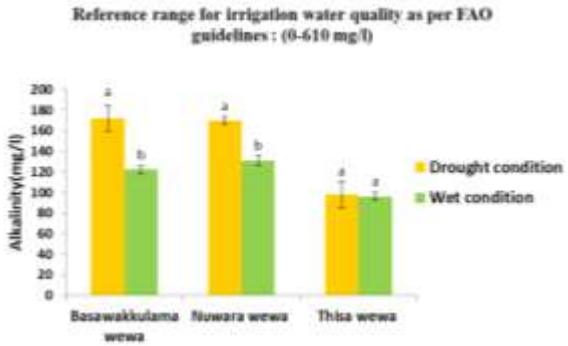

Figure 4. Temporal variation of water alkalinity during dry (drought) and wet conditions of Basawakkulama Wewa, Nuwara Wewa and Thissa Wewa (Values followed by same letter are not significantly different at P=0.05 in each reservoir at dry (drought) and wet conditions)

Variation of Dissolved Reactive Phosphorus (DRP) in tanks

The dissolve relative phosphorus of dry (drought) and wet condition varied from 0.03 mg/l to 0.02 mg/l in Basawakkulama wewa, 0.67 mg/l to 0.02 mg/l in Nuwara wewa and 0.25 mg/l to 0.01 mg/l in Thissa wewa. The critical value for occurrence of eutrophication for phosphates is 0.08 mg/l (USEPA 1976). These phosphorus levels in the water contribute to eutrophication. Eutrophication is the process by which water bodies grow in biomass productivity (Oliveira & Machado 2013). Large increases in total nutrient concentrations have been observed during droughts associated with large water level declines, although dissolved nutrients can remain at low concentrations due to rapid uptake by algae. However, according to USEPA guidelines, av. P levels in almost all the reservoirs were sufficient to occur eutrophication. According to the Figure 3.5.1 DRP has shown variable responses in lakes during dry and wet periods.

Variation of nitrate – nitrogen (NO_3-N) In tanks

Nitrate nitrogen of dry (drought) and wet condition varied from 3.37 mg/l to 0.85 mg/l in Basawakkulama wewa, 1.18 mg/l to 1.24 mg/l in Nuwara wewa and 2.51 mg/l to 1.45 mg/l in Thissa wewa. Water NO_3^-- N values in the Basawakkulama wewa, Nuwara wewa and Thissa wewa were within the acceptable range (0-30 mg/l) according to FAO irrigation water quality standards (FAO 1985).

Variation of ammonium – nitrogen (NH_4^+ -N) In tanks

The ammonium nitrogen (NH_4^+-N) of dry (drought) and wet condition varied from 4.55 mg/l to 1.02 mg/l in Basawakkulama wewa, 3.22 mg/l to 0.47 mg/l in Nuwara wewa and 1.71 mg/l to 0.97 mg/l in Thissa wewa. The maximum permissible NH_4^+ -N level prescribed for irrigation water is 5 mg/l. The measured ammonium nitrogen (NH_4^+-N) values in all the water samples were within the permissible level according to WHO standards for irrigation water quality guidelines. During the dry (drought) season, ammonium nitrogen concentration can rise. This may be due to increasing nutrient concentrations during the droughts has occurred in surface water resources where point sources of nutrients (industrial, domestic, agricultural wastewater discharges) are present (and remain relatively constant during drought) and a lack of dilution occurs.

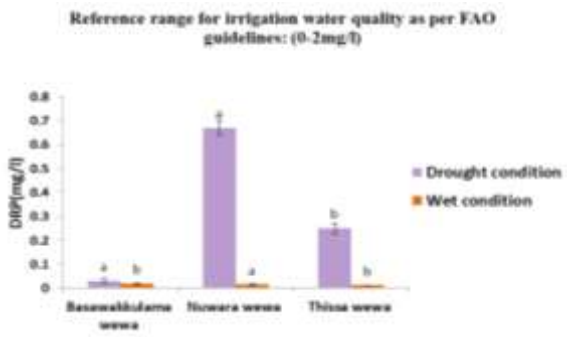

Figure 5. Temporal variation of water DRP during dry (drought) and wet conditions of Basawakkulama Wewa, Nuwara Wewa and Thissa Wewa. (Values followed by same letter are not significantly different at P=0.05 in each reservoir at drought and wet conditions)

Variation of potassium in tanks

The potassium (K^+) of dry and wet condition varied from 0.20 meq/l to 0.11 meq/l in Basawakkulama wewa, 0.20 meq/l to 0.12 meq/l in Nuwara wewa and 0.14 meq/l to 0.10 meq/l in Thissa wewa. Permissible range of potassium concentration in irrigation water is between 0 and 2 meq/l according to the FAO standards for irrigation water quality (FAO 1985). Therefore, potassium (K^+) values in the all collected water samples were within the permissible range according to FAO standards for irrigation water quality guidelines. Water potassium concentration slightly fluctuated over the study period in a given sampling location of each studied reservoir.

Variation of calcium in tanks

The calcium of dry and wet condition varied from 3.14 meq/l to 0.95 meq/l in Basawakkulama wewa, 3.35 meq/l to 0.86 meq/l in Nuwara wewa and 2.27 meq/l to 0.71 meq/l in Thissa wewa. Permissible range of calcium concentration in irrigation water is between 0 and 20 meq/l (FAO 1985). So, calcium concentrations of the collected water samples were within the permissible range. Water calcium concentration slightly fluctuated over the study period in a given sampling location of each studied reservoir. Calcium also showed higher concentrations during dry condition (Van Vliet et al. 2008).

Variation of SAR In tanks

The measured SAR of drought and wet condition varied from 0.92 meq/l to 1.24 meq/l in Basawakkulama wewa, 0.29 meq/l to 1.79 meq/l in Nuwara wewa and 0.36 meq/l to 0.99 meq/l in Thissa wewa. Permissible range of SAR in irrigation water is between 0 and 15 meq/l (FAO 1985).

Conclusion

Water quality in all three reservoirs is suitable for irrigation purpose according to FAO guidelines. Water quality in each reservoir is highly influenced by the climate, sampling time and location. Among the water quality parameters, dissolved organic matter and micro pollutants (heavy metals) are susceptible to increase in the concentration or number as a consequence of temperature increase and heavy rain falls in the dry zone region of Sri

Lanka. By consenting to the result, the pH, total dissolved soils (TDS), dissolved relative phosphorus (DRP), ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3-- N), alkalinity, total calcium and potassium of studied reservoirs had significantly greater values under dry condition compared to the wet condition. By consenting to the results, Total sodium, sodium adsorption ratio (SAR) and sodium percentage (Na%) of the studied reservoirs had significantly greater values under wet condition compared to the dry condition. Hence, there is an urgent need to study the effects of dry and the wet condition on surface irrigation water quality to prevent any adverse impacts on lake water quality in the dry zonal tanks in Sri Lanka.

Acknowledgement

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Climate Action Symposium (CAS) 2025 – Extended Abstracts
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Social Inclusion in Climate-Smart Water Governance: Lessons from a Community-Led Pipeline Extension in Tharanikkulam in Sri Lanka

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Introduction

Access to safe drinking water remains a major challenge in post-conflict, marginalized communities. Tharanikkulam village in Vavuniya District of Northern Sri Lanka exemplifies this challenge, as resettled families continue to face displacement-related vulnerabilities, poverty, and limited access to safe water. To address these issues, the Climate Resilience Integrated Water Management Project (CRIWMP) implemented a community-led pipeline extension aimed at improving water accessibility and promoting inclusive governance. Beyond infrastructure, the project actively engaged women, youth, and other marginalized groups in decision-making and implementation, fostering social inclusion and local ownership.

In this context, this study explores how community mobilization in Tharanikkulam contributed to equitable water access, strengthened local governance, and enhanced climate resilience in a rural, post-conflict context.

Despite significant investments in rural water infrastructure, top-down approaches often fail to account for the social dynamics that shape access and ownership. In communities affected by displacement and marginalization, reliance on unregulated water sources reinforces existing inequalities and health risks. This underscores the need for inclusive, community-driven governance models that can address structural barriers and ensure equitable, resilient water distribution.

This study analyzed the application of inclusive governance practices in the Tharanikkulam pipeline extension project, examined the participation of women, youth, and marginalized community members in decision-making and implementation processes, and assessed the impact of social inclusion on project sustainability and community resilience in a post-conflict setting.

Methodology

This study adopted a qualitative case study approach to examine social inclusion in climate-smart water governance within a resettled community in Sri Lanka's Northern Province. The research focuses on Tharanikkulam, a village established in 2001 to accommodate displaced families from multiple districts, now administered under the Vavuniya Divisional

Secretariat. Data was collected through direct field observation, stakeholder engagement, and governance evaluation linked to a pipeline extension initiative. Participatory methods ensured that community voices and lived experiences shaped the analysis. A mixed-method strategy was employed, including: observations of local interactions and project activities, review of project documents, attendance records, and institutional frameworks, and pre- and post-evaluation questionnaires administered to 40 purposively selected participants.

Thematic analysis was used to identify patterns in participation, trust-building, and governance outcomes. This approach enabled a context-sensitive understanding of inclusion dynamics in post-conflict rural water governance

Results and Discussion

Household Water Access before the Project

Before the implementation of the pipeline extension project, the village relied on a mix of common and private water sources (Figure 1). However, these sources were largely used for secondary purposes such as washing and bathing, due to concerns over water safety. For drinking water, the majority of the community relied on Reverse Osmosis (RO) water, purchased from three private RO outlets and two community-managed RO plants in Tharanikkulam.

This reliance on external sources reinforced social inequalities, as economically weaker families faced greater difficulties in accessing safe drinking water, often having to collect it from distant locations. A survey of 40 households revealed that only 5 families were able to rely on their private wells, while 35 families depended on external collection points such as RO water outlets and common wells. Figure 2 clearly illustrates that a majority of the households (80.8%) spent between 301–500 LKR per week on RO water. This situation reflects the inequitable access to basic needs like safe drinking water.

Despite the widespread use of Reverse Osmosis (RO) water from private sellers in Tharanikkulam, the absence of proper regulation and quality assurance raises serious concerns about its safety, reliability, and long-term health effects.

Addressing Marginalization through Inclusive Governance

In Tharanikkulam, most residents rely on unstable, low-wage jobs in Vavuniya town, with limited local employment and minimal agricultural activity due to poor soil conditions. Despite receiving government-built housing, the lack of formal land deeds has devalued property and constrained economic mobility.

In this context, the intentional inclusion of marginalized groups through CRIWMP was not merely beneficial, but a necessary step toward equitable development.

Women-Headed Households in Water Governance

Figure 3 illustrates that 96 female-headed households in Tharanikkulam had post-conflict vulnerabilities shaped by displacement, separation, and informal unions. Initially hesitant to engage in project activities—due to both personal reluctance and community-level

resistance—their inclusion was gradually achieved through sustained mobilization, trust-building, and participatory planning. Despite traditional barriers, targeted awareness and trust-building efforts enabled their active involvement in governance and resource planning. Mobilization meeting data above shows a steady rise in women's active participation, moving beyond male-dominated discussions.

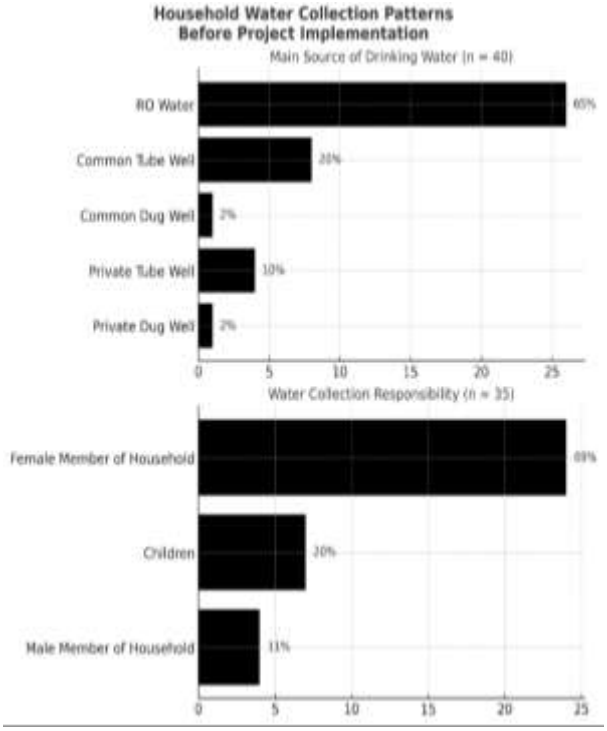

Figure 1. Household water collection patterns before project implementation

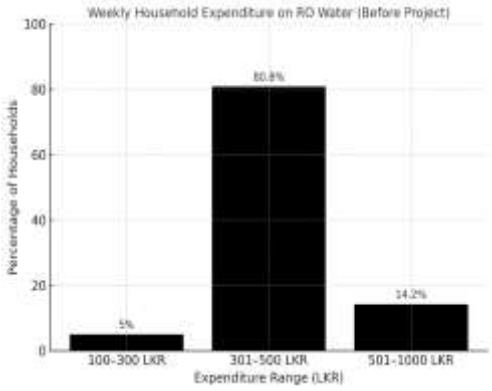

Figure 2. Weekly household expenditure on RO water (Before Project)

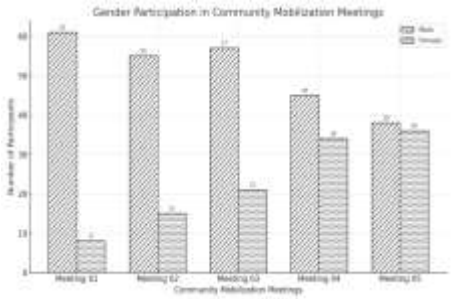

Figure 3. Gender participation in community mobilization meetings.

Collective Action and Social Cohesion

As part of social mobilization strategy, community-based events were organized to foster social inclusion and cohesion (Table 1). These gatherings functioned as platforms for collective engagement, strengthening social capital in a post-conflict setting. Participation data below from these events illustrates their role in promoting inclusive community involvement:

Table 1. Community –based events organized to foster social inclusion and cohesion

Event	Adult Male	Adult Female	Youth Male	Youth Female	Children	Total
Sports Meet	22	12	43	15	38	130
Temple festival	33	40	10	15	8	106
Church Gathering	20	23	7	5	2	57
Community cleanup drive	18	12	11	9	5	55
Awareness/Dialogue Sessions	25	28	14	10	3	80

Community-Based Implementation and Inclusive Participation

Project implementation was initially led by the Tharanikkulam Rural Development Society (RDS), a traditionally male-dominated community organization. As the project progressed, the Women's Rural Development Society (WRDS) was actively integrated, marking a shift toward inclusive participation. WRDS members handled key tasks such as collecting applications, conducting awareness campaigns, and mediating local conflicts. Joint activities—like meetings, site visits, and post-implementation education—were later co-managed by both groups.

Inclusive Labour Strategies for Community Empowerment

The project's strategic engagement of local labour reinforced social inclusion by actively involving women, youth, and persons with disabilities in infrastructure development. By employing community members in specialized tasks such as butt fusion machine operation and water meter column assembly, the initiative fostered skill acquisition and created meaningful employment opportunities, thereby empowering marginalized groups and enhancing local capacity.

Equity in Access: Supporting Marginalized Groups

The project's participatory approach ensured equitable infrastructure allocation, directly benefiting families with persons with disabilities (17) by reducing physical hardship associated with water collection.

Recommendations

Based on the results of the study, with a view to institutionalize inclusive water governance, the proposed recommendations are, (1) Community Leadership: Formalize community-led decision-making with active roles for women, youth, and marginalized groups, (2) Gender Inclusion: Enforce policies that ensure women's participation, technical training, and representation monitoring, (3) Youth Engagement: Provide vocational training and climate education to build leadership and resilience, (4) Accessibility: Integrate disability-inclusive design in infrastructure and governance, (5) Economic Viability: Promote cooperative management and affordability through capacity-building and government support, and (6) Scalability: Replicate successful models in resettled villages and embed them in national policy frameworks.

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Development of a Real-Time Flood Forecasting and Early Warning System for the Mi Oya River Basin

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Introduction

Sri Lanka's Dry Zone has been experiencing increasingly frequent and severe flooding, largely attributed to the impacts of climate change. The Mi Oya Basin, located in the North-Western Dry Zone and spanning the Puttalam and Kurunegala Districts, is particularly vulnerable due to its topographic and hydrological characteristics. Seasonal floods in the basin disrupt livelihoods, damage infrastructure, and threaten food security. Recognizing the urgent need for improved flood preparedness and climate adaptation, the Climate Resilient Integrated Water Management Project (CRIWMP) funded by the Green Climate Fund (GCF) and implemented by the Ministry of Irrigation with technical support from UNDP— initiated the development of a real-time flood forecasting and early warning system tailored to the Mi Oya Basin. Covering an area of 1,498 km², the Mi Oya Basin exhibits low elevation variation and flows east to west, draining into the Puttalam Lagoon. The region is heavily reliant on reservoir- based irrigation, with Inginimitiya and Tabbowa being the major storage reservoirs. These structures, while essential for agricultural water supply, can amplify flood risks during high- intensity rainfall events. Eight Divisional Secretariat Divisions (DSDs) in the basin are highly flood-prone, placing nearly 30,000 people and 7,500 households at risk.

In response to these challenges, CRIWMP designed a data-driven, real- time flood forecasting system incorporating hydrological and hydraulic models. The system aims to generate accurate flood forecasts and early warnings to support proactive disaster management and improve community resilience for flood management in these three critical river basins to help safeguard climate-sensitive livelihoods and improve resilience.

Methodology

Data Collection

The development of the model was supported by a rich dataset that included (a) *Terrain Data*: A bathymetric and cross-sectional survey of the Mi Oya and its floodplain was conducted by the University of Sabaragamuwa. Cross-sections were recorded at 50 m intervals and merged with SRTM30 digital elevation data (30 m resolution) to produce a high-resolution DEM of the basin, (b) *Rainfall and River Flow Data*: Automated rain and river gauges installed under the "*Wari Soba*" initiative by UNDP provided current hydro-meteorological data. Historical rainfall and river stage data, including those from

Galgamuwa gauge station, were used for model calibration. Forecast rainfall data were obtained from the Open-Meteo platform to support real-time simulation, (c) *Reservoir Data*: Six reservoirs, including Inginimitiya and Tabbowa, were integrated into the model. Technical parameters such as area- elevation curves, spillway characteristics, and operational rules were obtained from the Department of Irrigation for accurate reservoir behaviour simulation, and (d) *Flood Inundation Data*: UNDP-led household surveys identified flood-affected households from 2010 to 2020. This information supported flood extent mapping and model validation. Vulnerability assessments covered 192 GN Divisions across 25 DSDs in the three basins, with Mi Oya serving as the pilot.

Model Development

A suite of integrated models was developed using freely available US Army corps HEC software platforms. The HEC suite is widely used and tested models for hydrological and hydrodynamic applications around the world.

Hydrologic Modeling: A rainfall-runoff model of the basin was developed using HEC-HMS 4.8. A separate sub basin was developed for each reservoir inlet. Calibration was performed using the 2016 flood event, and validation was done against 2019 flood data. Output of the HEC HMS model was utilized as the input data for the reservoir operation model.

Reservoir Simulation: HEC-ResSim was used to model storage, release, and inter-reservoir water transfers. There are six reservoirs in the in the Mi Oya River basin namely Iginimitiya, Tabbowa, Mediyawa, Ambakolawewa, Ataragalla, Palukadawala. Apart from these reservoirs Radevibedi Ela canal which linking Iginimitiya and Tabbowa reservoirs were also incorporated into the model. Model simulations were done using the results of the Hydrological model as the input data and the model provided data for the Hydrodynamic model.

Real-Time Integration: The hydrologic and reservoir models were coupled using HEC-RTS to enable real-time analysis and forecasting. The system produces outputs such as river flow time series and reservoir operations. HEC RTS.

Hydrodynamic Modelling: A hydraulic model of flood routing was developed using HEC-RAS 6.0, simulating inundation extents, flood depths, and velocities. The model ingests river flow outputs from HEC-RTS for flood propagation. Two separate zones were identified for build the flood model as the upstream and the downstream of the Iginimitiya Reservoir.

Web Interface: A web interface was developed for result dissemination and model automation using JAVA script. Flood thresholds were given to generate the flood alert based on its severity.

Automation and Forecasting: The model setup was automated to extract input data, run simulations, generate flood inundation maps, and issue alerts on a daily basis. Scenario analysis was performed using Gumbel distribution for flood frequency, and projections were

considered to account for climate variability and land use changes.

Calibration and Validation

The hydrological and reservoir models were calibrated using data from the 2016 flood event, while 2010 flood data were used for validation. Calibration focused on the upper catchment reservoir network Mediyawa, Ataragalla, Ambakolawewa, and Palukadawala to reflect the basin's upstream control system. The HEC-HMS parameters (e.g., curve number, lag time) were calibrated for rainfall-runoff response. The HEC-ResSim was calibrated using estimated reservoir elevations in the absence of recorded gate operations, and the Muskingum routing coefficients were adjusted accordingly. The coupled models were executed through HEC-RTS, and outputs were used for hydraulic modelling and inundation mapping.

Conclusion

The real-time flood forecasting and early warning system developed for the Mi Oya Basin marks a significant advancement in climate adaptation and integrated flood risk management in Sri Lanka. By combining field-verified data, advanced hydrologic-hydraulic modelling, and automation, the system provides timely and actionable forecasts to support emergency preparedness and reduce flood impacts on vulnerable communities. The model not only strengthens the technical capacity of the Irrigation Department and related agencies but also offers a replicable framework for flood-prone basins such as Malwathu Oya and Yan Oya. This initiative contributes meaningfully to national resilience-building efforts and supports sustainable water resource management under increasing climate pressures.

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Understanding Traditional Weather Forecasting: A Comparative Analysis of Indigenous Knowledge Systems

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Introduction

Globally, there is growing recognition of the importance of indigenous and local knowledge in weather forecasting. Such knowledge is deeply rooted in location-specific ecological observations and cultural practices, particularly among rural and agrarian communities (De Zoysa and Inoue 2014). Traditional forecasting systems often rely on biological and environmental indicators—such as animal behaviour, insect activity, plant changes, and sky patterns—which have been used over generations to anticipate rainfall and other weather events (Manandhar et al. 2011; Singh et al. 2015).

In recent years, global climate discourse has increasingly emphasized the need to bridge scientific forecasting systems with traditional and community-based knowledge to enhance resilience, particularly in vulnerable regions of the Global South. The Intergovernmental bodies like the IPCC and UNFCCC have acknowledged the epistemological value of indigenous knowledge, not merely as anecdotal or supplementary, but as a system of knowledge embedded in long-term environmental interactions. This recognition has stimulated interdisciplinary research across anthropology, climatology, and development studies, highlighting the need for inclusive approaches that honor local knowledge in early warning systems.

Numerous studies in Sri Lanka and India have documented these practices, for instance, Madduma Bandara (2010) and De Zoysa and Inoue (2014) have recorded numerous indicators used by Sri Lankan farmers to predict seasonal changes and rainfall patterns, but, typically within limited geographical or thematic scopes. This gap is particularly concerning given the increasing frequency of weather anomalies and disasters, which often disproportionately impact communities dependent on rain-fed agriculture. Traditional forecasting practices, if systematically compiled and analysed, could enhance locally relevant response strategies, especially in contexts where scientific infrastructure is limited. This study seeks to build on that foundation by compiling and analyzing a wide range of weather prediction indicators across multiple regions in India and Sri Lanka, with a primary focus on rainfall forecasting—identified as the most prevalent concern in traditional systems**.**While there is substantial traditional knowledge related to weather forecasting in South Asia, existing research is often fragmented, with studies focusing narrowly on

particular regions or single indicator types. This limits our understanding of the broader ecological patterns and shared knowledge systems that exist across communities. Additionally, much of this knowledge remains undocumented or under-utilized in formal climate response strategies. There is currently no comprehensive database that brings together traditional weather forecasting indicators across diverse regions and weather types. This study addresses this gap by compiling a wide range of indigenous weather indicators and systematically categorizing them to uncover patterns of usage, distribution, and relevance.

The primary objective of this study is to compile and analyze indigenous weather forecasting indicators from diverse regions in India and Sri Lanka. By bringing together data from both literature and local knowledge holders, the study aims to provide a comprehensive view of how traditional ecological knowledge is used to anticipate various weather phenomena. A particular focus is placed on rainfall forecasting, which emerged as the most frequently predicted weather condition in the collected dataset. In addition, the study seeks to categorize these indicators according to the specific types of weather events they predict—such as rainfall, drought, seasonal transitions, and extreme weather—and by the type of ecological observation they involve, such as animal behavior, plant responses, insect activity, and atmospheric patterns. Through this classification, the study intends to identify both common patterns shared across regions and unique, location-specific forecasting practices. By analyzing the regional distribution of indicators, the research also aims to highlight the cultural and ecological diversity underlying traditional forecasting systems. Ultimately, the study hopes to contribute to the preservation of this valuable knowledge and to explore its potential integration into contemporary climate adaptation and early warning strategies.

Methodology

The research methodology combined secondary data collection from existing literature with primary qualitative insights from local knowledge holders. An initial literature review was conducted to extract indigenous weather forecasting indicators from ten peer-reviewed and grey literature sources that documented traditional practices across various parts of India, Sri Lanka, and Bangladesh. These included studies on bio-indicator-based forecasting among the Bodos (Ajith 2019; Wary 2020), in Mizoram (Chinlampianga 2011), Tamil Nadu (Usha et al. 2025), and Uttarakhand (Rautela and Karki 2015). Sri Lankan contributions encompassed analyses of traditional weather prediction practices and related agricultural systems by Dharmasena (2021), Gunasena (2023), Wickramarathne (2025), and Hirimuthugodage (2018). Additionally, the application of indigenous knowledge in disaster risk reduction was reviewed through the work of Nowreen and Mohiuddin (2021) from Bangladesh.

From these ten studies, a total of 294 indigenous weather forecasting indicators were extracted. Each indicator was carefully recorded along with its associated observational cues and corresponding forecasted weather outcome. Following this, the indicators were systematically categorized along two dimensions: (1) the type of weather condition they are believed to predict (e.g., rainfall, drought, temperature change), and (2) the nature of

the biotic or abiotic signals involved. This classification scheme included major observational types such as animal acoustic behavior, insect movement, plant phenology, atmospheric signs, and other ecological cues. The resulting categories were designed to reflect the diverse sources of environmental knowledge embedded in local weather prediction systems.

Result and discussion

Analysing the Diversity and Focus of Indigenous Weather Forecasting Indicators Across Different Weather Categories

A total of 294 indigenous weather indicators were collected from 10 research papers and were categorized according to the type of weather condition they predict. As shown in the graph, the majority of indicators (168 or 57.14%) were found to be related to the prediction of rainfall, highlighting the central role rain plays in traditional knowledge systems, especially in agrarian societies. A notable number (49 indicators or 16.67%) were associated with adverse weather conditions such as floods, storms, and cyclones, indicating the importance placed on anticipating extreme weather events for preparedness and safety.

Daily weather changes were represented by 20 indicators (6.80%), suggesting that short-term weather shifts are also monitored through indigenous methods. Predictions related to drought and the dry season were reflected in 27 indicators (9.18%), emphasizing concern for water scarcity and crop survival. Seasonal transitions, including those for summer, winter, spring, and monsoon, were identified in a smaller portion (15 indicators or 5.10%), indicating that general seasonal change is less frequently emphasized. Only a few indicators were found to address temperature, humidity, wind, and soil moisture, showing that these elements are less commonly focused on in traditional forecasting.

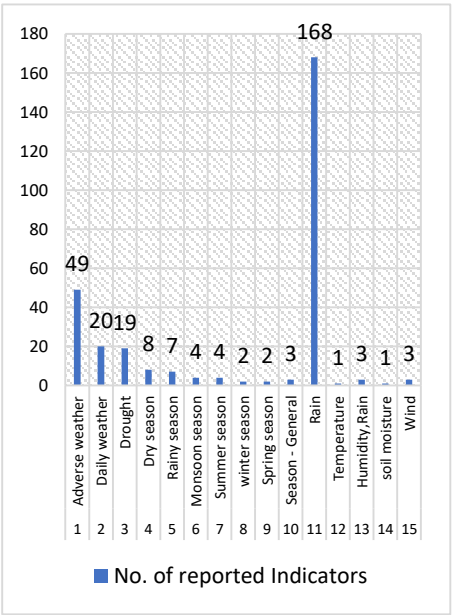

Figure 1. Distribution of Indigenous Weather Forecasting Indicators by Predicted Weather Type

Types of Environmental Indicators and Their Observational Prevalence

According to Figure 2, The classification of indicators used for predicting general weather conditions highlights the depth and diversity of traditional ecological knowledge across regions.

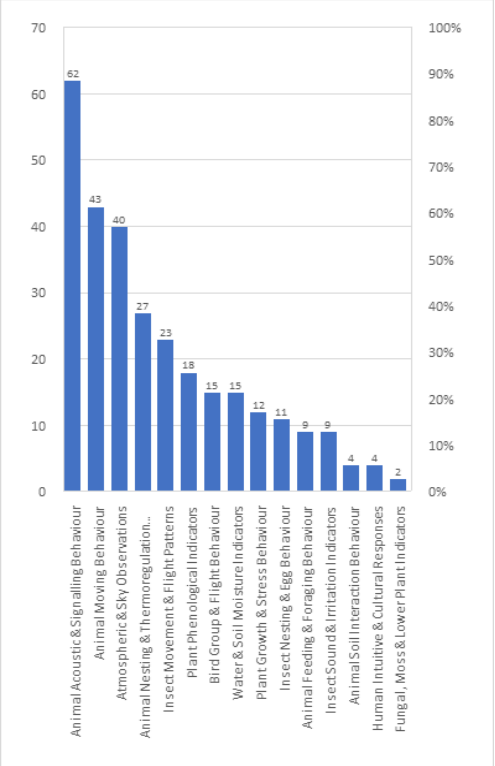

Figure 2; Categorization and frequency of traditional environmental indicators used for rain and weather prediction

Among the various categories, Animal Acoustic & Signalling Behaviour emerges as the most frequently cited (62 indicators), showing how communities closely observe animal sounds—such as vocal calls, silences, or rhythmic patterns—as early signs of changing weather. This is followed by Animal Moving Behaviour (43), where movements like sudden migrations, unusual activity levels, or animals seeking shade or shelter are interpreted as responses to temperature fluctuations, wind shifts, or impending atmospheric changes.

Atmospheric & Sky Observations (40) remain integral to forecasting, with visual cues like cloud formations, sun halos, or changes in wind direction offering direct readings of the sky. Similarly, Animal Nesting & Thermoregulation Behaviour (27) and Insect Movement & Flight Patterns (23) underscore the importance of smaller fauna whose nesting, burrowing, and flight behaviours reflect responses to environmental variations such as heat, cold, or humidity.

Plant-related categories such as Plant Phenological Indicators (18) and Plant Growth & Stress Behaviour (12) indicate how vegetative cues—like flowering, leaf folding, or stress signs—are linked to seasonal and short-term weather shifts. Bird Group & Flight Behaviour (15) and Water & Soil Moisture Indicators (15) also feature as reliable signals; for example, low bird flights or sudden soil dampness are interpreted as forewarnings of changing weather.

Other insightful yet less frequently reported categories include Insect Nesting and Egg Behaviour (11), Animal Feeding & Foraging Behaviour (9), and Insect Sound & Irritation Indicators (9), all of which reflect keen ecological observations on behavioural changes in relation to weather. Finally, rarer categories such as Animal Soil Interaction Behaviour (4), Human Intuitive & Cultural Responses (4), and Fungal, Moss & Lower Plant Indicators (2) demonstrate how even subtle cues, including human bodily sensations or fungal growth patterns, are used within certain cultural contexts to interpret upcoming weather conditions.

Overall, this distribution reflects a multi-layered understanding of the natural world, where observations across animal, plant, insect, and atmospheric domains are carefully interpreted to anticipate shifts in weather patterns. It emphasizes the value of both common and locally unique indicators in traditional forecasting systems.

The table presents a comparative overview of indigenous rain prediction indicators across diverse regions in India and Sri Lanka, highlighting how communities use biotic and abiotic cues to interpret approaching rainfall. Tamil Nadu stands out with the highest number of indicators (58), followed by the Bodos of North East India (30) and Uttarakhand (29), reflecting deeply rooted traditions of ecological observation geared toward anticipating rain events. Among the most widely used categories for rain prediction are Animal Acoustic & Signalling Behaviour, Animal Moving Behaviour, and Atmospheric & Sky Observations, which appear across multiple regions, suggesting their broad relevance and perceived reliability in forecasting rain. Insect-related behaviours—such as flight patterns, nesting, and sound—also serve as key indicators in regions with high biodiversity, providing short- to medium-term clues about upcoming rainfall. Meanwhile, areas like Ngailzawl village in Mizoram report only a single indicator, pointing either to limited use of rain-related cues or gaps in documentation. The distribution of these indicators reveals how local environmental familiarity, livelihood needs, and cultural practices contribute to traditional systems of rain forecasting. These insights underscore the value of preserving and integrating such knowledge into climate adaptation and early warning systems, especially in rain-fed agricultural areas.

Across the regions studied, several common threads emerge in how communities interpret signs of impending rain. Most regions rely on animal behaviour, especially sound-based signalling and movement, which are often seen as early indicators of changing weather, including rainfall. Similarly, sky and atmospheric observations—such as cloud types, wind direction, or changes in humidity—are consistently used to detect the likelihood and timing of rain. These similarities suggest a shared ecological understanding, despite geographic and cultural differences. However, regional differences are also prominent. Tamil Nadu displays the broadest range of rain prediction indicators, with data spanning nearly all categories—from animal and insect behaviours to plant phenology and soil moisture—indicating a highly developed and layered forecasting system. In contrast, Ngailzawl (Mizoram) and parts of Manipur and Sri Lanka have fewer documented indicators, possibly due to under recorded knowledge systems or narrower ecological focus. Notably, plant-based indicators, such as phenological changes and growth stress, are more commonly reported in southern and central India, while insect nesting and flight patterns are particularly prevalent in North East India and Uttarakhand.

These patterns illustrate both the shared foundations and regional uniqueness in traditional rain prediction systems. They highlight how different communities have developed locally adapted methods based on their immediate surroundings and lived experience. Such diversity strengthens the case for preserving these systems as valuable, place-based complements to scientific meteorology—especially in regions vulnerable to climate variability and rainfall uncertainty.

Conclusion

This analysis underscores the central role of rain prediction in indigenous weather forecasting, with over half of the 294 collected indicators focused on anticipating rainfall. Communities also monitor extreme weather, drought, and daily changes through keen

observation of animals, insects, plants, and the atmosphere. The most common cues include animal sounds, movement, and sky patterns, reflecting a multi-sensory, ecologically grounded approach. Regional variations reveal both shared practices and local specializations—Tamil Nadu, for example, shows the broadest range of indicators, while other areas have fewer, possibly due to under documentation. These systems embody deep environmental knowledge tailored to local needs. As climate challenges intensify, integrating such traditional wisdom with modern science can enhance localized forecasting and climate resilience.

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Application of Agro-met Advisory and Water Management by Dry Zone Farmers: Best practices

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Introduction

A significant number of people are engaged in the agricultural system. Close to 1.3 billion people, or 39.2% of the global workforce, were employed in agri-food systems in 2021 (FAO 2024). About 70 percent of agri-food system employment in Africa and Asia is in agriculture, while in the Americas, Europe, and Oceania, this proportion is around 40 percent (FAO 2024).

Agriculture can be considered a major source of income in Sri Lanka, and 26.5% employed in agriculture in Sri Lanka Department of Census and Statistics 2023). Cultivation is mainly carried out during the two growing seasons, *Yala* and *Maha*. Paddy cultivation is a major crop cultivated entire country. During the 2023/2024 season, 334,123 acres (approx. 135,215 ha) of crop year have been out of which 148,881 ac (approx. 60,250 ha) under major irrigation, 140,115 ac (56,703 ha) minor irrigation, and 45,127 acres (approx. 18,202 ha) are rainfed (Paddy Statistics 2024). Paddy farming directly and indirectly affects the country's economy and contributes greatly to meeting the staple food of the people.

It is possible to identify several problems faced by many people who operate an agriculturally based economic system in the world. Among them, changing and variable climatic conditions are one of the main factors. This affects the success or failure of agriculture since agriculture is highly dependent on climate and environment. Hence, it is important to know the climate and weather parameters of a particular area to select crops suitable for the area, to increase crop production, and minimize crop losses due to adverse weather conditions.

Being a tropical island in the Indian Ocean, Sri Lanka has consistently been placed among the top ten countries at risk of extreme weather events by the Global Climate Risk Index. Sri Lanka ranked second in 2019, in the Global Climate Risk Index (GCRI) among the countries most affected by extreme weather events from 1998 to 2017 (Climate Risk Index 2024). Changes in temperature and weather patterns throughout

time are referred to as climate change (United Nations 2021). This has a major impact on paddy cultivation.

Sri Lankan dry zone, accounts for about two- thirds of the country's land area. That community mainly depends on agriculture, which relies on four main rainfall seasons, throughout the entire year (Punyawardena 2010). It is also highly vulnerable to climate variability and water scarcity. Small-scale farmers are facing a crisis due to these changes. In this context, it is essential to integrate agro-met advisory services with efficient water management practices to ensure sustainable agricultural productivity and livelihood resilience.

The Climate Resilient Integrated Water Management Project (CRIWMP) has adopted a holistic approach to enhancing water management in dry zones and agricultural productivity. It includes climate-smart initiatives aimed at mitigating the impacts of extreme weather events. The project is introducing adherence to cultivation practices based on the agro-met advisory as a method of climate adaptation. This study assessed the adoption and application of agro-met advisory and water management strategies in part of the Dry zone in Sri Lanka, focusing on best practices and their effectiveness in adapting to climate uncertainties.

Methodology

A literature review was conducted on the impacts of climate change on agriculture in Sri Lanka. The study employed a mixed-method approach, combining quantitative surveys with qualitative interviews across selected districts (Cascades), namely, Anuradhapura (Palugaswewa), Kurunegala (Mamunugama), and Puttalam (Medda Rabawewa). The key variables assessed included awareness, accessibility, and use of agricultural advisories provided by the Department of Meteorology and the Department of Agriculture, as well as rainwater harvesting and both traditional and modern water management practices adapted in these irrigation systems. During the research, attention was also given to the agricultural co development programs implemented in the districts, and the information disseminated through these programs.

Based on the results, the incremental land extent due to the saving of water and the possibility of cultivation ~~as~~ a third season was taken to assess the effectiveness of the adaptation of agro-met advisories as a decision support service in expanding the cultivation.

Results and Discussion

Kurunegala, Anuradhapura, and Puttalam are some of the main rice-growing districts in Sri Lanka's dry zone. The average annual rainfall in this zone is less than 1,750 mm, with a distinct dry season from June to September. The project has introduced several agro-meteorological advisories, weather forecasting, and improved water management techniques for rice farmers in these districts. As a result of these efforts,

farmers' knowledge of climate-smart agricultural practices and adaptation methods has increased in recent times. A prime example of this progress is the collection of data from rain gauges. Prior to the project, awareness about climate change and updated weather forecasts was very low among farmers. The activities implemented by the project successfully enhanced their knowledge levels. One such activity involved installing rain gauges near irrigation systems.

Additionally, depth gauges were set up to monitor tank capacities (Table 1). Multiple training sessions were held to gather data on water levels and seasonal rainfall amounts. Consequently, it became possible to calculate the rainfall received in each area.

Table 1. Gauges Details

Name of cascade	No of rain gauge	No of depth gauge
Mamunugama	04	06
Palugaswewa	05	09
Meddarembewa	10	24

(Source: Water management data system of CRIWMP, 2025)

By obtaining rainfall data from these gauges, farmers have been able to plan their growing season and make necessary decisions. The weather forecast received through the project also supported their decision-making process. The total average annual rainfall expected for this DL1b agro-ecological zone is 631.2 mm (Punyawardena 2010). According to the data obtained from rain gauges, the Palugaswewa has received 1528.3 mm, in 2021, 1676.9 mm in 2022, 2204.4 mm in 2023, and 1831.4 mm in 2024, while the Mamunugama has received 867.7 mm in 2021, 1249.4 mm in 2022, 1411.64 mm in 2023, and 1222.41 mm in 2024 of rainfall. It was observed that the study area has received high rainfall over the past years. These observations help to capacity building of farmers to plan and manage their agricultural and livelihood activities, and There is a growing tendency to follow of agro- met advisory systems. Usually, these agro met advisories are disseminated to farmers through village-level government officers who are assisting farmers in agriculture (Agriculture Instructors and Agriculture Research and Production Assistants (ARPAs) By adhering to agro-met advisories, they have been able to protect the water in the tank and secure the water facilities required for their crops and other uses such as fish farming, flower farming, etc., Farmers use several ways to exchange this information coming from agro-met advisories and to cultivate an extra crop season (third season). These best practices support farmers in observing rainfall patterns and building the capacity to adapt to the changing climate and extreme weather events. Also, farmers used this knowledge on the amount of rainfall, for their cultivation practices, including irrigation water supply for paddy and upland crops, fertilizer application, agrochemical application, harvesting, and post harvest management.

Before 2019, farmers had very little knowledge of the weather and their decision-making capabilities. The project concepts implemented through the project improved

the decision-making capabilities of the farmers, which motivated them to plan more successful cultivation seasons. A special activity that contributed to this was receiving weather advice and updated information about the weather. They made more accurate decisions based on weather advice. Before the project interventions, farmers cultivated only during the *Maha* season. The entire cultivated area was not cultivated, and only a selected area of land was cultivated in Yala season. In some small tanks paddy cultivation was not exist during the Yala season. Using the forecasts, the cultivation of the Yala season was also started. For this, they also used the information obtained from the depth gauges installed in the tanks (Table 2).

According to the agro-met advisory and data of water management, farmers properly plan their cultivation throughout the year. According to Table 02, the cropping intensity of each tank shows less than 1.0 in 2019. After adapting to above practices, cropping intensity is increased up to 2.0 in each tank. The reasons for the increase are due to farmers cultivating both the Maha and Yala seasons, and additionally, mid-season between the above two major seasons. Higher cropping intensity of the Mamunugama, Yakadagaswewa and Medda Rambewa tanks was observed. Agro-met advisories encourage farmers to cultivate short-term paddy varieties and other field crops including mung bean, cowpea, black gram, and groundnut in the Yala season to minimize crop damage due to adverse weather conditions. Additionally, agro-met advisories advise farmers to minimize crop damage due to extreme rainfall during the seasons. The farmers practice cultivating the short age paddy varieties and OFC in the *Yala* season and OFC in mid mid-season. Mid-season cultivation maximizes the utilization of available tank water and also enhances the soil nutrient content. The farmers consider the soil drainage in their lands and improve the soil drainage for their OFC cultivation. The higher cropping intensity enhances the income of farmers due to the cultivation of Yala and mid-season crops. Additionally, farmers use daily weather forecasts for their pre- and post-harvest practices, including planning the irrigation water schedule, fertilizer application, agrochemical application, harvesting, and processing.

Agro-met advisory and weather forecast also help farmers with their livestock management and enhance the alternative livelihood activities. They used the rainfall forecast to carry out daily activities of cattle and poultry farming, cutting and drying the bricks, and food processing activities. This has helped to increase the additional income and enhance the resilience of farmers against climate change. The decisions taken at the pre-seasonal meeting, when issuing the agro-met advisory, on the date for the commencement of cultivation, the best age class and varieties to be grown, availability of water in the reservoir, availability of seeds and the findings reveal how awareness of agro-met advisory has increased the targeted project efforts in increase the crop production and farmer income even with the negative effects of climate change. However, practical problems were also identified such as limited technical knowledge, poor infrastructure, and a lack of localized forecasts. However, successful studies show how timely weather forecasts, crop calendars, and irrigation scheduling advice have helped progressive farmers reduce crop losses and improve water use efficiency.

Table 2. Tank Season Cultivations, Project CI database (AC): (Source: Water management data system of CRIWMP, 2025)

District	Name of the cascade	Tank name	Command area (ac)	Year	Maha (ac)	Yala (ac)	Third season (ac)	Cropping intensity
Kurunegala	Mamunuwa	Mamunugama Wewa	36.00	2017	36	10	0	1.27
				2018	36	12	0	1.3
				2019	0	0	0	0
				2020	15	20	0	0.97
				2021	36	13.9	12	1.71
				2022	36	6	0	1.16
				2023	36	20	0	1.55
				2024	36	20	0	1.55
Puttalam	Medde Rambewa	Maha Meddawawa	71.1	2017	66	0	0	0.9
				2018	66	0	0	0.9
				2019	71.1	0	0	1
				2020	71	71.1	0	1.99
				2021	71.1	71.5	20	2
				2022	71.1	71	0	1.99
				2023	71.1	66	0	1.92
				2024	71.1	71.1	0	2
Anuradhapura	Palugaswewa	Yakandagaswe wa	89.9	2017	89.9	15	0	1.16
				2018	89.9	10	0	1.1
				2019	89.9	0	0	1
				2020	89.9	32	0	1.35
				2021	89.9	89	10.0	2.1
				2022	89.9	89	18.7	2.19
				2023	89.9	69	25	2.04
				2024	89.9	89	10	2.1

Recommendations

Further suggestions can be made to increase farmers' awareness about the use of agro-met advisory, creating agro-weather forecasts that include regionally important weather information, preparing the necessary providing practical knowledge of agricultural advice to officers and farmers, introducing water management and agricultural planning, conducting awareness programs for school children, increasing the level of knowledge of farmers through posters, drawings, appointing one officer to provide information for the season meeting and forming small groups through him, management have emerged as effective platforms for knowledge exchange and collective action. The paper concludes by identifying a set of best practices for scaling up the adoption of agro-met advisory and water management strategies, emphasizing the need for multi-stakeholder collaboration, capacity building, and policy support. It presents a roadmap for improving climate agriculture in Sri Lanka's dry zone, which can contribute to national goals of food security, water sustainability, and rural development.

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Toward Climate-Responsive Agricultural Insurance: A case study of Vavuniya District of Sri Lanka

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Introduction

Climate change is becoming a source of significant additional risks for agriculture and food systems. Climate projections suggest that impacts will include shifting average growing conditions, increased climate and weather variability, and more uncertainty in predicting climate and weather conditions. More concretely, these impacts will translate into an overall warming trend, an increasingly erratic distribution of precipitation, more frequent as well as far more devastating extreme events and spatial shifts in the occurrence of pests and diseases (World Bank 2015).

Rice is the staple food of the community in Sri Lanka. As agriculture is an occupation largely deals with weather and climate risk, agriculture or crop insurance can be identified as a risk management strategy that usually transfers the risk to an insurer by paying a premium. Pooling is the concept use to build up the risk fund and it is crucial to maintain a sustainable financial condition among insurers and also for sustainable operation of the insurance scheme.

With the introduction of the Agricultural and Agrarian Insurance Board Act. No 20 of 1999, the Agriculture Insurance Board (AIB) was converted into the Agricultural and Agrarian Insurance Board (AAIB). The major role of AAIB is to implement the government insurance programs broadly covering various crops, and agricultural activities, including paddy, horticultural crops, medicinal plants, livestock, fisheries, forestry, storage, and preservation of agricultural produce and agricultural equipment.

The insurance covers the main climate-related risks (floods, droughts, dry spells, and excess water) and damages caused by pests and diseases and wild elephant attacks. However, the insurance beneficiaries of AAIB were mostly limited to the requirement of obtaining agricultural loans from formal credit sources (Wickramasinghe 2019).

The AAIB Act has also permitted private-sector insurers to enter the crop insurance market to eliminate the monopoly. The insurance product introduced by the private sector is similar to AAIB insurance and mostly function as loan protection schemes. Despite the

presence of crop insurance in Sri Lanka for more than five decades with the involvement of both government and private sectors, the level of insurance penetration among the farmers was very low. It has been reported that, on average, only 2.45% of the paddy extent cultivated is under any crop insurance program from 1998 to 2017 (Wickramasinghe 2019).

Despite the regulatory framework and the various insurance products available in Sri Lanka, there is low uptake of agricultural insurance by farmers in the country. This is particularly true for rural small holder farmers due to the limited knowledge and understanding on insurance products currently available, as well as lack of confidence about the insurance solutions in general. For example, a case study found that "over 31% of interviewed farmers were not aware of how crop insurance worked, and another 23% had doubts regarding crop insurance (SLYCAN Trust 2022).

This paper attempted to analyse the crop insurance claims of AAIB from 2011 to 2023 period in Vavuniya district of Sri Lanka to understand the local context and farmer behaviours.

Methodology

Study area

Paddy crop Insurance claims received under nine (9) Agrarian Service Centres (ASCs) in Vavuniya district, namely, Cheddikulam, Kanagarayankulam, Kovilkulam, Kurukkalputhukkulam, Madukande, Nedunkerny, Omanthai, Pampaimadu, and Ullukulama were selected for this study. Paddy is the main crop cultivated in these ASC areas and farmers use both irrigation and rain water for their paddy cultivation. *Kakulan* cultivation is the most wide-spread method use in rainfed cultivation, where farmers distribute dry seed paddy with the on-set of rainfall. This method is one of the highly climate vulnerable farming methods, mainly depending on the rainfall intensity and pattern.

Data Collection:

The insurance claims paid by Agricultural and Agrarian Insurance Board (AAIB) in Vavuniya District for six consecutive cropping seasons form *2021 Yala* (March to September) to 2023/24 *Maha* (October to February) used for this analysis. The rainfall decadal (10 days) data from the Climate Hazards Group Infra-Red Precipitation with Station data (CHIRPS) were used to elaborate the Standerdized Precipitation Index (SPI) values and identify whether the said hazard has occurred or not in the field. The CHIRPS is a 35+ year quasi-global rainfall data set.

Data analysis:

The national level data representing claims on crop damage and insurance indemnities provided to farmers across several agricultural seasons from 2019 to 2022 were analysed initially to get an idea about the contribution done by the national economy to provide National Agricultural Insurance Scheme. Then the claims data of Vavuniya District were analysed and the total number of claims paid was 3822, which comprise of 1988 payments for Droughts, 1478 for Floods, 282 for Wild elephant trampling, and rest of 68 for Pest and Diseases attacks.

Results and Discussion

The number of affected farmers and the extent of damaged acreage were generally higher during the *Maha* seasons compared to the *Yala* seasons. For instance, the 2019/20 *Maha* season saw the highest damage, with 97,000 acres (approx. 39,254 ha) affected and Rs. 1.4 billion paid in indemnities. In contrast, the lowest damage were during the 2021 *Yala* season, with only 13,700 farmers impacted and Sri Lanka Rupees (LKR) 0.2 billion (approx. US$ 666,666) in compensation. Overall, the data highlighted the seasonal variability in agricultural losses and the corresponding insurance support provided.

According to the data, 1,988 cases (52.1%) were due to drought, and 1,478 cases (38.7%) were caused by floods. This clearly indicates that climate-related hazards, particularly drought and flooding are the most common causes of damage in the region. An exception to this trend is seen in Ullukulama area, where the majority of damage cases (81 out of 88) were due to wild elephant attacks, making it the only ASC where wildlife conflict is significant. In contrast, all other ASCs were predominantly affected by climate hazards. Flood-related damage (Figure 1), predominantly occurs early in the crop cycle, with most claims clustering between 15 and 30 days from the cultivation date where indemnity payments approximately vary widely from LKR 0 to 75,000 (approx. US$ 0 to 250), reflecting significant flood impact variability. In contrast, drought damage (Figure 1) tends to occur later with a higher concentration of claims between 60 and 105 days after cultivation. Wild elephant damage primarily affects crops between 45 and 105 days after cultivation, with Ullukulama being notably high, as it shows a significant number of such claims with indemnity payments up to LKR 75,000 (approx. US$ 250). The other ASCs, including Cheddikulam, Kanagarayankulam, Madukande, and Kurukkal puthukkulam, have also experienced wild elephant damage within this timeframe, though less frequently. Disease-related damage (Figure 1), is notably rare across the Vavuniya District, with only a few claims observed in, and associated indemnity payments are typically high.

Figure 2 illustrates the count of drought cases and flood cases over time by season, with the left y-axis showing the SPI values and the right y-axis indicating the damage count. Shaded areas represent the season. In the *Maha* season, from September 2021 to March 2022, a significant flood peak is observed, the though damage cases remain low may be due to the COVID-19, where agriculture production was restricted. From cultivation time ranges for each September 2022 to March 2023, the *Maha* season experiences a drought peak with a corresponding increase in damage cases (Figure 2). In contrast, the *Yala* season, with its cultivation period indicated by shaded areas, shows no extreme events. While no significant flood cases are recorded in Yala, there are some drought cases noted compared with *Maha* season.

Further, In *Maha* 2022/23, droughts caused the most damage in Stage 2, Level 2, with 1,739 cases, matching a drought peak shown in the SPI graph. In *Maha 2023/24*, floods were mainly tied to Stage 1, Level 1 damage, with 1,380 cases, aligning with a major flood spike. During *Yala* 2023, moderate droughts led to Stage 2, Level 2 damage in 195 cases, consistent with the SPI's observed drought activity.

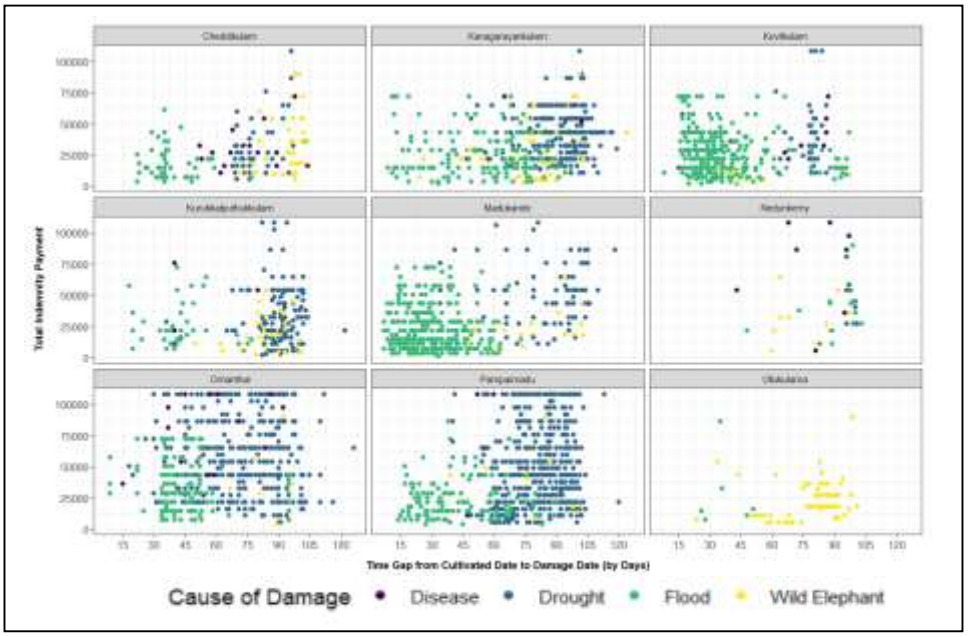

Figure 1. ASC wise Payment Time gap from cultivated date to damage date

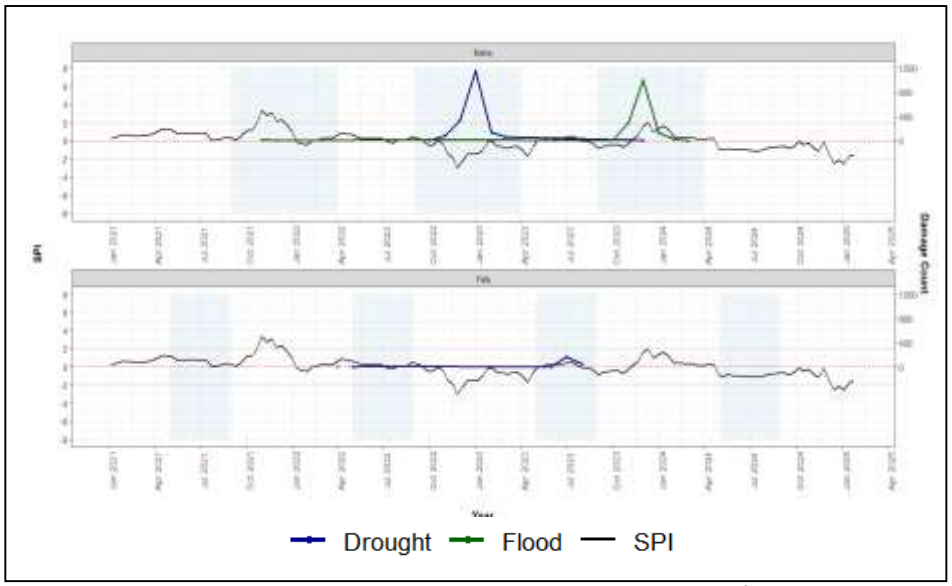

Figure 2. Damage intimated period plotted against SPI index derived from CHIRPS Data

Conclusion

The analysis revealed that huge amount of funds are allocated for the National Insurance Programme. This warrants to maintain a sustainable and transparent payment system to satisfy farmers and to motivate them for increase contribution to the national paddy production of Sri Lanka. Floods and droughts are the main causes of crop damage in

Vavuniya District, with floods occurring early and droughts striking later in the crop cycle. Indemnity payments closely follow SPI trends, highlighting the role of climate risks. However, most damages fall within one severity level, suggesting possible subjectivity in damage assessments. To improve fairness and accuracy in compensation, the use of weather index insurance is recommended as a more objective alternative follow with a suitable field level survey is recommended as the one severity level may not represent the true damage of the field.

Acknowledgement

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Application of Water Management Advisory for Crop Productivity Enhancement in Athaudagama, Mamunugama, and Ulpath Tanks in Kurunegala District of Sri Lanka

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Introduction

Minor tanks have been built to stabilize agricultural livelihood and ensure survival of the rural community by storing the excess rainfall in the *Maha* season and use it during the water-short period. Water thus stored in these tanks are being used to supplement the rainfall to cultivate crops. The *Maha* season is considered as the major cultivation season in the dry zone since the highest rainfall is received during this period. The water requirement of crop is mainly met by this rainfall. Stored water in the tank is released to supplement the water received by rainfall only when there is a water shortage. This becomes very necessary if the area receives less than the average rainfall. If the rainfall during the *Maha* season is adequate to meet the water requirement of the crop, the water stored in the tank could be used to cultivate crops during the *Yala* season, mainly through irrigation.

Assuming that this tank watershed is a closed system, a simple water balance calculation could be performed for a period of one season (or year covering both *Yala* and *Maha* seasons) to decide the optimum crop mix. To get the highest production from the system, water received from the rainfall needs to be stored and sparingly used to satisfy crop water requirement and other unavoidable losses. The irrigation water requirement is the combination of crop water requirement and the water losses during irrigation (Kandiah et al. 2023).

Crops must be provided with sufficient water of good quality to obtain optimum yields and a high-quality harvested product. The required amount of water to be applied is determined by the prevailing climatic conditions, the crop, and its stage of growth, soil properties (such as water holding capacity) and the extent of root development. The cultivable area can be increased if the cultivated extend of paddy, which consumes highest quantity of water, is partly substituted for less water demanding crops, such as vegetables/pulses, provided if there are no constraints for drainage. Short duration crops have less crop water requirement. The irrigation interval can be extended if sufficient rainfall is received and thereby stop sending scheduled irrigation water to the crop. Correctly estimating the irrigation requirement means calculating the quantity, or depth of irrigation water needed

to produce the desired crop yield and quality. This quantity of water must be supplied at appropriate amounts (in volume or depth) at appropriate interval of irrigation.

Methodology

The farmers were made aware of the basics of irrigation water management based on the water management advisory (CRIWMP 2023). The extent to be cultivated during the season is determined at the beginning of the cultivation season primarily using agro-met advisory, water stored in the tank, and crop water requirement. The rainfall and depth of water in the tank is monitored at regular intervals to ensure that water wastage is kept to the minimum. In addition, the following interventions were made by the project to save water as much as possible so that the saved water can be used to cultivate a crop during a Yala/or if possible, for a third season. The findings from three tanks monitored during the project period is described as follows.

Adoption of the Alternative Wetting and Drying method (AWD):
The implementation of AWD in the Paddy field has significantly reduced the number of water releases from the tanks, decreasing them from 12 to 8 per season. This method enhances water use efficiency and helps conserve water resources.

Renovation of the water distribution system:
The water distribution system, including the canal dam system and water diversions, has been renovated to improve water flow and reduce wastage. This ensures a more efficient and equitable distribution of water across the fields.

Continuous awareness raising on water management:
Ongoing efforts to raise awareness about water management practices have been crucial. This includes educating local farmers and stakeholders on best practices for water conservation, irrigation techniques, and maintaining sustainable water use.

Continuous reporting and analysis of hydrometer and rainfall data:
The regular collection and analysis of hydrometer and rainfall data have been integrated into the water management strategy. This information is used to calculate the irrigation duty, enabling better planning and decision-making for water releases and irrigation scheduling.

Using the rotation system for irrigation water distribution:
The rotation plan is implemented to ensure fair and equitable water distribution. In this approach, water is first released to the farthest paddy field in the irrigation area to the nearest paddy field in the tank, following a prescribed rotation plan. This ensures that each part of the field receives water at specific times. The rotation system helps to conserve water, reduce wastage and ensure that all fields receive adequate irrigation.

Results and Discussion

All three tanks, namely Athaudagama, Mamunugama and Ulpathwewa were able to cultivate the entire command area during the Maha season from 2015 to 2024. Therefore, the information about the extent cultivated during the *Maha* season and the Irrigation duty values are not given in the Tables 1a to 1c. However, the extent cultivated during the *Maha*, Yala and 3rd Seasons were considered to estimate the cropping intensity. The project interventions, as stated above, had been made around 2019. Paddy was primarily grown in *Yala* season at all three tank catchments, though not covering the entire command area. It was also possible to cultivate a limited extent of other field crops during a third season by saving water during the *Yala* season.

Table 1. Type of crop, cultivated area, yield, cropping intensity and irrigation duty during *Yala* and third season in selected tanks.

a). Athaudagama (Command Area = 8.09 ha)

Year	Yala season			3rd Season			Cropping Intensity	Irrigation Duty (m)
	Crop	Cultivated area (ha)	Yield (t)	Crop	Cultivated area (ha)	Yield (t)		
2015	N/C	0.0	0.0	N/C	0.0	0.0	1.0	N/D
2016	Paddy	4.04	N/D	N/C	0.0	0.0	1.5	N/D
2017	N/C	0.0	0.0	N/C	0.0	0.0	1.0	N/D
2018	Paddy	4.05	1.0	N/C	0.0	0.0	1.5	N/D
2019	N/C	0.0	0.0	N/C	0.0	0.0	1.0	N/D
2020	Paddy	2.83	0.70	N/C	0.0	0.0	1.4	N/D
2021	Paddy	4.05	1.0	Green gram	0.61	0.6	1.6	1.05
2022	Paddy	4.45	1.1	N/C	0.0	0.0	1.6	1.09
2023	Paddy	4.05	1.0	Green gram	3.24	3.2	1.9	1.11
2024	Paddy	4.86	1.2	Green Gram/Cowpea	2.03	2.0	1.9	1.10

b). Mamunugama (Command Area =14.56 ha)

Year	Yala season			3rd Season			Cropping Intensity	Irrigation Duty (m)
	Crop	Cultivated area (ha)	Yield (t)	Crop	Cultivated area (ha)	Yield (t)		
2015	N/C	0.0	0.0	N/C	0.0	0.0	1.0	N/D
2016	NC	0.0	0.0	N/C	0.0	0.0	1.0	N/D
2017	Paddy	4.05	1.0	N/C	0.0	0.0	1.3	N/D
2018	Paddy	4.86	1.2	N/C	0.0	0.0	1.3	N/D
2019	Paddy	7.28	1.8	N/C	0.0	0.0	1.5	N/D
2020	Paddy	4.36	1.2	Green gram	4.86	4.8	1.7	N/D
2021	Paddy	6.09	1.5	Cowpea	2.02	2.02	1.6	1.15
2022	Gherkin	2.83	35.0	N/C	0.0	0.0	1.2	0.52
2023	Paddy	8.09	2.0	N/C	0.0	0.0	1.6	1.09
2024	Paddy	7.28	1.8	N/C	0.0	0.0	1.5	1.19

c). Ulpathwewa (Command area= 3.64ha)

Year	Yala season				3rd Season		Cropping Intensity	Irrigation Duty (m)
	Crop	Cultivated area (ha)	Yield (t)	Crop	Cultivated area (ha)	yield (t)		
2015	N/C	0.0	0.0	N/C	0.0	0.0	1.0	N/D
2016	Paddy	1.61	N/D	N/C	0.0	0.0	1.4	N/D
2017	N/C	0.0	0	N/C	0.0	0.0	1.0	N/D
2018	Paddy	1.62	8.2	N/C	0.0	0.0	1.4	N/D
2019	N/C	0.0	0.0	N/C	0.0	0.0	1.0	N/D
2020	Paddy	1.21	6.15	N/C	0.0	0.0	1.3	N/D
2021	Paddy	1.11	5.64	N/C	0.0	0.0	1.3	1.05
2022	Paddy	1.62	8.2	N/C	0.0	0.0	1.4	1.07
2023	Green gram	3.24	16.4	Green gram	0.40	0.40	2.0	0.49
2024	Paddy	3.64	18.45	Green gram	0.40	0.40	2.1	1.03

The results also show (Figure 1) that the cropping intensity has gradually increased over the years irrespective of the decreasing rainfall trend over the years from 2021 to 2024, where annual rainfall was 1561mm, 1235mm, 1411 and 1174 mm, for years 2021, 2022, 2023 and 2024 respectively. The review of irrigation duty shows that the observed values are comparable to the recommended values by the Department of Agrarian Development (Vitharana 2012).

The overall results from all three selected tanks have shown that the farmers were unable to cultivate during *Yala* season before the intervention of the project in 2019. Therefore, the impact of the water management advisory and its adaptation by farmers has not only helped to cultivate a *Yala* crop but extend it to a third season thus increasing the water and land productivity.

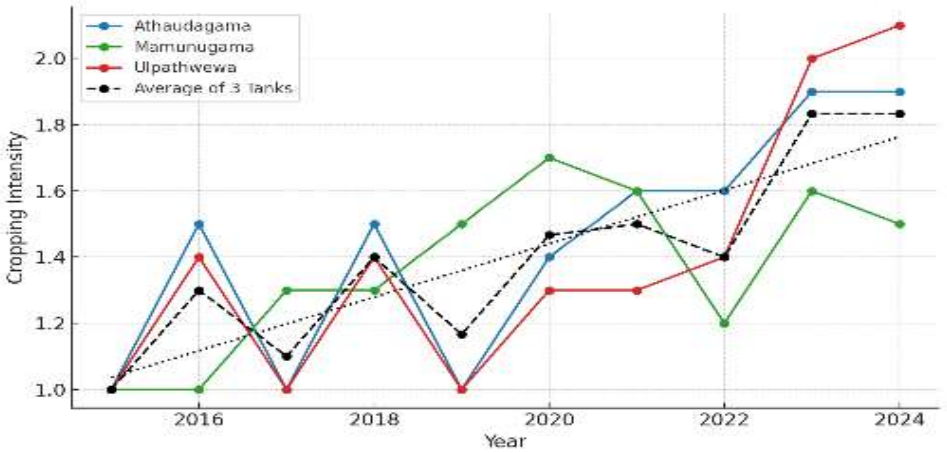

Figure 1. Cropping Intensity over time (2015-2024)

Conclusion

Cropping intensity in the Dry zone of Sri Lanka can be improved by integrating agro-met advisories with efficient crop water management practices by way of water management advisories tailored to local tank cascade systems. Though annual rainfall exhibited a gradual decreasing trend between 2019 and 2024, the application of water management advisories, especially during the *Yala* season—when rainfall is low and evaporation rates are higher than in *Maha*—proves essential in optimizing the use of limited irrigation water. Evidence from the three tanks studied indicates that adopting advisory-based planning has increased the cropping intensity and the yield. This approach not only supports multiple cropping seasons or cropping intensity but also strengthens the climate resilience of traditional small tank cascade systems in Sri Lanka.

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Scaling Nature-Based Solutions for Anticipatory Action: Case Studies from Sri Lanka's Environmental and Livelihood Sectors

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Introduction

Anticipatory Action (AA) is a proactive approach aimed at mitigating disaster impacts by taking early measures based on forecasted risks (UNDRR 2019). By shifting the focus from reactive response to early intervention, AA is increasingly recognized as a critical element in resilience-building strategies in the face of compounding risks such as climate change, ecosystem degradation, and extreme weather events (UNDRR 2019; IPCC 2022). This strategy enhances resilience, reduces vulnerability, and minimizes economic and social disruptions by shifting the focus from reactive disaster response to prevention and preparedness. However, anticipatory strategies in many development sectors such as agriculture, often remain narrowly focused on technical or engineered interventions, overlooking the systemic value of ecological infrastructure in long-term risk reduction (Chausson et al. 2020).

Nature-Based Solutions (NbS) provide a sustainable alternative by harnessing natural processes to mitigate disasters while delivering co-benefits for biodiversity, livelihoods and ecosystem services (Seddon et al. 2021). NbS are actions to "protect, sustainably manage, and restore ecosystems" to address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits (IUCN 2020). NbS such as wetland restoration, reforestation, regenerative agriculture practices and agroforestry, enhance water retention, soil stability and regulate microclimates (Cohen-Shacham et al. 2016). Empirical studies demonstrate that NbS can reduce disaster risk cost-effectively while supporting climate adaptation and food security (Kapos et al. 2019), yet their integration into AA frameworks remains limited, particularly in Sri Lanka.

The integration of these NbS with AA helps reduce disaster risks and promotes long-term economic sustainability. These interventions are cost-effective, improve water security, enhance livelihoods through nature-based income sources, and contribute to climate resilience through ecosystem restoration and local climate regulation.

The study focuses on identifying and promoting suitable NbS for mitigating disaster risks related to drought and flood in two highly climate-vulnerable regions of Sri Lanka: Mahawilachchiya in the Anuradhapura District, which is severely affected by recurrent droughts, and the Batticaloa District, which experiences frequent and intense flooding. The study explores potential NbS interventions for flood management, particularly in the

context of four key river basins (Figure 1) in Batticaloa. The strategies related to NbS included wetland restoration, riparian buffer replanting, floodplain zoning, and nature-integrated drainage systems to reduce peak flow and enhance natural water retention. The main objective of the study is to introduce NbS as a foundation for anticipatory disaster risk management, shifting the paradigm from a reactive to a proactive approach.

Methodology

This study adopts a qualitative case study approach to explore the implementation of NbS for climate disaster anticipation. One case study was on Mahawilachchiya (a drought-prone area in the nuradhapura District) and the other case was on flood risk mitigation in Batticaloa, an increasingly flood-vulnerable district in Eastern Sri Lanka. For Mahavilachchiya, the research reviewed two development projects which incorporated NbS into their anticipatory action (AA) frameworks, implemented between 2020 and 2024.

Figure 1: Four River Basins in Batticaloa District, where recurrent and intense Flood occur

Data collection was conducted through Key Informant Interviews (KIIs) with project implementers, and desk reviews of project reports, evaluation documents, and relevant policy briefs. These data sources were analysed using thematic content analysis to identify common patterns, contextual challenges, and the effectiveness of NbS for proactive drought risk reduction.

For Batticaloa, the study focused on identifying viable NbS interventions that could be integrated into both flood mitigation and eco-tourism development strategies. The methodology included desk reviews on eco-tourism, nature-based interventions, and flood risk in the region, key informant interviews (KIIs) and focus group discussions (FGDs) with local stakeholders, including farmers and local government officers, and site assessments based on feedback from communities and technical experts

Results and Discussion

Case study on Integrating Forest Landscape Restoration for Drought Anticipation

This case study highlights the application of a Forest Landscape Restoration (FLR) strategy to enhance community resilience to recurrent droughts in a Mahawilachchiya study site. The project, guided by the IUCN Global Standard for FLR, successfully restored over 35 hectares of degraded forest land using around 19 diverse native and climate-resilient tree species. The restoration efforts were strategically planned to align with ecosystem-based adaptation (EbA) principles, ensuring long-term ecological, social, and economic benefits. The interventions produced significant ecosystem services critical for anticipating and mitigating the adverse impacts of prolonged droughts, including improved water retention, reduced surface runoff, and buffered microclimatic extremes.

The key outcomes of the interventions on integrating forest landscape restoration for drought anticipation are as follow.

- Increased vegetation cover through innovative models such as food forest gardens, silvopastoral systems, and avenue plantations, which enhanced soil moisture retention, reduced evapotranspiration, and promoted biodiversity conservation.

- The Forest Landscape Restoration (FLR) interventions demonstrated substantial climate mitigation potential. Within the six-year project period, approximately 5,000 tons of CO_2 equivalent were sequestered. Projections estimate that over a 20-year period, these interventions will restore and sequester a total of 35,000 tons of CO_2 equivalent, underscoring the long-term carbon benefits of nature-based approaches. As estimated by Abeykoon et al. (2025) the runoff and soil erosion under different land cover types within the project landscape, i.e. Bare land (no NbS) has ~7,500 m^3/ha/year runoff, semi-forested land (partially restored) has ~5,927 m^3/ha/year runoff while forest area (fully FLR) has ~2,539 m^3/ha/year runoff. These findings underscore the substantial impact of FLR on reducing surface runoff and soil erosion, both of which are critical for sustaining groundwater recharge and maintaining agricultural productivity during drought periods.

- Improved groundwater recharge supported the sustainability of agriculture and livestock-based livelihoods, even during peak dry seasons, contributing to local food and water security.

- A participatory planning approach, engaging local communities, farmer groups, and extension services, facilitated social inclusion and built community ownership, enabling early livelihood interventions and anticipatory responses to drought signals.

- Capacity building and awareness programs helped local stakeholders adopt sustainable land management practices, contributing to the long-term climate adaptation goals of the region.

According to the above outcomes, the integrated FLR interventions, when coupled with participatory planning and local ecological knowledge, can serve as a robust Nature-based Solution (NbS) for drought risk reduction and climate-resilient development.

Case study on nature-based flood mitigation initiatives in Batticaloa

Manmunai West and Poratheevu Pattu Divisional Secretariat Divisions of Batticaloa are highly vulnerable to flooding, as large parts of the district lie below mean sea level (MSL). FGDs and stakeholder sessions revealed that, although there were low-lying areas that could be utilized as water retention zones to divert floodwater from paddy lands and other vulnerable areas, those have not been effectively used. Thus, floodwater drains without contributing to any productive use.

The project adopted a community architecture approach to design and transform selected low-lying lands into functional water retention areas. This approach enabled active community participation from the outset, allowing local needs to be identified and sustainable practices to be embedded into the design process.

Implemented as part of an AA project, the initiative also incorporated livelihood components such as fishing and eco-tourism (Vyddiyaratnam et al. 2023, Nuskiya et al. 2024). A portion of the income generated from these activities will be directed into a pooled community fund, which can be used as pre-financing during future AA protocol activations. Additionally, the intervention has shown positive environmental impacts, particularly through the effective recharge of groundwater in the targeted areas.

The key outcomes of the interventions on nature-based flood mitigation initiatives in Batticaloa are as follow.

- The creation of community-designed water retention areas has effectively mitigated flood risk by diverting excess floodwater away from agricultural and residential areas.
- The intervention contributed to improved groundwater levels through natural recharge processes, addressing seasonal water scarcity in the targeted communities.
- The community architecture approach fostered strong local engagement, ensuring that interventions reflected community priorities and supported long-term sustainability.
- Integration of eco-tourism and inland fisheries has created alternative income streams for residents, enhancing economic resilience in flood-prone areas.
- Income generated from livelihood activities is pooled into a fund to support anticipatory action protocols, enabling quicker and more locally led responses to future flood risks.
- The participatory, multi-functional use of flood-prone land demonstrates a replicable model that combines disaster risk reduction with sustainable development.

Conclusion

This study demonstrated the feasibility and effectiveness of integrating nature-based solutions into climate disaster anticipatory action frameworks in two climate-vulnerable districts of Sri Lanka, Mahawilachchiya and Batticaloa. In Mahawilachchiya, Forest Landscape Restoration significantly enhanced resilience to drought through carbon storage, reduction of soil erosion, improved soil moisture, groundwater recharge, and participatory land management. In Batticaloa, the integration of nature-based solutions offers a promising approach to flood preparedness while simultaneously supporting local development objectives. The dual benefits of nature-based solutions, in terms of risk reduction and livelihood enhancement, make them particularly suitable for Sri Lanka's climate-vulnerable areas. However, mainstreaming these interventions will require deliberate policy integration, sustained financing, and inclusive implementation mechanisms. As Sri Lanka moves toward a more climate-resilient future, these case studies offer scalable models for how ecosystem-based adaptation can be localized and institutionalized across diverse geographic and socioeconomic contexts.

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Trends and Sources of Agricultural Greenhouse Gas Emissions in Sri Lanka: Towards reduction strategies

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Introduction

Agriculture is a major contributor to global greenhouse gas (GHG) emissions, with rice cultivation, livestock management, and soil fertilization playing pivotal roles in emission patterns (Barker et al. 2022; Lal 2021). In Sri Lanka, rice farming remains the dominant source of methane emissions, primarily due to the anaerobic conditions created in flooded paddy fields (Wassmann et al. 2000). As the agricultural sector continues to grow, the need for targeted strategies to reduce its environmental impact becomes increasingly important. This study seeks to analyze the trends in agricultural emissions in Sri Lanka, using data from ClimateTrace.org from 2015 to 2024, with a particular focus on identifying mitigation opportunities.

The objectives of this study are to assess the main sources of agricultural emissions in Sri Lanka, track their trends over the past decade, and compare Sri Lanka's emissions to global agricultural patterns. Additionally, the study aims to identify potential mitigation strategies to reduce GHG emissions in the agricultural sector, particularly from rice cultivation and livestock management. This research is critical for informing policy decisions and encouraging the adoption of sustainable agricultural practices that align with global climate goals. The rationale behind this study lies in the recognition that Sri Lanka's agricultural emissions are rising, driven primarily by methane from rice cultivation and emissions from livestock operations. While previous studies have highlighted the importance of these sectors, there is a lack of comprehensive data and analysis focused on the trends and mitigation opportunities within Sri Lanka's unique agricultural context. By analyzing emissions data and identifying key trends, this study provides valuable insights that can inform both local and national climate strategies, with an emphasis on reducing the carbon footprint of Sri Lanka's agricultural sector.

Methodology

Data from ClimateTrace.org covering Sri Lanka's agricultural emissions from 2015 to 2024 were analysed. Emission sources included rice cultivation, livestock enteric fermentation, synthetic fertilizer application, and soil management.
Emissions were measured in CO_2e (100-year global warming potential). The analysis focused on trends over time and compared Sri Lanka's emissions to global agricultural patterns.

Results and Discussion

Figure 1 illustrates the greenhouse gas emissions from Sri Lanka's agriculture sector in the years 2015 and 2024. Emissions originate from several sources, including rice cultivation, emissions from other agricultural soils, and enteric fermentation. Enteric fermentation includes methane emissions from cattle housed in operational facilities such as feedlots, barns, and dairy farms, with estimates calculated at the facility level using remote sensing and artificial intelligence to identify the location of operations and estimate herd sizes. Additional sources include enteric fermentation from other livestock, synthetic fertilizer application, and enteric fermentation from cattle grazing on pasturelands. Methane emissions from pasture-based cattle are estimated using spatially gridded pasture data combined with FAOSTAT herd numbers, as provided by Climate TRACE. These pasture-based systems typically yield higher methane emissions per animal due to the higher fiber content of forage compared to feedlot operations. Further contributors to GHG emissions include crop residue management, manure management from cattle operations, cropland fires, manure left on pasture, manure management from other livestock, and manure applied to soils.

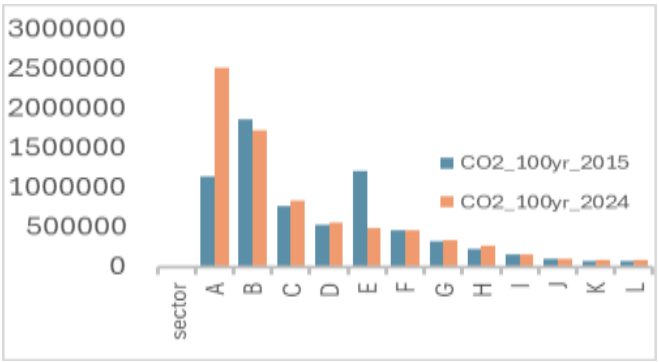

Figure 1. Greenhouse gas emissions from Sri Lanka's agriculture sector in 2015 and 2024, categorized by different emission sources. The emissions are represented in terms of CO_2-equivalent (CO_2e) using the 100-year global warming potential (GWP) values from 2015 and 2024. The sectoral labels are defined as follows: A – Rice Cultivation, B – Other Agricultural Soil Emissions, C – Enteric Fermentation (Cattle Operation), D – Enteric Fermentation (Other), E – Synthetic Fertilizer Application, F – Enteric Fermentation (Cattle Pasture), G – Crop Residues, H – Manure Management (Cattle Operation), I – Cropland Fires, J – Manure Left on Pasture (Cattle), K – Manure Management (Other), L – Manure Applied to Soils.

The results of this study highlight the significant contribution of rice cultivation to agricultural emissions in Sri Lanka, with the highest CO_2e-100 year values recorded in 2023 and 2024 at 2,525,486 CO_2e, followed closely by 2022 (2,450,898 CO_2e) and 2021 (2,120,170 CO_2e). These findings align with previous studies, which emphasize rice cultivation as a major source of greenhouse gas emissions, particularly methane, due to the anaerobic conditions in flooded paddy fields (Chen et al., 2024). The increasing CO_2e values

over recent years in Sri Lanka reflect both the intensification of rice production and the lack of significant mitigation strategies aimed at reducing emissions from this (Muneer 2023). This trend mirrors global patterns where rice cultivation continues to be a dominant contributor to agricultural greenhouse gas emissions (Hong et al. 2021). While alternative rice farming practices such as alternate wetting and drying have been suggested to mitigate these emissions (Sriphirom et al. 2019). Figure 2 illustrates the Trends in greenhouse gas emissions from rice cultivation and other agricultural soil emissions in Sri Lanka from 2015 to 2024.

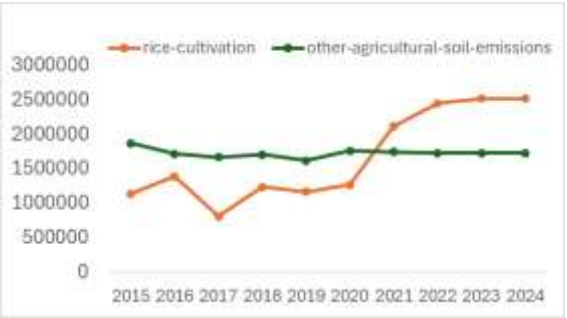

Figure 2. Trends in greenhouse gas emissions from rice cultivation and other agricultural soil emissions in Sri Lanka from 2015 to 2024. The graph shows the CO_2-equivalent emissions (CO_2e, 100-year GWP) for both sectors, highlighting variations over the years. Rice cultivation emissions (blue line) are primarily driven by methane (CH_4), while other agricultural soil emissions (red line) are influenced by carbon dioxide (CO_2) and nitrous oxide (N_2O).

Analysis of GHG emission trends reveals a dramatic increase in 2021 and the value has continued till the end of the study period in 2024, particularly from rice cultivation. This spike in emissions is closely associated with Sri Lanka's abrupt shift to organic agriculture in 2021 (Drechsel et al. 2025). In April of that year, a nationwide transition to organic farming, enforcing an immediate ban on chemical fertilizers and pesticides was mandated. While the policy aimed to promote sustainable agriculture, it instead led to severe agricultural disruptions. Rice yields fell sharply, with some estimates indicating a 30% reduction, and short-term yield losses reaching up to 53%. As a result, rice production dropped by 32% (Stifel 2025). The lack of proper training in organic farming led to inefficient practices, and the absence of chemical inputs prolonged the crop growth cycle, extending the duration of methane-producing flooded conditions. Compounding to the issue, conventional continuously-flooded systems (CF) foster anaerobic soil which supports methanogenic microbial activity in rice paddies. Without suitable water-management techniques like alternate wetting and drying (AWD), prolonged flooded periods in 2021 amplified methane emissions for each crop cycle (Lakshani et al. 2023). Collectively, these factors contributed to a paradoxical rise in GHG emissions from rice cultivation, despite overall reductions in yield, highlighting the unintended environmental consequences of the poorly planned organic transition.

In addition to rice cultivation, the study also examined other sources of agricultural emissions in Sri Lanka, including emissions from agricultural soil management and livestock operations. Emissions from other agricultural soils showed a gradual decrease over the period from 2015 to 2024, with values declining from 1,871,832 CO_2e in 2015 to 1,732,703

CO_2e in 2024. This decline is consistent with global findings, where improvements in soil management practices and technological advancements have led to reduced emissions from soil sources (Lal 2013). However, the rate of reduction was slow, indicating that further interventions may be necessary to accelerate this decline. Studies have suggested that more aggressive strategies, such as improved nutrient management and agroforestry, could provide additional long-term benefits (Kidd and Pimentel 1992). The stabilization of emissions between 2022 and 2024 suggests a potential plateau, emphasizing the need for ongoing monitoring and adaptive policy frameworks to achieve more substantial reductions in emissions from agricultural soils.

Synthetic fertilizer application and enteric fermentation from livestock also emerged as the two largest contributors to agricultural emissions in Sri Lanka in recent years. In 2021, synthetic fertilizer application accounted for 979,294 CO_2e (100-year), while enteric fermentation from cattle operations contributed 844,081 CO_2e. The emissions from cattle operations remained consistent through 2024, indicating that efforts to mitigate emissions from this sector have had limited success. These trends align with previous studies highlighting the significant role of livestock and fertilizer use in Sri Lanka's agricultural greenhouse gas emissions (Rathnayake and Mizunoya 2024). The stable emissions from enteric fermentation suggest that livestock management practices and feed improvements have not yet resulted in substantial reductions in methane emissions, which is consistent with regional studies (Wolf et al. 2017). Additionally, the continued high levels of synthetic fertilizer use underscore the ongoing challenge of balancing agricultural productivity with environmental sustainability (Zhang et al. 2024). Addressing these emissions will require comprehensive policy interventions, including the adoption of more efficient fertilizers and advanced livestock management techniques. The findings of this study also revealed that certain agricultural sectors, while contributing less to overall emissions, still play a role in Sri Lanka's agricultural emissions profile. Emissions from the "manure-applied-tosoils" sector showed a steady increase from 74,037 CO_2e in 2015 to 86,732 CO_2e in 2024. Similarly, emissions from other manure management other increased from 80,857 CO_2e in 2016 to 97,781 CO_2e in 2024, and "manure-left-on pasture-cattle" emissions remained relatively high, ranging from 104,115 CO_2e in 2015 to 105,455 CO_2e in 2021. These results are consistent with studies that highlight the role of livestock and manure management in agricultural emissions (Chadwick et al. 2011). While these sectors exhibit moderate emissions in comparison to rice cultivation, they still contribute substantially to the total agricultural emissions in Sri Lanka, indicating the need for sustainable livestock management practices to mitigate emissions from these sources (Aryal et al. 2020).

Furthermore, the dominant source of CO_2 emissions from the agricultural sector was from "other agricultural soil emissions" with values ranging from 1,494,723 tons in 2017 to 1,697,631 tons in 2015. These emissions remained relatively stable at 1,540,210 tons in 2022 and continued to level off through 2024. The primary sources of these emissions are attributed to fertilizer use, rice cultivation, and general soil management practices (Linquist et al. 2012). In contrast, emissions from cropland fires remained low, fluctuating between 122,305 tons in 2017 and 179,748 tonnes in 2020, with no significant changes post-2020. This supports earlier studies indicating that agricultural soil management is a significant contributor to greenhouse gas emissions in Sri Lanka (Rathnayake and Mizunoya 2023).

Although there has been some decline in emissions from soil over time, further research is needed to assess the full impact of improved agricultural practices and verify whether these trends are due to ongoing mitigation efforts.

Lastly, the study revealed that rice cultivation remains the primary contributor to CH_4 emissions in Sri Lanka, followed by enteric fermentation from cattle operations. The data shows a marked increase in methane emissions from rice cultivation, with 90,519 tonnes recorded in 2023, up from 39,827 tonnes in 2015. This rise reflects the continued reliance on flooded fields, which create anaerobic conditions conducive to CH4 production, as noted in previous studies (Pulliam, 1993). Enteric fermentation from cattle operations also plays a significant role in methane emissions, contributing 31,032 tonnes in 2023. While emissions from other sources, such as manure management and cropland fires, remained stable or low, the dominance of rice cultivation and enteric fermentation emphasizes the need for targeted mitigation strategies to address methane emissions, such as improved rice farming techniques and more efficient livestock management (Mousa et al. 2023).

Conclusion

Sri Lanka's agricultural emissions have continued to rise, driven primarily by methane from rice cultivation, with emissions reaching 2,525,486 CO_2e in 2024. While soil emissions have shown modest declines, emissions from livestock and fertilizer use remain substantial. The emission estimates provide a global perspective but may not fully capture local Sri Lankan farming conditions. Future research should integrate local field measurements with satellite data to improve estimate reliability and develop region-specific emission factors that account for traditional farming practices and seasonal variations. These findings have significant implications for Sri Lanka's Paris Agreement commitments and Nationally Determined Contributions (NDCs). The 127% increase in methane emissions from rice cultivation between 2015 and 2023 requires targeted sectoral emission reduction strategies. The agricultural sector should be integrated into national carbon accounting frameworks with specific targets for reducing methane emissions from rice cultivation by 15-20% by 2030 through alternate wetting and drying techniques. Addressing these challenges requires comprehensive policy interventions promoting sustainable rice farming, efficient livestock management, and optimized fertilizer application. Further research and policy implementation are critical to reducing Sri Lanka's agricultural climate footprint while aligning with national climate commitments and maintaining food security.

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Strengthening Anticipatory Action in Sri Lanka through the AWARE Platform: A Decision Support System for Early Warning, Early Action, and Early Finance

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Introduction

South Asia stands at the frontline of the global climate crisis, and Sri Lanka, as an island nation within this region, is increasingly exposed to a rising frequency and severity of hydrometeorological hazards. Floods, droughts, landslides, and other climate-induced extreme events are intensifying due to shifting rainfall patterns and rising temperatures (Samaraweera et al. 2024). These hazards not only disrupt lives and livelihoods but also pose significant threats to national development goals, food and water security, public health, and the resilience of vulnerable communities, particularly smallholder farmers and marginalised populations residing in climate-vulnerable areas (Gamage et al. 2025). Within this context of escalating risk, Sri Lanka is undergoing a pivotal shift in disaster risk management, transitioning from reactive, response-oriented approaches to a more proactive, anticipatory framework that emphasises early preparedness, informed planning, and risk reduction (Hettiarachchi and Weeresinghe 2014). This transformation aligns with the country's national priorities for adaptation. It supports the global ambitions outlined in the Paris Agreement, the Sendai Framework for Disaster Risk Reduction, and the Sustainable Development Goals.

AWARE is a web-based platform developed to strengthen climate resilience by linking early warning with early action and early finance. It addresses a critical gap in Sri Lanka's climate action landscape by enabling risk-informed decision-making, timely anticipatory action, and integrated coordination across sectors. It empowers national and local disaster management authorities, planners, agricultural extension officers, and community-based organisations to act promptly and mitigate the impacts of climatic shocks. Therefore, the objectives of this paper are to examine how the AWARE Platform enhances forecasting and early warning capabilities and how it integrates these improvements with actionable insights to enable anticipatory decision-making for proactive disaster risk management.

Materials and Methods

Study Area**:** Sri Lanka is an island nation situated just south of India in the Indian Ocean. Owing to its geographical location and diverse climate, the country is highly susceptible to recurring natural hazards such as floods, droughts, and landslides. The AWARE platform has

been developed to cover the entire territory of Sri Lanka, offering functionalities that enable users to visualize and analyze data across various administrative levels, from provinces to individual districts. This extensive spatial coverage facilitates localized decision-making and boosts the country's ability to manage disaster risks proactively.

Data**:** To support accurate and timely decision-making, the AWARE platform integrates a wide range of meteorological, hydrological, and satellite-based datasets from globally recognised sources. For weather forecasting, the platform accesses short-range forecasts from Open Weather and NOAA-GFS, medium-range forecasts from ECMWF, and long-range forecasts from IRI, all retrieved via API connections. Flood forecasting capabilities are enhanced using data from GeoGLOWS and GLOFAS, also accessed through APIs.

For monitoring ongoing and historical hazard conditions, AWARE utilizes satellite-derived indicators via Google Earth Engine (GEE), including dry spell monitoring using GPM, Soil Moisture Condition Index (SMCI) using GLDAS, and Integrated Drought Severity Index (IDSI) from MODIS. Additionally, rainfall monitoring incorporates data from CHIRPS and GPM, while flood extent mapping leverages imagery from both MODIS and Sentinel-1. This multi-source data integration ensures robust and comprehensive hazard analysis to support Anticipatory Action planning and early warning dissemination.

Method**:** As per the AWARE concept (Figure 1), the platform has been developed entirely in the cloud platform based on an N-tier client/server architecture, which involves organizing the application into multiple distinct layers or "tiers," each responsible for a specific set of functionalities. This architectural model separates the user interface, application logic, and data management functions into distinct components that are deployed independently but can interact through well-defined interfaces and communication protocols.

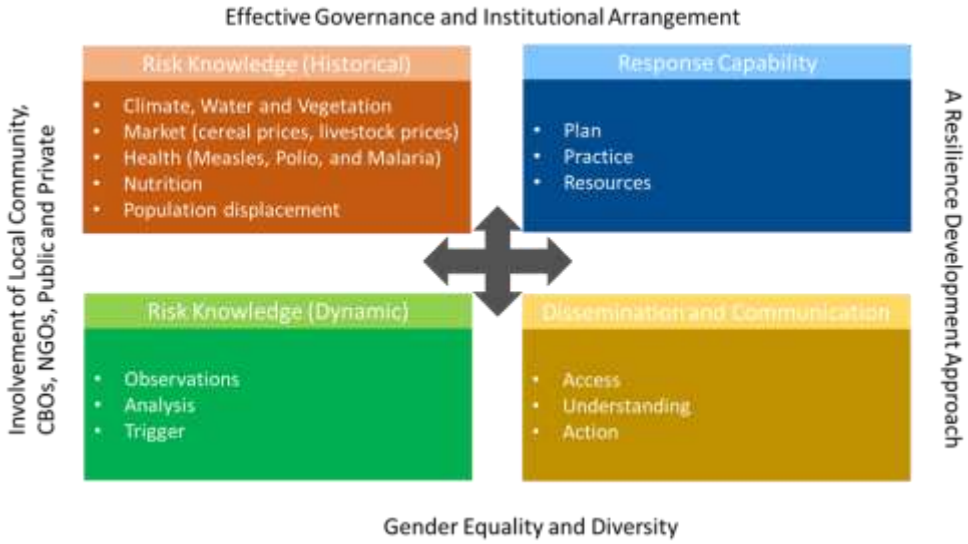

Figure 1. AWARE Concept (https://aware.iwmi.org/)

In this design, each tier, such as the presentation layer (user interface), the application layer (business logic), and the data layer (databases and data services), can be maintained, updated, or scaled independently without affecting the overall system's performance. This modular approach enhances the platform's flexibility, scalability, and maintainability, allowing for easier integration of new features, technologies, or data sources.

Results and Discussion

The AWARE Platform has been implemented in Sri Lanka as a critical step toward strengthening Anticipatory Action within the national Disaster Risk Management (DRM) framework. The AWARE enables a shift from reactive crisis response to proactive risk management by integrating Early Warning, Early Action, and Early Finance mechanisms modules together. Furthermore, the alert dashboard, rapid response mechanism, online bulletins, and user guides significantly (Figure 2) enhance the end-to-end functionality of the system, supporting users both before and during a crisis.

Early Warning

The Early Warning module of the platform enables users to visualize and analyse forecast, near-real-time, and historical data by leveraging a wide range of satellite and model-based datasets. In this module, forecast indicators are directly tied to the trigger mechanisms for Anticipatory Action, while monitoring indicators represent the current and historical conditions of hazards such as floods, droughts, and landslides. These triggers and thresholds for Anticipatory Action have been developed in close collaboration with relevant technical agencies to ensure both scientific accuracy and operational relevance.

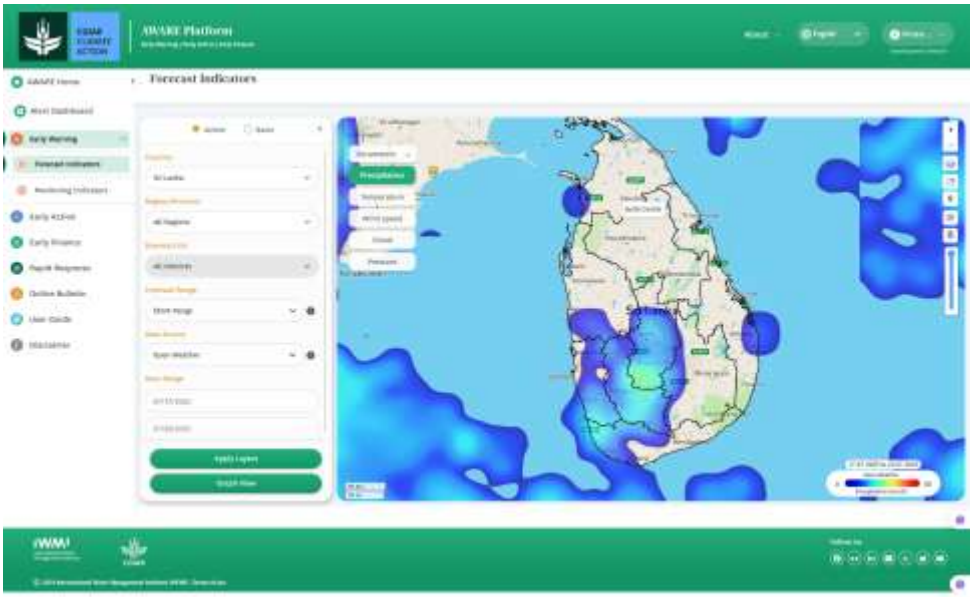

Figure 2. AWARE platform overview of the Early Warning Module

Early Action

The Early Action module of the AWARE platform acts as a vital link between early warning signals and timely, coordinated response efforts aimed at minimizing disaster impacts before they occur. This module provides predefined, actionable protocols that are triggered by forecast-based thresholds. The Alert Dashboard of the AWARE platform is specifically designed to trigger anticipatory action phases, preparedness, readiness, and activation using short-term, medium-term, and long-term forecast data.

Early Finance

The Early Finance module of the AWARE platform connects financial planning with the operationalization of anticipatory action. It enables the timely release of funds based on predefined triggers and community impact assessments, ensuring that early action protocols can be implemented effectively to minimize human, economic, and environmental losses. Importantly, the Early Finance module of the AWARE platform allows users to define financial arrangements aligned with sector-specific approaches, ensuring that resources are allocated strategically across priority areas.

The Alert dashboard

The AWARE's Alert Dashboard plays a critical role in strengthening the anticipatory action as it presents real-time alerts based on predefined sub-national triggers and thresholds, allowing users to understand the current phase of anticipatory action, whether it is Preparedness, Readiness, or Active. Based on the alert phase, the system links to corresponding Anticipatory Action Protocols through the Early Action Module.

The Early Action module translates these warnings into pre-defined, actionable steps, ensuring that responses are timely, coordinated, and effective. Whether it's pre-arranged finance, pre-evacuation planning, resource mobilisation, or infrastructure reinforcement, this module helps align responses with evolving risk levels. It connects to the Early Finance Module to ensure that financial resources are mobilized quickly when warning thresholds are met. This supports smooth evacuations, continuous food supply, and the protection of lives and livelihoods before a disaster fully develops.

Rapid Response and Online Bulletin

Furthermore, the platform enhances rapid disaster mapping through a robust and streamlined approach integrated within its Rapid Response Module. In the event of a disaster, this mechanism enables the identification of hazard-affected areas by analysing rainfall conditions and mapping flood inundation using near-real-time satellite data. Additionally, it supports rapid damage assessment by estimating the impact on exposed populations, agricultural areas, and critical infrastructure, thereby providing timely and actionable insights for emergency response and recovery planning. Additionally, the Automated Online Bulletin feature significantly strengthens information dissemination, ensuring that stakeholders and communities receive accurate, actionable insights in real-time. Together, these capabilities make AWARE a powerful tool for proactive disaster preparedness and response.

Strengthening Anticipatory Action Simulations through the AWARE Platform

In 2023 and 2024, the AWARE platform facilitated the conduct of Sri Lanka's first anticipatory Action Simulation for flood and drought enabling stakeholders from central ministries, provincial councils, and local authorities (Alahacoon et al. 2023; Alahacoon and Giriraj 2024).

Both simulations assessed the feasibility of implementing forecast-based early actions and pre-financing through the distribution of cash vouchers. The major outcome of the simulation included the Validation of early warning triggers, Identification of bottlenecks in communication and resource mobilization, and the Strengthening of institutional operating procedures. These insights informed the development of integrated Standard Operating Procedures (SOPs) that are now being used to mainstream anticipatory action into district-level disaster preparedness plans.

AWARE Synergies with National Adaptation and Governance Frameworks

The AWARE Platform aligns with and enhances several ongoing initiatives, including the Climate Smart Governance (CSG) Dashboard, developed by IWMI in collaboration with Sri Lanka's National Planning Department (NPD), the Ministry of Finance, and the Climate Change Secretariat (CCS) and the Ministry of Environment. The National Adaptation Plan (NAP) and National Disaster Management Plan (NDMP). Sectoral adaptation efforts in agriculture, irrigation, health, and environment. Furthermore, AWARE complements global initiatives such as the Early Warning for All (EW4All) campaign and the Sendai Framework for Disaster Risk Reduction. It acts as a regional model, demonstrating how anticipatory action platforms can be adapted and scaled in other climate-vulnerable countries.

Capacity Building and Stakeholder Engagement

A series of training sessions, field-level consultations, and simulation exercises have been conducted to build institutional capacities and promote platform adoption. Key stakeholders trained include National and International Humanitarian organisations, Government officials representing the Disaster Management Centre (DMC), the Department of Agriculture, the Department of Meteorology, the Department of Irrigation and District Disaster Management Units. This capacity development engagement enables the ensuring of last-mile connectivity and the uptake of localised alerts.

Conclusion

The AWARE Platform represents a transformative approach to climate risk governance in Sri Lanka, enabling a shift from reactive to proactive disaster management approaches. By integrating science, technology, and governance, it empowers decision-makers and communities with the insight and tools needed to safeguard lives, livelihoods, and ecosystems. As a climate risk discipline, the AWARE platform offers a scalable and inclusive pathway for building climate resilience in Sri Lanka and beyond.

With the official launch of the AWARE platform in collaboration with the Disaster Management Centre (DMC) and other technical agencies, the following steps focus on

strengthening both institutional capacity and system sustainability. A key priority is to build capacity among stakeholders for effective utilization of the platform, supporting the enhancement of Anticipatory Action across the country. The critical step is the technical transition of the platform to the designated hosting agency, ensuring long-term ownership and integration into national systems. Strengthening coordination with technical agencies for data sharing will further enhance the platform's reliability and responsiveness. In addition, the platform should facilitate the development of community-level protocols and serve as a central repository for anticipatory action protocols, ground-level data, and response records.

Acknowledgement

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Sustainable Operation and Maintenance of Village Irrigation Systems

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Introduction

Sri Lanka's village irrigation systems (VIS) have played a crucial role in sustaining rural livelihoods for centuries. These small-scale irrigation structures, often managed by local farming communities, are essential for ensuring food security and agricultural productivity, especially in water-scarce regions (Madduma Bandara 1985). However, the long-term sustainability of these systems has been challenged by factors such as inefficient operation, inadequate maintenance, lack of community engagement, and weak financial models (Dharmasena 2011). The deterioration of VIS not only threatens agricultural production but also exacerbates rural poverty and environmental degradation.

The government and development agencies introduced the Climate Resilient Integrated Water Management Project (CRIWMP) to enhance the sustainability of VIS. CRIWMP upgraded village irrigation systems and promoted home gardens, perennial crops, and groundwater recharge methods to improve water management and increase economic benefits (Imbulana et al. 2023). Despite these efforts, sustainable operation and maintenance (O&M) of irrigation systems remains a persistent issue, requiring integrated approaches that strengthen governance, financial sustainability, and stakeholder participation (Aheeyar 2006). The study was conducted with the objectives to analyze the key challenges affecting the sustainable operation and maintenance of village irrigation systems (VIS) in Sri Lanka, including, identify factors leading to inefficient management, inadequate stakeholder participation, and financial constraints and propose sustainable and economically viable solutions for improving the operation and maintenance of VIS through enhanced governance structures, participatory management approaches, and innovative financial models.

Methodology

Data Collection Tools and Analysis Techniques

This study examined the sustainable operation and maintenance of village irrigation systems (VIS) in Sri Lanka using a mixed-methods approach. Analysis of 25 Preliminary Investigation

Reports (PIR) and Participatory Climate Risk Vulnerability and Capacity Assessments (PCR & VCA) and 05 Cascade Assessments was used to identify issues related to governance, infrastructure, and financial issues pre- and post-CRIWMP. Focus group discussions with five Farmer Organizations were conducted to identify the challenges in maintenance and fund transparency. Key tools like O&M Plans, Rotational Plans, and Water Capacity Tables were reviewed.

Mechanisms such as daily monitoring records and CMC reports were used to identify the potential for improved governance. A questionnaire survey carried out by the project staff (Cascade Assessment Tool) was used to understand the community perception of O&M strategies introduced by the project approaches.

Results and Discussions

Operation and maintenance process before the project

Before the implementation of the Climate Resilient Integrated Water Management Project (CRIWMP), many village irrigation systems (VIS) in Sri Lanka faced serious structural and operational challenges. These traditional small-scale systems, vital for agricultural livelihoods, suffered from poor maintenance, siltation, and weak water management. For instance, systems like Karuwalagas Wewa showed signs of neglect, with poorly maintained bunds, damaged sluices, and spillways blocked by weeds and silt. Tank ecosystems were also degraded, with key components such as "*Kattakaduwa*" and "*Gas-Gommana*" either missing or poorly maintained, affecting water retention and biodiversity. Although traditional practices like Kanna meetings existed, the implementation of water distribution mechanisms was weak. The lack of water level and rainfall monitoring contributed to inefficient use.

The O&M arrangements were largely inadequate, resulting in poor water distribution and unsustainable system use. In Karuwalagas Wewa, Mottapeththewa cascade, routine tasks like bund clearing were carried out by the Farmer Organization (FO), but major repairs were delayed due to financial and technical constraints. Structures such as sluices and regulators needed urgent repairs, but no structured system existed to address these needs. Farming was limited mainly to nearby paddy lands under the "*Bethma*" system, with little effort to expand cultivation or monitor tank capacity. These issues highlighted the urgent need for an integrated O&M framework, which the CRIWMP project aimed to introduce through improved governance, financial planning, and community participation (PIR-CRIWMP 2017).

Challenges to sustainable O&M

Operation and maintenance (O&M) of village irrigation systems in the project area face persistent challenges that affect long-term functionality. Farmers, engaged in multiple livelihoods, often lack time for regular maintenance, while limited government funding restricts critical repairs. These systems are farmer-managed, with state support limited to emergencies, leading to over-reliance on institutions like the Department of Agrarian Development (DAD), weakening community ownership. Maintenance typically focuses on main structures, neglecting spillways, inlets, and environmental features, reducing system sustainability.

To overcome these issues, structured and participatory strategies are essential. Empowering Cascade Management Committees (CMCs) to monitor and guide maintenance using inspection tools can improve accountability. Strengthening farmer participation and maintenance funds through transparent mechanisms is also vital. Where appropriate, contract-based maintenance under local supervision can enhance efficiency. Additionally, government subsidies and incentives can encourage active farmer involvement. These measures collectively support sustainable, resilient irrigation systems.

An overview of the operation & maintenance practices employed by the CRIWMP

The CRIWMP project introduced several structured and participatory practices to enhance the sustainability and efficiency of Operation and Maintenance (O&M) in village irrigation systems. Key among these is the Operation and Maintenance Plan implemented before each season, which includes tools such as the seasonal Pangu List and maintenance schedules, providing clear operational guidelines to farmers and Farmer Organizations (FOs). The project also introduced a Rotational Plan for Completed Downstream Works, improving equitable water distribution through better-managed and rehabilitated canal systems. To support technical water management, Water Capacity Tables have been developed for each tank, correlating water depth measurements with storage capacity, enabling better planning for irrigation.

Furthermore, Record Books for daily logging of water levels and rainfall were introduced, allowing for continuous monitoring and data-driven decision-making. The Cascade Water Resources Development Plan, managed by the Cascade Management Committees (CMCs), outlines seasonal water management responsibilities, enhancing collective accountability. The Format for Progress of Irrigation System Operation and Maintenance and Maintenance Fund Reports support transparency and tracking of seasonal O&M activities. Additionally, Maintenance Fund Account Ledgers, Equipment Disposal/Re-acceptance Records, and Irrigation Water Requirement Spreadsheets provide robust financial and technical documentation, empowering communities to maintain systems effectively and sustainably through evidence-based and participatory management

Community Perception of the improved O&M methodologies

The assessment dimensions included availability of OM plan, implementation of the OM plan, responsibility assigned among farmers, availability of Maintenance Fund in a bank account, the fund is used for maintenance effectively, availability of meeting minutes, the regular audits of the Department of Agrarian Development, fish ladders (biodiversity concerns), bathing steps with handrails (facility for the disabled and elders), operation-friendly gates, and upgrading of the (community perception). The Cascade Assessment Tool assessed across these 11 dimensions related to sustainable O&M practices.

Palugaswewa scored the highest with 96 out of 100, indicating strong compliance with key indicators. *Mamunugam*a followed with 91, while *Sivalakulama*, *Thuduvakkaikulama*, and *Mottapeththewa* scored 85, 84, and 82 respectively. High scores were recorded in areas such as availability of O&M plans, operation-friendly gates, and positive community perception of system upgrades. However, weaknesses were noted in fund utilization, regular audits, and the inclusion of biodiversity-friendly features like fish ladders and bathing steps.

Table 1: Results of the questionnaire survey.

Key area for evaluation	No. of Assessment Dimensions	Marks	Baseline	*Palugaswewa*	*Mottapeththewa*	*Sivalakulama*	*Mamunugama*	*Thuduvakkaikulam*
Climate-resilient and sustainable upgrading of VISs	1	5	-	5	5	5	5	5
	2	10	-	10	10	6	10	8
	3	5	-	5	5	5	5	4
	4	10	-	10	10	6	10	7
	5	10	-	10	10	6	6	8
	6	5	-	5	4	5	5	4
	7	5	-	5	5	5	5	5
	8	10	-	10	10	8	10	7
	9	10	-	10	0	10	10	10
	10	10	-	10	10	10	10	10
	11	20	-	16	16	16	15	16
Total		**100**	-	**96**	**85**	**82**	**91**	**84**

(Source: Survey findings, 2025)

The results reflect both the improvements made under the CRIWMP and areas that require further attention. While most cascades show progress in governance and infrastructure, gaps remain in financial transparency and inclusive design. These findings underline the importance of continuous monitoring and community engagement to achieve sustainable and climate-resilient irrigation system management.

The figure1 highlights significant variations in financial allocations over time, reflecting both improvements and persistent challenges in irrigation system management. While some cascades, such as *Palugaswewaa* and *Sivalakulama*, and *Mamunugama* demonstrate substantial increases in fund availability, others, like *Mottapeththewaa* and *Thuduvakkaikulama*, show stagnation or depletion, indicating disparities in financial sustainability across districts.

The results underscore the effectiveness of the CRIWMP in mobilizing resources, yet also reveals gaps in fund utilization and replenishment strategies. Cascades with declining or stagnant funds may require enhanced financial governance mechanisms, transparent contribution models, and strengthened community participation to ensure long-term

sustainability. The review suggests the need for continuous fund monitoring and adaptive financial frameworks to support minor irrigation system resilience in Sri Lanka.

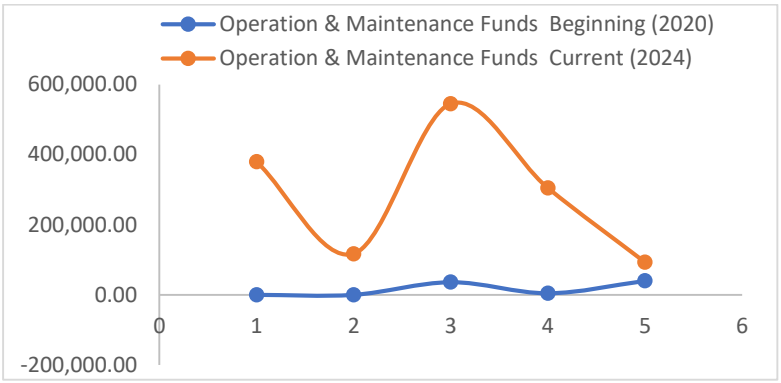

Figure 1. Comparison of Beginning and Current Operation & Maintenance Funds for Cascades by District and Farmer Organization.
(Source: Survey findings 2025)

This research explores sustainable and economically viable solutions to improve O&M in VIS. By addressing inefficiencies and engaging stakeholders in participatory governance, irrigation systems can be maintained effectively, ensuring long-term resilience. Strengthening financial models through cost-sharing mechanisms and community-led initiatives can further enhance their viability. A well-managed VIS contributes not only to agricultural productivity but also to climate resilience and rural development (Vidanage el al. 2022). This study aims to provide actionable insights to policymakers and practitioners to enhance the sustainability of VIS, ultimately fostering food security and economic stability in Sri Lanka.

Sustaining the Operation and Maintenance (O&M) of village irrigation systems (VIS) in Sri Lanka requires a structured, community-driven approach, integrating governance improvements, financial sustainability, and technical advancements. The Climate Resilient Integrated Water Management Project (CRIWMP) introduces participatory mechanisms such as Operation and Maintenance Plans, Rotational Plans for Downstream Works, and Water Capacity Tables, ensuring system efficiency and equitable water distribution. Strengthening Farmer Organizations (FOs) and Cascade Management Committees (CMCs) is crucial, as these bodies facilitate collective decision-making and long-term engagement. Financial sustainability can be enhanced by reinforcing maintenance fund accounts, introducing cost-sharing mechanisms, and offering government subsidies to incentivize participation. Additionally, incorporating structured maintenance schedules and inspection checklists ensures systematic monitoring of critical infrastructure, such as bunds, sluices, and spillways. Encouraging contract-based maintenance under local supervision can improve efficiency and accountability, while Record Books for water logging and rainfall tracking enable data-driven decision-making. By integrating governance reforms, financial accountability, and technical best practices, VIS can achieve long-term resilience, improving agricultural productivity, food security, and climate adaptability in water-scarce regions. A

participatory and transparent framework is essential to ensuring sustainable irrigation operations that support rural livelihoods while preserving Sri Lanka's traditional irrigation systems.

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A Field Study on Canal System Failures in Village Irrigation Systems (VIS) and Recommendations for Climate-Resilient Rehabilitation

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Introduction

Village Irrigation Systems (VIS), also known as minor tanks, have been the cornerstone of agricultural livelihoods in Sri Lanka's dry zone for centuries. These ancient, cascade-based systems sustain food security and local ecosystems by distributing stored rainfall through earthen canal networks (Gunawardena 2000). Despite their heritage value and cost-effectiveness, these systems face growing challenges due to structural deterioration of canals, which compromises water conveyance efficiency.

Earthen canals, while easy to construct, are highly vulnerable to erosion, siltation, overtopping, and damage from livestock and floods (Fernando & Madduma Bandara 2018). The problem is most severe at sluice outlets, where high-energy flow from sluice barrels rapidly erodes unlined canal sections. Traditional patchwork repairs, such as short reinforced concrete linings, fail to address this root cause and often transfer the problem downstream.

While studies on VIS functionality exist (Gunawardena 2000; Fernando & Madduma Bandara 2018), there remains a critical empirical gap regarding field- based assessments of canal degradation and the practical effectiveness of structural interventions. This paper aims to fill that gap by presenting evidence from the Climate Resilient Integrated Water Management Project (CRIWMP) and by proposing a hydraulically sound solution for outlet protection. The study's objective is to demonstrate how integrating energy dissipators can ensure the long-term durability and resilience of VIS canals under changing climatic conditions.

Methodology

Field investigations were conducted across 41 village irrigation system (VIS) sites within eight cascade systems in the Medawachchiya, Galenbindunuwewa, Horowpothana, and Mihinthale Divisional Secretary's Divisions of the Anuradhapura District of Sri Lanka. Site surveys included visual inspections, stakeholder consultations, and technical measurements of discharge capacity, flow head, and existing damage patterns. The study analyzed the extent of canal degradation — especially scouring, water pooling, and embankment breaches using photographic records and cross-sectional profiles. Engineering diagnostics were guided by established open-channel.

hydraulics theory (Chow 1959) and practical design standards for small canal structures (USBR 1987).

Table 1. Village Irrigation Systems in different cascades with identified issues and silutions

Cascade Name	Village Irrigation System (VIS)	Command Areas (Ac)	Identified Issues (A)*				Mitigation / Solution Taken (B)
			a	b	c	d	
Diwulwewa	Minhettigama	110	1	1			1,2
	Parasanwewa	100	1				1
	Yodhawewa	72	1	1			1,2
	Guruneerawa	25	1				1
	Thilangala	28	1	1			1,2
	Kuda Bellankadawala	36	1				1
	Makichchawa	45	1	1			1,2
Thuduwakkai	Damanewewa	15.5	1				1
	Thammennawa maha wewa	140	1				1
	Puhudiwula wewa	55	1				1
	Kudagam wewa	34	1				1
	Aelapathwewa	14	1	1			1,2
	Bogaswewa	13	1				1
	Manelwewa	10	1				1
	Nelumwewa	18	1				1
	Andarawewa	12	1				1
	Aluthgamawewa	25	1				1
Aluth Halmillewa	Koonwewa	12	1				1
	Koongollewa	120	1	1		1	1,2,4
	Katukeliyawa	7	1				1
	Ahugahawewa	25	1				1
	Aluth Halmillewa wewa	110	1	1		1	1,2,4
	Wdikkarayagewewa	22.25	1				1
	Kadawathawewa	8	1				1
	Puhudiwulawewa	45	1				1
	Etabagaskada	110	1			1	1,4
	Palugollewa wewa	50	1				1
	Makichchawa wewa	85	1				1
Weehena karabawewa	Puliyankulama	126.25		1		1	2,4
Siwalakulama	Pahala Aliyawetunuwewa	50	1				1
	Ihala Aliyawetunuwewa	20	1				1
	Wembuwewa	25	1				1
	Palugollagama	98	1				1
	Muriyakadawala maha wewa	292			1		3
	Kolongaswewa	68	1				1

	Thibiriwewa	15	1				1
	Aluthwewa	30	1				1
	Siwalakulama mahawewa	268	1				1
	Rabakulamawewa	30			1		3
	Araluwewa	35	1	1			1,2
	Weragala wewa	30			1		3
	Bathalewewa	16	1				1
Rathmale	Rathmale Kudawewa	72		1	1		2,3
	Galapitagala	16	1				1
	Nagaragalawewa	16			1	1	3,4
Bandara Kubukwewa	Diyathiththa Mahawewa	37	1				1
	Berawayagama wewa	72	1	1			1,2
	Kakiragamawewa	27	1				1
	Badapuwewa	50	1				1
	Kudagama wewa	40	1				1
	Diyathiththa kudawewa	150	1	1			1,2
Maha Kirindegama	Katupotha	165					2
	Miris Katukaliyawa	58	1			1	1
	Katukeliyawa	56		1			2
	Wellamorana	48	1				1
	Maha Kirindegama	76	1				1
	Total Number of cases		**48**	**13**	**5**	**6**	

In Table 1, Column (A) is the codes (a) to (b) are represented by (a) Water pooling at the sluice outlet/ canal bund washed off with the high flow, (b) Canal bund damaged/Scoured due to animals and human activities, (c) Water pooling at the beginning of a canal due to Spill water and (d) Seepages appeared through the canal bund. The Column B in Table 1, the codes 1 to 4 are represented by (1) Introduce reinforced concrete lining section with energy dissipater, (2) Introduce reinforced concrete canals with tractor crossings, (3) Introduce reinforced concrete canals and an overcrossing, and (4) Introduce reinforced concrete canal lining

Results and Discussion

Field evidence confirmed a consistent pattern of failures. As shown in **Table 1**, nearly all surveyed canals exhibited significant scouring at sluice outlets, water pooling, and downstream erosion. Without energy dissipators, the kinetic energy of these flows exceeded soil resistance, resulting in severe scouring. It indicates that most of the failures (a) observed at the outlets of the sluice are due to scouring of the canal bunds. where reinforced concrete lining abruptly ends, transferring erosion to the next unlined reach. Previous literature stresses the hydraulic risk of unmanaged flow transitions (Chow 1959). The USBR Design Manual (1987) highlights that stilling basins, drop structures, or baffle

blocks are standard engineering solutions to dissipate excessive flow energy. However, these are rarely incorporated into VIS rehabilitation in Sri Lanka due to limited design capacity and cost- saving compromises (Fernando & Madduma Bandara 2018).

This study demonstrates that incorporating simple energy dissipators immediately downstream of the sluice barrel can significantly reduce flow velocity, prevent bed scouring, and stabilize the canal lining. Pilot interventions under the CRIWMP confirmed that combining an energy dissipator with reinforced lining achieved sustained flow control, minimized pooling, and reduced maintenance costs.

Conclusion

The findings clearly indicate that canal failures in VIS are rooted in overlooked hydraulic design gaps. While reinforced concrete lining can protect sections of canals, it cannot function effectively without first dissipating the excess flow energy exiting the sluice barrel. This study recommends that VIS rehabilitation guidelines must require outlet protection structures such as stilling basins or drop structures tailored to site-specific discharge and soil conditions. This approach aligns with proven global design practices (USBR 1987) and directly supports climate resilience by securing reliable water delivery for smallholder farmers. Integrating energy dissipators will safeguard public investments, reduce maintenance burdens, and prolong the operational lifespan of Sri Lanka's traditional cascade irrigation systems.

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Lessons Learned in the Depth Gauge Installation of Small Tanks: Field Based Study from Climate Resilient Integrated Water Management Project

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Introduction

Accurate water level monitoring in reservoirs and tanks plays a vital role in effective water resources management, especially in regions where agriculture, ecology, and domestic needs heavily depend on surface water availability (Weeks Drilling & Pump Company 2023). In Sri Lanka, small tanks and medium-scale reservoirs form a crucial part of the irrigation infrastructure, particularly in the Dry zone (DZ), where surface water storage is essential due to high seasonal rainfall variability. However, the implementation and maintenance of water level monitoring infrastructure, such as gauging stations or automated depth gauges, remain a considerable challenge due to financial, technical, and institutional limitations.

With approximately 18,000 small tanks, both operational and abandoned, spread across 70 well-defined river basins in Sri Lanka's Dry Zone (Panabokke 2004), installing automated water level measurement systems in each of these reservoirs is not economically or logistically feasible. Moreover, even when such systems are installed, their long-term functionality is often compromised due to a lack of proper understanding of design requirements, insufficient capacity for maintenance, and limited stakeholder engagement. This has led to frequent failures and abandonment of gauging stations, undermining data continuity and reducing the effectiveness of water management decisions. The lack of reliable water level data not only impairs day-to-day reservoir operation but also hinders scientific research, hydrological modelling, flood forecasting, and climate change adaptation planning. Vellela et al. (2024). Therefore, identifying sustainable, cost-effective, and community-adapted solutions for water level monitoring is a global research need.

This study aimed to address this challenge by exploring practical, field-tested approaches to improve the sustainability of tank water level monitoring in cascade systems. Drawing from experiences within the Climate Resilient Integrated Water Management Project (CRIWMP), this research identifies context-specific constraints and lessons learned in the implementation of depth gauge system.

Methodology

Research was conducted across 20 cascade systems located within six districts; Anuradhapura, Kurunegala, Puttalam, Trincomalee, Vavuniya, and Mannar, spanning three major river basins: Malwathu Oya, Mi Oya, and Yan Oya. An initial assessment of the small tanks led to the classification of tanks based on sluice structure and site conditions. Two primary sluice types were identified: Headwall type and Tower type sluices (Irrigation Department of Sri Lanka 2020). Based on these sluice types and corresponding site-specific characteristics, five distinct categories of tanks were identified for field evaluation (Table 1). Field investigations, stakeholder consultations, and on-site assessments were carried out to validate and document classifications. For each tank type, various water level monitoring techniques were evaluated, including: manual depth gauges mounted directly on the sluice wall; manual depth gauges mounted on reinforced concrete columns within the tank bed; manual gauges installed on pre-fabricated steel posts accessed via pontoon; and automated monitoring systems with submersible sensors as multiple phases.

Table 1. Five Types of Tanks Identified for Field Assessment

Tank Type	Description
Type 1	Headwall Type with year-round accessibility and minimal structural or wildlife risk
Type 2	Headwall Type exposed to wildlife damage during dry season (e.g., elephants)
Type 3	Tower Type with tank bed accessible during dry season; feasible for permanent structures
Type 4	Tower Type with tank partially submerged; limited dry period for concrete work
Type 5	Tower Type with permanently high-water level; structure submerged year-round

The methodology involved reviewing technical records, site inspection notes, and photographic documentation collected during multiple installation phases. Field teams assessed sluice types, recorded site-specific challenges, and documented the performance of each monitoring method under varying operational conditions. An adaptive, iterative approach was followed, with installation designs refined based on practical constraints such as accessibility, fluctuating water levels, and wildlife interference. The observations and adaptations made during implementation were analyzed to identify common patterns and critical decision points, which formed the basis for the decision matrix presented in the conclusion, aimed at guiding future gauging station planning in similar agro-ecological contexts.

Results and Discussion

As part of the water monitoring interventions for a better water management, the project initially adopted a simple, cost-effective, and technically feasible method for installing manual depth gauges in small tanks. The first phase involved the installation of fiberglass-reinforced depth gauges at sluice structures as shown in Figure 1. These gauges, ranging in

height from 2 to 6 meters, were selected based on the vertical distance between the Bund Top Level (BTL) and the Sluice Sill Level (SSL), rounded up to the nearest metre to ensure full coverage of the tank's operational water level.

Figure 1. Manual depth gauge mounted on a headwall-type sluice at Ihala Thimbiri Wewa, Trincomalee.

The design specifications prioritized accuracy, visibility, and field durability. Each gauge featured a least count of 1 cm to enable precise water level readings. A high-contrast yellow-and-black scale was embedded within the fiberglass surface to improve visibility under various lighting conditions. Additionally, the gauges were standardized to a width of approximately 150 mm, ensuring legibility and structural resilience under typical field conditions.

Field implementation revealed structural variations at sluice locations, with two primary types identified: headwall-type and tower-type sluices. Headwall-type sluices, constructed directly within the tank bund (embankment), typically at the toe or near its base facilitated straightforward depth gauge installation. These structures are easily accessible from the bund throughout the year, regardless of the tank's water level, allowing installation and maintenance to proceed with minimal constraints.

In contrast, tower-type sluices are located within the tank bed, often at a significant distance from the bund, and are surrounded by water when the tank is full. This configuration presented considerable challenges for depth gauge installation. During periods of high-water levels, accessing the tower structure for installation was difficult and often unsafe. Conversely, in dry periods when the structure was exposed, the installed depth gauges were highly susceptible to damage, specially from wild elephants. These site-specific constraints revealed critical limitations in the original installation design and underscored the need for context-appropriate modifications to ensure the long-term durability and operational effectiveness of the water level monitoring system, particularly in tanks with tower-type sluices.

In the following phase, to address the issue of accessibility, construction difficulty due to water level and damage caused by wild elephants during dry seasons, reinforced concrete column posts were adopted as a protective and stable mounting solution for depth gauges as shown in Figure 2. These columns were constructed at strategically selected locations

within the tank bed. The height of each column was adjusted based on the required elevation of the corresponding depth gauge to ensure complete coverage of the operational water range. Notably, the zero level of the depth gauge was aligned with the Sluice Sill Level (SSL) during construction to enable accurate water level measurement. These columns provided a durable platform for mounting the manual depth gauges, enhancing structural stability and offering protection against wildlife-induced damage.

The footing size is 1.5 m x 1.5 m with the thickness of 0.5m and column size is 0.225 m x 0.225 m. Colum height is varying depending on the gauge height. Additionally, the column reinforcement includes four T10 bars and R6 stirrups spaced at 150 mm intervals. However, a significant limitation was that construction could only be carried out during dry periods, when water levels were sufficiently low to permit safe access. During periods of higher storage, submerged conditions and restricted access rendered the construction of concrete columns impractical.

Figure 2. Mounting the manual depth on concrete column at Indikatuwa Wewa, Trincomalee.

To overcome this constraint, the installation of steel column posts using pontoons was introduced as an alternative method for tanks with consistently high-water levels, where conventional concrete construction was not feasible as shown in Figure 3.

Figure 3. Steel depth gauge post installation: before and after

However, in some tanks—particularly those with tower-type sluices that retain substantial water levels year-round—even pontoon-based steel post installations proved impractical. In such cases, as this study ~~a~~dopted a more advanced solution, the deployment of automatic water level monitoring systems (Figure 4). This transition marked a significant evolution in the monitoring strategy, offering a non-invasive, continuous, and remotely accessible alternative to the traditional manual gauges.

Figure 4. Automatic water level monitoring system, Kumbuk Wewa

This system consisted of several integrated components tailored for field resilience and operational precision. A submersible level sensor, installed at the Sluice Sill Level (SSL), required a minimum submergence depth of 0.25 m to function effectively. The sensor was securely housed within a protective casing, mounted inside the sluice gate well to prevent physical damage. It operates with a supply voltage range of 6V to 40V, supports an operating pressure range of 0 to 5 bar (0~50m water) or 0 to 14 bar (0–140 meters), and functions within an operating temperature range of 0 °C to 50 °C. The rechargeable battery backup system is capable of maintaining operations for a minimum of 15 days with complete absence of solar power. A solar-powered digital display and GSM transmitter, enclosed in a waterproof housing, was mounted externally on the sluice gate structure.

The system captured water level readings at 5-minute intervals, with an accuracy of ±2 cm over a 5-meter range. These readings were transmitted hourly to a cloud-based server via 2G/4G GSM connectivity. Users could access real-time data and historical trends remotely through a mobile application, with the interface easily accessible *via* a QR code affixed to the display enclosure.

This automated monitoring approach provided several clear advantages. It enabled safe installation and uninterrupted operation in fully submerged or structurally inaccessible environments. The availability of accurate, high-frequency water level data greatly enhanced decision-making for irrigation scheduling, drought preparedness, and cascade-level water management. Furthermore, the system's low maintenance requirements, being solar-powered and remotely accessible, significantly reduced the need for frequent manual inspections and field visits. However, routine maintenance activities such as checking battery health, inspecting cable connections, and occasional sensor cleaning are still necessary to ensure optimal performance.

Introduction of this technology offered an important lesson in aligning monitoring methods with field realities, demonstrating that context-sensitive automation can significantly improve resilience and data reliability, particularly in complex and variable agro-ecological settings. Success of this intervention suggests strong potential for scaling automated monitoring solutions across similar small tank systems in Sri Lanka and other regions facing comparable climate and infrastructure challenges.

Conclusion

Based on field experience and technical insights gained during the CRIWMP project, the following conclusions are proposed as practical guidance for depth gauge installation in small tanks, particularly in the DZ of Sri Lanka (Table 2). The decision framework considers sluice type, site conditions, and cost-effectiveness to support informed planning and replication in similar settings.

Table 2. Recommended Depth Gauge Installation Approach

Sluice Type	Site Condition	Recommended Method
Headwall Type	Year-round accessibility; minimal structural or wildlife risk	Manual depth gauge mounted directly on sluice wall
	Exposed to wildlife damage during dry season (e.g., elephants)	Manual depth gauge mounted on reinforced concrete column constructed within the tank bed
Tower Type	Tank bed accessible during dry season; feasible to construct permanent structures	Manual depth gauge mounted on reinforced concrete column constructed within the tank bed
	Tank partially submerged; insufficient dry periods for concrete work	Manual depth gauge mounted on pre-fabricated steel post installed using pontoon access
	Permanently high-water level; structure submerged year-round	Automated water level monitoring system with submersible sensor and GSM-based telemetry

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Contract management adopted in the village irrigation systems upgrading – pros and cons

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Introduction

The Village Irrigation System (VIS) is a cornerstone of Sri Lanka's traditional agricultural landscape, particularly in the Dry Zone, where communities rely on small-scale reservoirs and canals to sustain paddy cultivation and secure livelihoods. These systems, many of which are centuries-old, serve as vital infrastructure for water storage and distribution during the bimodal rainfall seasons — *Maha* and *Yala*. Their functionality is central to local food security and climate adaptation.

Over the last seven years, a series of rehabilitation and upgrading initiatives have been undertaken to restore and improve the efficiency of VIS schemes across the country. These projects, primarily funded through donor-assisted mechanisms and implemented under national procurement procedures, aimed to modernize irrigation infrastructure, mitigate climate-related risks, and build institutional capacity for long-term water resource management.

The rehabilitation of VIS is inherently time-sensitive due to the need to coordinate project implementation between the conclusion of the Yala cultivation season and the start of the next Maha monsoon. This window—typically lasting only a few months—places significant pressure on surveying, designing, tendering, and construction processes. In certain cases, early dry-season interventions were also pursued for smaller tanks with limited water retention.

However, these efforts encountered numerous challenges. The outbreak of the COVID-19 pandemic severely impacted material supply chains and labour availability, while structural issues such as inadequate contractor capacity, staff shortages, and insufficient machinery further hindered progress. Some contractors failed to mobilize appropriately, often misusing advance payments or relying on hired resources that became unavailable due to regional demand. As a result, several contracts had to be terminated or extended, leading to cost escalations and community dissatisfaction.

These setbacks highlight the urgent need for improved contract management frameworks that accommodate climatic, logistical, and institutional realities. Effective contract execution in VIS projects requires more than just regulatory compliance; it demands precise

planning, realistic scheduling, proper contractor selection, adaptive management, and seamless coordination among all stakeholders. This paper aims to evaluate the contract management practices applied in VIS rehabilitation projects, assess their outcomes, and identify practical solutions to enhance project delivery, stakeholder satisfaction, and long-term system sustainability.

Methodology

A mixed-method approach was employed to assess the effectiveness of contract management practices in village irrigation systems (VIS) projects. Primary data was collected through structured interviews with VIS custodians (stakeholders), project engineers, contractors, and representatives of farmer organizations. In addition, secondary data sources—including contract agreements, financial progress reports, and implementation records—were reviewed for triangulation. Quantitative data was analyzed using basic statistical tools to identify recurring patterns, key performance indicators, and potential bottlenecks in the contract execution process.

Table 1. Analytical Focus across Project Phases

Project Phase	Key Aspects Analyzed	Indicators/Tools Used
Pre-construction Planning	Contractor selection, mobilization advances, scheduling	Review of tender evaluation reports, timeline analysis
Construction & Implementation	Machinery deployment, workforce availability, adherence to technical specs	Site progress records, statistical analysis of delays/cost overruns
Post-completion Monitoring	Defect liability compliance, community feedback, sustainability measures	Stakeholder interviews, satisfaction ratings, contract closure reports

Results and Discussion

The findings reveal that inadequate resource planning—particularly in manpower, machinery, and financial capacity—combined with weak enforcement mechanisms, were major contributors to project delays. Common issues included the unavailability of machinery due to contractors' commitments to multiple projects, insufficient engineering staff on-site, and the misallocation of mobilization advances, which were often diverted to unrelated activities.

The rigid nature of contract clauses proved to be a further obstacle during unforeseen challenges such as the COVID-19 pandemic. Several contracts had to be prematurely terminated due to non-compliance with engineering specifications and directives issued by the client. Feedback from local communities and farmer organizations indicated that many stakeholder expectations were unmet, largely due to unrealistic timelines and limited flexibility in project execution. Improvements were noted in cases where adaptive contract

management practices were implemented. These included revisiting contract terms, applying enhanced monitoring procedures, and selecting contractors with proven performance records and resource availability.

Contractor selection, as guided by the Construction Industry Development Authority (CIDA 2020) and national procurement guidelines, posed challenges in practice. While financial capacity, technical expertise, and access to equipment and skilled staff are the core evaluation criteria, in reality, the latter two were often not aligned with the documents submitted. Staff turnover and the hiring of temporary machinery significantly affected implementation. Notably, machinery shortages and breakdowns became pronounced during the dry season when demand peaked, contributing to further delays.

Moreover, project cost estimates increased significantly from approximately LKR 10–15 million before the economic crisis to LKR 20–40 million afterward. Fortunately, this escalation was partially mitigated by the project's funding structure, which was denominated in USD. Despite these adjustments, cost escalations added pressure to maintain timelines and quality under tight procurement and execution conditions.

These findings emphasize the importance of aligning contractor commitments with actual capabilities and enforcing stricter compliance checks during and post-award stages to enhance the resilience and timeliness of VIS rehabilitation efforts.

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Harnessing Artificial Intelligence for Climate-Resilient Water Management: A Concept Paper on IWRM in the Mahaweli Cascade

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Introduction

Sri Lanka possesses extensive water resources, comprising 103 river basins, ~2,539 reservoirs under the Irrigation Department, 71 reservoirs managed by the Mahaweli Authority, and ~14,400 minor tanks overseen by the Department of Agrarian Development. Climate change threatens these resources, necessitating Integrated Water Resources Management (IWRM) to balance socio-economic and environmental needs. Artificial Intelligence (AI), including machine learning (ML) and deep learning (DL), offers transformative tools to enhance IWRM, particularly in mitigating climate impacts within the Mahaweli Cascade.

Climate change is known to disrupt water systems. This is mainly through rising temperatures altering hydrological cycles, thus, reducing water availability (IPCC 2023), high-intensity rainfall causing flash floods, while droughts intensifying water scarcity (Rai 2023), water scarcities leading to over-extraction and reduced surface/groundwater threatening agricultural and domestic supplies, ecosystem degradation altering flows and water quality impairing aquatic biodiversity and ecosystem services, and socio-economic risks as water challenges and exacerbate food insecurity, health issues, and economic instability.

Artificial Intelligence (AI) enhances water management through different means. For example, ML models (e.g., Long Short-Term Management - LSTM) refining regional climate forecasts using satellite and sensor data, improving extreme event predictions (Liu et al. 2015), integrating IoT and remote sensing to track water quality, reservoir levels, and groundwater in real time (Mahardhika and Putriani 2023), AI-driven irrigation and smart grids reducing waste and ensure equitable urban water distribution, LSTM and CNN models outperforming traditional methods in predicting floods and droughts, e.g., Google's flood forecasting using Earth Engine (Rai 2023), and synthesizing hydrological, meteorological, and land-use data to optimize water allocation and environmental sustainability (Krishnan et al. 2025) are some noteworthy results of using AI for eater management.

Integrated Water Resource Management (IWRM) coordinates water, land, and resource management for equitable, sustainable outcomes. AI enhances IWRM through digital twins

for basin modeling (Yang et al. 2024) and real-time decision support, e.g., SCADA systems in the Mahaweli Cascade. AI also aids site selection for dams and salinity barriers using 3-arc DEM and hydrological data, addressing water scarcity and salinity intrusion. This paper investigated AI-driven IWRM strategies, focusing on generative AI and LSTM-based Decision Support Systems, to enhance sustainable water management in the Mahaweli Cascade under climate change pressures.

Methodology

This study employed a systematic qualitative review, synthesizing findings from prior research on AI-based water resource management systems. The concept paper proposes integrating hydrodynamic model outputs with deep learning models, such as Long Short-Term Memory (LSTM) networks, to enhance decision-making in Integrated Water Resources Management (IWRM) (Xue et al. 2022). The methodology included (a) **Literature Review** to analyze global and regional studies on AI applications in IWRM, focusing on flood forecasting, water allocation, and infrastructure planning. (b) **Data Integration**: Combining hydrological, meteorological, and socio-economic data (e.g., 3-arc DEM, salinity maps) to train AI models for the Mahaweli Cascade, (c) **Model Development**: Developing LSTM-based Decision Support Systems (DSS) to optimize reservoir operations and site selection for dams and salinity barriers, and (d) **Scenario Analysis**: Simulating management scenarios to evaluate AI-driven IWRM strategies under climate change conditions. The AI implementation methodology is illustrated in Figure 1.

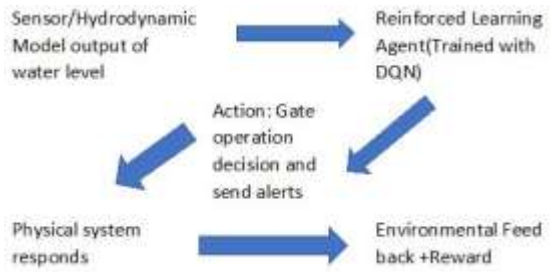

Figure 1. AI implementation methodology

Results and Discussion

Sri Lanka, a tropical island nation, faces heightened vulnerability to climate change, including rising temperatures, erratic rainfall, sea-level rise, and increased frequency of floods and droughts. These impacts challenge water resource management, particularly in the Mahaweli Cascade (Figure 2), Sri Lanka's largest river basin system. The Nilwala and Ambatale salinity barriers exemplify conflicting demands between drinking water supply and flood management, underscoring the need for IWRM. The AI applications in the Mahaweli Cascade, including but not limited to, are presented in Table 1.

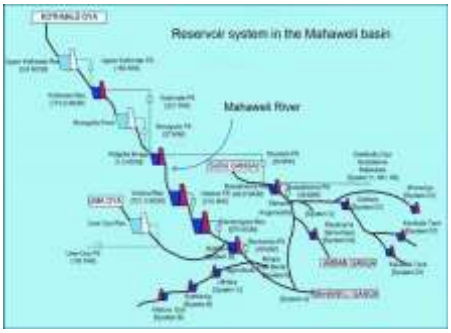

Figure 3. Mahaweli Cascade

Table 1. The AI applications in the Mahaweli Cascade

Application	Description
Reservoir Optimization	The Dam and Reservoir Control Centre (DRCC) of the Mahaweli Authority collects real-time data (e.g., reservoir levels, downstream discharge, weather) from stations like Kotmale, Polgolla, Victoria, and Moragahakanda. AI models, such as Fuzzy Logic Control (FLC) and LSTM, optimize dam operations for water release and power generation (Ehelapitiya and Dias n.d.; Ekanayake et al. 2021)
Flood Forecasting	LSTM-based models enable accurate flood predictions, leveraging Global Satellite Mapping of Precipitation (GSMAP) data (Nimanthika n.d.).
Infrastructure Planning	AI analyzes topographic (e.g., 3-arc DEM) and hydrological data to identify optimal sites for dams and salinity barriers, addressing water scarcity and saltwater intrusion
Digital Twins	The Water-Energy-Budget Rainfall-Runoff-Inundation (WEB-RRI) model supports continuous river basin simulations, paving the way for AI-driven digital twins (Illangasingha 2024).

These applications position the Mahaweli Cascade as an ideal candidate for AI-driven IWRM, enhancing resilience to climate change impacts.

Conclusions

Climate change poses escalating challenges to water resource management in Sri Lanka, necessitating innovative solutions. AI-integrated IWRM offers transformative potential for the Mahaweli Cascade, an ideal testing ground for advanced water management strategies. By leveraging deep learning models (e.g., LSTM), digital twins, and real-time Supervisory Control and Data Acquisition (SCADA) systems, AI can optimize water allocation, enhance flood forecasting, and guide infrastructure planning, such as dam and salinity barrier placement. Continued efforts are needed to pilot AI-driven IWRM projects in the Mahaweli Cascade, foster capacity building, and establish global partnerships with successful IWRM frameworks, such as the Murray-Darling Basin. Collaborative implementation of such

strategies can mitigate climate change impacts, ensuring sustainable and equitable water resource management.

Acknowledgement

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The participation of Civil Society and Local Institutions in Rehabilitating Village Irrigation Systems: Lessons from CRIWMP

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Introduction

Minor irrigation systems—commonly referred to as "village tanks"—are vital to the agricultural economy of Sri Lanka's dry zone. These tanks not only provide essential irrigation but also function as community-managed assets deeply embedded in the social, cultural, and environmental life of rural communities (Panabokke 2009). Ensuring their long-term sustainability, however, requires active and sustained stakeholder engagement throughout all phases of rehabilitation—from planning to operation and maintenance.

Stakeholder participation has emerged as a key success factor in tank rehabilitation initiatives across the country. Involving a range of actors—including local communities, Civil Society Organizations (CSOs), Farmer Organizations (FOs), and technical agencies—has enhanced water governance, built resilience, and strengthened rural livelihoods.

Community knowledge of local climate, agriculture, and water use is invaluable in designing realistic and context-specific interventions. When community members participate in decision-making, it fosters a sense of ownership, encourages long-term commitment, and enhances infrastructure sustainability. Open dialogue during planning and implementation also helps resolve potential disputes over water sharing, land use, and maintenance responsibilities early on. Equitable participation—particularly of women, smallholder farmers, and marginalized groups—ensures fair distribution of benefits.

Rehabilitating these tanks is inherently complex due to the involvement of multiple stakeholders. In addition to farming communities and FOs, several government agencies such as the Department of Agrarian Development (DAD), Central and Provincial Irrigation Departments play key roles. The ecological, historical, and cultural importance of many tanks also brings in agencies like the Departments of Wildlife, Archaeology, Environment, and Agriculture (Madduma Bandara 1985). As a result, field officers often navigate varied and evolving situations that require adaptive strategies. Documenting these diverse experiences is essential for capturing practical insights, informing best practices, and enhancing future interventions.

While much of the existing literature emphasizes technical and infrastructural outcomes, there is relatively little attention paid to the process-oriented dimensions of rehabilitation—such as capacity building, institutional coordination, and long-term system performance. Field-based evidence on what makes stakeholder engagement truly meaningful and effective is also limited. In particular, little is known about how stakeholder roles and participation evolve across the different stages of project implementation.

This study seeks to address these gaps by examining stakeholder engagement in the rehabilitation of village irrigation systems under CRIWMP in Sri Lanka's Kurunegala District. Based on 324 documented events spanning the planning, implementation, and post-rehabilitation phases, it explores participation patterns, institutional roles, and their collective contribution to equitable and sustainable tank governance. Further this study explains the stakeholder involvement in CRIWM project, how the stakeholders were engaged throughout the project cycle, their roles, the process adopted to engage them, and how this involvement will guarantee long-term sustainability. During the study the proper models identified as successful stakeholder interventions in different contexts were documented for future learning.

Methodology

This study examined stakeholder engagement in the rehabilitation of four cascades under the CRIWMP in the Kurunegala District of Sri Lanka. It drew on a dataset of 324 documented events from 2018 to 2024, maintained by the Sri Lanka Red Cross Society. Events were categorized into planning, implementation, and post-rehabilitation phases to assess participation trends. Key stakeholders—including community members, Farmer Organizations (FOs), Civil Society Organizations (CSOs), government officers, and technical agencies—were analyzed in terms of their roles, coordination mechanisms, and contributions across phases. Quantitative data on attendance and demographics were complemented by qualitative insights from meeting records to evaluate the quality, inclusiveness, and sustainability of engagement. Special attention was given to gender and youth participation, as well as the role of the CSO-led monitoring system in ensuring transparency and continuity throughout the project.

Results and Discussion

A total of 324 events have been conducted across three major phases, namely, planning (113 events, 35%), implementation (137 events, 42%), and post-implementation (74 events, 23%). This distribution reflects a comprehensive approach that addresses the entire project lifecycle, with a notably balanced emphasis on each stage. In comparison, past minor tank and irrigation rehabilitation projects often show a less even distribution, where planning activities typically constitute only 20–30% of total events, while implementation dominates with 50–60%, and post-implementation monitoring and maintenance receive limited focus, often just 10–20% (Meinzen-Dick 2007; Shah and Van Koppen 2006). The relatively higher proportion of planning events in this project suggests

a stronger commitment to thorough preparatory work and stakeholder engagement early on, which is critical for effective design and coordination. Equally significant is the post-implementation phase, where this project's 23% share of events surpasses the usual low engagement levels found in many previous initiatives.

The CRIWMP project has maintained sustained post-rehabilitation participation through diverse activities such as grievance meetings related to soil and land issues, awareness sessions on operation and maintenance (O&M) equipment and fund management, distribution of IT and O&M equipment to local agrarian and farmer organizations, as well as community and divisional validation meetings, cascade water management committee meetings, and seasonal stakeholder gatherings. These deliberate and structured engagements align with best practices documented in the literature, emphasizing that continued post-project involvement is critical for securing the long-term functionality and resilience of rehabilitated water infrastructure (Ratner et al. 2013; FAO 2017). Overall, the distribution of events and the emphasis on post-implementation activities demonstrate a holistic project approach that balances construction with thorough planning and sustained follow-up, thereby enhancing sustainability and adaptive management of minor tank systems.

The participation data shows that several key stakeholders have consistently demonstrated commitment to rehabilitation efforts. The CSOs have participated in effectively in all events (100% in planning, 99% in implementation, and 97% in post-rehabilitation). Similarly, the FOs and other community actors remained actively engaged across all stages, reflecting deep-rooted interest, ownership, and trust in the process. Agriculture Research and Production Assistants (ARPAs), PMU and *Grama Niladharis* (GNs) exhibited increased participation over time, especially post-rehabilitation. This points to their growing role in supporting sustainability and linking tank systems to broader development goals. The implementation stage recorded the highest overall participation across most stakeholder types. This reflects strong project coordination, field mobilization, and the operational commitment of both institutional and community actors.

In planning, implementation and post-rehabilitation, participation of ARPAs were at 68%, 72%, 84%, and GNs at 28%, 41%, 42% of the events, respectively (Figure 1). This demonstrated increasing involvement of those officers over time—an encouraging sign of capacity strengthening and adaptive responsiveness. This trend suggests growing institutional alignment and a strengthening of local governance capacity to support long-term sustainability. Their connection to farming communities and familiarity with local contexts made them key enablers in both implementation and post-rehabilitation stages

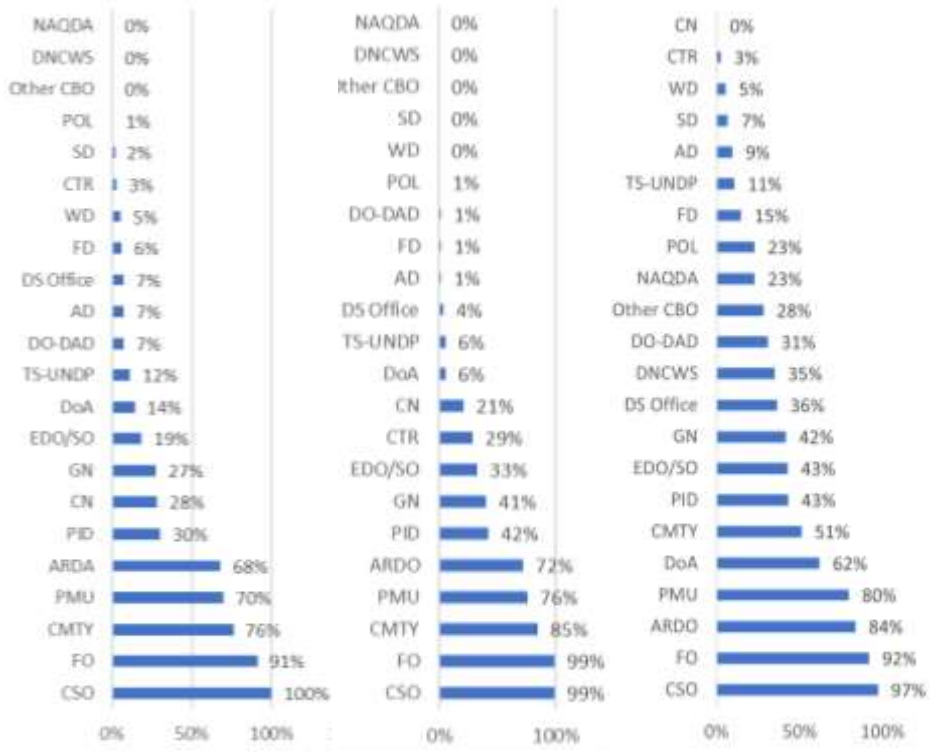

Figure 1. Stakeholder attendance during initial Planning Activities (A), initial Implementation Activities (B) and during Post-Rehabilitation Activities. NAQDA – National Aquaculture Development Authority, DNCWS – Department of National Community Water Supply, CBO – Community-based Organizations, POL – Police, SD – Survey Department, CTR – Contractor, WD – Department of Wildlife Conservation, FD – Forest Department, DS Office – District Secretariat Office, AD - Department of Archaeology, DO-DAD – Divisional Officer of the Department of Agrarian Development, TS-UNDP – Technical Specialist of the United Nations Development Programme, DOA – Department of Agriculture, EDO/SO – Economic Development Officer/*Samurdhi* Officer, GN – Grama Niladhari, CN – Consultant, PID – Provincial Department of irrigation, ARPA – Agriculture Research and Production Assistant, PMU – Project Management Unit, CMTY – Community, and FO – Farmer organizatin

The CSO-led Monitoring & Evaluation (M&E) mechanism emerged as a pioneering model throughout the CRIWMP implementation across all seven districts. It consistently operated during the entire project period and was widely acknowledged by stakeholders for its effectiveness and credibility.

Further, it has enabled consistent, transparent, and structured documentation of events across all phases. The presence of CSOs at every stage has helped ensure community representation, information sharing, and timely feedback, thereby contributing to greater local ownership. The Project Management Unit (PMU) sustained steady involvement

across all phases (70% in planning, 76% in implementation, and 80% during post-rehabilitation), reflecting its central coordination role.

The data indicated low participation from technical agencies such as the Wildlife Department (5%), and Forest Department (6%) during the planning stage (Figure 1). This does not necessarily reflect a policy or procedural shortcoming. The current project framework already mandates clearances from all relevant departments for each rehabilitation activity. In practice, however, the relatively low engagement from some agencies in the selected districts can be attributed to the location of the tanks—most of which were situated outside forest reserves, archaeological zones, or ecologically sensitive areas—thereby reducing the necessity for intensive involvement from Departments like Forest, and Wildlife Conservation.

A number of technical departments—such as the Department of Wildlife Conservation, Forest Department, and Archaeological Department—participated in select events. By proactively involving these agencies during the planning phase, future projects can benefit from more robust site assessments and streamlined approvals, especially in environmentally sensitive areas.

The Divisional Secretariat and PMU played steady roles throughout the project cycle. Strengthening formal multi-stakeholder platforms at divisional and provincial levels could enhance dialogue, reduce duplication, and support integrated planning, particularly when scaling these efforts across districts. While post-rehabilitation engagement showed a natural decline, the presence of ARPAs, GNs, and community actors highlights a strong base to build a sustainability-focused follow-up system.

Establishing district-level Multi-Stakeholder Coordination Committees is essential to formalize collaboration among implementing agencies, community actors, and technical departments, thereby enhancing planning coherence and responsiveness to field-level challenges. In the current project, this approach has already taken shape through the successful initiation of Cascade Management Committees, which convene every two months following the rehabilitation of each cascade. These committees, chaired by the Divisional Secretary and inclusive of all relevant line agencies, serve as a crucial coordination mechanism, especially during the post-rehabilitation phase. Their structured format has helped bridge the typical gaps in follow-up engagement, which are common in similar projects. As a result, the project has achieved notably higher post-rehabilitation stakeholder participation compared to conventional conditions, supporting better maintenance, monitoring, and adaptive management of rehabilitated systems. This experience underscores the potential of localized coordination structures in sustaining long-term outcomes and fostering institutional accountability.

High-engagement partners such as FOs and CSOs should be formally recognized and supported for their vital contributions to the success of VIS rehabilitation. In the CRIWMP project, farmer participation was particularly significant, with many individuals investing substantial time and effort—often at the cost of their regular livelihoods. Acknowledging this, the project took proactive steps to develop the capacity of Farmer Organization

leaders and selected farmers to serve as local resource persons for future interventions. These individuals were provided with targeted training in irrigation management and tank rehabilitation, along with modest benefits to incentivize their continued involvement. This approach not only honors their contributions but also lays the groundwork for long-term sustainability by embedding technical and leadership capacity within the community itself. Moving forward, similar strategies—such as performance-linked micro-grants, peer-to-peer training models, and scheduling activities at times that do not disrupt farmers' work—can further strengthen local ownership and ensure that project benefits endure well beyond the implementation period.

The CRIWMP project has already taken important steps in this direction by developing the leadership capacity of Farmer Organization leaders and training selected farmers in irrigation management and tank rehabilitation. These individuals were provided with basic incentives and are now positioned to act as community-based trainers and resource persons in future interventions. This strategy not only empowers local stakeholders but also embeds critical technical knowledge within the community—an essential factor for long-term sustainability. Institutionalizing such roles across similar projects can enhance peer learning, reduce dependency on external actors, and strengthen post-project resilience.

The increasing involvement of environmental departments and surveyors provides a strong foundation for more integrated and ecologically sound planning. Introducing early-stage checklists and joint clearance procedures can streamline approval processes while ensuring that vital environmental safeguards are upheld. The monitoring system implemented under this project offers a valuable model for replication in other water and climate-related initiatives across Sri Lanka and beyond. Key features include: (1) comprehensive longitudinal data that supports trend analysis and adaptive management; (2) standardized formats across districts and time periods, enabling transparency and comparability; (3) community-driven monitoring, which fosters trust and improves data accuracy; (4) coverage of all three project phases—planning, implementation, and post-rehabilitation—for a holistic view; and (5) integration of both technical experts and local communities, enhancing on-the-ground problem-solving.

Importantly, the CRIWMP project, in partnership with the Sri Lanka Red Cross, has maintained a consistent seven-year database containing detailed event sheets and reports. These records include participant breakdowns by stakeholder type—such as officers and farmers—and have proven critical for analyzing participation patterns over time. The use of a unified reporting format has demonstrated significant value in supporting future project design and evaluation. However, some activities conducted by government agencies (e.g., forest visits or progress review meetings) were not always captured in this centralized system. This gap underscores the need for a formalized policy to ensure that all implementing agencies and stakeholder groups share attendance records, activity reports, and lessons learned. Such a policy would improve institutional learning, enable more robust stakeholder analysis, and contribute to the effectiveness and accountability of future development efforts.

Given the strong community turnout and consistent participation across project phases, future initiatives have a valuable opportunity to build on this foundation by further empowering women, youth, and marginalized farmers. Unlike many earlier studies, this analysis took a gender-sensitive approach, examining 286 community events and 168 officer events to better understand inclusive participation.

Encouragingly, women made up over 35% of total community participants (3,025 out of 8,575) and 34% of officer participation (859 out of 2,525), indicating a meaningful level of engagement across both groups. Youth and persons with disabilities were also represented, albeit in smaller numbers, highlighting the importance of designing more targeted outreach in future efforts.

These findings show a promising shift toward more inclusive engagement. By strengthening women's roles in water user groups, leadership positions, and training programs, future projects can deepen community ownership and ensure that diverse voices continue to shape decision-making. Proactive gender integration and inclusive participation strategies will be essential for sustaining momentum and maximizing long-term impact.

Conclusion

The CRIWMP minor tank rehabilitation project stands out for its balanced, inclusive, and sustainability-focused approach, with well-distributed efforts across planning (35%), implementation (42%), and post-rehabilitation (23%) phases. Unlike many previous projects that concentrated heavily on construction, CRIWMP emphasized early stakeholder engagement and strong post-project follow-up. High levels of participation from CSOs, FOs, and local officers (ARPAs and GNs), along with a CSO-led monitoring model, ensured transparency, accountability, and community ownership. Post-rehabilitation activities such as grievance resolution, training, and regular cascade-level meetings further strengthened long-term functionality and governance. The project also demonstrated significant progress in gender and social inclusion, with over 35% female participation and efforts to involve youth and marginalized groups. Moving forward, future projects should replicate this lifecycle-based model, institutionalize local coordination platforms, expand community leadership roles, formalize monitoring and data-sharing systems, and enhance early environmental planning. These practices can help ensure that minor tank rehabilitation efforts are not only technically sound but also socially rooted, resilient, and sustainable.

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Assess the Benefits of Small Tanks Rehabilitation Programs on Socio-Economic and Institutional Perspectives in Dry Zone of Sri Lanka: A case at the Sivalakulama Cascade in Anuradhapura District

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Introduction

Water has long played a foundational role in shaping human civilizations, fostering agricultural societies, and enabling economic and cultural development (Azategui 2021). From early human settlements in river valleys such as the Nile and Indus, to highly organized irrigation systems in Asia, water access and management have been central to societal growth (OLDEST.ORG 2019; Mukherji et al. 2009). Sri Lanka is no exception; its ancient civilization also evolved along river basins, notably beginning with the settlement of Prince Vijaya along the Malwatu Oya in the 6th century BCE (Withanachchi 2018). Over time, this led to the development of an intricate and sustainable irrigation infrastructure that remains vital today.

The hallmark of Sri Lanka's ancient water management is the tank cascade system. Derived from the Portuguese word *tanque*, the local term *wewa* refers to human-made reservoirs. These tanks, built in a series within micro-catchments, store and manage rainwater from seasonal rivulets. The systems are referred to as "tank cascades"—a sophisticated and integrated network of small to large tanks designed for irrigation, domestic use, livestock, fisheries, and ecological stability (Madduma Bandara 1985). These structures are primarily located in Sri Lanka's dry zone, where average rainfall is around 1,750 mm and high evaporation causes frequent water shortages.

Sri Lanka's dry zone, covering the North Central, Northern, Eastern, and Southern provinces, experienced a remarkable transformation due to this hydraulic civilization. By the 12th century BCE, the country had already established over 10,000 tanks, many of which remain functional. These irrigation systems supported a predominantly agrarian society that relied on rainwater harvesting during the *Maha* season. The economic and ecological sustainability of this system is evidenced by its longevity and capacity to balance multiple water-dependent functions, including agriculture, animal husbandry, and wetland biodiversity (Madduma Bandara 1995).

The development of the tank cascade system was largely driven by royal patronage. Kings such as Wasabha (67–111 AD) initiated medium-scale irrigation projects, while King Mahasen (274–301 AD) expanded them significantly. The golden era of irrigation occurred under King Parakramabahu I, who constructed hundreds of tanks, canals, and sluices and institutionalized their maintenance (Withanachchi 2018). These monarchs not only built the

infrastructure but also established administrative systems to ensure its upkeep, reflecting a highly advanced understanding of water governance for that era.

Despite this legacy, modern challenges threaten the effectiveness and sustainability of the tank cascade system. A pivotal moment came in 2018, when the World Food Programme recognized Sri Lanka's ancient tank cascades as a World Heritage Agro-ecological Site (FAO 2018). This led to renewed interest and significant investment from government, NGOs, and the private sector in rehabilitating these systems to improve climate resilience and agricultural productivity, particularly for smallholder farmers in the Dry zone. However, the current rehabilitation efforts raise critical concerns. Observations from cascade systems in regions like Anuradhapura reveal mixed outcomes. While there is evidence of increased cropping intensity, issues such as ecosystem degradation, land-use irregularities, and inefficient water management continue to persist. These issues stem from several underlying factors, including a shift from ecological to commercial farming, external economic pressures, poor community awareness, and weak governance systems. As a result, the intended outcomes of enhanced productivity and environmental sustainability are not being fully realized.

This context points to a clear research gap as there is insufficient empirical evidence assessing the tangible social, economic, and environmental benefits delivered to communities through these rehabilitation efforts. Furthermore, there is limited analysis on whether the existing governance and operational models are suited to address contemporary challenges in water resource management in the dry zone.

Given the above issues, the study was designed to investigate the research problem, "Do the beneficiaries of small-scale tank rehabilitation programs achieve the expected improvements in living conditions, including social, economic, and environmental outcomes? To explore this overarching problem, the study focuses on three key research questions: (1) What are the social, economic, and environmental benefits received by settlers from cascade rehabilitation programs? (2) What alternative approaches can be considered to enhance the effectiveness of future cascade rehabilitation initiatives? and (3) What challenges do current cascade rehabilitation programs face in meeting the expectations of local communities? This research aims to bridge the gap between infrastructure development and meaningful community-level outcomes, providing insights that can inform more inclusive and sustainable water management policies in Sri Lanka's dry zone.

Methodology

The selected study site was the Sivalakulama tank cascade in the Anuradhapura District of Sri Lanka, where all 20 small irrigation systems have been recently rehabilitated. This area was chosen due to its diversity in farming practices, community structures, and recent comprehensive rehabilitation interventions.

Probability sampling method was applied in this study while stratified sampling technique in this study ensured more precise conclusions by ensuring that every subgroup is properly represented in the sample. The sample includes 73 participants (approximately 5% of the farming population across three *Grama Niladhari* Divisions), selected to reflect demographic and livelihood diversity.

A mixed data collection method was used. Primary data were collected through pre-tested structured questionnaires, key informant interviews (KIIs), focus group discussions (FGDs), and direct observations. Analysis methods such as scaling, frequency analysis, and perception tracking were used to gather insights into water management, ecosystem improvements, agricultural productivity, and social well-being. Secondary data were sourced from government offices, seasonal agricultural reports, and satellite imagery to analyze historical patterns, cropping intensity, land use, and tank catchment changes.

Data analysis involved both descriptive and inferential methods, including frequency distributions, averages, and stakeholder perception analysis, to evaluate the overall performance and sustainability of the rehabilitation initiative. Data analysis done by MS Excel Software.

Results and Discussion

Downstream paddy cultivation

Tank rehabilitation programs generate diverse benefits to the economy of the settlers and the environment. Increased water storage capacity led to increase crop yields, especially for other field crops in the third season by water management. Thus, cropping intensity of rehabilitated tanks increased from 0.9 to 1.4, which has led to increase income of the farmers which is a major benefit as results of tank rehabilitation. Under the tank rehabilitation, removed limited quantity of sediments would help to increase water capacity in the tank while managing water for paddy cultivation thus farmers enable to cultivate more acres of paddy in the *Yala* season.

Downstream other field crops

Due to the water saving and agro-met advisories which have been provided under the tank rehabilitation program, farmers promoted to cultivate additional (third) season. Famers in this cascade have been received seeds and agriculture extensions to third season resulted to earn additional income.

Upland cultivation

The multi-dimensional approach in the cascade development process, the rehabilitation of rural irrigation systems and the promotion of climate-smart agricultural practices have led to a new trend in commercial agriculture in the area. This includes introducing farming techniques in protected houses, using drought-resistant seed varieties, implementing water management practices, introducing perennial crop verities, and establishing market linkages. Several interventions were introduced for upland agriculture to enhance tank catchment ecosystem characteristics. Introducing long-term perennial crops in the tank

catchment resulted in a significant increase in green cover and a reliable source of income for farmers.

Commercial agriculture

Although commercial agriculture is carried out on a large scale in cascade areas, it has had a detrimental impact on the ecosystem. The widespread use of chemical fertilizers and agrochemicals, as well as illegal encroachments, land use, and land preparation practices, have contributed to this negative impact. Cascade rehabilitation program has stepped in to provide the necessary inputs, training, and technology to support more sustainable and responsible commercial agriculture practices in the region. The program has also contributed to enhancing the ecosystem in the tank catchment areas. It has helped to control soil erosion, recharge groundwater, and increase green cover. Overall, the tank rehabilitation program in Sivalakulama.

Social Connections

The program has created opportunities for community engagement and participation in rehabilitation works and tank operation and maintenance. Additionally, farmers in the area have had the chance to participate in varies capacity-building training, allowing them to share their experiences and knowledge with each other. This has resulted in better relationships between farmers and government officials, leading to improved services for the community.

Overall benefits

In summarizing the overall result of the rehabilitation program of Sivalakulama cascade system, its overall socioeconomic and environmental benefits can be analyzed as follows.

Economic benefits: The study confirms that significant economic benefits can be achieved through the rehabilitation of village irrigation systems. In particular, as a result of promoting downstream water management practices in paddy cultivation and climate-smart agricultural practices among farmers, the cropping intensity has increased from 0.9 to 1.4. Consequently, the paddy yield per acre has risen from about 60 to 98 bushels, leading to an approximate 30% increase in income.

Furthermore, farmers who adopted water management practices were able to cultivate other field crops (OFC) during a third season, which further enhanced their income, while the use of climate-smart farming practices reduced input costs. The study also revealed that the gradual shift of farmers from seasonal and short-term crops to long-term perennial crops has contributed to increase and sustain household income level.

Social benefits - According to the results of the study, the social benefits gained from this project remained at an average level. However, it appears that as a benefit of the project's social mobilization process, this has provided an opportunity to build social connectivity among different communities. These interactions fostered relationships between various groups and institutions, improving access to quality services and creating sustainable collaborative initiates. Communities have also engaged in making decisions in water

management at local level participating at “Seasonal Meeting” at village, particularly women engaged in water sharing and disseminating agro-met advisories. It's noteworthy that women were actively engaged in construction monitoring during the tank rehabilitation process and ecosystem development.

Environmental impacts - According to the findings revealed in the study, attention has been given to the conservation, enhancement, and development of ecosystems during the process of cascade rehabilitation program. Accordingly, activities such as the development of interceptor, establishment of forest plantations and agroforestry in catchment areas, soil conservation, removal of invasive species, desilting, groundwater recharge, and aquaculture have been carried out. Observations indicated that these activities have contributed, to some extent, to the provision of ecosystem services. For instance, as a result of developing the tank interceptor, salty water in the downstream areas is regulated. Similarly, due to the establishment of upstream soil bunds that control erosion and tank sediments, proper water levels in the tank are maintained. Agroforestry provided food for both animals and humans, and also supported carbon sequestration. However, it was noted that sufficient time needs to be allowed for a proper evaluation of ecosystem services.

Knowledge Transfer - As part of rehabilitating the tank cascade system, farmers received training on ecological agriculture, leading to both environmental and economic benefits. Previously, due to lack of knowledge and understanding about climate change, the rural community was not sensitive about it. However, through effective mobilization programs, farmers have been motivated to adapt to the changes caused by climate change.

Institutional Development - The active participation of both public institutions and private organizations in the cascade rehabilitation program has led to a more effective organizational structure. This eliminated inefficiencies in traditional government service delivery approaches in the agriculture and water management sectors. Farmer organizations in the project location improved their capacity for tank operations, maintenance, and water management, resulting in a sustainable village irrigation system. The government has improved agriculture technology and services in agriculture during the tank rehabilitation process which was a significant change made by the project.

Challenges

The future rehabilitation of tank cascades faces several challenges. Engaging farmers in restoration efforts is difficult due to their limited participation in recent programs, which has diminished trust and enthusiasm. Many rehabilitation efforts have lacked effectiveness and efficiency, further discouraging community involvement. Village-level irrigation system maintenance also suffers due to poor financial management and weak performance by farmers' organizations, hindering proper operation and upkeep. Additionally, transitioning to climate-smart agriculture is challenging, as traditional, inefficient water management practices persist. The gap between government officials and farmers in terms of water governance and collaboration adds complexity to managing future water crises. Lastly, preserving traditional knowledge, values, and control mechanisms is increasingly difficult in

the face of rapid social change and modern behaviors. Balancing heritage with innovation remains a pressing concern in sustaining these ancient systems.

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Dam Safety Concerns of Sri Lanka in the Light of Climate Change: A review

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Introduction

Sri Lanka's dam network consists of about 350 medium to large dams and over 12,000 small dams and, according to the classification by the International Commission on Large Dams (ICOLD), 80 are large structures (Fernando 2008). Currently, the ownership and responsibility for dam operation remains with various organizations ranging from farmer organizations through provincial councils to national level organizations such as the Irrigation Department, Mahaweli Authority and Ceylon Electricity Board. Irrigation Department holds the responsibility for the majority of the dams and acts as the main body for dam safety management in the country. This extensive dam network plays a pivotal role in the country's socio-economic development, supporting irrigated agriculture, hydro power generation, water resource management and flood control (Kamaladasa 2020).

Despite the substantial social and economic benefits of dams, ensuring the safety of dams in the face of extreme climate events such as high intensity rainfall and prolonged drought has been an emerging concern (Ginige et al. 2022; Siriwardana 2024). Notably, the majority of the dams in the country, particularly those built in the ancient era, face significant challenges in withstanding climate extremes in the present due to structural ageing (Perera et al. 2021). Consequently, enhancing dam safety in the country has become a major concern and a timely responsibility of governing authorities (Attewill et al. 2004). In this context, this review paper is developed based on existing literature related to dam safety management in Sri Lanka. The objective is to review crucial dam safety concerns in Sri Lanka while identifying the vulnerabilities of dam infrastructure to extreme climate events. By addressing these critical concerns while drawing insights from the historical experiences, the ultimate aim of the study is to strengthen disaster resilience of Sri Lanka's dam infrastructure in the light of climate change.

Methodology

The present study adopted literature review as the methodology, wherein the referred literature includes local and international dam safety guidelines, research studies on proactive dam safety management practices under climate change impacts, and scholarly articles related to dam safety concerns in Sri Lanka spanning the last 25 years. The insights

and recommendations drawn from the reviewed literature were pivotal in shaping the outcomes of this review.

Critical Concerns Related to Dam Safety in Sri Lanka

While the country's ancient irrigation systems are historically admired, critical concerns persist in the present regarding safety and resilience of our dam infrastructure. In this paper four major concerns, namely ageing of dams and related structural deficiencies, reservoir sedimentation, cascade system effects, and challenges from extreme rainfall events, are discussed referring to the literature while drawing insights from the historical experiences.

Ageing of Dams and Related Structural Deficiencies

The majority of the dams of varying scale in Sri Lanka are earthen embankment dams and notably, almost all of these dams might have surpassed their effective life span. In fact, the ancient reservoirs built in the Anuradhapura-Polonnaruwa era have existed for centuries while being subjected to challenging climate extremes (Kamaladasa 2020). As should be anticipated, the majority of these ancient dams demonstrate structural deterioration (Attewill et al. 2004).

Most are suffering from seepage issues including major dams such as Kalawewa, Giritale, Minneriya, and Parakrama Samudraya, etc (Liyanage et al. 2025). Over time, earthen dams tend to develop preferential seepage paths leading to piping and ultimately structural failure. Notably, the majority of the earthen dams in Sri Lanka exhibit heavy tree growth in the downstream slope which can elevate potential piping initiation and compromise the structural integrity of the dam (Dai et al. 2024). Kantale Dam failure (Figure 1), which is considered as the most severe dam failure in Sri Lanka's recent history, is a realistic illustration of seepage-induced dam failure and a crucial reminder of the importance of periodic inspection, regular monitoring and maintenance. The catastrophic breach of Kantale Dam in April 1986 made a heavy toll, reporting 130 lives lost, complete destruction of nearly 600 private and government buildings, partial damage to another 630 buildings, substantial damage to agriculture, and washed away roads and other infrastructure (Kamaladasa 2020).

The seepage issues not only intensify the potential risk of dam failure but also impel the dam owners to maintain the water level significantly lower than the Full Supply Level (FSL), resulting in reduced effective storage capacity of the reservoir, which negatively affects the ability to meet agricultural water demand (Dolage et al. 2012; Liyanage et al. 2025). Usgala Siyamabalangamuwa, Thissa Wewa, Samanalawewa and Giritale are a few of the reservoirs which have been heavily suffered from this issue. For instance, Liyanage et al. (2025) in their study highlighted that around 210 acres of possible annual irrigable area is lost because of the existing seepage issues in Thissa Wewa. According to Dolage et al. (2012) and Liyanage et al. (2025), the water level of Vendarasankulam reservoir has been maintained at a 10 m head which is far below the FSL, and at a loss of 6000 acre-feet storage capacity, due to the excessive seepage issues observed in the earthen embankment dam.

Figure 1: Kantale Dam Breach in 1986 (International Water Power, 2008)

Structural deficiencies can also take the form of impaired mechanical integrity of the dams (Samarajiva et al. 2005). Mainly, sluice gate and spilling mechanism malfunctions become increasingly common as dams age. For example, gate mechanism malfunctions were experienced in Nachchaduwa and Rajanganaya reservoirs in the past, which could have led to severe consequences if not properly attended to (DSWRPP 2008). Most recently, following the heavy rainfall in January 2025, the earthen dam of Aluthdiwulwewa tank in Anuradhapura faced an emergency situation where the sudden influx led to significant stress on the tank bund resulting in a major piping scenario in the vicinity of the sluice gate (Sri Lanka Mirror 2025). The situation escalated to the point where the bund was at risk of collapse, prompting urgent interventions and immediate evacuation of downstream residents. Therefore, ageing of dams has been a critical concern and a major setback for enhancing dam safety in the country, as it amplifies the risk of potential dam failures during extreme climate events.

Reservoir Sedimentation

Reservoir sedimentation related effective storage loss has raised serious concerns relevant to efficient dam operation and maintenance in Sri Lanka (Attewill et al. 2004). Intensified rainfall patterns likely influenced by climate change and inappropriate land use practices such as deforestation, intensive agriculture, and irresponsible constructions have accelerated soil erosion and thus increased sediment runoff into the reservoirs (Yasanga and Dilantha 2019). For instance, Rantambe Reservoir in the Uma Oya catchment which is severely affected due to sedimentation has lost about 45% of its effective storage over its 34 year life span (Yasanga and Dilantha 2019). The majority of the rural tanks in Sri Lanka also have been suffering from the sedimentation issue for decades (Perera et al. 2021).

As the effective reservoir storage declines due to sedimentation, key problems emerge along with the operation, including (a) reduced storage capacity leading to increased risk of dam overtopping and increased flood frequency in the downstream, (b) degraded water quality disrupting the aquatic ecosystems, and (c) socio-economic issues associated with negative effects on the water balance and effective water use in the region, etc. (Dharmasena 2021).

Reduced storage capacity due to prolonged sedimentation not only increases the risk of overtopping induced failures thus endangering the dam and the downstream community, but also triggers crucial socio-economic impacts (Dharmasena, 2021). Given that irrigated

agriculture is the key source of livelihood primarily in the dry zone of the country, reduced storage capacity of rural tanks significantly affects the seasonal water allocation and coverage of irrigation water demand which ultimately leads to raise socio-economic disruptions among the communities and the dam authorities (Weerakoon 2005). Similarly in the wet zone, the reduced storage capacity of the reservoirs due to sedimentation severely affects the hydropower generation mainly during the dry season, causing island wide socio-economic concerns (Gunatilake and Gopalakrishnan 1999; Udayakumara and Gunawardena 2016).

Furthermore, the accumulation of sediments not only reduces effective reservoir storage but also severely disrupts the hydraulic performance of outlet works and spillways. Accumulated sediments can clog the sluice gates and outlet structures and disturb the operational mechanism of the turbines in hydropower generation, ultimately leading to complicated dam maintenance practices (Dharmasena 2021).

Aforementioned extracts from literature related to different aspects of reservoir sedimentation highlights the need for certain attention paid to management of reservoir sedimentation as we prepare for dam safety in the face of climate extremes in the future.

Cascade System Effect during Dam Failures

The tank cascade systems in Sri Lanka are identified as a connected series of small tanks feeding water to large scale reservoirs while reusing the water at each step within a micro catchment (Perera et al. 2021). Even though the concept of tank cascade is considered as a historical method of optimizing water usage, it also introduces the risk of systematic dam failure (Wang et al. 2023). In other words, when an upstream dam fails due to overtopping during an extreme rainfall event or by piping due to structural degradation, it rapidly transfers the excess water, overwhelming the next reservoir in sequence and so on. This can lead to a major catastrophe as it triggers a chain of breaches, amplifying the damage and making the mitigation measures more difficult (Cai et al. 2019).

The floods of December 1957 is one of the key examples of cascade system dam failures in Sri Lanka. The floods resulted in the breaching of 35 large dams, 53 medium dams, and 1500 small dams over a period of 3-5 days and heavily disrupted the country's irrigation network. One upstream tank failure in the cascade led to another in the downstream and consequently, the overall damage to the country's irrigation network was immense. Notably, major ancient dams in the country such as Kala Wewa (Figure 2), Nachchaduwa, and Hurulu Wewa were completely destroyed during the 1957 floods signifying devastation of cascade dam failure (Kamaladasa 2020). The part of the devastation may be due to the developments that has taken place since colonial times changing the landscape without in-depth understanding of the broader operational concepts of the ancient tank cascade systems; it is worthy to investigate if the relative arrangement of the ancient cascade systems that included the tank, community settlement, tree belts, the paddy fields, shrub lands etc., facilitated spread of water over the paddy lands and thereby reduced the speed and height of flood water minimizing the impact on the downstream infrastructure.

Figure 2. Kala Wewa Breach in 1957 (Kamaladasa 2020)

Challenges from Extreme Rainfall Events and Floods

Notably in the last 20 years, Sri Lanka suffered several extreme rainfall events including 2011 January, 2012 December and 2024 November floods. The intensified rainfall events likely influenced by climate change, posed significant challenges to ensuring dam safety in the country while overwhelming the present design capacities and flood routing systems (Wickramasuriya & Fernando 2012).

During the floods of January–February 2011, many major reservoirs spilled, while a few medium-sized and over 800 minor dams breached. Batticaloa experienced record rainfall, while Senanayake Samudraya, the country's largest reservoir spilled after 16 years. In this case, the emergency release of massive volumes of water from the reservoirs made a heavy socio-economic impact on the downstream communities. According to the estimates, a million number of people were rendered homeless, 62 lives were lost and the floods caused an enormous Rs. 66 billion in damages which included a massive Rs. 13 billion loss in the rice crop alone (Wickramasuriya and Fernando 2012).

Due to heavy rainfall in the latter part of 2012, the majority of the reservoirs in the country spilled releasing excess water to maintain the water level of the reservoirs at a safe operation level. However, this negatively affected 450,000 people due to flooding that resulted in 43 casualties and loss of 15,000 houses, paddy land and property costing Rs. 28 billion. The extreme precipitation led Kiulekada dam, a medium sized dam in Anuradhapura district, to severe damage while causing partial damage to 873 small dams severely disrupting the country's irrigation network (Wickramasuriya & Fernando 2012).

Most recently in November 2024, Cyclone Fengal brought prolonged extreme rainfall to Sri Lanka over a ten-day period where many reservoirs spilled; the Giritale reservoir spilled for the first time in 6 years. Given the fact that Giritale reservoir has been suffering from major seepage issues, the reservoir reaching its spilling level was considered as a critical situation (The Island 2025).

A critical review of these recent events provide evidence for inadequate storage and spill capacities, structural concerns that raise safety issues in maintaining water at spilling level, and lack of preparedness for flood routing.

In summary, ageing of dams and related structural deficiencies, reservoir sedimentation, cascade system effects, and challenges from extreme rainfall events are critical concerns in establishing safe dam practices in Sri Lanka.

The Way Forward for Climate-Resilient Dam Safety

As a country with an extensive but ageing dam network, Sri Lanka cannot afford to overlook the vulnerability of our dams to challenging climate events in the future. In response to the identified critical concerns, as highlighted in the existing literature, Sri Lanka should drive towards climate-resilient dam safety strategies including, (1) Giving primary attention towards rehabilitation or decommissioning of ageing dams posing high risk due to structural deficiencies (ICOLD 2020), (2) Promptly implementing reservoir desilting practices for the reservoirs which are suffering from sediment accumulation (Dharmasena, 2021), (3) Revising hydrological design standards using the updated rainfall data and climate foresights (Wickramasuriya and Fernando 2012), (4) Assessing dam safety not in isolation but as a systems approach, especially in cascade systems (Mudiyarise, 2009) (5) Effectively implementing real-time monitoring and early warning systems (Weerasinghe et al. 2022), (6) Integrating local knowledge and insights in assessing long-term dam performance (Mehta et al. 2020), (7) Enhancing institutional capacity building in dam organizations on climate change impacts (Attewill et al. 2004), and (8) Incorporating modern technological advancements as dams-related risk assessment tools (Kumar et al. 2017).

Together, the aforementioned dam safety strategies lead towards climate resilient dam safety management which ultimately enhances the disaster resilience of the dam infrastructure in the country.

Conclusion

This research was carried out based on a review of existing literature to study crucial safety concerns associated with Sri Lanka's dam infrastructure while identifying the vulnerabilities to extreme climate events. The identified key concerns of dam safety include ageing of dams and related structural deficiencies, reservoir sedimentation, cascade system effects, and challenges from extreme rainfall and floods. With the extreme climate events being frequent in the recent past, it is high time to reflect on the aforementioned critical concerns and to implement climate resilient dam safety strategies.

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Farmers' Preferences for Three Methods of Alternate Wetting and Drying for Water Management of Paddy Fields

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Introduction

Paddy (*Oryza sativa*) is a major crop cultivated throughout the country. It is preferred to grow in aquatic environments, with water being a key factor in paddy cultivation (Kumar and Ranjitha 2019). The main cultivation seasons are *Maha* (October to February) and *Yala* (March to September) which include both irrigated and rainfed systems. Irrigated paddy cultivation is classified into major, medium, and minor irrigation schemes, relying on irrigation for water supply, while rainfed cultivation depends on rainfall (Rathnayaka et al. 2019).

Climate change is impacting Sri Lanka, evidenced by rising air temperatures and changing rainfall patterns. This situation has resulted in a prolonged growing season due to water scarcity (Costa 2008), which adversely affects paddy cultivation. According to the Ministry of Agriculture, Livestock, Land, and Irrigation of Sri Lanka (2023), approximately 23,377 hectares of paddy land were damaged due to prevailing dry weather conditions in 2023.

Global warming poses a significant threat to humanity and the planet, primarily driven by greenhouse gas emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), with CH_4 and N_2O being more powerful than CO2. Consequently, these two gases are particularly significant contributors to global warming (Sun et al. 2016). Rice cultivation is one of the main sources of CH_4 and N_2O emissions into the atmosphere (Ramesh et al. 2020). In the context of Sri Lanka, the agriculture sector contributes 25.1% to total greenhouse gas (GHG) emissions, with the paddy sector alone accounting for 52.4% of emissions from agriculture (Sithari et al. 2021).

To mitigate crop losses due to water scarcity and reduce GHG emissions from paddy fields, the Alternative Wetting and Drying (AWD) method is recommended. The AWD is a water saving irrigation technique for lowland paddy cultivation, reducing water usage by 25% to 30% without negatively affecting yields, while also decreasing greenhouse gas (GHG) emissions by 30% to 50% (Kumar and Ranjitha 2019).

However, farmers often prefer easier methods for their farming activities. There are different factors affecting farmers adapt to various agricultural technologies. Such as age, experience, education, gender, income, easy access to labours (Tingtin et al. 2018). This study suggests implementing various types of AWD instruments during irrigation to encourage farmers to adopt AWD methods. The objective of this paper is to assess the farmers preferences of

different type of AWD instrument and identified the most easer type to handle the instrument during their irrigation practices.

Methodology

Three different types of AWD instruments were introduced by the Climate Resilience Integrated Water Management Project (CRIWMP) for water management in paddy fields in the project sites. These included the arrow type, sensor light, and commonly used pipe. The study was conducted across seven Dry zone (DZ) districts in Sri Lanka, namely, Anuradhapura, Kurunegala, Puttalam, Polonnaruwa, Mannar, Vavuniya, and Trincomalee. A random sample of 62 farmers was interviewed from the project implementation sites of the CRIWMP, which supported the establishment of the AWD method for selected village irrigation systems.

The CRIWM Project implemented AWD practices across seven districts. Three different types of AWD instruments were introduced to measure water levels in paddy fields. It includes (1) the arrow-type indicator, (2) the sensor light device, and (3) the commonly used perforated pipe. The arrow type AWD device measures water levels from 30 cm below to 10 cm above the soil surface and provides a visual cue for water management by indicating when to irrigate, with an arrow moving from the bottom to the top of the gauge. The sensor light device is an automated instrument that emits a red light when the water level falls below 15 cm from the surface, turning off when the level exceeds 15 cm. These two enabled real-time monitoring of field conditions with minimum farmer intervention. The commonly used pipe, a simple 20 cm perforated PVC tube, is manually monitored to assess water levels. All three types of AWD instruments were installed during field implementation, and farmers expressed varied opinions regarding their effectiveness, usability, and suitability under different field conditions.

The pre-tested structured questionnaire was developed and data were collected through interviews with respondents by enumerators from the project. Descriptive analysis was used to analyse the survey data, allowing for the comparison among various components.

Results and Discussion

The demographic analysis of the surveyed farmers indicates that the sample represents a diverse cross-section of the target population (Table 1). The majority of older farmers was observed in the Vavuniya District, whereas the Trincomalee District had a comparatively younger farming population. Regarding land ownership, the majority of farmers (88%) cultivated their own paddy lands, with 61.3% owning between 1 and 3 acres. In terms of farming experience, 43.3% of the respondents had between 35 and 45 years of experience in paddy cultivation. Concerning the adoption of Alternate Wetting and Drying (AWD) technology, 55% of the farmers had three years of experience, while 39% had practiced AWD for one year.

Table 1. Demographic characteristics of the sampled paddy farmers

Characteristics	Percentage or value
Males	69%
Average age	52 years
Age class distribution	32.8% in >60 years; 9.8% in <40 years
Education	67% completed Secondary Education
	17% [assed GCE A/L examination
	2% had a University degree
Farming as primary occupation	71%
Other Employment	21% employed in the government sector
Land ownership	88% owned paddy lands
Extent of land ownership	61% between 1 and 3 acres (0.4 and

The results revealed a statistically significant difference in farmer preferences across the three types of AWD instruments, based on different evaluation factors ($p < 0.05$). Among the options, the arrow type instrument considers as the most preferred by farmers for several key reasons as depicted in Table 2.

Table 2. Key reasons for favouring arrow-type AWD instrument by paddy farmers

Key Reasons	Respondents (%)
Easiness of handling	57.4%
Easiness in observing water level	63.4%
Durability	58.5%
Overall sustainability	59.4%
Long-term use	58.2%
Ability to observe water levels remotely	54.5%

In contrast, the sensor light type was particularly favoured in addressing external disturbances. It was preferred for its effectiveness in reducing interference by wild animals (51.7%) and minimizing human disturbance (57.8%). The commonly used pipe, despite being a traditional method, received relatively lower preference. Many farmers expressed negative opinions regarding its usability, visibility, and long-term practicality in field conditions.

Furthermore, the results indicate variations in farmers' preferences for AWD instruments across the seven study districts. The arrow type AWD instrument was the most preferred option among farmers in Anuradhapura, Vavuniya, Trincomalee, and Mannar Districts. Its simplicity, ease of observation, and adaptability under field conditions likely contributed to its popularity in these areas. In contrast, farmers in Polonnaruwa District showed a stronger preference for the sensor light type, possibly due to its automated features and effectiveness in minimizing disturbances from wild animals and human interference. Furthermore, in Kurunegala and Puttalam Districts, farmers expressed a relatively balanced preference for both the arrow-type and sensor light instruments.

Conclusion

The study concludes that, across the seven districts surveyed, farmers showed a higher preference for the arrow-type AWD instrument for its easiness in use, visibility, and durability. This preference was consistent throughout the study area. A higher preference to sensor-light instrument was reported in Kurunegala, Polonnaruwa, and Puttalam Districts. In contrast, the commonly used pipe presented several practical challenges during field implementation, making it less favourable compared to the other two instruments. The analysis further revealed that farmers' preferences were influenced by key demographic and socio-economic factors, including age, education level, primary occupation, farming experience, and duration of practice of AWD. These findings highlight the importance of considering user-friendly and easily adapted technologies to enhance the adoption and sustainability of AWD practices in paddy farming.

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Depth – Area Capacity Variation of Village Irrigation Systems along the Cascade

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Introduction

Water management has historically posed significant challenges, particularly in regions characterized by seasonal rainfall and prolonged dry periods. In Sri Lanka, an exemplary indigenous response to these challenges is the ancient tank cascade system - *Ellangawa*, which represents a highly sophisticated and sustainable hydrological innovation developed over two millennia ago. These systems consist of a series of interconnected small tanks designed to capture, store, and distribute surplus rainfall effectively to increase the irrigation potential.

With over 13,600 village tanks still in operation, they contribute to approximately 25% of the country's rice production and support a wide range of socio-ecological functions (Perera et al. 2020). This multifunctionality underscores their role not only as engineering marvels but also as keystones of rural livelihoods and ecosystem services.

Despite their historical value, many tank cascades have deteriorated due to poor maintenance, land use changes, and expanding agricultural demands. Smaller, unrepaired tanks often fail to meet increased irrigation needs, leading to inefficiencies and water insecurity (Dharmasena 2000). These issues are further intensified by climate change, especially in the dry zone, where altered rainfall patterns and extreme events threaten system stability (Eriyagama et al. 2010).

To address these challenges, national adaptation plans, including Sri Lanka's NDCs prioritize tank rehabilitation. The Climate Resilient Integrated Water Management Project (CRIWMP), supported by the Green Climate Fund (GCF) and implemented by the Ministry of Irrigation with UNDP assistance, aims to enhance climate resilience through integrated management and restoration of cascades in the Malwathu Oya, Yan Oya, and Mi Oya basins.

The CRIWMP, has developed Depth–Area–Capacity (DAC) curves, installed flow-measuring gauges at irrigation canal inlets, and prepared tank-specific operation and maintenance plans. Farmers were trained to interpret depth gauge readings and relate them to storage volumes derived from DAC curves, making these relationships essential for effective water management and planning. While these efforts have enhanced tank-level decision-making, there remains a knowledge gap regarding how DAC characteristics behave across an entire

cascade system. The present study focuses on a critical yet underexplored aspect of tank cascade systems: the spatial variation in DAC characteristics along a cascade. While DAC curves are typically developed for individual tanks, their potential to exhibit systematic trends particularly in relation to the spatial sequence of tanks from upstream to downstream has not been extensively investigated. Identifying such trends could contribute to improved planning, resource allocation, and hydraulic modeling in cascade-based irrigation systems.

Accordingly, the primary objective of this research is to examine whether a consistent pattern exists in DAC parameters along the cascade sequence. If such a trend is observed, the study seeks to adapt and refine a historically used empirical equation for more accurate application to tanks situated at upstream, middle, and downstream positions within a cascade. The intent is to enhance the practicality and accuracy of DAC approximations based on spatial context, thereby improving the efficiency of water management and rehabilitation efforts.

Methodology

Data Collection

This study utilized DAC datasets developed under the CRIWMP for tanks selected for rehabilitation. Ten tank cascades were selected, each comprising a sequence of tanks positioned along natural flow paths. Tanks were categorized based on their spatial location within the cascade as upstream, middle, or downstream. Only tanks with complete DAC data, including Full Supply Level (FSL) depth, surface area and storage capacity, were considered for analysis.

Theoretical Framework and Analytical Procedure

This study adopts a two-phase analytical framework to investigate DAC characteristics both across cascade sequences and within individual tanks. While the estimation of storage capacity through standard surveys is methodologically sound, its practical application is often constrained by limited accessibility, particularly when tanks are full or partially submerged. As a simplified alternative, Phase I of this study builds upon one of Sri Lanka's earliest empirical formulas (Equation 1), proposed by Kennedy (1933), to provide a preliminary approximation for estimating the storage volume of small village tanks:

$$V = 0.4 \times A \times D \quad \text{..... (Eq. 1)}$$

where, V is the capacity in acre-feet at depth D (feet) and A is the water spread area (acres) at that depth.

Phase I of this study seeks to refine this formula to better reflect volumetric characteristics at FSL based on the location of the tank within the cascade, specifically distinguishing upstream, middle, and downstream tanks. To enable this refinement, Equation (2) is rearranged to isolate a dimensionless empirical coefficient:

$$k = V/(A \times D) \quad \text{..... (Eq. 2)}$$

Here, k represents the ratio between observed volume and the product of surface area and depth at FSL. For each tank, the k value was computed using selected data, and values were grouped according to the tank's position within its respective cascade.

The analysis aimed to determine whether a systematic trend exists in k values along the cascade. If identifiable trends were present such as increasing or decreasing k values from upstream to downstream a representative average or range of k values was derived for each group. These values would then inform modified location-based empirical equations specific to upstream, middle, and downstream tanks, providing a more accurate yet approximation for DAC relationships at FSL.

In phase II, the study explored an alternative, cost-effective approach to estimating DAC relationships that reduces dependence on comprehensive topographic surveys. An empirical method previously introduced by Imbulana (2022) was selected for validation. This approach utilizes normalized variables depth, surface area, and storage expressed as fractions of their corresponding FSL values. It proposes a linear relationship as shown by Equation 3:

$$\frac{S}{C} = m \times \left(\frac{a}{A}\right) \times \left(\frac{d}{D}\right) \text{..... (Eq. 3)}$$

where, s is the storage at depth d; C is the total capacity at Full Supply Level (FSL); a is the surface area at depth d; A is the surface area at FSL; D is the depth at FSL; and m is the slope of the regression line through the origin.

To validate this method, data were extracted at five reference depths: zero depth, one-third depth (⅓D), the midpoint between 0 and ⅓D, two-thirds depth (⅔D), and full depth (D). For each level, relative values of depth (d/D), area (a/A), and storage (s/C) were computed. The product (a/A)·(d/D) was plotted against (s/C), and the slope m was derived from a regression line constrained through the origin. The resulting m-value, along with the Full Supply Level (FSL) parameters of the tank, was then substituted into Equation (3) to derive a tank-specific equation for estimating storage at any given depth. Using this equation, storage volumes were calculated at selected depths based on the corresponding surface area values. These estimated storage points were then plotted against depth to generate the capacity curve for the tank. However, it is important to note that all measurements were referenced from the Sluice Sill Level (SSL). Therefore, the estimated storage volumes represent only the active storage capacity of the tank.

Result and Discussion

The DAC characteristics across the cascade

In the initial phase, k-values were computed at Full Supply Level (FSL) for each tank across the ten selected cascades (Table 1), following the flow sequence from upstream to downstream as delineated in the schematic diagrams prepared for each cascade.

Table 1. The k values of tanks in Aluth Halmillewa Cascade

Tank Name	k Value
Maha Meegaskada Wewa	0.42
Kuda Meegaskada Wewa	0.37
Koan wewa	0.49
Divulgaskada Maha Wewa	0.42
Katukeliyawa Wewa	0.45
Thimbiri wewa	0.41
Divulgaskada Kuda Wewa	0.38
Etambagaskada Maha Wewa	0.31
Ahugaha Wewa	0.48
Kohomba Wewa	0.56
Galegama Wewa	0.41
Pan Wewa	0.53
Palugollawa Wewa	0.50
Puhudivula Wewa	0.45
Makichchawa Wewa	0.37
Kongollewa Maha Wewa	0.44
Kongollewa Kuda Wewa	0.43
Wedikkarayage Wewa	0.45
Lolugaswewa Maha Wewa	0.32
Rathmalwetiya Wewa	0.20
Kadawatha Wewa	0.39
Aluth Halmillewa Wewa	0.29

In the case of the Aluth Halmillewa cascade (Table 1), and similarly across the remaining nine cascades, no discernible spatial pattern was observed. There was neither a progressive increase nor a decrease in k values along the cascade flow paths. This lack of spatial consistency suggests that the DAC characteristics of tanks are governed more by local morphological and physical features such as tank geometry, terrain configuration, valley profile, siltation extent, and catchment shape than by their position within the cascade (Dharmasena 2024). Accordingly, the application of generalized empirical equations based solely on upstream, midstream, or downstream classifications appears ineffective.

Alternative approach to develop DAC curves

Validation of this method was first conducted using Maha Meegaskada Wewa, for which detailed DAC data were available. Relative area and storage values were calculated for the five specified depths (Table 2), and the resulting regression (Figure 2) yielded a slope of m=1.040 with a coefficient of determination R^2=0.972, indicating an excellent model fit.

Table 2. Computed Relative Parameters for Maha Meegaskada Wewa

Depth (m)	Relative Depth (d/D)	Relative Area (a/A)	Relative Storage (s/C)
0	0	0.019358	0.000000
0.5	0.196	0.110449	0.029427
0.75	0.294	0.173414	0.062635
1.75	0.685	0.574238	0.413950
2.554	1	1.000000	1.000000

From this, a site-specific DAC equation for Maha Meegaskada Wewa was derived (Equation 4):

$$s = 1.040\ C \times \left(\frac{a}{A}\right) \times \left(\frac{d}{D}\right) \text{.....(Eq. 4)}$$

By substituting the known FSL values, the equation simplifies to Equation 5:

$$s = 165{,}892.48 \times \left(\frac{a \,.\, d}{381{,}286.66}\right) \text{.....(Eq. 5)}$$

where *s* is in cubic meter, *a* in square meter and *d* in meter.

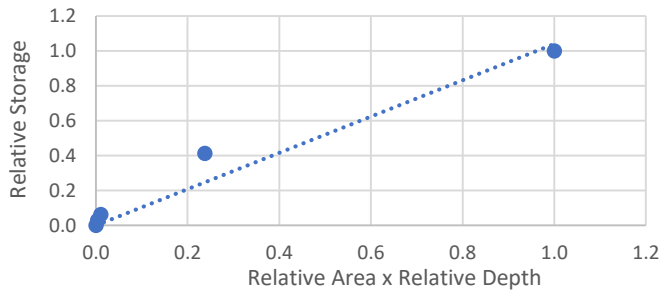

Figure 2. Graph of relative storage against relative area x relative depth in Maha Meegaskada Wewa

This formulation facilitates reliable estimation of intermediate storage volumes (Figure 3) based on available surface area data at specified depths, without requiring full-scale topographic mapping.

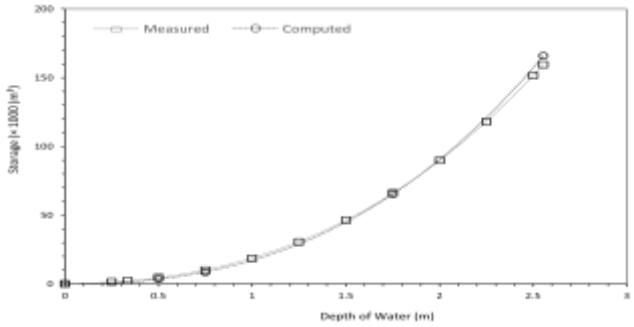

Figure 3. A Comparison of computed storage and measured storage against the depth of water - Maha Meegaskada Wewa

Subsequently, the same method was applied to four additional tanks; Koan Wewa, Kadawatha Wewa, Galegama Wewa, Lolugaswewa Maha Wewa and Aluth Halmillewa

Maha Wewa to evaluate its applicability across varying tank conditions. Table 3 summarizes the regression results across all five tanks.

Table 3. Regression outcomes for five validated tanks

Tank Name	Slope (m)	R^2
Maha Meegaskada Wewa	1.040	0.97
Koan Wewa	1.050	0.93
Kadawatha Wewa	1.025	0.96
Galegama Wewa	1.031	0.97
Lolugaswewa Maha Wewa	1.052	0.87
Aluth Halmillewa Wewa	1.018	0.97
Average	1.036	0.95

The consistently high R^2 values indicate strong agreement between observed and estimated storage volumes, despite differences in tank geometry. Although the slope values varied slightly due to basin shape and data resolution, the method demonstrated consistent performance and practical utility. Similar observations were made by Rodrigues and Liebe (2013) who found that while depth–area–volume relationships show strong correlations, the parameters are highly site-specific and not easily generalizable. However, some of the studied cascades showed less promising results due to various influencing factors. Therefore, further studies should be conducted.

Conclusion

The relative-variable regression method demonstrated strong potential for estimating DAC relationships at individual tank level. Its minimal data requirements and adaptability make it a practical tool for supporting tank rehabilitation and planning under field-level constraints.

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Collective Decision-making in Seasonal Cultivation Meetings as an Opportunity for Integrated Management

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Introduction

In the context of Sri Lankan agriculture, Seasonal Cultivation Meetings (SCMs) serve as critical junctures for farmers and agricultural stakeholders to collaborate in planning, decision-making, and resource sharing (Madduma Bandara 1985; Kekulandala 2021). These meetings are typically held at the start of each cropping season to decide what crops to grow, plan water releases in cascade irrigation systems, and integrate agro-meteorological advisory services (De la Poterie et al. 2018; Foster et al. 2023).

However, despite their long-standing role, SCMs have often been treated more as administrative formalities rather than as strategic platforms for adaptive planning (Kekulandala et al. 2024). Recent climate variability and increasing risks of droughts and erratic rainfall have created an urgent need for more integrated, participatory, and knowledge-based approaches to local agricultural decision-making (Arumugam 2022; National Disaster Management Centre 2020).

In Sri Lanka's Dry Zone, agriculture is highly dependent on small tank cascade systems and seasonal rainfall, which are both vulnerable to climate stressors (Madduma Bandara 1985; Kekulandala et al. 2024). Within this context, SCMs continue to be essential community forums where farmers collaboratively plan crop calendars, decide water allocations, and negotiate resource sharing (Foster et al. 2023). Historically viewed as routine administrative events, SCMs now present a unique opportunity to institutionalize integrated management strategies that bridge traditional ecological wisdom with scientific agro-meteorological advisories (De la Poterie et al. 2018).

This study brings a novel perspective by examining how collective decision-making within SCMs enables hybrid knowledge systems—where farmer experience intersects with scientific guidance to manage climate risks more effectively (Kekulandala 2021; Kekulandala et al. 2024). It also explores how deviations from agreed plans can impact cascade irrigation

performance, local food security, and community resilience (Arumugam 2022). This research aimed assessing how Seasonal Cultivation Meetings (SCMs) can become practical, inclusive platforms for integrated agricultural and water management in Sri Lanka's climate-vulnerable Dry zone (DZ). It focuses on how SCMs strengthen collective decision-making, align agro-met advisories with real practices, and bridge traditional knowledge with modern innovations to build community resilience.

Methodology

Study area

This study employed a mixed-methods approach, integrating both qualitative and quantitative techniques to comprehensively analyze the dynamics of collective decision-making in seasonal cultivation meetings (SCMs). A total of 171 respondents were selected using purposive sampling from three districts—Kurunegala (7 GN Divisions**),** Puttalam (50 GN Divisions)**,** and Vavuniya (30 GN Divisions)**.** The selection ensured adequate representation across diverse agro-ecological zones and cascade irrigation systems, particularly those operating under the Climate Resilient Integrated Water Management Project (CRIWMP)**.** This sampling strategy enabled the study to capture a wide range of perspectives and practices relevant to integrated agricultural and water management.

Figure 1. Surveyed Districts (source: CRIWMP 2020)

Data Collection

A total of 171 farmers were purposively selected across 12 Agrarian Service Centre (ASC) divisions to ensure diversity in agro-ecological zones, irrigation types (rain-fed and tank-fed), gender, and age. This sample size was considered technically feasible to capture community-level variation across three districts, with a minimum of 50 samples per district, providing sufficient representativeness for both statistical and thematic analyses. Data collection methods included structured interviews (with the questionnaire provided as an annex), focus group discussions (FGDs), direct observations of Seasonal Cultivation Meetings

(SCMs), a review of agro-meteorological advisory bulletins, and an analysis of cascade-level irrigation and water release records

Data Analysis

Quantitative data were analysed using descriptive statistics to identify patterns in demographic characteristics, advisory utilization, and decision-making behaviours. Qualitative data from observations and Focus group discussions were thematically analysed to understand the nuances of collective decision-making processes and knowledge integration dynamics.

Results and Discussion

Participant Demographics and Representation in seasonal cultivation meetings

Data were collected from 171 respondents across the three target districts, representing diverse agro-ecological zones and cascade irrigation systems. The demographic profile reveals significant patterns in seasonal cultivation meeting participation that have implications for integrated management approaches.

Approximately 71% of participants were male farmers with 29% female representation, reflecting the traditionally male-dominated nature of formal agricultural decision-making structures in Sri Lankan farming communities. However, the notable female participation suggests evolving gender dynamics in agricultural governance, particularly in CRIWMP-targeted areas.

There was a concentration among middle-aged farmers, where 58% were aged 31-50 years, followed by 30.7% in the 51-70 age bracket. Only 8% were below 30 years, indicating limited youth engagement in formal agricultural planning processes. This demographic skew toward older, experienced farmers has implications for knowledge transfer and the integration of traditional versus modern agricultural practices.

Respondents represented diverse farming systems: 63% cultivated lowland paddy, 20% engaged in single-season farming, and 16% practiced upland cultivation. This distribution aligns with the predominant rice-based agriculture in the study districts and reflects the cascade irrigation system's primary function of supporting paddy cultivation.

Integration of Agro-Meteorological Advisories in Decision-Making

The study revealed encouraging levels of agro-meteorological advisory integration in seasonal cultivation meetings. About 78.6% of farmers accessed government-issued weather forecasts, while 36% continued relying on traditional knowledge systems, including animal behaviour patterns and cloud observations. This dual reliance suggests that farmers are not abandoning traditional knowledge but rather integrating it with scientific advisories—a finding that supports the conceptual framework of hybrid knowledge systems in agricultural decision-making.

About 78% of the respondents reported that agro-meteorological advisories were formally presented during SCMs, indicating successful institutional integration. More significantly, 52% used this information consistently ("every time") for decision-making, demonstrating practical uptake beyond mere awareness.

Modern communication technologies have transformed advisory dissemination. 57% of farmers received advisories through smartphones and social media platforms, while 56% relied on television (Figure 2). Traditional channels showed lower penetration: field officers (36%), community leaders and development officers (20-30%), with radio and printed media being least utilized (<25%). The prominence of digital channels reflects Sri Lanka's high mobile penetration rates but also highlights potential digital divides. Agro-meteorological advisories found practical application across multiple farming activities.

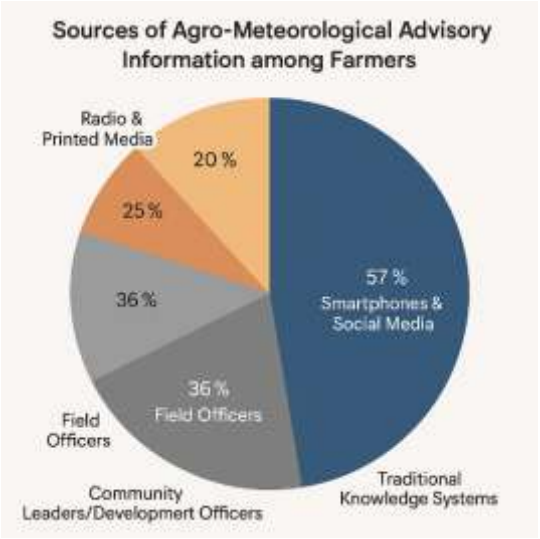

Figure 2. Integration of Agro-Meteorological Advisories in Decision-Making (Source Structures Questionnaire CRIWMP Project)

Agro-Meteorological Advisory Uptake

The study found that while 78.6% of farmers accessed scientific advisories, 36% still relied on traditional methods such as observing clouds and animal behavior, and only 52% consistently used the scientific advisories when making cultivation decisions. About 65% of decisions were made using a hybrid model—combining institutional and indigenous knowledge. Such integration improved decision relevance but lacked consistency in implementation.

The study found that 48% of farmers still relied mainly on their own experience to judge tank water levels, while only 10% reported actively participating in formal water scheduling, resulting in frequent deviations that directly affected downstream water access. About 30% of farmers deviated from agreed Seasonal Cultivation Meeting (SCM) decisions due to factors such as market fluctuations, late agro-met advisories, and a lack of trust or technical

understanding. Key barriers identified include a poor communication network (46%), delays in delivering advisories (33%), and low trust in forecast accuracy (24%). Over 80% of farmers found the training useful but expressed a need for more localized advisories, clearer visual formats such as charts and videos, and greater involvement in validating decisions and recommendations.

Knowledge Integration Patterns: A critical finding is that 65% of seasonal cultivation meeting decisions were influenced by a combination of local knowledge and formal advisories, while the remainder relied on either purely traditional (approximately 35%) or purely institutional guidance. This hybrid approach validates the theoretical framework of integrated management, where traditional and scientific knowledge systems complement rather than compete with each other.

Water management decisions showed interesting patterns: 48% of farmers estimated tank water availability using personal experience, while 44% used formal water-level markers and official data. Despite this reliance on experiential knowledge, 65.3% reported integrating agro-meteorological advisories into water management practices. However, a significant governance gap emerged: local co-management at the tank level remained low (<10% reporting active involvement). This finding highlights a critical disconnect between advisory reception and participatory irrigation governance.

There is noticeable disagreement with majority decisions among farmers, influenced by unpredictable rainfall patterns, market concerns, and resource constraints. This deviation rate suggests that while Seasonal Cultivation Meetings (SCMs) facilitate collective planning, individual farmer autonomy and risk perception continue to shape the actual implementation of decisions. Several key barriers limit the uptake of agro-meteorological advisories, including poor signal and communication coverage (46%), late delivery of advisories (33%), difficulty in understanding technical content (18%), and a lack of trust in the accuracy of the information provided (24%). These obstacles highlight a combination of technical and social challenges that require comprehensive and systemic interventions to improve advisory utilization and farmer responsiveness.

Over 80% of farmers who attended awareness programs found them useful, strongly supporting continued capacity building under CRIWMP and similar initiatives. This high satisfaction rate indicates that when properly designed and delivered, training interventions can effectively bridge the gap between scientific advisories and farmer application. Farmers emphasized several improvement areas such as (a) Simpler advisories in local languages, (b) More frequent and reliable delivery, (c) Enhanced training on interpretation, and (d) More inclusive planning at tank/ASC levels

The findings demonstrate that SCMs are successfully functioning as platforms for integrated management, facilitating the synthesis of traditional knowledge and scientific advisories. The 65% of farmers using hybrid knowledge approaches validates the theoretical framework while highlighting the continued relevance of indigenous knowledge systems.However, the low levels of participatory water management (<10%) reveal a critical governance gap that

constrains the potential for fully integrated cascade management. While farmers access and utilize weather information, their limited involvement in water allocation decisions represents a missed opportunity for enhancing system resilience. The successful integration of agro-meteorological advisories in 78% of SCMs provides a foundation for scaling up climate information services. The 30% deviation rate and various implementation barriers suggest that advisory systems must be complemented by supportive infrastructure, capacity building, and governance reforms.

Conclusion and Recommendations

This study demonstrates that seasonal cultivation meetings represent valuable platforms for integrated agricultural management, successfully facilitating the integration of traditional knowledge with scientific advisories. The research reveals both significant progress and persistent challenges in realizing the full potential of SCMs for climate-resilient agriculture. The key recommendations include (1) Strengthen digital infrastructure to address communication coverage gaps affecting 46% of farmers, (2) Develop simplified, localized advisory formats to improve comprehension and trust, (3) Enhance participatory water management to bridge governance gaps in cascade systems, (4) Expand capacity building programs given their demonstrated effectiveness, (5) Improve advisory timing and reliability to address delivery challenges, and (6) Develop mechanisms for validating advisory accuracy to build farmer confidence. The integration of traditional and scientific knowledge systems through SCMs offers a promising pathway for building climate resilience in Sri Lankan agriculture. However, realizing this potential requires addressing technical barriers, strengthening governance structures, and continuing capacity building efforts.

Acknowledgment

The authors wish to thank the participating farmers, Agricultural Instructors, and project staff from the Climate Resilient Integrated Water Management Project (CRIWMP). Special appreciation is extended to the Sri Lanka Red Cross Society, Janthakshana Gte Ltd, PLAM Foundation, and South Asian Partnership Sri Lanka for their collaboration and field support.

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Integrated management of surface water: scaling up tank level irrigation planning to cascade level

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Introduction

Climate change poses a significant threat to water resources worldwide, with Sri Lanka particularly vulnerable due to its dependence on agriculture (Warnakulasooriya & Shantha, 2021). Traditional village irrigation systems, consisting of small reservoirs (tanks) and diversions (anicuts), have formed the foundation of water management in Sri Lanka's Dry Zone. Many of these irrigation systems are hydrologically interconnected, forming tank cascades (Panabokken et al. 2002). They capture and distribute water efficiently, making them ideal for addressing seasonal water shortages. However, current irrigation planning predominantly focuses on individual tanks, limiting the potential benefits of a more integrated cascade-level approach (Kekulandala 2021). Given the increasing threat of climate change, it is important to assess the benefits of scaling up irrigation planning and management from the tank level to the cascade level. In this regard, the Climate Resilient Integrated Water Management Project (CRIWMP), introduced a strategy to manage water at the tank level and then has scaled it up to the cascade level (Ariyawanshe et al. 2023).

The objective of this paper is to present a surface water management strategy for the Dry Zone of Sri Lanka through an integrated cascade-level water management, as a measure of adapting to climate change.

Methodology

Study Area

The study selected the Medde Rambewa cascade in the Mi Oya River basin for the analysis. This Cascade is administratively located in the Nawagattegama Divisional Secretariat Division (DSD) of Puttalam District in the Northwestern Province of Sri Lanka. There are 25 Village Irrigation Systems within the cascade (Figure 1), with 24 village tanks and an anicut. The average annual rainfall received in the area is 1174 mm, and the average annual temperature exceeds 28–29 °C (Ariyawanshe et al. 2023).

Assessment of tank-level water management

This process included documenting the water management techniques practiced by the farmers before the CRIWMP, studying the tools and techniques for water management

introduced by the CRIWMP, and studying the results of water management-related indicators derived from those techniques. These indicators included irrigation duty and cropping intensity (Warnakulasuriya et al. 2024).

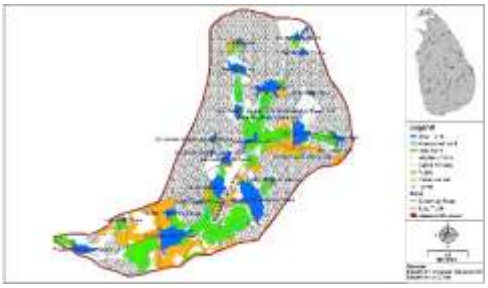

Figure 1. A diagrammatic representation of the *Medde Rambewa* cascade system. (Data Source: Department of Agrarian Development & Department of Survey)

Scaling up to cascade level

The effectiveness of scaling up water management was assessed by comparing the results of the system simulation model developed by the CRIWMP with the performance achieved through tank-level water management. For this exercise, the 2023/24 water year was selected. A System Dynamics (SD) model that incorporates the complexities and interaction among different activities in a cascade tank system facilitated strategic decisions on water sharing to help all water-use sectors of the area. The model was developed by the CRIWMP using the *Vensim* Simulation Environment (Nandalal and Imbulana 2022; Imbulana et al. 2023).

Water Balance Equation

This equation helps estimate irrigation duty, optimize water use efficiency, and plan cultivation seasons scientifically. The formula used in is presented below (Equation 1).

$$\text{Storage change} = \text{inflows} - \text{outflows} \quad \text{---------- (Eq. 1)}$$

The inflows include catchment runoff, rainfall over the tank surface, and drainage from the upstream cultivation (depending on the location of the tank in the cascade). The outflows include irrigation releases, evaporation from the tank surface, seepage and percolation losses from the tank, and spillages. Both tank level and cascade-level water management used this equation.

Results and Discussion

Tank-level water management before CRIWMP

Before the CRIWMP, the farmers did not have any idea about the tank storage. While they had a basic understanding of inflows and outflows, they did not know how to quantify them. Therefore, the area to be cultivated was only an educated guess based on past experience.

An overview of the tank-level water management techniques employed by the CRIWMP

The process begins with the establishment of depth-area-capacity curves and the installation of essential monitoring tools such as tank water depth gauges, flow measuring gauges, and rain gauges. These instruments facilitate the accurate collection of reliable hydrological data, enabling the assessment of water availability and use in village tanks using the water balance equation (Nandalal and Imbulana 2022). Water levels and rainfall were measured daily and continuously throughout the irrigation season. A spreadsheet model was developed by the CRIWMP to quantify irrigation duty and losses using the water balance equation (Table 1).

Table 1. Analytical results related to the 23/24 Maha season and 2024 *Yala* season in the *Medde Rambewa* cascade system

Tank Name	Crop	Cultivated Area (ac) *Maha* 23/24	Cultivated Area (ac) *Yala* 24	Irrigation Duty (acft/ac) *Maha* 23/24	Irrigation Duty (acft/ac) *Yala* 24
Pin Wewa	N/C*	N/C	N/C	N/C	N/C
Gallewa Wewa	Paddy	11.00	N/C	2.70	N/C
Pahala Weera Wewa	Paddy	1.00	N/C	N/D**	N/C
Moragaha Wewa	Paddy	50.85	15.00	2.84	3.39
Kivullewa Wewa	Paddy	64.00	N/C	2.75	N/C
Pahala Kivullewa	Paddy	1.00	N/C	N/D	N/C
Hatharas Wewa	N/C	N/C	N/C	N/C	N/C
Aliyawetunu Wewa	Paddy	13.00	N/C	N/D	N/C
Dangaha Wewa	Paddy	5.00	N/D	N/D	N/D
Rachiragama Wewa	Paddy	0.00	N/C	3.19	N/C
Maha Dodaneththawa	Paddy	110.00	70.00	2.81	4.71
Kurunduwetiya Wewa	Paddy	0.00	N/C	3.03	N/C
Meddewa Wewa	Paddy	48.00	30.00	3.02	3.50
Aluth Agara Wewa	Paddy	12.00	N/C	2.91	N/C
Medde Rambewa	Paddy	10.76	10.76	2.85	3.77
Mahameddewa Wewa	Paddy	66.00	66.00	2.39	3.09
Lolugoda Wewa	Paddy	4.00	N/D	N/D	N/D
Piyasumanagama	N/C	N/C	N/C	N/C	N/C

(Source: Water management data system of CRIWMP, 2025); *N/D = No data due to elephant damage to the water depth gauge; * N/C = not cultivated

The results of the system simulation model for 23/24 are presented in Table 3. The results of the spreadsheet model, representing the output of tank-level water management techniques employed by the CRIWMP, showed that they can produce indicators that can motivate the farmers to improve water use and productivity. A comparison of irrigation duties and cropping intensities at the seasonal cultivation meeting can encourage the farmers to use water more efficiently. This model is very useful to quantify irrigation water releases when flow measuring gauges are not operational. It also facilitates making rational assumptions on water use, catchment runoff/rainfall ratio, etc., for the simulation model. However, the spreadsheet model is constrained by its inability to incorporate the complex scenarios that can exist in a large cascade. For example, Kurudu Wetiya *Tank*, receiving inflows from Kuruduwetiya Meegaha Wewa, Kuruduwetiya Koongaha Wewa, and Dangaha Wewa, presents challenges in quantifying all inflows on a time scale due to the variability in rainfall, irregular upstream releases, unmonitored seepage, and fluctuating return flows

from agriculture, making precise hydrological assessments complex. A comparison of the results of the spreadsheet model with those of the simulation model shows that the cascade has the potential to improve productivity in the command area under some tanks. It also facilitates decision-making concerning possible diversions, tank capacity enhancements, etc.

Table 3. Cropping Intensity (CI) of 2023/24 Water Year

Tank Name	Command Area (ac)	Potential Cropping Intensity (Model results)	Actual Cultivated Area (%)		Cropping Intensity Achieved
			23/24 *Maha*	24 *Yala*	
Pin Wewa	6.00	1.6	0	0	0.0
Gallewa Wewa	21.93	1.5	50	0	0.5
Pahala Weera Wewa	8.00	1.7	13	0	0.1
Moragaha Wewa	50.85	1.0	100	29	1.3
Kivullewa	64.00	1.4	100	0	1.0
Pahala Kivullewa	11.67	1.7	9	0	0.1
Hatharas Wewa	19.32	1.7	0	100	1.0
Aliyawetunu Wewa	16.7	0.4	78	0	0.8
Dangaha Wewa	5.00	1.5	100	100	2.0
Rachiragama	14.62	1.8	0	0	0.0
Maha Dodaneththawa	114.2	1.5	96	61	1.6
Kurunduwetiya Wewa	18.81	2.0	0	0	0.0
Meddewa	65.00	2.0	74	46	1.2
Aluth Agara Wewa	14.52	1.3	83	0	0.8
Medde Rambewa	10.76	2.0	100	100	2.0
Mahameddewa Wewa	71.1	2.0	93	93	1.9
Lolugoda Wewa	8.03	1.7	50	50	1.0
Piyasumanagama	9.83	2.0	0	0	0.0

(Source: Unpublished data of the report on Surface Water Management plans, CRIWMP, 2025)

The simulation model can incorporate different scenarios, such as adopting field crops in the *Yala* season and cultivating a middle season *(Meda Kanna),* and produce a variety of options for the farmers and water managers to consider. Accordingly, the study presents that scaling up tank-level management to cascade-level water management can contribute to addressing the challenges of climate change, safeguarding agricultural livelihoods, and promoting sustainable development in the Dry zone. It can be seen that some tanks performed close to the potential performance indicated by the simulation model. Some others performed better, indicating high water use efficiency by the farmers. In some cases, such as Kurunduwetiya and Pahala Weera Wewa, social issues prevented farmers from realizing the potential.

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Need for Groundwater Management: A case study of the Sivalakulam Cascade in the Anuradhapura District of Sri Lanka

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Introduction

Groundwater sources within the cascades of Sri Lanka's dry zone have been widely used for agricultural purposes since the 1980s. Over the past 35 years, groundwater use for agriculture has increased significantly due to the rapid growth in the number of agricultural wells. There are about 150,000 agricultural wells, both large-diameter dug wells and shallow tube wells, within the cascades of the dry zone (Perera 2024). Well densities and groundwater extraction rates vary from one cascade to another. In some cascades, the agricultural well density reaches approximately 27 wells per square kilometer (IWMI 2003).

The Siwalakulam cascade is well known for cultivating cash crops using groundwater sources, particularly during the dry period. It has about 180 agricultural wells distributed across a 19.4 km² area in the regolith aquifer (well density-9.3 wells per square kilometer). The common groundwater intakes used for agricultural activities are lined and unlined dug wells, typically with an average diameter of 6 m and depths ranging from 4.5 m to 11 m. The cascade generally features flat to undulating terrain with isolated hillocks, with elevations ranging from 125 m to 175 m MSL. The area receives an average annual rainfall of 1,600 mm, with more than 180 mm typically recorded in April, October, November, and December, based on 30 years of rainfall data from the Anuradhapura Meteorological Station. There are about 20 Village Irrigation Tanks (VIS) located within three micro-basins (A, B, and C) of the cascade. The distribution of the project area, including VIS and land use in the cascade, is shown in Figure 1.

Groundwater within the cascade exists in a dynamic system and is replenished through the annual climatic cycle and available surface water bodies. When groundwater withdrawals exceed recharge over the long term, the groundwater environment changes compared to its natural condition. Continuous depletion of groundwater levels leads to deterioration in water quality and a reduction in the available groundwater quantity within the cascade. Communities that depend on this resource have experienced significant inconvenience due to the degradation of groundwater in terms of both quality and quantity.

In 2022, groundwater level and electrical conductivity (EC) monitoring were carried out in selected agricultural dug wells across the cascade. The objective of this study was to assess the groundwater behavior within the cascade. Such studies are essential for identifying the

current status of groundwater resources and for proposing strategies for the management of groundwater resources.

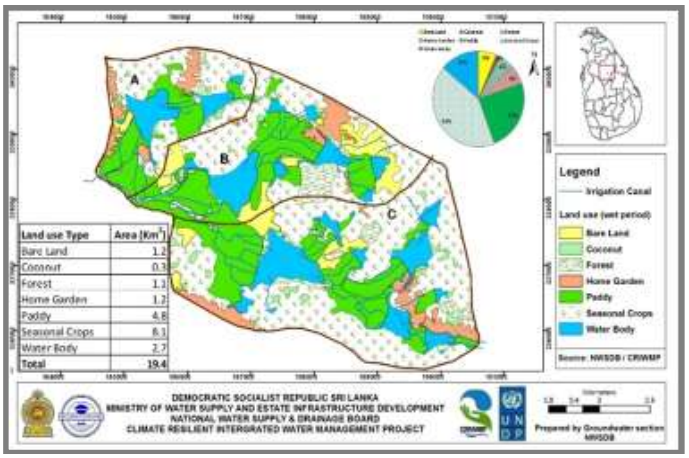


Figure 1. Village irrigation systems and land use of the Siwalakulam.

Methodology

The selection of agricultural wells for the study (Figure 2) was based on field inspections and interviews with local communities by Groundwater Unit (NWSDB). The well depth, water availability and quantity variation during the year, users view on water quality, water level variations, lifetime of well, etc. were collected using structured format.

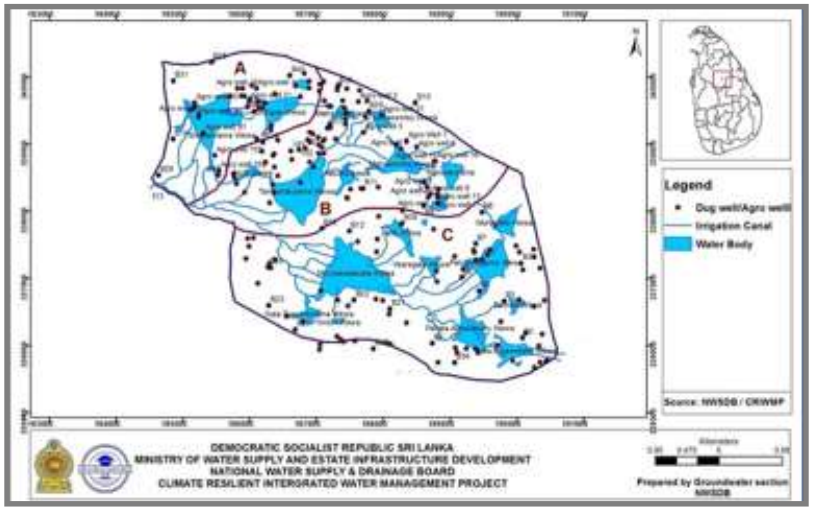


Figure 2. Locations of agricultural and normal wells within Siwalakulam.

Groundwater level variations in selected wells were monitored from February 2022 to November 2022 at monthly intervals. Field measurements of electrical conductivity (EC) were also taken in selected wells for said period. The collected data were analyzed using

GIS methods to prepare maps illustrating groundwater level and EC variations during the first inter-monsoon (May), dry spell (September), and northeast monsoon (November) periods.

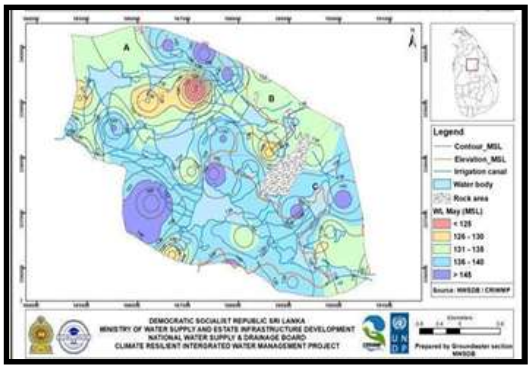
Results and Discussion

About 35 years ago, agriculture in the dry zone depended primarily on the irrigation tank system (Perera 2024). Generally, the cascade behaviour of Village Irrigation Systems (VISs) helps conserve most of the rainfall received within a cascade by reusing return flows from upstream VISs and paddy lands in downstream VISs and paddy lands.

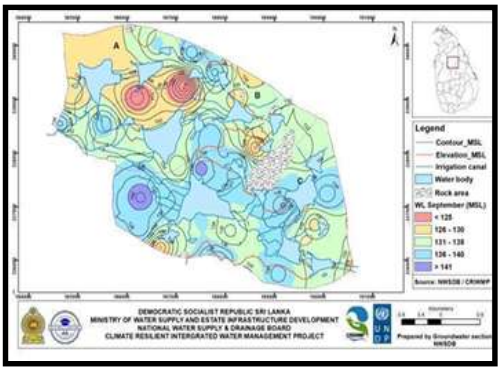
Dharmasena (1994) highlighted that the construction of small tank systems arranged in cascades in the dry zone was a major initiative to maintain groundwater levels. Several studies on the use of groundwater for agricultural purposes have been conducted by various researchers (Farmer 1950; Kikuchi et al. 2003; Panabokke 2002; Madduma Bandara 1973; Dharmasena and Goodwill 1999). Groundwater within a cascade exists in a dynamic system, replenished by the annual climatic cycle and available surface water bodies. Under natural conditions, fluctuations in groundwater levels due to the annual climatic cycle are normal. However, when groundwater withdrawal takes place, the groundwater environment begins to change. The extent of this change is influenced by the volume and pattern of withdrawals, as well as the hydrogeological and hydrological characteristics of the cascade.

Dillon (2009) described three environmental stages of groundwater systems influenced by withdrawals in relation to variations in the annual climatic cycle. The time taken to reach each stage varies depending on recharge conditions: Stage 1: If the annual climatic cycle allows recovery of both storage loss and aquifer drainage loss caused by withdrawals, significant impacts on the groundwater system are unlikely, as withdrawals and recovery remain in equilibrium. Stage 2: This stage can occur when annual rainfall falls below the long-term average in the recharge area. In this situation, recharge to extraction areas decreases, and groundwater withdrawals must be regulated to protect the groundwater environment. At this stage, the groundwater system should be re-evaluated, and withdrawals rescheduled with new, appropriate discharge rates. Stage 3: If groundwater development continues without considering recharge rates, the groundwater environment reaches a critical stage. Reductions in groundwater storage, decreased withdrawal capacity, and changes in chemical water quality may occur even during wet years. At this point, natural restoration of the groundwater environment is no longer possible.

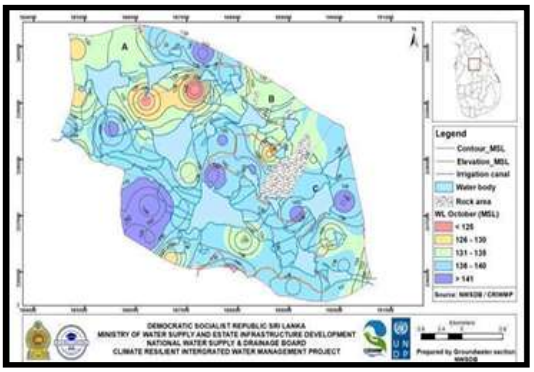
Furthermore, the groundwater environment is increasingly affected by the impacts of climate change. As a result, ecological systems and human communities that depend on groundwater are highly vulnerable, facing multiple challenges related to both groundwater quality and quantity. The variations in groundwater level and EC for May, September, and November are shown in Figure 3 (3.a; May, 3.b: September, 3.c: November), and Figure 4 (4.a; May, 4.b: September, 4.c: November), respectively.



3.a: For month of May`



3.b: For month of September



3.c: For month of November

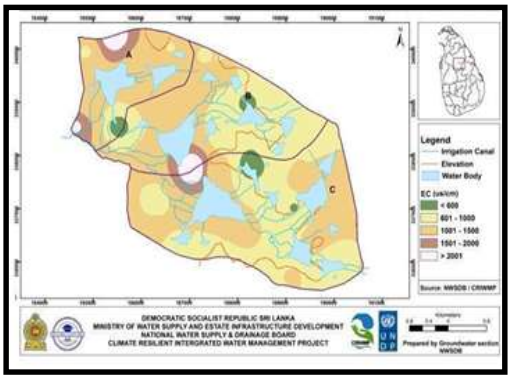
Figure 3: Variation of groundwater level in May, September, and November in 2022 in Siwalakulam (a = for the month of May, b – for the month of September, and c = for the month of November)

Groundwater withdrawal within the cascade is worst in September due to the prevailing drought. Some zones are in the initial stage of impact, while others have been affected for several years. The extent of the impacted area is smaller in May and November compared to September, owing to inter-monsoon and monsoonal rainfall. However, complete recovery of groundwater levels after rainfall has not been achieved.

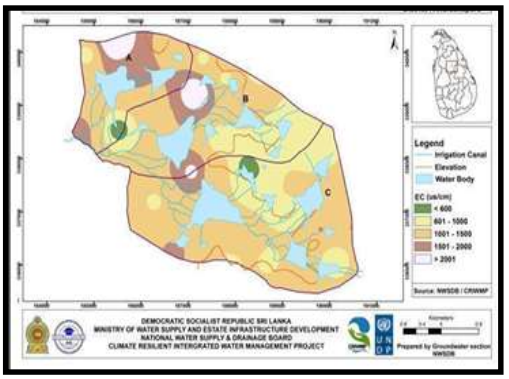
Continuous groundwater withdrawal following the current pattern within the cascade will likely cause further issues related to both water quality and quantity in the future. Also, there are indications for the expansion of impacted zones other than isolated issues. The results also indicate that, under the present withdrawal pattern, the chances of natural restoration of the groundwater environment to regain the loss of aquifer storage and aquifer drainage loss are rare. Therefore, Managed Aquifer Recharge (MAR) is required to restore the groundwater environment, taking into account hydrogeological, hydrological, social, economic, and financial conditions, along with continuous monitoring.

Figure 4 illustrates that relatively low EC patches developed in some impacted zones after the monsoonal rains in November, compared to the other two months. Managing

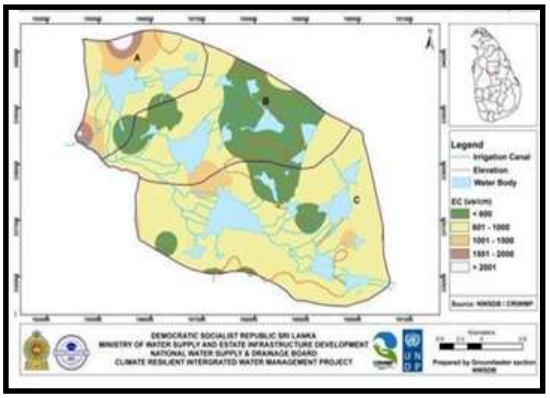
groundwater within a cascade resembles a “wicked” or “messy” problem (Rittel and Webber 1973), involving multiple stakeholders and decision-makers with competing goals.



4.a: For month of May



4.b: For month of September



4.c: For month of November.

Figure 4. Variation of Electrical conductivity (EC) in May, September, and November in 2022 in Siwalakulam (a – for the month of May; b – for the month of September, c – for the month of November)

At present, a system comprising committees at different levels exists to execute and monitor cascade activities, including those related to groundwater. Some activities within the system focus on regulatory measures, while others involve operational measures. However, there are many gaps in the current framework regarding groundwater development, monitoring, and management. Consequently, communities dependent on groundwater within the cascade face significant inconvenience due to the degradation of the groundwater system in terms of both quality and quantity, as well as well interference. The main issues affecting groundwater systems include system complexity, difficulties in characterization, the hidden nature of groundwater, long timeframes for degradation to become evident, interference from multiple users, lack of monitoring data (usage, quality, quantity, etc.), suboptimal governance, inadequate water availability in VISs, poor

management practices, over-extraction, land-use changes, and pollution from various sources. Effective implementation of groundwater management strategies to address these issues is essential to restore groundwater environment to its optimal state without delay.

Conclusion

The groundwater in Sivalakulam is a valuable resource and it has been used cultivation of cash crops for 35 years. The study revealed that groundwater within the Sivalakulam cascade is under threat in terms of quality and quantity due to mismanagement. Therefore, the Effective implementation of groundwater management strategies is essential to restoring the groundwater environment to its optimal state without delay.

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Hydrological and Hydrogeological Characteristics in Selected Cascades for Application of Managed Aquifer Recharge (MAR)

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Introduction

Managed Aquifer Recharge (MAR) has emerged as an effective method to enhance groundwater storage by recharging aquifers using surplus surface water resources. Sustainable groundwater management is crucial for regions dependent on seasonal rainfall and vulnerable to droughts. In Sri Lanka's dry zone, traditional cascade systems networks of small tanks and reservoirs play a vital role in storing and regulating surface water for agriculture and domestic use. However, over-extraction, erratic rainfall, and climate variability have increased the risk of groundwater depletion. This study assesses the hydrological and hydrogeological characteristics of selected cascades to evaluate their suitability for MAR implementation. This study was conducted in Mamunugama, Medderambawa, Sivalakulam and Thuduwakkaikulam cascades (Figure 1).

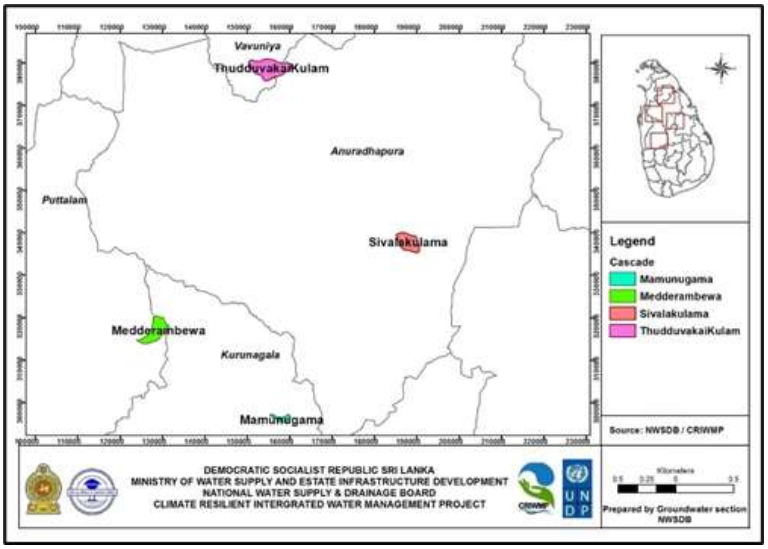

Figure 1. The spatial distribution of the four cascades under CRIWMP

This study attempted to (a) Identify and describe shallow and deep aquifer systems, including overburden thickness, regolith layers, and fractured rock zones, (b) Examine soil types, permeability and infiltration rates to understand groundwater storage and flow patterns, (c) Evaluate the quantity and seasonal variation of groundwater in selected

cascades, (d) Assess the influence of rainfall, temperature, and monsoonal patterns on groundwater recharge and depletion, and (e) Identify suitable sites and design strategies for Managed Aquifer Recharge.

Methodology

Hydrological analysis was carried out using 30 years of rainfall and temperature records to estimate runoff and recharge via the Rational Equation and SCS method. Infiltration rates and hydraulic conductivity were measured in both wet and dry seasons. Aquifer characterization combined well inventory, water level monitoring, and geophysical surveys (1D and 2D) to map aquifer distribution, geometry, and properties. Auger drilling was undertaken to calculate permeability of different land use types and the soil infiltration tests were conducted using double ring method. Pumping tests were conducted to determine aquifer parameters using the Muskat method. Flow nets and overburden maps were developed for both dry and wet periods. The findings indicated the groundwater potential assessment for dry and wet seasons, leading to the preparation of extraction guidelines. Well and aquifer protection measures were developed and supported by awareness programs for local users.

Results and Discussion

Hydrological condition of the cascades

Sri Lanka's tropical monsoonal climate creates three climatic zones wet, intermediate, and dry based on rainfall and physical factors. Areas with annual rainfall below 1,750mm are classified as the dry zone, which experiences a distinct dry period from June to September and frequent seasonal droughts. All four cascades in this study are located within this Dry zone. Across all cascades, temperature patterns follow similar seasonal trends, peaking around March-April and reaching their lowest in December. Mamunugama and Sivalakulama peak in March (~34.6-34.7 °C), Madderambawa in March (33.5 °C), and Thuduwakkaikulam in April (34.9 °C). December records the lowest averages (29.6-30.5 °C), with extremes ranging from about 25.5 °C to 37.45 °C. Temperature variations generally correspond with rainfall patterns.

Rainfall analysis (1992-2022) shows distinct patterns among the four cascades. Mamunugama has the highest average annual rainfall (1454 ± 437 mm) with an increasing trend of 11.14 mm/year, peaking in multiple months. Madderambawa records the lowest (1175 ± 265 mm) with no significant trend. Sivalakulama averages 1400 ± 360 mm, rising 16 mm/year, with seasonal increases. Thuduwakkaikulam receives more rain in October to January and April, and the less in June, July, and March. First inter-monsoon rains usually start in April but can be delayed to May.

Hydrogeological conditions of the cascades

Across the cascades, overburden thickness and geological conditions vary, influencing shallow groundwater availability. In Mamunugama, thickness ranges from about 7 m downstream to 4 m upstream, with bedrock often exposed; mapping revealed both two-layer systems (overburden and bedrock) and three-layer systems with a weathered rock

zone that forms a key groundwater source. In Madderambewa, the overburden 6-12 m in some areas and 15-20 m in others is the main water-bearing zone; resistivity surveys provided subsurface profiles despite reduced clarity from high soil conductivity, and dug wells, 10-22 m deep in clay-rich weathered zones, showed infiltration rates mostly at 6 mm/hr but much higher near certain tanks.

In Sivalakulam, surveys found the topsoil (0.5-1.5 m of Reddish Brown Earth) overlying semi-permeable clay or sandy clay, with some areas containing a 1 m iron-rich nodular layer above a thin clay barrier; beneath lies the weathered rock zone where all wells are excavated. In Thuduwakkaikulam (Figure 2), mapping from resistivity and well data showed an average overburden of about 7 m, thinning to 6-8 m in upstream northeast and southwest areas underlain by garnetiferous charnockitic gneiss, and thickening in the central north over garnetiferous quartzofeldspathic gneiss; upstream and downstream areas commonly have 6-8 m thickness over hornblende biotite gneiss, with local variations along weathered seams.

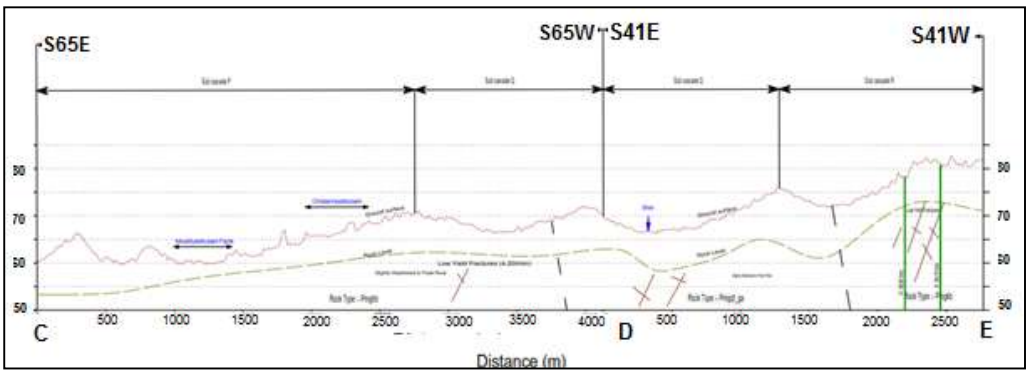

Figure 2. Cross Section across the Thuduwakkaikulam cascade

Behaviors of Aquifers in the cascades

Across the cascades, shallow regolith aquifers act as unconfined aquifers while deeper fractured aquifers are semi-confined, with seasonal variations in water table levels affecting shallow aquifers and limited recharge to deeper ones. In Mamunugama, overburden is thicker in the middle valley and downstream, with 1D and 2D resistivity surveys detailing subsurface conditions. Medderambewa features clay-rich soils with occasional sand layers, two small shallow groundwater basins, and moderate fractured aquifer productivity; infiltration rates range from near zero in paddy fields to 54-180 mm/hr and transmissivity of 0.48-7.45 m^2/day.

In Sivalakulam, aquifers are similarly structured, with climate strongly affecting the shallow aquifer, low infiltration in paddy fields, and transmissivity of 13.82-33.58 m^2/day, while irrigation channels provide most hydrological flow. Overall, residual soils from local rock weathering from the regolith aquifer, with deeper fractured aquifers offering low to moderate productivity. Transmissivity varies in Thuduwakkaikulam from 1.09 - 14.34 m^2/day.

Behaviors of Groundwater level in the cascades

Groundwater levels in all cascades fluctuate with climate, withdrawals, land use, topography, and geology, dropping from June to August and rising from September to January. Upstream areas show larger declines, while downstream areas have smaller changes. Even in dry periods, groundwater sustains springs, streams, and surface water, with observation wells providing essential data on aquifer behaviour. Across the cascades, groundwater levels were monitored from January to November 2023, showing clear seasonal variations. In Mamunugama, levels declined steadily until August due to drought, then rose rapidly with inter-monsoon rains. In Medderambewa, monitoring in the cascade areas showed fluctuations from 73.8- 44.15 m during the wet season and 73.11-41.09 m in the dry season, with maximum drawdown of 5.95 m; groundwater generally flows from upper to lower areas, with significant recharge during the northeastern monsoon. In Sivalakulam, shallow groundwater occurs in the south and deeper in the northeast, with the lowest levels in September and peak saturation in December; inter-monsoon rains cause a minor rise, and a lag exists between rainfall and aquifer response. In Thuduwakkaikulam, groundwater levels ranged from 82.7-54.2 m in the wet period and 80.1-52.9 m in the dry period, with a maximum drawdown of 5.1 m, reflecting seasonal and climatic influences on local hydrogeology.

Groundwater storage in the aquifers

Groundwater storage across the cascades varies with overburden thickness, soil type, and seasonal conditions. In Mamunugama, thin upstream overburden limits storage and stresses vegetation during the dry season, while the upper-middle and downstream sections retain substantial groundwater, with dug wells showing 3-4 m fluctuations. In Medderambewa, clayey soils with low porosity and conductivity result in low water-bearing capacity, with storage varying according to assumed specific yields. Sivalakulam shows full saturation of the overburden during the wet season, particularly in sub-cascades B and C, with porosity ranging from 0.2 to 0.5 and specific yield assumptions used for calculations. In Thuduwakkaikulam, the regolith aquifer holds most groundwater, achieving full saturation in the rainy season due to substantial overburden, though deeper aquifers have limited storage; groundwater levels decline in the dry season, highlighting the dependence of water availability on seasonal recharge and overburden storage capacity.

Groundwater potential in the cascades

Groundwater potential within cascades varies with geological, hydro-geomorphological, and climatic conditions. In Mamunugama, upstream rocky areas with thin overburden have low potential, the middle valley has high potential, and the middle zones are moderate. Groundwater is higher in the wet season, with limited deep aquifer occurrence. In Medderambewa, groundwater is easily accessible during the wet season, but dry-season levels drop, particularly downstream, though wells near large tanks are less affected. Agriculture is limited in dry periods due to climate and water scarcity. Sivalakulam shows moderate to high potential, especially in middle and lower sub-catchments B and C, with dug wells maintaining 2.5 m of water even in the dry season; groundwater is extensively used for cash crops but replenishment largely mitigates significant drawdown. In Thuduwakkaikulam, wet-season groundwater availability is high, supporting agricultural use, but levels decline in the dry season, limiting water for most crops except those

strategically relying on groundwater, such as papaya and coconut. Overall, seasonal and spatial variations strongly influence groundwater potential and usability across the cascades. Based on overburden depths and water level variations in different months, groundwater potential zones were mapped in each cascade (Figure 3).

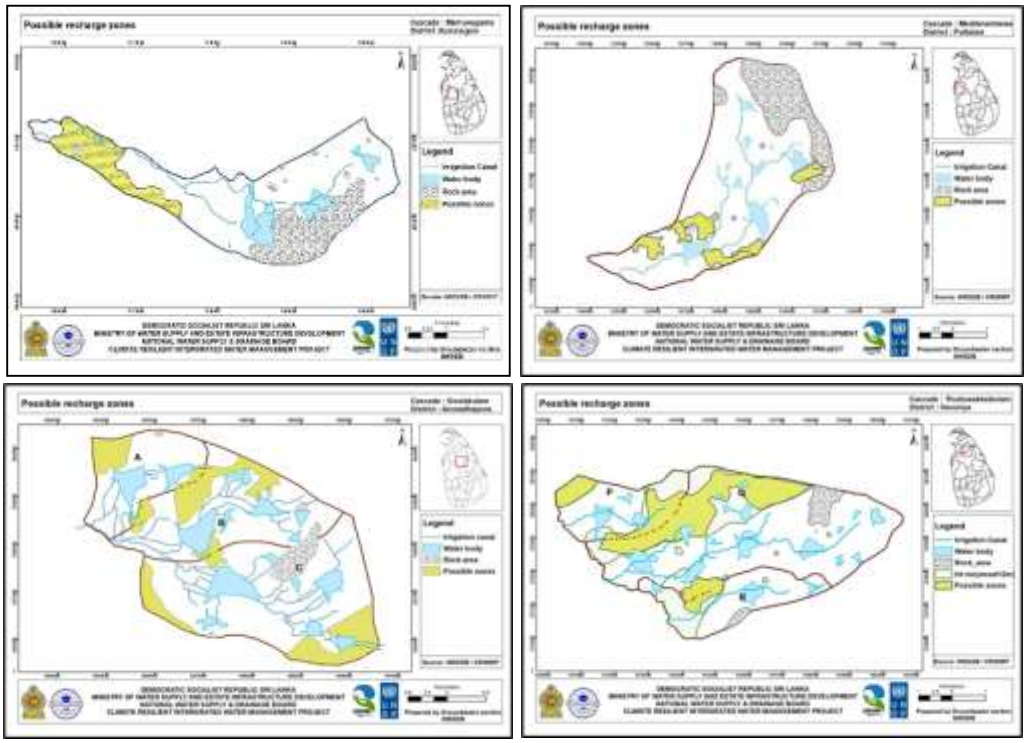

Figure 3. The possible recharge area map of Mamunugama, Medderambewa, Sivalakulam and Thuduwakkaikulam cascade

Conclusion

The hydrological and hydrogeological assessment confirms that the selected cascade systems have promising conditions for implementing MAR techniques. By enhancing natural recharge processes, MAR can help improve water security, sustain agricultural productivity, and build resilience against climate extremes. Further pilot studies and stakeholder engagement are recommended to design site-specific MAR structures and management frameworks. In Mamunugma, Sivalakulam, and Thuduwakkaikulam, groundwater recharging is possible in the identified areas in the inter-monsoon periods, while during the wet season there are no spaces to recharge due to the rising of the water level. In the Medderambewa cascade, the identified areas in the lower part of the cascade are possible for groundwater recharging, but the upper part is not possible for recharging due to having clay-rich soil.

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Community-Based Watershed Rehabilitation: The water towers project on Maragalakanda in Sri Lanka

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Introduction

Climate change effects including increasing temperature, rainfall variability (Lee et al. 2023), and decreasing soil moisture (Seo et al. 2025) impact global water and food security (Turral et al. 2011). In relation to Climate change effect, it has been reported that, ambient temperature, rainfall variability and the frequency of extreme climatic events are increasing (Eriyagama & Smakhtin 2010) while soil moisture is decreasing (De Silva 2006) in Sri Lanka. All these changes impact water supply, agriculture, and human health (Panella et al. 2020; ADB 2021). Forests play an important role in regulating temperatures and freshwater flows (Ellison et al. 2017). Deforestation and anthropogenic land use changes exacerbate climate change impacts, especially in populous countries like Sri Lanka. Rehabilitating forests in watersheds will succeed only if it benefits the people who live there.

The Neo Synthesis Research Centre (NSRC) has rehabilitated several Sri Lankan watersheds for over 25 years. This study describes the rehabilitation of the Maragala Oya watershed at Maragalkanda from 1999-2004 with the aim of creating opportunity for its proliferation. Showcased here is the work done in one landholding of a farmer (pseudonym Rani) where short-term monitoring (1998-2004) and long-term evaluation (2012-2016) revealed how rehabilitation increased livelihood security, reversed forest loss, and sustained watershed health.

Methods

Project Area:
Located in Moneragala District, Maragalakanda receives 1750–2500 mm of rainfall annually in two separate monsoon seasons. Being the watershed of the Maragala Oya Maragalakanda also feeds the Kumbukkan Oya. It has semi-evergreen, tropical wet evergreen, riverine and secondary forests, rubber plantations, grasslands, savannah and traditional *chenas* (swidden agriculture with land rotation and extended fallow). The area is rich in biodiversity, encompassing 427 floral and 353 faunal species (IUCN 2014). Watershed degradation has first occurred in the area when forestland was cleared for tea, sugarcane, and rubber plantations and continues through non-traditional swidden agriculture (modern *chena* done without land rotation or extended fallow) which leads to declining of fertility followed by land abandonment, and eventual reversion to secondary forest. Estate Tamil communities live in the upper watershed area, who do not own land, have limited access to housing, potable water or sanitation, generate meagre incomes

through *chena* cultivation or as labourers. Downstream Sinhala farmers who own land also clear forests for *chena* cultivation. Unsustainable land management, high poverty rates, high biodiversity values and hydrological significance, made the Maragala Oya watershed an ideal choice for watershed rehabilitation.

Rehabilitation aligned with the natural process of seral succession in forest establishment (Fig. 1). Three methods were used including regenerative agriculture, analog forest and conservation forestry.

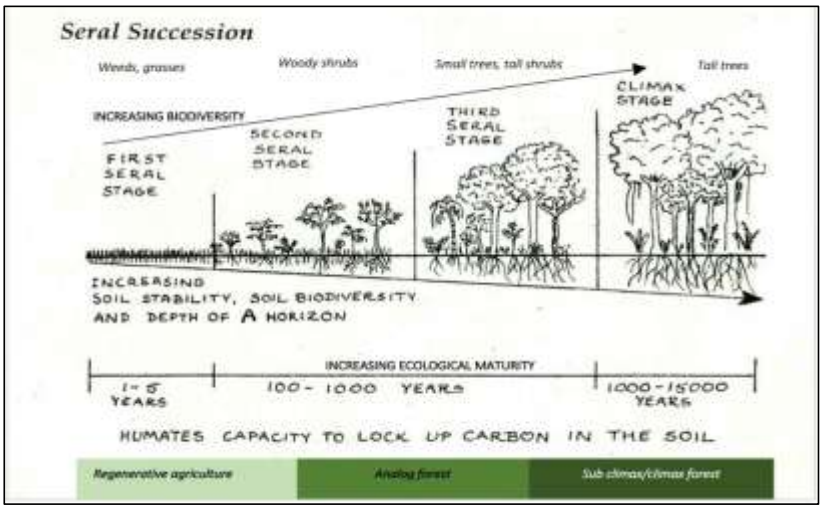

Fig 1. Seral succession depicting regenerative agriculture, analogue forest and climax forest(Source: Senanayake & Jack 1998; Falls Brook Centre 1997). *Note: Regenerative Agriculture means farmers engage in regenerative agriculture that promotes the cultivation of diverse annual and semi-perennial crops using biological inputs only. Analog forest or forest garden (FG) is tree-dominated ecosystem similar in structure and ecological function to the natural forest and formed from regenerative agriculture with seeds of shrubs and trees brought in by birds and animals or that were deliberately cultivated. Analog forestry economically empowers rural communities and continue to become sub climax/climax forests*

The reporting case

Rani was one the farmers who engaged in watershed rehabilitation. Initial discussions focused on households' issues where mainly low and inconsistent on-farm income from *chena* cultivation ($US 95 in the year 2000), was the biggest challenge. The situation was acute in the dry season, with no food stocks in the store and no income generation for the season as stream water neither potable nor sufficient for cultivation. Rani left with no option rather to fell the forest to earn a living.

Uncertain of how to resolve this situation, Rani's household welcomed the prospect of consistent income, food, medicine, firewood, and timber from an Analog Forest or forest garden (FG). They allocated the largest portion of their land to FGs and the balance to cash crop and *chena* cultivation because cash income was essential to satisfy immediate needs.

In 1999, Rani's 3.2 ha landholding was part of a landscape mosaic comprised of undisturbed and disturbed natural forest remnants, feeder streams of the Maragala Oya, another farmer's landholding and paddy fields. It was a slopy, rocky and eroded land. Sparse vegetation provided minimal habitat for wildlife. There was no water source except three gullies where streams had dried up. Growing conditions were unfavourable.

Establishment of Forest garden:

The proposed FGs were modelled on the forest above Rani's landholding. Vegetation mapping (Küchler & Zonneveld 1988; Senanayake 1989) of this forest revealed broad-leaved and evergreen trees and shrubs across four strata (ground, low, mid and upper), as well as other growth forms including forbs, climbers, grasses and lichens. A low density of species, 6–25% canopy closure, and the presence of exotic species signified that the forest was disturbed. This context was used for the landscape design of the FG which also considered topography, water, and wind flows of the location.

The FG landscape design mimicked the vegetation structure of the adjacent forest and aimed to provide the same ecological functions and services by using both crop and non-crop species. Annual crops were initially cultivated across central open areas in raised beds using soil excavated from contour drains dug to prevent erosion and increase water infiltration. Perennial, small, and large trees for fruit, nut, spice, timber, and firewood were planted in between the vegetable beds. Table 1 describes the species used in Rani's FGs by stratum, height class and ecosystem services.

Over 5000 plants in 175 species were established of which half provided food, medicine, timber, firewood, ornament and biopesticides and were either used for household consumption or sold to generate income. Several plants had multiple values, such as jak provides food, timber and fodder while actively increasing soil organic matter owing to its voluminous leaf litter. Plants with ornamental values, pesticide effects, ecosystem regulator effects, mitigation of soil erosion were grown to improve the stability of the system. Use of native forest species in the boundary of the disturbed forest enabled biodiversity movements across the buffer zone.

Table 1. Species used in Rani's FGs by stratum, height class and ecosystem services

Ecosystem Services	Height Class	Crops
Food and Medicine	**Upper Mid**	*Vateria acuminata* Avocado, Bengal quince, Breadfruit, Brindleberry, Cashew, Ceylon almond, Ceylon cherry, Ceylon date, Ceylon olive, Cloves, Cocoa, Curry leaf, Ice cream bean, Indian gooseberry, Jak, King coconut, *Madhuca longifolia*, Malay apple, *Mangifera zeylanica*, Mango, Mangosteen, Pebble tamarind, Rambutan, Sapodilla, Soursop, Tamarind, *Terminalia bellerica*, *Terminalia chebula*, Woodapple

	Low	Banana, Bilimbing, Cardamom, Cinnamon, Coffee, Custard apple, Drumstick, Guava, Jam fruit, Lemon, Lime, Mandarin, Orange, Papaw, Pomegranate, Pomelo, *Sesbania grandiflora*, Starfruit, *Wrightia antidysenterica*
	Forest floor	*Alternanthera sessilis*, *Amaranthus spp.*, Aubergine, Bird chillie, Bitter gourd, Black gram, Bottle gourd, Bush bean, *Canna indica*, Capsicum chillie, Cassava, *Cassia auriculata*, Cowpea, Ginger, Horse gram, *Lasia spinosa,* Leafy cabbage, Long bean, Melon, Okra, Pineapple, Pumpkin, Purple yam, Radish, Red chillie, Ridge gourd, Snake gourd, Squash, Taro, Tomato, *Trianthema portulacastrum*, Turmeric, Winged bean
	OGF	Palms: Caryota urens, Coconut, Climbers: Ceylon spinach, *Cardiosperm halicacabum*, Gotukola, Kankun, Passionfruit, Black pepper, *Piper betel, Piper longum, Salacia chinensis,* Sweet potato. Grasses and tuft plants: Lemongrass, *Pandanus amaryllifolius*
Riparian buffer, water filtration	**Upper**	*Calophyllum sp., Horsfieldia eriya, Mathuca longifolia, Mangifera zeylanica, Terminalia arjuna*
	Mid	*Garcinia terpnophylla, Mesua nagarissum, Mimusops elengi, Myristica dactyloides, Nauclea orientalis, Pongamia pinnata*
	Low	*Alpinia calcarata, Alpinia nigra, Alpinia zerumbet, Clerodendron sp., Clerodendrum chinense, Dillenia retusa, Pagiantha dichotoma, Strobilanthes asperrima*
	Forest floor	*Aponogeton crispus, Acorus calamus, Costus speciosus, Jussueia repens, Lagenendra sp., Nymphaea nouchali, Spathyphyllum pattini*
	OGF	Palms: Arecaunt; Grasses and tuft plants: *Pandanus kaiida*, Yellow bamboo
Shade, covering rocks	**Upper**	*Alstonia scholaris, Ficus racemosa, Samanea saman*
	Mid	*Adenanthera pavonina, Bridelia retusa, Dimocarpus longans, Ficus bengalensis, Mallotus phillipensis, Sterculia foetida, Syzyguim assimile, Tetrameles nudiflora, Trema orientale*
	Low	*Ficus hispida*
	Forest floor	*Munronia pumila*
	OGF	Palms: *Calamus rotang; Climbers: Anamirta cocculus, Pothos scandens;* Succulents: *Aloe vera, Kalanachoe pinnata, Sansevieria zeylanica*
Ornamental	**Upper**	*Delonix regia*
	Mid	*Cassia spectabilis*, *Lagerstromia speciosa, Spathodea campanulata, Tabebuia rosea*
	Low	*Caesalpinia pulcherrima, Heliconia spp., Tecoma stans*
	Forest floor	*Anthurium sp.*

	OGF	Epiphytes: *Orchid spp.*
Timber, firewood	**Upper**	*Antiaris toxicaria, Berrya cordifolia, Melia dubia, Michelea champaca*
	Mid	*Chloroxylon swietenia, Chukrasia tabularis, Diospyros ebeneum, Filicium decipiens, Vitex altissimia*
Biopesticide	**Upper**	Neem
	Low	*Vitex negundo*
	Forest floor	*Andrographis paniculata*, Marigold, *Sida spinosa*
	OGF	Grasses and tuft plants: *Vetiver zianoides*
Green Manure	**Mid**	*Ceiba pentandra*
	Low	*Cassia alata, Erythrina lithosperma, Gliricidia sepium, Pavetta indica*

Note: ES - Ecosystem services; Upper - > 20m, Mid: 2-20 m, Low understorey - 0.5-2m, Forest floor or ground - 0.1-0.5m; OGF - Other growth forms

Since Rani had no water source, water from a wetland above the landholding was diverted and distributed through the dry gullies into a series of holding ponds that in time would percolate into the ground and recharge dormant aquifers. An irrigation line supplied stream water from the upper watershed for household needs.

Record keeping and monitoring:

Once the tree crops started to mature and shade conditions were established, annual crops were gradually replaced with shade-loving, semi-perennial crops (e.g., black pepper). The majority (52%) of all FG crops were trees. Planting records were monitored by mapping trees and other vegetation planted annually. Also assessed were changes in shade, leaf litter, soil organic matter, and biodiversity: surface (butterflies, birds, mammals, ants, snails, reptiles, amphibians), soil (earthworms) and aquatic (fish). These rapid assessments indicated that with high volumes of leaf litter from trees there was greater organic matter in soils and more frequent observations of soil biodiversity.

Two long-term evaluations of rehabilitation were undertaken after the project ended. The first assessed biodiversity changes after project closure in 2004. Birds were selected as indicators of habitat quality, and their species richness, diversity and community composition compared between Rani's FGs and adjacent forest remnants (Gunasekera 2004). Results revealed that bird species richness in Rani's FGs was nearly the same as that in the forest plots surveyed. The mean number of non-forest bird species in Rani's FGs was higher than the mean number of specialist forest bird species, signifying that habitat in these four- year-old FGs was not as ecologically mature as in forest remnants.

The second evaluation undertaken in 2012-2016 (Melvani 2019) was multidisciplinary and focused on why and how farmers at Maragalakanda including Rani, valued FGs.

Results and Discussion

The economic evaluation revealed that there the greater crop diversity provided Rani's household with income throughout the year. Data revealed that annual income increased from $US 95 in 2000 to $US 280 by 2004. During the FG establishment process, the microclimate in the landholding has been regulated by shade created by 20 species of fast-growing trees, palms, climbers, and succulents planted around and between rocks. Leguminous and non-leguminous trees, shrubs and grasses used as hedgerows on contours for soil conservation or for green manures have been useful in making compost and liquid fertilizer, essential to regenerative agriculture.

By 2013, vegetation in Rani's landholding had matured into distinctive land use areas, including four FGs (1-4), paddy fields, *chena* and cash crop plots (Figure 2). Shade conditions had increased bringing a cooler microclimate owing to greater canopy closure in FGs 1, 2 and 3. Conversely, FG 4 had open conditions because trees had been harvested for timber. In contrast, the previously open and very rocky *chena* area had greater vegetation and canopy closure. The cash crop area, however, still maintained semi-open conditions.

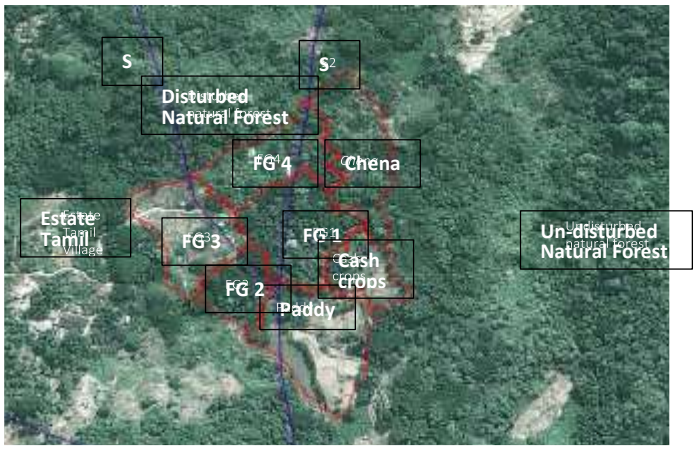

Figure. 2. Google Earth image of Rani's landholding in September 2012, 13 years after rehabilitation began in 1999, depicting forest gardens, FG1-4, *chena* and cash crop plots, paddy fields, an adjacent Estate Tamil village, feeder streams S2 and S3 of the Maragala Oya (in purple), and disturbed and undisturbed natural forests.

Although Rani cultivated diverse crops across her landholding, crop diversity was higher in FGs compared to all other land uses. Most crops provided food and Ayurvedic medicine, while others provided firewood and timber (Melvani Bristow et al. 2020). By the year 2013, more than half of Rani's landholding was under FG land use which had become the biodiversity corridor between disturbed and undisturbed forests prompting Rani to say that, "I hear birds singing and realise that the value of my land has increased" (Melvani et al. 2022). Increased leaf litter in Rani's FGs had resulted in higher organic matter in soils and consequently greater soil moisture retention, fertility, and productivity. This was evident in 2013 when Rani's total income increased to $US 32,241. Of this value, almost 80% ($US

25,642) was from FGs. Substantial income was generated from the sale of timber harvested in FG 4 ($US 22,918), and the sale and household consumption value of vegetables, pepper, coconut, and fruits ($US 2,724) cultivated in FGs 1–3. The household was food secure because nearly 60% of what they consumed was grown in FGs. Greater financial prosperity enabled Rani to educate all her five children, buy land and vehicles for them, and hence the family did not need to clear forests for their livelihood anymore.

While timber sales generated massive returns in 2013, the estimated Net Realizable Value of remaining timber and firewood stocks in Rani's landholding had increased to $US 3,308 by 2016 (Melvani Myers et al. 2020). These biological assets were her insurance against new challenges including increasing rainfall variability, animal pests and the rising cost of purchases (fuel, electricity) (Melvani et al. 2022). Moreover, many Maragalakanda farmers acknowledged that deep-rooted trees and other riparian vegetation planted around holding ponds and along gullies had enabled aquifer recharge of dead streams (Oakes & Penna 2014). Watershed rehabilitation undertaken at Maragalakanda increased livelihood security, reversed forest loss, and sustained watershed health.

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Understanding relationships between ocean atmospheric oscillations and rainfall for better irrigation water management

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Introduction

The ocean-atmospheric circulations involve distributing the thermal energy received from the sun and balancing the Earth's climate system in an annual pattern. Nevertheless, the Earth's climate endures regular cyclical/repetitive/recurring changes which have different time scales from a few months to decades and influence global weather patterns. This repetitive phenomenon is declared as climate oscillation or ocean-atmospheric oscillation (OAOs) and they are based on the changes in atmospheric air pressure, sea level pressure (SLP) sea surface temperature (SST), and wind direction over oceans.

Despite many OAOs, some could act as precursors for changes in weather in the Indian Ocean and allied countries, and some originated from the Indian Ocean itself. It is identified that El-Nino Southern Oscillation (ENSO) intensity is the primary mode which influences the diversity of the South Asian summer monsoon by modulating the Walker circulations. ENSO is the oscillation in the tropical Pacific Ocean at 2 – 7 years of periodic fluctuation in SST in the eastern and central equatorial Pacific Ocean. ENSO is monitored through SST anomalies in four equatorial Pacific regions commonly known as Nino regions, i.e., Nino 1&2, Nino 3, Nino 3.4, and Nino 4. SST anomaly over +0.5°C identified as El-Nino (warm ENSO) phase and on the other hand, -0.5°C was declared as La-Nina (cold ENSO) phase.

On the other hand, the SST variation in the Indian Ocean causes changes in the Indian Ocean Walker circulation, which changes the tropical monsoon patterns and the precipitation in the affected regions including tropical regions, the Arabian Sea region, and the Australian continent. Therefore, the Indian Ocean Dipole (IOD), commonly known as Indian Nino, is the OAO derived based on the dipole pattern of SST between western (10◦S–10◦N, 50◦E–70◦E) and eastern (10◦S–0◦, 90◦E–110◦E) Indian Ocean (Pathirana et al., 2024; Park et al. 2024).

The spatial and temporal diversity of rainfall of Sri Lanka depends on the location of Sri Lanka a) in the Indian Ocean, b) near to the land mass of India, and c) within the Bay of Bengal, and the presence of a perpendicular central mountainous region in Sri Lanka and vulnerable to the influence of ENSO and IOD (Kajakokulan et al. 2025; Abeysekera et al. 2019).

Since OAOs are large-scale, it is suggested that micro-scale i.e., country-level impact identification, is necessary to mitigate disasters originated due to the changes in phases of OAOs (Sumathipala 2014). This study aimed to identify the relationship between ENSO and IOD in annual and seasonal rainfall in Anuradhapura, Sri Lanka.

The staple food Sri Lanka – rice requirement is catered by paddy cultivation under rainfed and irrigated agriculture. Furthermore, the paddy crop is highly susceptible to changes in the availability of water during its cultivation period. Anuradhapura district in the Dry Zone of Sri Lanka has the highest potential to cultivate paddy due to the fertile soils in the region, and it is the bread-winning income for the people residing in the region (Jeewanthi et al. 2021). Therefore, changes in mean annual or seasonal rainfall could influence agriculture as well as aligned sectors, including food security and the economy of Sri Lanka.

Methodology

The daily rainfall data was collected for Anuradhapura station for the duration of five decades i.e., 1961 to 2015 from the Meteorological Department of Sri Lanka. The daily rainfall data were arranged into monthly rainfall data and mean annual rainfall, total monthly and total seasonal rainfall i.e., December to February (DJF), March to May (MAM), June to August (JJA), June to September (JJAS), September to November (SON), and October to December (OND) were calculated to assess the above/below average monthly and seasonal rainfall.

The five-month mean monthly SST anomaly data were downloaded from the Japan Meteorological Agency (https://data.coaps.fsu.edu/pub/JMA_SST_Index/) to calculate ENSO phases. The SST anomalies within the ±0.5℃ were identified as neutral ENSO phase. The SST anomalies of +0.5℃ and –0.5℃ were identified as warm and cold ENSO phases, respectively. Nino 3.4 region was selected for the study.

Dipole Mode Index (DMI) Monthly Time-series data were downloaded from the NOAA Physical Science Laboratory (https://psl.noaa.gov/data/timeseries/month/DMI/) to identify the positive and negative IOD modes. The SST anomalies of +0.4℃ and –0.4℃ were identified as positive and negative IOD phases, respectively. The correlation analysis was performed to identify the relationship between different indices on total seasonal rainfall.

Results and Discussion

Anuradhapura region receives more rainfall from the northeast monsoon for *Maha* (Major) cultivation season

The annual total rainfall for the Anuradhapura station varied between 767.9 mm (in 1988) and 2483.2 mm (in 2014) and the average annual total rainfall for the station is 1326 mm. Jeewanthi et al. (2021) identified low annual rainfall of 892–1159 mm from 1985 to 1989 and a gradual increase from 1990 to 2014. Moreover, based on the Mann-Kendall test, a significant increasing trend ($P<0.05$) in annual rainfall was identified for the station. The location of Anuradhapura favours the reception of high rainfall during October to March

from the second inter-monsoon, northeast monsoon, and onset of the first inter-monsoon. The mean monthly rainfall results revealed that the study region received higher rainfall during October to December and gradually decreased during January to March (Table 1).

Table 1. Mean monthly rainfall distribution in Anuradhapura station

Month	Mean monthly rainfall (mm)
January	88.5
February	56.2
March	68.5
April	165.1
May	80.2
June	13.5
July	25.7
September	38.8
October	70.7
November	258.7
December	247.4

The mean seasonal rainfall during the SON, OND, DJF, and MAM seasons showed higher seasonal rainfall compared to residual seasons (Figure 1).

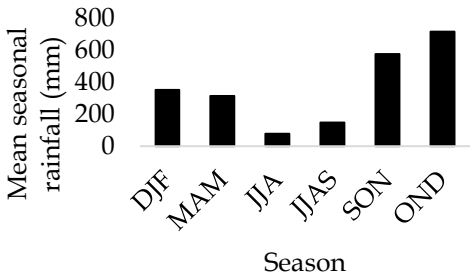

Figure 1. Mean seasonal rainfall distribution of Anuradhapura station

The *Maha* (Major) cultivation season falls from September to March and, according to the results, the mentioned season is wet compared to the *Yala* (minor) cultivation season in the study region (Figure 1). Furthermore, Jeewanthi et al. (2021) concluded that rainfed agricultural activities in the Anuradhapura area are at low risk because of a significant increase in annual and seasonal rainfall i.e., during *Maha* and *Yala* seasons.

The prominent below-average rainfall – an eye opening for drought mitigation

The results identified that all the months received below-average monthly rainfall for more than 60% of the years considered for the study (1961 to 2015) except for October, November, and December it is more than 56%. All the seasons showed more than 50% of below-average seasonal rainfall for the selected study period. Therefore, considered OAOs; IOD and ENSO could modulate the circulation of the winds carrying moisture over Anuradhapura station.

The correlation results showed that mean monthly rainfall in May and October is positively correlated with the positive IOD and warm ENSO phases at higher magnitude compared to other months (Table 2).

Table 2. Correlation of mean monthly rainfall and indices based on sea surface temperatures in the Indian Ocean and Pacific Ocean (Nino .4 region)

Month	Correlation	
	DMI	SST anomaly at Nino 3.4 region
January	0.068	-0.283
February	-0.096	-0.243
March	0.046	-0.294
April	0.078	0.084
May	0.124	0.368
June	-0.056	0.059
July	-0.054	-0.264
August	-0.208	-0.008
September	-0.227	-0.025
October	0.376	0.372
November	0.068	0.306
December	-0.106	0.060

The presence of positive IOD and warm ENSO during the onset of the main rainfall seasons i.e., the southwest monsoon begins in May and the second inter-monsoon begins in October would give above-average rainfall for Anuradhapura. It is necessary to understand that the opposite phenomenon could be observed during negative IOD and cold ENSO phases. Nevertheless, positive IOD and warm ENSO phases trigger the below-average seasonal rainfall for the study region during the offset of the southwest monsoon i.e., June to September (Table 2). Hence, the offset of the southwest monsoon falls on the *Yala* cultivation season and the onset of the *Maha* season. Therefore, precautions have to be taken to safeguard the remaining water available in the major reservoirs and minor tank cascade systems available in Anuradhapura district for irrigated cultivation. Furthermore, strategies have to be adopted to conserve the antecedent moisture levels for the upcoming *Maha* cultivation.

The coupled influence of IOD and ENSO on changes in mean monthly rainfall in Anuradhapura is yet to be studied. The northeast monsoon is the most important rainfall season for Anuradhapura district and is highly susceptible to changes in ENSO phases. Warm ENSO phases could give below-average seasonal rainfall and persistent El Nino events could migrate into drought conditions in the region, which could affect agriculture, domestic water and food requirements. Furthermore, the food security of the country could prevail for upcoming cultivation seasons, too.

1982/83 and 1997/98 are identified as the strongest *El Nino* years observed in the world (Paek et al. 2017). Based on the results, 1982/83 received below average rainfall for the northeast monsoon and the first inter-monsoon rainfall seasons. Nevertheless, during 1997/98, only the first inter-monsoon was affected and received below-average seasonal rainfall.

The prevailing positive IOD phase weakened the offset of the southwest monsoon and the onset of second inter-monsoon (Table 2). Furthermore, the same IOD phase triggers the above-average seasonal rainfall during the first inter-monsoon for the study region, which favours rainfed farming, i.e. rainfed land preparation.

Conclusion

The paddy cultivation in Anuradhapura district practice extensively due to the presence of fertile soils and water availability a) during the northeast monsoon and the first inter-monsoon, and b) presence of major reservoirs and minor tank cascade systems. Nevertheless, OAOs such as ENSO and IOD alter the regular rainfall pattern in the region and this study identified that the presence of ENSO warm phases provides below-average seasonal rainfall and may trigger the drought conditions in the region. Furthermore, positive IOD phase provides above-average seasonal rainfall during the first inter-monsoon for Anuradhapura region.

Therefore, understanding the behaviour of OAOs associated with Sri Lanka is crucial to a) managing water resources, especially reservoirs and the minor tank cascade systems in Anuradhapura region, and b) mitigating natural disasters caused by the drought. The prediction of ENSO and IOD indices is available in easily accessible online sources, and research institutions/Universities could develop statistically validated predictive tools to forecast a) spatial and temporal rainfall occurrences, b) water availability in the reservoirs/tanks, and c) antecedent moisture content in the soils. The integration of predictive tools and their information for decision making in cultivation i.e., type of crop, cultivated area, cultivating strategies, and reservoir scheduling would provide effective resources to cater to integrated water resources management as well as to secure food availability in Sri Lanka.

Acknowledgement

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Changes in Socio-Economic Status of Women Due to the Establishment of Roadside Markets in the Polonnaruwa District of Sri Lanka

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Introduction

In rural Sri Lanka, women's economic participation has traditionally been constrained by socio-cultural norms, limited mobility, and inadequate market access. The establishment of roadside markets in the Polonnaruwa District of Sri Lanka represents a localized intervention aimed at addressing these barriers by creating accessible, low-cost business opportunities. While such initiatives are often praised for income generation, their broader impact on the socio-economic status and empowerment of women has not been thoroughly explored.

This study addresses a critical gap by examining how participation in roadside markets affects women's income, employment patterns, household decision-making, and social roles. The research aims to assess these impacts in a structured, empirical manner, thereby contributing to both gender studies and local economic development literature.

Methodology

The study adopted a mixed-methods approach, combining quantitative and qualitative data collection. A pre-tested structured questionnaire and follow up interviews were administered to 26 women vendors across multiple roadside market sites in Polonnaruwa, Sri Lanka. The survey captured data on income levels, sources of goods, education, expenditure patterns, business ownership, and perceived empowerment.

Data Collection:
Twenty-six (26) women vendors from multiple roadside markets in Polonnaruwa District were randomly selected.

Data Analysis:
Variables assessed were the Income level, product sourcing, expenditure patterns, educational background, empowerment indicators, and support needs. Quantitative data were analyzed using descriptive statistics (frequency, range, averages). Qualitative

responses were coded thematically to identify recurring patterns related to empowerment, decision-making, and community engagement.

Results and Discussion

Economic Impact

The establishment of roadside markets has enabled women to enter income-generating activities with minimal financial investment. Earnings vary significantly, reflecting differences in business scale and product type, where the monthly income (Table 1) ranged from less than LKR 5,000 (approx. US$ 16) to over LKR 50,000 (approx. US$ 167). The primary expenditure included children's education, food and daily necessities, healthcare expenses, and home improvement (sanitation, roofing, etc.). This illustrates that the markets directly support family welfare and intergenerational benefits.

Table 1: Monthly Income Distribution of Women Vendors (n=26)

Income Range (LKR)	Number of Respondents	% of Sample
Less than 5,000	4	15
5,001 – 15,000	9	35
15,001 – 30,000	8	30
30,001 – 50,000	3	12
Above 50,000	2	8

Employment and Business Ownership

A substantial number of women in the study are self-employed, using the roadside markets as a means of achieving economic independence. Product sourcing is largely localized, with goods obtained from home gardens, local farms, neighbouring producers, and forests, thus reinforcing the importance of natural and community-based resources in sustaining their livelihoods. The types of businesses operated by these women are diverse, including the sale of vegetables, fruits, cereals, forest products, medicinal herbs, honey, and spices, showcasing their versatility and entrepreneurial spirit.

Social Changes

Participation in the markets has led to broader social changes, especially in the roles women play within their households and communities. The observed transformations include, (a) Married women (majority) contributing directly to household finances, (b) Varied education levels of women, but success was not limited by formal schooling, and (c) Women have gained greater decision-making power, confidence in managing finances, community respect as business owners. These align with empowerment theories that emphasize capability development and control over resources (Sen 1999).

Challenges and Support Needs

Despite gains, women vendors have faced several challenges. Price discrimination, difficulty in negotiating with customers, insufficient storage, and limited vending space were among the most frequently mentioned issues. However, many participants acknowledged receiving

support through development projects, including access to shop spaces, training programs, packaging materials, and financial assistance. Future support needs include capacity-building training, machinery access, improved infrastructure, and working capital to scale up operations and sustain market participation.

Opportunities for Growth

Sales volume tends to peak during weekends and public holidays, capitalizing on increased traffic from tourists, commuters, and local shoppers. The strategic location of the markets—along the Trincomalee main road—plays a crucial role in ensuring visibility and customer flow. Respondents also expressed a desire to diversify their product range, with ambitions to introduce processed foods, dairy items, poultry products, and value-added agricultural goods, highlighting their growth mind-set and potential for business expansion.

The establishment of roadside markets in Polonnaruwa in Sri Lanka has emerged as a transformative initiative for rural women, offering not only income-generating opportunities but also a platform for socio-economic mobility. This study provides empirical evidence that such markets have facilitated increased income, employment, and business ownership for women, despite socio-cultural constraints that typically limit their public and economic participation.

Ability of women to translate economic gains into household welfare improvements—notably in education and health—is a critical indicator of sustainable development. These findings align with broader development literature that underscores women's income as a direct pathway to enhanced family outcomes and community resilience (Kabeer 1999; World Bank 2012).

Moreover, the increase in decision-making power and self-confidence reported by the participants signifies a shift in gender dynamics. Business ownership has enabled women to challenge traditional domestic roles, contributing to their personal empowerment and social recognition. This aligns with Sen's capability approach, where real freedom to act and make choices is central to empowerment (Sen 1999).

However, the persistent barriers related to infrastructure, market competition, and access to financial services signal the need for continued institutional and policy-level interventions. Public-private partnerships, inclusive training programs, and targeted subsidies could further enhance these market models, especially when tailored to the specific needs of rural women entrepreneurs.

Conclusion

The roadside markets in Polonnaruwa, Sri Lanka have made a positive and measurable impact on the socio-economic status of rural women. Through increased income, business ownership, and enhanced decision-making capacity, women have experienced greater financial independence and empowerment. The markets have also played a pivotal role in improving family well-being, especially in education and health.

Nevertheless, challenges remain—particularly regarding price fairness, infrastructure limitations, and business expansion support. Addressing these gaps through targeted policy interventions and capacity development programs will be vital for maximizing the long-term benefits of this initiative.

As such, the roadside market model presents a scalable and sustainable approach for rural economic development and gender empowerment. Replicating and strengthening such interventions in other districts may yield similar benefits, contributing to inclusive growth and social transformation in Sri Lanka.

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Effects of mobile markets on Livelihoods of Rural Women in Anuradhapura, Kurunegala, and Trincomalee Districts in Sri Lanka

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Introduction

Rural women in Sri Lanka play a vital role in agriculture and food security, contributing significantly to the country's agricultural workforce (UNDP, 2023) They face numerous challenges, including limited access to markets, finance, and technology, which hinders their economic empowerment, leading to food insecurity, poverty, and inequality (FAO 2018; Perera and Wickramasinghe 2018). There is a significant research gap in assessing the potential effects of mobile marketing in improving rural women's livelihoods. Previous studies have focused on the effects of mobile technology on agricultural productivity and market access with limited attention to the specific needs and challenges of rural women. A temporary selling and buying place for agricultural products produced through climate-smart agriculture (CSA), such as conservation agriculture, agroforestry, and integrated pest management, promotes sustainable agriculture and ecological products, and offers a potential solution to these challenges.

The broad objective of this study was to evaluate the women's economic development, food security, and women's empowerment through the establishment of mobile markets. The specific objectives were (i) to evaluate the product diversity, value-addition, (ii) to evaluate the access of the mobile market by women, (iii) to evaluate the food security of vendors, producers, and customers, and (iv) to measure the customer, vendor, and producer satisfaction related to the mobile market.

Methodology

Data were collected from customers, women vendors, and women farmers in mobile markets established in the Provincial Department of Agriculture, Provincial councils, hospitals, university premises, and the district secretary's office in Anuradhapura, Kurunegala, and Trincomalee districts by the Climate Resilient Integrated Water Management Project (CRIWMP). Farmers and vendors were selected purposely, and customers were selected randomly when they came to purchase the products. Twenty customers, 20 farmers, and three vendors selected from each district. A survey was conducted using a pre-tested structured questionnaire. Socio-demographic information

from customers, vendors, and farmers was obtained. Information on land size, type of home garden, selling products, the way of supply products for the market, reason for mobile marketing, monthly income from the market, main expenditures from the market and vendor details were reason for mobile marketing, main opportunities gain through the mobile market, monthly income, project support, high sales observed, main challenges, main requirements for further developments, main expenditures for income from mobile market, main changes due to project intervention and under customer survey section visit frequency to mobile market, products purchase, aware about the market type, main opportunities for customers were obtained from the farmers. Field observations were conducted to gather qualitative data on the mobile marketing initiatives and the challenges faced by rural women. Observations were recorded using a field observation guide. Quantitative analysis was done using SPSS.

Results and Discussion

The demographic data revealed that the majority of mobile market vendors were women (89%), all of whom were married and engaged in farming-related occupations. Their educational backgrounds were mostly limited to secondary and GCE O/L level, indicating that mobile markets serve a population with moderate educational attainment. Most women had moderate agricultural experience, with about 74% involved in mobile marketing for more than two years. Furthermore, 85% of vendors owned home gardens, emphasizing that mobile markets are predominantly supplied by self-grown products. This demographic profile underscores the importance of mobile markets in empowering women with limited mobility and formal education. The high participation of women suggests that mobile markets are accessible and culturally acceptable platforms for female engagement in economic activities. The proximity to farms and the ability to perform other domestic responsibilities concurrently were primary motivators, supporting the concept that mobile marketing is a flexible, low-barrier strategy for livelihood enhancement among rural women.

A variety of products were sold in the mobile markets. The most common were vegetables (74%) and fruits (59%), followed by leafy vegetables (26%), eggs (22%), cereals (22%), and processed products (18%). However, the sale of products like spices, honey, forest extract vegetables, wood, and poultry feed was minimal or absent. The significant product preference for vegetables and fruits was associated with the type of home garden and the vendor's experience in mobile marketing. Notably, the sale of processed products showed a significant correlation with monthly income and mobile market experience, implying that value addition could enhance financial outcomes. However, the relatively low percentage (18.5%) of selling processed products indicates an untapped potential for income diversification through agro-processing. This implies that while fresh produce dominates current sales, value-added products remain underexplored. Given that such products can command higher prices and longer shelf lives, initiatives such as skill development in food preservation and packaging could expand women's earning potential.

Women primarily sourced products from their home gardens (85.2%), and very few depended on neighbours or outside sources. This self-reliant supply system underscores

the importance of land ownership and household-level agriculture in women's economic empowerment. Furthermore, the vendors' experience in mobile marketing was significantly related to their likelihood of selling products from their gardens. Additionally, demographic variables such as gender and age were significantly associated with higher monthly incomes through the mobile market. For example, women with more experience in mobile marketing tended to earn between LKR 10,000–50,000 (approx. US$ 33-167) per month. This reveals a strong linkage between continuous participation and economic gains. Despite this, constraints such as a lack of awareness about broader market opportunities and limited transport infrastructure persist. Mobile marketing addresses some of these issues by bringing the market closer to producers and consumers. Vendors cited factors such as proximity to farms, higher profitability, and the ability to manage household duties simultaneously as key reasons for participating in the mobile market. This reflects how mobility barriers are reduced and household labor is optimized through such market models.

From the producer's perspective, the consistent sale of fresh produce and staple items like vegetables, fruits, and cereals points to enhanced income flows, which are critical for food security. The most common expenditure categories among vendors were food items (74%), medicine (78%), and children's education (63%), suggesting that mobile market income directly contributed to essential household needs. Interestingly, income spent on infrastructure or entertainment was notably low. This spending pattern suggests a prioritization of basic welfare and developmental needs over luxury, indicating that income from mobile marketing plays a crucial role in improving food and health security at the household level. From the consumer side, most customers purchased 1–2 kg of goods per week and spent LKR 1,000-2,000. The affordability and accessibility of fresh products in the mobile market contribute to local food availability and dietary diversity. Customer preference was highest for vegetables (83%) and fruits (66.6%), followed by processed products (61%). However, cereals and forest-extracted products were less favoured, indicating potential areas for demand stimulation. The high acceptance of mobile markets by customers—72.2% visiting weekly—demonstrates their integration into routine food procurement. This signifies that mobile markets contribute positively to community-level food security by improving access to affordable, fresh, and locally grown food.

Customers reported several benefits from the mobile market model. The highest-rated attributes were product freshness (100%), affordability (67%), and product attractiveness (16.6%). However, aspects such as "a change in buying experience" and "convenience" scored lower. Newspaper advertisements were the least effective in raising awareness about the market, while casual encounters (e.g., passing by, roadside signs) and word-of-mouth (neighbors, friends) were more effective. The lower effectiveness of formal advertising methods indicates that mobile markets thrive on informal communication networks. This insight is crucial for future interventions aimed at improving outreach and participation. From the vendors' perspective, income from the mobile market was seen as adequate to meet basic expenses. Monthly income levels varied, with 36% earning Rs. 10,000–25,000 (approx. US$ 33-83) and another 36% earning Rs. 5,000–10,000 (approx. US$ 16-33). Only 16% exceeded Rs. 50,000 (approx. US$ 167). Importantly, vendors with more mobile marketing experience showed a higher likelihood of being in the upper income

brackets. The satisfaction was further reflected in the purpose of spending: with a focus on essentials, the income was impactful in improving living standards. This supports the conclusion that mobile markets not only offer a viable economic activity but also uplift the quality of life by fulfilling critical household expenditures.

The study shows compelling evidence of increased women's agency through participation in mobile markets. Ownership of home gardens, active involvement in marketing, and control over income use suggest a shift toward economic autonomy. Approximately 70% of producers identified the wife as the primary cultivator of the farm area, indicating direct female involvement in production. Moreover, by eliminating middlemen and selling directly to customers, women gain negotiation power, market exposure, and financial independence. The mobile market model inherently promotes flexible entrepreneurship, aligning well with the socio-cultural roles of rural women. However, while the majority of participants were women, deeper empowerment aspects—such as decision-making authority, financial control, and participation in planning—need further exploration. Although income is a critical metric, empowerment is multidimensional and includes confidence, leadership, and social status—all areas worth expanding in future studies.

Conclusion

While mobile markets are beneficial, several limitations have emerged. For instance, product diversity remains limited to perishable items. The lack of value-added goods, meat, honey, and spices signals a need for training and infrastructure support in food processing. Additionally, environmental conditions (e.g., lack of shade as noted by 33% of customers) affect customer comfort. The informal nature of market advertisement (mainly word-of-mouth) may limit reach. Investment in better market shelters, promotional tools, and logistics would enhance the model's effectiveness. The mobile market initiative across Anuradhapura, Kurunegala, and Trincomalee districts demonstrates measurable improvements in women's economic conditions, food security, and entrepreneurial participation. The mobile market model not only promotes self-reliance through home garden-based supply chains but also boosts income and enhances household well-being. Nevertheless, the success of this model depends on enabling conditions such as continuous training, access to basic infrastructure, support for product diversification, and policy interventions. By leveraging these opportunities, mobile markets can serve as a transformative tool for rural women's empowerment and sustainable community development.

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Empowering Women in Climate-Resilient Irrigation: Challenges from the Divulwewa cascade in Sri Lanka

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Introduction

Climate change poses serious and wide-ranging challenges for agricultural communities, particularly in developing countries like Sri Lanka, where rural livelihoods heavily depend on consistent water access and agriculture. In regions such as the North Central Province and the Anuradhapura District in Sri Lanka, minor irrigation systems—especially cascade systems—are central to sustaining agriculture and food security. As climate variability exacerbates water scarcity, managing these irrigation systems becomes increasingly critical for local resilience. In response, the Sri Lankan government initiated the *Wewgampubuduwa* Climate Resilience Improvement and Water Management Project (CRIWMP) with a main focus on empowering rural women, recognizing their crucial role in managing water resources and contributing to climate adaptation strategies.

Although the role of women in climate resilience is increasingly acknowledged, research continues to overlook the specific obstacles they face and the contributions they make in the context of minor irrigation systems. Previous studies tend to concentrate on physical infrastructure, policy frameworks, or agronomic techniques, often neglecting gendered perspectives, particularly the everyday experiences of women interacting with these systems. In areas like the Divulwewa cascade system, which consists of interconnected irrigation tanks both socially and hydrologically, there is a clear lack of data on how women are included in water governance, what institutional supports or constraints they face, and how they respond to environmental stress. This study seeks to address that gap by focusing on women's involvement in minor irrigation management, the challenges they encounter, and the opportunities for strengthening their role in the face of climate change.

This research draws on multiple theoretical perspectives, including Gender and Development Theory (Moser 1993), Social Capital Theory (Putnam 2000), and Integrated Water Resources Management (IWRM) (GWP 2000), to explore how social structures, collective agency, and participatory governance shape women's participation. Empirical studies such as those by Carr and Thompson (2014), Doss et al. (2018), and Kabeer (2016) highlight the socio-cultural and institutional barriers women face. However, examples like

women-led irrigation groups and empowerment programs (Buechler et al. 2016) show the potential of inclusive practices. Guided by these insights, this study examines socio-cultural norms, economic access, institutional governance, and climate impacts as key factors influencing women's involvement. Focusing on the Divulwewa cascade system in Sri Lanka, the study aimed to assess women's participation in decision-making, evaluate their adaptation strategies, and recommend gender-responsive policies. While limited in scope and reliant on self-reported data, the research contributes meaningful perspectives on promoting equitable water management and climate adaptation at the community level.

Methodology

The study adopted a quantitative survey-based research design to investigate the role of women in climate change adaptation and minor irrigation management within the Divulwewa cascade. A total of 120 participants—comprising 60 women and 60 men engaged in agriculture—were selected using a stratified sampling technique to ensure diverse representation across different socio-economic backgrounds. Structured, self-administered questionnaires were developed to gather both demographic and perceptual data, focusing on women's roles, specific adaptation strategies, and the barriers they face in irrigation decision-making processes.

Data were collected from primary sources through field surveys using these tailored questionnaires. The responses were analysed using descriptive statistics to summarize participant characteristics and trends, while Bayesian inference (with Beta prior: 2,2) was applied to estimate posterior probabilities related to women's participation. Additionally, one-sample binomial tests were employed to assess the statistical significance of observed patterns. This methodological approach enabled a comprehensive understanding of gender dynamics in climate adaptation within the selected context.

Results and Discussion

Table 1 reveals a community deeply rooted in traditional agricultural practices. The majority were between the ages of 36 and 55 (51.7%), with 85% having attained secondary-level education. Most women (60%) reported farming as their main occupation, and 95% were married, indicating close adherence to conventional family and community structures.

Despite promising levels of climate adaptation awareness (mean = 0.797) and strong verbal support for women in decision-making roles (mean = 0.922), practical engagement remains limited. Women's nomination for leadership roles was moderate (mean = 0.500), but actual responses to nominations were significantly low (mean = 0.047), suggesting symbolic rather than substantive participation. Barriers to participation include cultural norms (mean = 0.516) and nearly balanced male opposition (mean = 0.484). Female opposition and personal constraints appeared minimal, with means of 0.047 and 0.109, respectively.

Table 1. Demographic Characteristics of the Female Respondents

Category	Frequency	Percentage (%)
Age 36–55	31	51.7
Secondary Education	51	85.0
Farming	36	60.0
Married	57	95.0

Statistical analysis revealed that 15 out of 18 variables demonstrated significant deviations from equal distribution, confirming structural imbalances in areas such as decision-making, technical knowledge access, and inclusion in discussions. However, perceptions regarding irrigation technology use and law compliance were balanced, signaling potential entry points for improvement. Figure 1 illustrates the posterior mean probabilities of key variables, emphasizing the contrast between awareness/support and actual engagement.

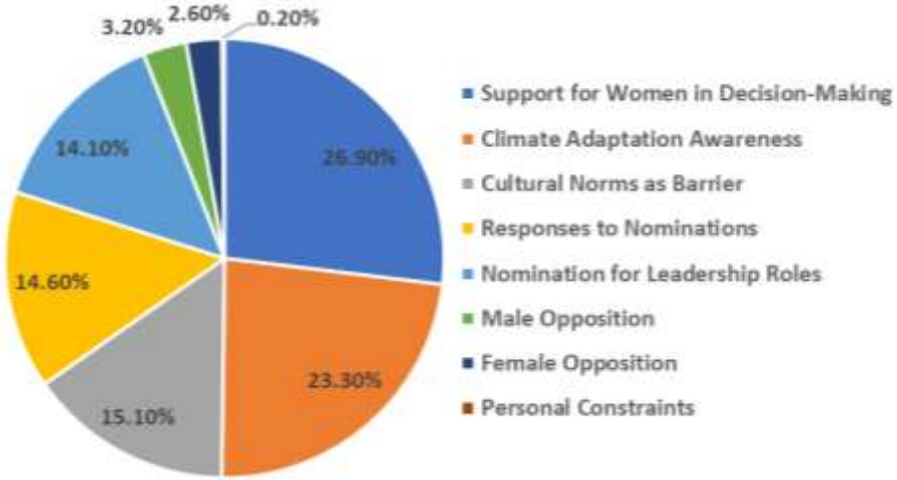

Figure 1. Posterior mean probabilities of key variables

Figure 1 visualizes the various factors and barriers influencing women's participation in climate adaptation efforts. Each slice represents the relative mean value of awareness, support, engagement, and barriers.

This research has successfully uncovered critical insights into the gendered dynamics of climate change adaptation and irrigation management in the Divulwewa cascade system. While there is strong community awareness and verbal support for women's involvement, the findings reveal a persistent gap between endorsement and actual participation. Women remain underrepresented in leadership roles and decision-making processes, underscoring the influence of deep-rooted socio-cultural norms and institutional barriers. The study not only confirms these disparities with statistical significance but also demonstrates the urgency of moving beyond symbolic inclusion to meaningful engagement. These findings contribute valuable evidence to the discourse on gender equity in climate resilience, offering a solid foundation for future policy and community interventions.

Recommendations

To address these challenges and translate awareness into action, the recommendations proposed are (a) Implement targeted gender-sensitization and capacity-building programs to challenge cultural norms and build leadership confidence among women, (b) Institutionalize female representation within Farmer Organizations**,** ensuring women's voices are formally included in governance structures, (c) Enhance access to irrigation technologies and relevant training to empower women with practical tools for active participation, and (d) Promote gender-transformative approaches that go beyond surface-level inclusion and actively reshape power dynamics for long-term, equitable climate adaptation.

These recommendations, grounded in evidence from the field, aim to foster a more inclusive and resilient agricultural future for the Divulwewa cascade in Sri Lanka, and beyond.

Acknowledgement

We wish to acknowledge the support of the CRIWMP Project, the Ministry of Irrigation, and the communities of the Divulwewa cascade system for their participation and insights, which enabled us to conduct research on real field issues in Sri Lanka.

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Strengthening Social Safeguards through Community-Based Grievance Redress: Lessons from CRIWMP

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Introduction

Grievance redress mechanisms (GRMs) are essential components in ensuring transparency, accountability, and inclusiveness in development projects. The Climate Resilient Integrated Water Management Project (CRIWMP) in Sri Lanka had a multi-stakeholder engagement, which naturally leading to grievances that, if unresolved, can undermine project effectiveness. Common complaints include delays in construction, unfair benefit distribution, inadequate consultation, and procedural irregularities.

Effective grievance handling plays a vital role in securing the trust and participation of affected communities. A well-structured GRM can not only resolve disputes but also function as a feedback mechanism for adaptive project management (Smith 2020). This study explores the grievance redress framework implemented by CRIWMP in Kurunegala District, with an emphasis on how it ensures the rights and well-being of project-affected individuals.

Methodology

This study adopted a mixed-method approach, incorporating quantitative data analysis and qualitative evaluation of GRM operations. Grievances were classified into technical, social, and procedural categories. Data were collected from CRIWMP's official grievance registers and satisfaction surveys conducted among 378 complainants. In addition to numerical data, stakeholder interviews and field observations provided insight into the strengths and challenges of the grievance resolution process. The roles of *Grama Niladhari* (GN)-level and divisional-level forums were also evaluated.

Results and Discussion

The CRIWMP's GRM employs a tiered structure for managing grievances. The GN-level forums, composed of community leaders and local officers, resolve most community-level concerns through participatory dialogue. Divisional-level forums, consisting of senior officials, address complex or escalated cases. This structure promotes timely and culturally

appropriate conflict resolution while supporting institutional oversight (Jones and Taylor 2021).

A total of 390 grievances were analyzed, including 152 complaints and 35 requests from the village irrigation system (VIS) component and 175 complaints and 28 requests from the drinking water (DW) component. As shown in Table 1, the majority of grievances in both components were resolved within a week to one month. Specifically, 69 out of 152 VIS complaints and 106 out of 175 DW complaints were resolved within a week, reflecting the GRM's efficiency in managing a high volume of issues in a timely manner. However, the VIS component exhibited a relatively higher number of unresolved grievances (n = 32), as well as delays extending up to two months, indicating potential gaps in case follow-up or capacity constraints. Table 1 presents the timeframes within which grievances were resolved under different components and categories.

Table 1. Grievance resolution by category and timeframe (CRIWMP Project)

Component	Category	Number of Grievances	Resolved less than				Unresolved
			1 week	2 weeks	1 month	2 months	
VIS	Complaint	152	69	18	13	15	32
VIS	Request	35	26	4	0	0	2
DW	Complaint	175	106	1	5	12	0
DW	Request	28	13	3	2	2	0

VIS = village irrigation system; DQ = drinking water

To assess the effectiveness of the GRM from the beneficiaries' perspective, a structured perception survey was conducted with 378 stakeholders who had submitted grievances. Figure 1 illustrates the overall satisfaction levels. The results showed that 324 respondents (85.7%) were satisfied with the redress process, 29 were moderately satisfied, and only 25 reported dissatisfaction.

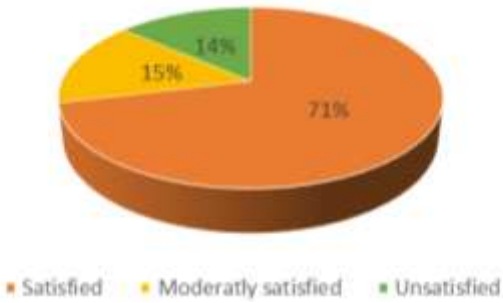

Figure 1. Satisfaction levels of stakeholders regarding grievance redress process (n=378) *Note: The majority of respondents under both village irrigation system (VIS) and drinking water (DW) components reported "Satisfied" status. Only a small fraction under VIS reported being "Unsatisfied."*

Notably, all 197 respondents from the DW component reported satisfaction or moderate satisfaction, whereas the VIS component accounted for all 25 unsatisfied responses (Figure 1).

To further analyze the relationship between satisfaction level and project component, a Chi-square test of independence was performed. The test revealed a statistically significant association between the component and satisfaction level ($\chi^2 = 35.27$, df = 2, $P<0.001$), confirming that the satisfaction level of stakeholders varied meaningfully between VIS and DW. Specifically, the DW component demonstrated a higher success rate in achieving stakeholder satisfaction, with no recorded instances of dissatisfaction. In contrast, the VIS component showed a greater distribution of unsatisfied and moderately satisfied responses, suggesting that grievance handling under this component may have been perceived as less effective or responsive.

The CRIWMP also adopted a two-tiered awareness strategy. Administrative awareness programs targeted Divisional Secretaries, while community-level campaigns engaged *Grama Niladhari*, religious leaders, and local civil society organizations. Visual materials such as brochures and posters reinforced key messages. These efforts improved grievance reporting and the legitimacy of the mechanism among stakeholders. Among the 378 respondents, 298 indicated GN-level forums as the preferred level of grievance handling. This aligns with literature emphasizing the value of decentralized mechanisms in increasing responsiveness and trust (Smith 2020; Jones and Taylor 2021). Divisional-level forums, while more formal and policy-aligned, were viewed as secondary options, particularly for grievances involving legal or administrative complications.

By integrating the GRM with real-time project monitoring and community engagement, CRIWMP has created a feedback loop that improves responsiveness and inclusiveness. This aligns with the recommendations made by Fernando et al. (2022), who emphasize the importance of grassroots grievance handling in sustaining large-scale development projects.

Conclusion

The grievance redress mechanism implemented under the CRIWMP in Kurunegala District demonstrates how structured, participatory approaches can enhance social accountability and ensure the well-being of affected communities. The tiered structure spanning community to divisional levels has effectively resolved the majority of grievances within acceptable timeframes, while promoting transparency and equity. High levels of stakeholder satisfaction and the preference for GN-level forums highlight the importance of local engagement and culturally responsive mechanisms. Despite some unresolved grievances and procedural delays in certain components, the GRM overall has functioned as a dynamic tool for both conflict resolution and continuous project improvement. Embedding the mechanism within project governance has facilitated real-time feedback, improved adaptive management, and strengthened institutional trust. As a best practice model, the CRIWMP's GRM offers valuable insights for designing grievance frameworks in similar multi-stakeholder development contexts.

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Management Strategies Adopted by Women in Socio-Economic Transformation: A study of CRIWMP's impact on empowering women in rural Sri Lanka

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Introduction

The role of women in rural development is increasingly recognized as a crucial element in advancing sustainable socio-economic transformation (Adinan 2024). This is particularly relevant in countries like Sri Lanka, where agriculture and natural resource management continue to serve as the foundation of rural livelihoods. Consequently, many development interventions are strategically designed to focus on women's empowerment as a pathway to inclusive and sustainable growth (Aniebonam et al. 2022).

The concept of women's empowerment is inherently multi-dimensional (Sarkar and Das Gupta 2024). It encompasses the process through which women are enabled to take control of their lives, make autonomous decisions, and access equal rights and opportunities across social, economic, political, and educational spheres. This process involves dismantling structural and cultural barriers that hinder women's participation and aims to address gender-based inequalities. Ultimately, it seeks to promote gender justice and cultivate an environment in which women can fully realize their potential and contribute meaningfully to society (Mallepu 2025).

Moreover, Women's empowerment often leads to or reflects a shift in traditional gender roles (Aniebonam et al. 2022). Traditionally, women were confined to unpaid domestic and agricultural labor, often excluded from leadership or decision-making positions (Panda 2021). However, Women's empowerment often leads to or reflects a shift in traditional gender roles by challenging long-standing norms that confine women to domestic or subordinate positions. As women gain greater access to education, economic opportunities, and decision-making spaces, their roles within households and communities expand beyond conventional expectations. As a result, women are increasingly required to adopt and develop management strategies to navigate and contribute effectively to processes of socio-economic transformation (Mutinda et al. 2025).

The Climate Resilient Integrated Water Management Project (CRIWMP), funded by the Green Climate Fund and implemented by the Government of Sri Lanka, has mainly focused on enhancing the resilience of rural communities in Sri Lanka to climate variability and water-related challenges. With the theme of sustainable livelihoods, the project targets empowering women as key agents of change in rural development. Through capacity development of women beneficiaries, climate-resilient agriculture development, livelihood generation activities, and leadership opportunities, CRIWMP is a key driver of socio-economic change and of promoting gender equality in vulnerable areas.

However, the realization of this transformation is not straightforward. Despite project interventions, many rural women face obstacles of limited access to resources, lack of exercising decision-making power, and traditional gender roles that constrain them to domestic responsibilities. These deep-rooted cultural practices often clash with the new chances and anticipations resulting from development interventions like CRIWMP. While the project has provided women with opportunities to learn skills, earn living, and take up leadership roles, these gains are unequal unless social and cultural barriers are also addressed by technical and economic means. Therefore, interventions alone may not be sufficient—unless these norms are either strategically balanced or consciously challenged and transformed, the empowerment process may remain limited or uneven.

Despite the growing recognition of women's roles in rural development, there is limited empirical research on how empowered women in Sri Lanka adopt context-sensitive management strategies to navigate shifting gender roles and sustain socio-economic transformation. The majority of project reports emphasize outputs and achievements but overlook the daily strategies women use in bridging tradition and culture, overcoming cultural barriers, and maximizing opportunities. This gap directs towards the need for investigation of actual life management practices that rural women adopted in an effort to drive their own socio-economic transformation in the context of CRIWMP initiatives.

In this study, the proposed research problem was: What are the impacts of the management strategies adopted by women in navigating socio-economic transformation under the CRIWMP in rural Sri Lanka? The significance of this study lies in its contribution to policy formulation, gender-sensitive development planning, and a deeper understanding of grassroots resilience in the context of women's empowerment and socio-economic transformation.

Methodology

This study purposively selected 50 women beneficiaries from five CRIWM Project implementing districts, based on Output Monitoring Survey database conducted to capture the output of the inputs distributed through woman beneficiaries under CSA component. In each district, 5 adapted and 5 mal-adapted women were chosen, totally 25 in each group. Adapted women successfully integrated project activities, while mal-adapted women faced barriers. Data were collected through interviews exploring their

experiences and analysed thematically to compare socio-economic adaptation, empowerment, and challenges among the two groups.

Results and Discussion

Strategies for Socio-Economic Adaptation

Rural women adopted various adaptive strategies in response to socio-economic changes introduced by CRIWMP, including home gardening, poultry raising, agro-processing, and small-scale enterprises as key livelihood activities. These economic activities were often integrated into their daily domestic routines. To manage time effectively, women reorganized schedules, balanced unpaid domestic work with productive tasks, and creatively merged caregiving with livelihood work. Key strategies included:

An integrated caregiving with livelihood activities was adopted by women with the involvement of their children in simple tasks such as watering plants or feeding poultry. This approach not only ensured that work progressed efficiently but also strengthened emotional bonds and taught children's basic agricultural skills, fostering a shared sense of responsibility within the family.

Women adjusted activities based on climate seasons and home priorities to time appropriately. Livelihood activities were structured based on home routines. Many engaged in farming activities early in the morning before household chores began and prepared meals in advance. This allowed them to attend trainings or run their enterprises during the day without neglecting family obligations.

Practical time-saving techniques such as bulk cooking, meal planning, and organizing household work more efficiently were adopted by women. These adjustments helped free up valuable time for participating in CRIWMP activities, training sessions, or managing livelihood tasks more consistently.

Some women developed informal group arrangements where they alternated attendance at trainings or shared labor duties. This collective strategy ensured that everyone had the opportunity to benefit from project activities while maintaining essential household or community responsibilities and to reduce individual burdens.

Recognizing time constraints, women used informal and already scheduled social gatherings such as religious events, school meetings, or family functions as platforms for discussing project-related experiences, sharing knowledge, and building mutual support networks.

Transformative Outcomes of Empowered Participation

Over 80% of the women who successfully adapted to the program were actively engaged in income-generating or skill-based activities. Their monthly incomes increased significantly, with earnings from CRIWMP-related interventions ranging between LKR 10,000 and 35,000 (Approx. US$ 33 – 116). A substantial portion of this income was

reinvested in livelihood tools or allocated to support household needs. Notably, many women have built collective support systems and have utilized their earnings to "buy time" by hiring assistance or directing profits into savings and productive inputs, thereby enhancing both economic stability and work-life balance.

A majority of women who successfully adapted to the program reported increased influence in both household and community decision-making. Some assumed leadership roles as group leaders, trainers, or committee members. Their confidence grew through various experiences, such as (a) Negotiating with husbands or elders – demonstrating the tangible benefits of their participation in CRIWMP-related activities, and (b) Taking on less visible yet influential roles – managing group funds, coordinating activities, and contributing to organizational decisions behind the scenes.

Many women have expressed pride in their personal transformation and have been recognized both formally and informally. Some have received certificates, public praise, or gained respect within their communities. This recognition has often been achieved by maintaining traditional roles to build trust while gradually introducing innovations, thus avoiding confrontation. Moreover, women have turned their traditional identities such as their roles as mothers or elders into tools of empowerment, using their social status to influence and lead within their households and communities.

One of the key challenges identified was the need to balance new responsibilities with long-standing domestic expectations. Women managed these through, (a) Delegating domestic tasks to daughters or mothers-in-law, (b) Multi-tasking while engaging in traditional duties, and (c) Using mobile phones for remote engagement when physical presence wasn’t possible

Those who struggled often labelled as mal-adapted cited time constraints, fatigue, and lack of support as primary obstacles. In contrast, adapted women received substantial support from spouses and family members. As a result, their sense of sustainability and empowerment was stronger.

Most adapted women have expressed a desire to continue their home gardening, poultry keeping, or processing activities even after the conclusion of project support. Their sustained efforts and optimism are closely linked to the confidence they have built through successful adaptation. However, women who have dropped out or disengaged from the program have cited reasons such as health issues, limited market access, and overwhelming domestic responsibilities.

Conclusion

This study demonstrated that CRIWMP enabled many rural women to develop innovative strategies for balancing traditional gender roles with emerging economic responsibilities. These women adapted by merging caregiving with livelihood activities, reorganizing time effectively, and building peer and family support networks. Their experiences illustrate

that empowerment is a negotiated, creative process deeply rooted in daily realities and social contexts.

However, the presence of mal-adapted women those who faced structural, social, and health-related barriers to full participation highlights critical gaps in program inclusivity. Their challenges should not be viewed as individual shortcomings but as signals for the need to design more flexible, gender-responsive, and context-sensitive interventions. Supporting diverse realities through adaptive programming is essential to promote equitable participation, long-term sustainability, and socio-economic resilience among rural women.

Recommendations

Based on the results of the analysis, the study makes six recommendations, i.e. (a) Expand Gender-Sensitive Training: Provide more targeted, localized, and flexible training that considers women's time constraints and caregiving responsibilities, (b) Formal Recognition of Women's Roles: Offer public acknowledgment and leadership development pathways to reinforce women's empowerment, (c) Promote Household-Level Support: Engage men and elders through family-based awareness programs to reduce resistance and promote shared responsibilities, (d) Integrate Cultural Values in Programming: Frame empowerment messages in alignment with local religious and ethical values to enhance acceptance and sustainability, (e) Encourage Peer Networking: Foster networks of women to share knowledge, rotate responsibilities, and support collective progress, and (f) Monitor Wellbeing and Time Use: Develop simple tools to track how project activities affect women's daily routines, stress levels, and care responsibilities.

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Assessing the Impact Project Activities on Women: A post-intervention analysis in agricultural communities in Sri Lanka

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Introduction

Sri Lanka has prioritized integrated and gender-responsive approaches to water resource management with increasing climate variability and water scarcity. The Climate Resilient Integrated Water Management Project (CRIWMP), funded by the Green Climate Fund and implemented in selected cascades within the Dry zone of Sri Lanka, aimed at strengthening adaptive capacities, improve agricultural resilience, and ensure equitable access to water resources.

A critical dimension of this project is the active involvement of women in planning, implementing and benefiting from interventions across four key cascades: Mamnunugama (Polpithigama), Anguruwella (Ehetuwewa), Mottapeththewa and Kadawala (Galgamuwa). Traditionally underrepresented in water governance and agricultural decision-making, rural women face layered vulnerabilities. The CRIWMP's interventions, ranging from rehabilitation of tanks and canals, promotion of climate-smart agriculture to capacity-building initiatives, offer a unique opportunity to assess how gender-sensitive strategies can shift socio-economic dynamics and empower women in agricultural communities.

This study, therefore, seeks assessed the impact of CRIWMP on women across these cascades by examining changes in livelihoods, participation, and empowerment, and how these outcomes contribute to building climate resilience at the household and community levels.

Methodology

Research Design

This study adopted a quantitative descriptive research design to assess the impact of project interventions on women in four selected cascades based on the project interventions in the Kurunegala District of Sri Lanka. The design was chosen to systematically collect and analyze numerical data to identify patterns and measure changes in women's livelihoods, participation, and empowerment after project activities.

The structured design allowed for the use of closed-ended questions and statistical summaries to provide an objective overview of the outcomes.

Study Area and Sampling

The research was focused on four cascades, namely, Mamunugama, Anguruwella, Mottapeththewa, and Kadawala in Sri Lanka, comprising 2,115 women beneficiaries. A sample of 40 women was selected based on the purposive sampling criteria of relevance to the study area, specific demographic characteristics, experience and expertise related to the study topic, and their willingness and ability to participate in the research process. The selection specifically targeted women who had actively participated in and benefited from the CRIWM project. This sampling strategy was appropriate given the project-specific nature of the research and the intention to assess outcomes among direct participants.

Data Collection

Data collection for this study was carried out using a pre-tested structured questionnaire, which was carefully developed to capture a comprehensive set of quantitative indicators relevant to the assessment of women's empowerment and participation following project post-interventions. The questionnaire was designed to ensure consistency and comparability across all 40 respondents and focused on key thematic areas aligned with the project's gender goals. The questionnaire consisted of five major sections, namely, (a) Income and livelihood changes, (b) Participation in household and community decision-making, (c) Access to resources, (d) Involvement in leadership or group activities, and (e) Knowledge and skill improvements.

Data Analysis

The collected quantitative data were entered into a database and analyzed using descriptive statistical methods to summarize and interpret the findings effectively. To ensure a more in-depth analysis, all data were disaggregated by gender where relevant, which helped identify trends and differences among subgroups. The analyzed results were presented using tables, making the findings visually accessible and easier to interpret for reporting and decision-making purposes.

Ethical Consideration

Informed consent was obtained from all participants. Anonymity and confidentiality were maintained, and gender-sensitive facilitation was applied throughout the data collection process.

Results and Discussion

The demographic information of the study sample is presented as Table 1.

The socio-economic changes experienced by women in the selected cascades

To assess the socio-economic changes experienced by women following CRIWMP interventions in the Mamunugama, Anguruwella, Mottapeththewa, and Kadawala

cascades, key demographic data were analyzed. The majority of the women surveyed was within the age range of 41–60 years (Table 1), with 32.5% aged 41–50 years and 35% aged 51–60 years. This confirmed that more than two-thirds (67.5%) of respondents were middle-aged. This age group is highly relevant to CRIWMP interventions, as middle-aged women typically manage household responsibilities while actively contributing to agriculture and community affairs. Aladuwaka and Momsen (2010) reported that this demographic often leads local water initiatives and sustains community development when empowered with resources and decision-making opportunities.

Table 1. Demographic information of women in the project sites (Data Source – Field Survey, 2025)

Category	Number	Percentage
Age (years)		
30 - 40	6	15
41 – 50	13	32.5
51 - 60	14	35
61 – 70	7	17.5
Level of Education		
Completed primary Education	13	32.5
Completed Secondary Education	20	50
Completed Higher education	7	17.5
Didn't go to school	0	0
Income per month*		
Less than LKR 20,000	15	37.5
20,000 – 40,000	16	40
40,000 – 60,000	9	22.5
60,000 – 80,000	0	0
More than 100,000	0	0
Household (HH) Head		
Yes	3	7.5
No	37	92.5

*US$ = approx. LKR 300

Educational data showed that 50% of the women had completed secondary education, and an additional 17.5% had pursued higher education, while 32.5% had completed only primary schooling. Notably, none of the participants reported having no formal education, indicating a favorable baseline for effective engagement in development interventions.

The CRIWMP effectively leveraged this educational foundation by introducing technical training programs and awareness campaigns tailored to the learning capacities of the women. As emphasized by Mateo-Sagasta (2021), development projects that align training approaches with the educational levels of women are more likely to foster meaningful participation, particularly in rural settings such as the four selected cascades.

Income distribution reveals that 37.5% of women earned less than LKR 20,000 per month, and 40% earned between LKR 20,000–40,000 (Table 1). Only 22.5% earned between LKR 40,000–60,000 per month, with no women reporting income above LKR 60,000. These values confirm that a majority (77.5%) of the women are situated within low-income households, facing economic vulnerability. The CRIWM project's introduction of home gardening, input distribution, and market linkage support was therefore timely and appropriate. These interventions contributed to supplementing household incomes and reducing dependency on unpredictable external sources. Similar outcomes were noted in the Tank Irrigation Modernization Project (TIMP) in Sri Lanka, where community-focused rehabilitation improved income stability among low-income households (Murray-Rust and Rao 1987).

Only 7.5% of women identified themselves as heads of household (Table 1), primarily due to circumstances such as the death of a spouse, divorce, or being a single parent. The vast majority (92.5%) reported living in male-headed households, reflecting the persistence of traditional patriarchal family structures, where women's leadership often remains informal and unrecognized.

Despite this reality, the CRIWMP actively promoted collective participation of women in community groups and water management committees. The project acknowledged that even within male-headed households, women play crucial roles in decision-making related to water use, farm management, and climate adaptation. As noted by Zwarteveen and Athukorala (1994), effective water governance must extend beyond formal titles and focus on empowering women in both household and community-level decision-making, a principle that the CRIWM project successfully began to implement.

Extent of women's participation and leadership in project activities.

The study findings revealed a high level of participation among women in activities under the Climate Resilient Integrated Water Management (CRIWM) project (Table 2). Of the 40 women surveyed, 80% had engaged in project-related training, particularly in tank renovation (85%) and home gardening (50%). These trainings not only enhanced women's technical skills and climate-adaptive practices but also strengthened their engagement with local institutions and development actors, contributing to both household resilience and community involvement (Mateo-Sagasta 2021).

Table 2. Women's Involvement in decision-making within households and communities (Data Source – Field Survey 2025)

Before the Project				**After the Project**			
Household level		**Community Level**		**Household Level**		**Community Level**	
Yes	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**
95%	5%	97.5%	2.5%	97.5%	2.5%	100%	0%

However, despite strong participation, only 62.5% of respondents held leadership positions, indicating a gap between involvement and formal recognition. This aligns with

the findings of Zwarteveen and Athukorala (1994), who noted that women's contributions in water management are often undervalued in decision-making spaces. Bridging this gap calls for targeted leadership development, inclusive governance, and the creation of enabling environments that amplify women's roles not just as participants, but as leaders in climate-resilient agricultural systems.

Shifts in gender roles and decision-making power within households and communities.

A core objective of the CRIWMP was to promote gender equity by enhancing women's roles in household and community-level decision-making. As shown in the data, women's involvement in domestic decisions was already high before the project (97.5%), with a slightly lower 95% indicating involvement in household financial matters (Table 2). However, community-level participation increased from 97.5% to 100% following the project's implementation.

This shift highlights a positive change in gender roles, where women moved beyond traditional domestic responsibilities to participate more actively in community governance, particularly in areas such as water resource management and climate adaptation. CRIWM's integrated approach, through training, group mobilization, and inclusive engagement, helped transform women into active contributors and leaders, not just beneficiaries. As Zwarteveen and Athukorala (1994) emphasized, empowering women requires recognizing their roles in both formal and informal decision-making spaces. The CRIWM's strategy aligns with such gender-transformative approaches, supporting long-term resilience and inclusive development.

Analyzing women's access to resources

Improving women's access to productive resources is essential for advancing gender equality and livelihood resilience. The CRIWMP had a notable impact in this regard, as evidenced by significant increases in access across multiple areas. Access to agricultural equipment and training programs rose sharply from 10 to 30 women, while access to water sources improved from 11 to 29 (Table 3).

Table 3. Women's access to resources. (Source – Field Survey 2025)

Resource	Before the Project	After the Project
	Numbers	
Banks/Financial Institutions	13	27
Agricultural Equipment	10	30
Training Programs	10	30
Water Source	11	29
Information Technology	17	23

Similarly, the number of women reporting access to banks or financial institutions increased from 13 to 27. These improvements reflect the project's targeted interventions, such as input distribution, training on sustainable farming practices, and the establishment of community cultivation initiatives.

These gains enabled women to participate more actively in agriculture, boost household food security, and take on decision-making roles traditionally dominated by men (Aladuwaka and Momsen 2010). They also aligned with IWMI's guidance on integrating gender into water and resource management (Mateo-Sagasta 2021).

However, challenges remain. Although financial access improved, a notable gap persists, many women still face barriers to credit such as lack of collateral and limited financial literacy. This underscores Zwarteveen and Athukorala's (1994) argument that resource access must be paired with institutional support to ensure long-term empowerment.

To bridge this gap, future efforts must combine physical resource provision with strategies that promote financial inclusion and systemic support, enabling women not only to participate, but to lead in climate-resilient agricultural systems.

Enabling and hindering factors influencing women's empowerment and sustained participation in climate-resilient agricultural systems.

The success of women's participation in climate-resilient agricultural systems is shaped not only by access to resources but also by enabling and hindering social and structural factors. This study examined women's perspectives during and after the CRIWM project, highlighting key drivers and barriers to sustained involvement.

According to the data, family support was universally recognized as a key enabler (100% of respondents; Table 4), aligning with findings by Aladuwaka & Momsen (2010), who emphasized the role of household cooperation in empowering women within development initiatives. Support from spouses and family members helped women attend trainings and engage in agricultural and decision-making activities.

Table 4. The key enabling and hindering factors influencing women's empowerment and sustained participation in climate-resilient agricultural systems (Data Source: Field Survey 2025).

Factors	Is it an Enabling Factor?	Is it a Hinder Factor?
Trust	40	0
Time	40	0
Family Support	40	0
Limitations in transportation	30	10
Knowledge	39	1

Knowledge and awareness were also identified as enabling factors by 97.5% of participants. Through targeted trainings and peer learning, women enhanced their technical and climate-adaptive skills, echoing similar capacity-building outcomes observed in Mateo-Sagasta (2021). Increased knowledge boosted women's confidence and participation in local planning.

Conversely, transportation limitations emerged as a major hindrance for 25% of the respondents, with 10 women indicating it as a barrier. Distance to training venues and lack of transport options reduced access to key activities, an issue similarly noted by Zwarteveen and Athukorala (1994), who underscored mobility as a critical constraint in women's participation in rural water management systems.

Other significant enablers included trust and time availability (each cited by all 40 respondents), reinforcing the importance of reliable project relationships and supportive time arrangements, consistent with lessons from Murray-Rust and Rao (1987) on participatory project design.

These findings underscore the need for climate adaptation programs to address both supportive and limiting factors. Interventions that strengthen family involvement, improve mobility, and invest in knowledge-building can more effectively ensure women's long-term engagement in resilient agricultural practices.

Conclusion

Based on the insights gathered from the four cascades assessed through this study, several key recommendations have emerged to enhance the gender responsiveness of future climate adaptation and water management interventions. These recommendations are grounded in the perspectives and lived experiences of the 40 women respondents who directly participated in CRIWM project activities.

A central theme across responses was the need for more targeted and inclusive training programs tailored specifically to the unique needs, interests, and challenges faced by women in agricultural communities. Respondents emphasized that understanding the real-life obstacles women encounter, such as time poverty, limited mobility, and lack of access to information, is crucial to designing effective interventions. They stressed the importance of conducting gender needs assessments at the project planning stage to ensure that training content and delivery methods are relevant, practical, and accessible to women across different age groups and social roles.

In addition to technical knowledge, women called for continuous capacity-building initiatives that not only strengthen their skills in agriculture, water management, and climate adaptation but also boost their confidence and leadership capabilities. Respondents highlighted that such efforts should be designed and delivered in consultation with women themselves, thereby ensuring that their voices and insights are meaningfully incorporated into program design and implementation.

Another strong recommendation was to increase women's representation in local planning committees, farmer organizations, and project governance structures. Many women noted that despite active participation in project activities, their influence in decision-making spaces remains limited. Promoting inclusive leadership opportunities is essential to

transform women from beneficiaries into leaders and change agents within their communities.

Lastly, respondents underscored the need for ongoing awareness-raising campaigns on gender equality, both for women and the broader community. These efforts should challenge harmful gender norms, encourage male allyship, and promote a shared understanding of the value of women's contributions to climate resilience and sustainable development.

These findings highlight the importance of moving beyond participation numbers and embracing genuinely inclusive and gender-transformative approaches in future projects. Doing so will not only enhance the effectiveness and sustainability of interventions but will also empower women to take ownership of climate adaptation and water governance in their communities.

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Gender Responsive Climate Security Assessment for Sri Lanka

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Introduction

Sri Lanka faces a complex interplay of climate change, gender inequality, and security challenges that threaten its fragile post-conflict peace and socio-economic stability. While the country has made strides in climate mitigation and adaptation, the human security risks posed by climate change remain deeply gendered, with men, women, and marginalized groups experiencing these challenges in profoundly different ways.

Existing research on climate security in Sri Lanka has largely overlooked the critical intersection of gender and climate risks, leaving significant gaps in understanding how climate stressors exacerbate vulnerabilities and undermine resilience. The present assessment seeks to address these gaps by offering a pioneering analysis of how climate change intersects with gender dynamics to shape risks and resilience across diverse communities.

Building on established frameworks such as the UN Climate Security Mechanism's Toolbox and the sustainable livelihoods approach, this study adopts a gender-transformative and intersectional lens to critically examine structural inequalities and their implications for climate security in four districts in Sri Lanka.

This assessment is the first of its kind in Sri Lanka to investigate how climate-induced livelihood disruptions, environmental degradation, migration patterns, and unequal access to services disproportionately affect marginalized groups, particularly women-headed households, youth, and ethnic minorities, enabling link climate security with gender and intersectionality. This offers a roadmap for inclusive and equitable climate actions. By addressing the unique vulnerabilities and capacities of different demographic groups, the study aims to inform policies that not only mitigate climate risks but also promote social cohesion and peacebuilding, critical for Sri Lanka's post-conflict context.

Methodology

This assessment employs the Weathering Risk methodology, adapted to Sri Lanka, to explore how climate change intersects with gender, peace, and security (Rüttinger et al. 2023). The Weathering Risk methodology is particularly valuable for Sri Lanka, as it integrates advanced climate data with conflict analysis to inform locally relevant responses to acute climate-security risks, thereby supporting the country's fragile peace, and promoting social cohesion. A mixed-methods approach integrating qualitative and

quantitative methodologies, including stakeholder consultations and field-level data collection were conducted in Mullaitivu, Batticaloa, Hambantota, and Badulla districts which were selected for their diverse socio-economic, geographic, and climate vulnerabilities.

Local researchers conducted 243 semi-structured interviews using a storytelling approach to capture diverse risks and resilience pathways, ensuring representation across gender, age, and ethnicity. A story-telling approach uses narrative techniques during data collection to elicit richer, more nuanced insights into participants experiences and perspectives. Data were analysed using a grounded theory approach with a gender-sensitive and intersectional lens. Findings were validated through stakeholder workshops in April and May 2025, ensuring accuracy and relevance for policy and programming.

Results and Discussion

The assessment identified five key pathways through which climate stressors and security risks undermine human security in Sri Lanka. These pathways highlight the intersection of climate change with socio-economic vulnerabilities, governance challenges, and community resilience, with distinct impacts across the four districts studied: Badulla, Batticaloa, Hambantota, and Mullaitivu.

Climate Impacts on Livelihoods and Migration

Erratic rainfall, rising temperatures, and extreme weather events are disrupting traditional livelihoods, particularly in agriculture and fishing (SYCLAN Trust 2022). In Mullaitivu, recurrent droughts and flash floods have forced farmers, especially women-headed households, to abandon traditional crops, driving many into low-paying informal labour. Batticaloa faces similar challenges, with lagoon fishers reporting declining stocks due to ecosystem degradation. In Hambantota, sea level rise and coral bleaching have rendered artisanal fishing increasingly unsustainable. These disruptions are driving migration, particularly among youth, which, while offering short-term financial relief through remittances, often exacerbates inequalities and leaves rural communities vulnerable to future shocks (Bhandari 2020).

Marginalization and Unequal Access to Services

Disparities in access to essential services, such as irrigation, agricultural support, and disaster relief, are eroding resilience. Farmers in Batticaloa and Mullaitivu reported systemic neglect and governance failures, while plantation workers in Badulla face structural inequalities that limit their ability to adapt. Perceptions of bias in resource allocation, particularly in the North and East, exacerbate feelings of exclusion and weaken trust in institutions, further undermining social cohesion.

Human-Wildlife Conflict

Human-wildlife conflict has escalated due to habitat encroachment and climate-induced changes, with significant impacts on livelihoods and safety (Kopke et al. 2024). In Badulla, crop destruction by elephants and other wildlife has strained rural incomes, while

Hambantota communities reported an increased encounters with displaced wildlife due to development projects (Jayathilaka et al. 2021). Governance gaps and perceptions of bias in wildlife management exacerbate tensions, particularly in marginalized regions.

Climate Change and Education

Climate-induced disruptions, such as floods and droughts, are undermining access to education, particularly in rural areas. Seasonal agricultural labour and caregiving responsibilities disproportionately affect girls, while boys are more likely to drop out to support their families. In Batticaloa and Mullaitivu, poor infrastructure and limited access to quality education deepen vulnerabilities, leaving youth unprepared for future challenges.

Health System Strain

Sri Lanka's healthcare system, already marked by underfunding and inequalities, is increasingly strained by climate impacts (De Alwis and Noy 2019). Rising temperatures and water scarcity are driving health risks such as chronic kidney disease and vector-borne diseases, while extreme weather events disrupt healthcare access. Marginalized groups, including women and plantation workers, face the greatest challenges, with limited access to preventive care and mental health support (Geldin 2025).

Conclusion

Sri Lanka's economic recovery and progressive governance offer a unique opportunity to address long-standing vulnerabilities worsened by climate change. While strides in climate mitigation are commendable, the marginalized groups facing systemic barriers. Climate stressors, such as erratic rainfall and extreme heat, exacerbate inequalities and fuel grievances, particularly in conflict-affected regions. Addressing these challenges requires integrated, equitable, and gender-responsive solutions that link climate adaptation to peacebuilding ensuring that no one is left behind in the pursuit of resilience and sustainability. With strategic investments and inclusive governance, Sri Lanka can build resilience, foster trust, and chart a path toward a more cohesive and sustainable future. This research contributes to the global discourse on climate security, providing valuable lessons for other conflict-affected regions grappling with similar challenges.

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CRIWMP Project's Impact on Women's Entrepreneurial Resilience in Vavuniya District of Sri Lanka

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Introduction

Sri Lanka's dry-zone agriculture faces severe climate stress – erratic rainfall, frequent droughts and floods have damaged ancient irrigation systems, reduced crop yields and heightened food insecurity (UNDP 2023). The Climate Resilient Integrated Water Management Project (CRIWMP), financed by the Green Climate Fund and implemented by the Government of Sri Lanka with UNDP support, was launched (2017–2025) to address these challenges. Its core aim is to rehabilitate and modernize village irrigation tanks and water networks across three northern river basins (Malwathu Oya, Mi Oya and Yan Oya), thereby securing reliable water for agriculture and drinking (UNDP 2022). In addition to infrastructure works, CRIWMP emphasizes community livelihoods and resilience: for example, it provides climate-smart agricultural inputs and training to farmers and fosters complementary income-generating activities. A key objective is to empower women smallholder farmers and entrepreneurs in the Dry zone – recognizing that women's livelihoods (through agriculture, home gardening and small businesses) are crucial for household food security and climate resilience (UNDP 2023).

In fact, UNDP reports that CRIWMP targets "the resilience of smallholder farmers, particularly women, in the Dry Zone" (UNDP 2022). By mid-2023, CRIWMP had delivered climate-smart agricultural packages to over 459,000 farmers (with men and women equally represented), and enabled more than 7,000 women (including widows and persons with disabilities) to adopt new farming technologies (UNDP 2023).

Within this broader context, the current study examines one aspect of CRIWMP's socio-economic interventions in the Vavuniya District of Sri Lanka: support to women entrepreneurs and household producers. Specifically, we analyse project data (administrative records and survey tables) on women beneficiaries in Vavuniya, their business activities, and the equipment or material inputs they requested and received. Our goal is to understand the types of enterprises women pursued (e.g. food processing, tailoring, handicrafts), the nature of assistance provided (e.g. machinery, tools), and the geographic spread of these activities across divisional secretariats (e.g. Vavuniya Town, North, South, Chettikulam).

This analysis was focused on how CRIWMP's non-irrigation components have contributed to women's economic empowerment and livelihood resilience, aligning with the project's goal of fostering inclusive climate adaptation (UNDP 2023).

Methodology

This study examines the impact of the CRIWMP in Vavuniya District using both administrative data and qualitative interviews. Data were sourced from the CSA beneficiary database and district reports on women entrepreneurs, covering over 1,200 beneficiaries across various project components such as paddy farming, home gardening, and micro-enterprises. Key variables analysed include gender, socio-economic status, location, project type, and distributed outputs like equipment or livestock. A mixed-methods approach was used, combining quantitative analysis of records with qualitative interviews of 18 women beneficiaries engaged in enterprises like food processing, tailoring, and handicrafts.

Findings reveal a strong presence of women in income-generating activities, with food-processing being the most common. Interview themes highlighted improved income, self-reliance, and community recognition. Ethical standards were maintained throughout the study, ensuring informed consent and confidentiality. The research offers a holistic view of CRIWMP's livelihood support and its role in empowering women in the district.

Results and Discussion

Enterprise types among women beneficiaries

Women beneficiaries under CRIWMP engage in four main types of enterprises. The largest group (11 women) works in food and agricultural processing, producing items like chili sauce, herbal drinks, manioc chips, and coconut oil, supported with equipment such as grinders, sealers, and oil mills. Three women run tailoring and garment businesses using overlock sewing machines. Another three focus on handicrafts made from coconut shells and wood, aided by band-saws and grinders. One woman produces leather goods, supported with display tables and hangers. This range of micro-enterprises highlights how equipment provision plays a vital role in helping women grow and sustain their businesses. Among the women beneficiaries, 11 were engaged in food processing and sales, 3 in tailoring, 3 in handicrafts, and 1 in leather goods production. Food processing is the most common enterprise among women beneficiaries, supported by equipment for value-added agriculture like chili paste and coconut oil. Tailoring and handicrafts are also backed with appropriate tools. These efforts align with CRIWMP and UNDP's focus on agro-based livelihoods for women in the dry zone.

Equipment and support provided

The project support to these women largely took the form of machinery and equipment to enhance productivity. Table 2 lists the main equipment items delivered to the entrepreneurs, along with the number of women who received them. (Only items that were actually delivered are counted here.

Nearly all requested equipment was successfully delivered to support a variety of women-led enterprises across Vavuniya District, including food processing, tailoring, handicrafts, and leather goods. This equipment has boosted productivity and aligns with CRIWMP's climate-smart, market-oriented objectives. The 18 women beneficiaries are well distributed throughout the district across Vavuniya Town, Vavuniya South, Cheddikulam, and Vavuniya

North mostly from rural or semi-urban outskirts, demonstrating an inclusive and widespread outreach. The program also prioritizes vulnerable groups such as widows, women-headed households, persons with disabilities, and welfare recipients, reflecting its commitment to empowering marginalized rural populations.

Table 1. Types of equipment provided to women entrepreneurs.

Equipment provided	No. of women recipients
3HP chilli-grinding machine	3
15kg electric food sealer	2
8" handheld sealer (for packets)	3
Over lock (3-thread) sewing machine	2
Shop saw (band saw for wood cutting)	2
3HP copper cutter (for coconut oil mill)	2
Manioc (cassava) slicer	1
38L air compressor	1
Diesel-operated grinder (Dei grinder)	1
5HP electric motor (standalone)	1
6'×4' display table (with bag stands)	1
10'×10' temporary hut (sales stall)	1

The CRIWMP's socio-economic interventions boost women's entrepreneurship and livelihood resilience by supporting value-added enterprises, particularly in food processing. This helps women move beyond subsistence farming to earn income even during dry spells. Providing equipment like grinders and sealers enables them to turn surplus produce into marketable goods, aligning with the project's climate-smart approach and creating sustainable micro-enterprises. CRIWMP effectively meets women's business needs by providing equipment tailored to their enterprises, lowering entry barriers and boosting productivity. This in-kind support acts like micro-finance, with income gains often reinvested in family welfare. The program's reach is equitable, extending to remote areas like Cheddikulam, benefiting rural women. However, gaps remain such as low participation from Vavuniya North and one unmet equipment request highlights the need for improved logistics and targeted outreach. CRIWMP's support strengthens gender empowerment by equipping women with tools and resources that enhance their economic roles. This leads to greater family resilience, as women often reinvest income in health, education, and nutrition. The support also builds women's skills and confidence, promoting long-term self-reliance and aligning with broader development goals.

To maximize impact, additional support such as training in marketing, bookkeeping, and equipment maintenance is essential for sustainability. Although records don't detail such efforts, CRIWMP plans include field schools and extension services. Future evaluations should assess whether women received business training and market access. Access to finance is also crucial, as some enterprises may need capital beyond the provided equipment to expand.

Interviews in Vavuniya show that CRIWMP support boosted women's income, independence, and social status through improved productivity in small businesses. While

women valued the support, many highlighted the need for more training. These results reflect CRIWMP's broader success in empowering women—part of its goal to benefit over 770,000 people and show how livelihood support complements ecological interventions for climate resilient development.

Conclusion

Data from Vavuniya District show that CRIWMP's livelihood support has effectively empowered diverse women-led enterprises by providing targeted equipment aligned with their business needs. Beneficiaries include vulnerable groups across the district, with a strong focus on climate-resilient food processing, alongside tailoring and handicrafts. Mechanization has boosted productivity and income, which women reinvest in family welfare, enhancing community resilience. This case illustrates how gender-sensitive economic support complements climate adaptation efforts.

However, improvements are needed in ensuring complete equipment delivery, offering ongoing training and market access, and expanding outreach to underrepresented areas. Collecting long-term impact data would strengthen future assessments. Overall, women report increased production and business growth, highlighting CRIWMP's positive role in fostering climate-resilient livelihoods and women's entrepreneurship in rural Vavuniya.

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The Study of Operation and Maintenance, Consumption, and Post-Sustainability Measures of Advanced Water Filtration Systems Installed in Dry Zone Schools

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Introduction

Access to safe drinking water remains a critical challenge in Sri Lanka's dry zone, where communities are particularly vulnerable to water scarcity and health issues such as Chronic Kidney Disease of Unknown Etiology (CKDu). Among these populations, children are particularly vulnerable to waterborne diseases, and the effects of climate change have further exacerbated the scarcity and quality of available water resources, especially in rural areas (Hettithanthri et al. 2021). Poverty acts as a barrier to purchasing treated water, while the lack of accessible potable water continues to impose a serious community-based adaptation (CBA) burden on local livelihoods. Previous studies have identified a strong correlation between health issues and the lack of access to safe drinking water (Centre for Policy Alternatives 2023).

In response, the installation of Advanced Water Filtration Systems (AWFSs) has emerged as a key intervention, providing potable water to students who face year-round difficulties in accessing clean drinking water. Such AWFSs widely used in Sri Lanka; Nano filters use membranes with pore sizes ~15–100 nm, removing bacteria and some viruses while retaining monovalent ions. RO systems use membranes with ~0.0001 µm (0.1 nm) pores, effectively removing both monovalent (e.g., Na^+) and bivalent ions (e.g., Ca^{2+}, Mg^{2+}), along with heavy metals and microbes (Cooray, et al. 2019). RO has used above 700 ppm TDS and high fluoride contaminated sources in the regions.

As part of the climate-resilient infrastructure improvements under the Climate Resilient Integrated Water Management Project (CRIWMP), AWFS units were installed in schools prone to waterborne diseases, poor water quality and access. These systems are designed not only to meet immediate drinking water needs but also to serve as sustainable assets supported by training, institutional engagement with back up supports, and community-based mechanisms. This study investigates the operational performance, consumption

trends, and post-installation sustainability of these filtration systems, drawing on feedback from 52 school principals across the dry zone.

In response, numerous donors, government agencies, and both public and private sector partners have implemented various interventions, including the installation of advanced water filtration systems in schools. However, many of these systems have become non-functional due to a lack of funds for repairs, inadequate technical knowledge on system operation and maintenance, absence of institutional support mechanisms, lack of sustainable financial models, and insufficient training for school-based operational teams (Wijesekera 2020).

To address these shortcomings, the CRIWMP initiated a comprehensive program to install approximately 100 advanced water filtration systems in selected schools. This initiative was carried out with the collaboration of relevant stakeholders, including the National Community Water Supply Department (DNCWS) and other government agencies. The program introduced improvements such as service agreements for all interventions, routine maintenance protocols once a month, non-specific but community- driven fundraising mechanisms such as support from SDSs, sponsors from well- wishers…etc., and regular water quality testing, alongside capacity building and training for long-term sustainability. However, preliminary observations indicate that many AWFS units face operational disruptions, irregular maintenance, lack of institutional ownership, and absence of sustainable funding or technical support, limiting the intended benefits. This study was designed to evaluate the extent to which this new modality has succeeded in ensuring effective operation, maintenance, and sustainability of the installed systems.

Methodology

The study employed a structured survey designed under CRIWMP monitoring guidelines. Research population 100 AWFSs units installed in schools and sample was school principals from 52 (52%) schools across North Central, Northwestern, and Northern Provinces. The tool collected quantitative data on installation details, water usage, maintenance logs, stakeholder support, and satisfaction. The data collection process was carried out in 2023 by CSO's Field Coordinators (FC) under the guidance of Senior Social Mobilizers (SSM). Descriptive and inferential statistics were used to analyse system performance across variables such as province, water source, system type, installation year, and training received. Descriptive statistics were used to summarize demographic characteristics, while graphical representations such as tables and figures illustrated key findings.

Results and Discussion

All 52 systems were reported operational at the time of assessment. Results have summarized demographic and technical data of AWFSs across all 52 schools. The majority (80.8%) used dug wells, with tube wells (19.2%) more common in the Northern and Northwestern provinces. The Reverse Osmosis (RO) filters dominated (90.4%), while

nano-filters were less common (9.6%) as less amount of treatable water availability which shall less than 700 ppm of TDS value. Most installations occurred in 2021 (32.7%) and 2024 (42.3%). While all systems in the North Central Province were handed over in 2021, 40.4% of the total systems. Warranty expirations varied, with most concluding in 2023 (42.3%).

All schools reported using filtered water exclusively for drinking. Overall satisfaction with water quality was high (96.2%), though two schools in the Northern Province expressed concerns. Water quality testing was conducted in 88.5% of schools, with the North Central Province achieving full compliance. These results indicate positive user reception, though gaps in water testing, particularly in the Northwestern and Northern provinces, suggest a need for routine quality monitoring.

Testing frequency varied, with 42.3% of schools conducting it annually, predominantly in the Northwestern Province. Despite this, 32.7% reported deviations from anticipated results, mainly from Northwestern schools. However, all issues were resolved within one week, with 98.1% addressed within 72 hours. This reflects strong service responsiveness but emphasizes the need for more frequent testing, especially in areas prone to water quality issues.

All systems were reported to be functional, with 100% maintaining clean tap structures and storage areas. However, only 78.8% of wastewater effluent treatment units were working properly, with the Northwestern Province showing the highest rate of malfunction (33.3%). Overall, 78.8% of schools met all four performance criteria, while 21.2% fell short, primarily due to issues with effluent treatment, indicating a gap in comprehensive system maintenance.

Furthermore, teacher count and student population showed no significant association with AWFS condition ($p > 0.05$), indicating these factors do not influence system performance. No significant relationship was found with non-academic staff presence, water source, or type of filtration system ($p > 0.05$). However, a statistically significant association ($p = 0.046$) was observed with system capacity—schools with lower-capacity systems (≤2500 L/day) were more likely to meet all four operational conditions, suggesting manageability may influence sustained performance of AWFS units.

The association between AWFS condition and installation or handover year also examined. Although statistical significance could not be calculated due to small cell sizes, notable patterns emerge. Systems installed in 2021 and 2023 achieved 100% compliance with all four operational criteria, while those installed in 2024 showed the lowest performance (59.1%). Similarly, schools with systems not formally handed over had the highest rate of underperformance (42.9%), suggesting that recent installations and lack of official handover may hinder optimal system functionality.

While statistical significance couldn't be calculated due to small sample sizes, trends suggest

systems with warranties expiring in 2025 had the poorest performance, while those with warranties expiring in 2024 or 2026 performed better. Additionally, systems with untested water showed higher failure rates (66.7%), and all unsatisfied users had fully functional systems, indicating perception alone may not reflect technical performance. Regular testing appears linked to better system outcomes.

Systems tested every three months showed the highest compliance (100%), while those tested annually had a higher failure rate (40.9%), suggesting frequent testing supports better system upkeep. Although statistical significance was not established, systems with recorded water quality issues had a greater likelihood of underperformance (29.4%).

The operation and maintenance data reveal significant regional variations in the management of AWFS across 52 schools. While 98.1% of respondents reported receiving O&M training, only 32.7% had formal backup agreements with the DNCWS, notably absent in the North Western Province. Though 65.4% had signed service agreements, only 53.8% of schools-maintained logbooks, with the Northern Province performing best in this aspect. Encouragingly, all schools practiced essential upkeep such as backwashing, tank cleaning, and lid closures. However, 32.7% reported system leakages. Overall, while system upkeep is commendable, inconsistencies in formal maintenance arrangements and documentation highlight key areas for strengthening long-term sustainability. About 69.2% of schools demonstrated good operation and maintenance of AWFS, while 30.8% showed poor performance. This highlights that although most schools manage systems effectively, nearly one-third require strengthened support and monitoring to achieve consistent, sustainable filtration system performance.

The statistical analysis explores the associations between the overall O & M of AWFS and various contextual and institutional factors across 52 dry zone schools. While no significant differences were found by district, province, or zonal division, a notable association was observed between O&M and student population ($p=0.045$), where schools with fewer than 500 students showed better maintenance. Additionally, schools using tube wells had significantly better O&M than those relying on dug wells ($p=0.022$), and expired warranty periods were linked with poorer maintenance, especially among systems expiring in 2023. Importantly, significant relationships were found for frequency of water quality testing and the presence of unsuitability issues in test reports ($P=0.000$), emphasizing that regular testing and prompt issue resolution are crucial for sustaining system performance. These findings underscore the importance of institutional commitment, timely servicing, and user engagement for AWFS sustainability.

The sustainability assessment of AWFS, revealed varied effectiveness across provinces and influencing factors. Formation of school-based CBOs was highly effective in the North Central Province (100%) but only moderately so in others. Continuous training and the provision of SOPs were considered extremely useful by most schools (71.2% and 67.3%, respectively). While solar installations and seed funds moderately supported

sustainability, their impact was uneven across provinces. Sanitation awareness programs and three-year maintenance agreements were reported as extremely effective by most, though reliance on project-based maintenance remains high. Notably, only a small number of schools developed independent sustainability mechanisms. Stakeholder involvement showed gaps, with limited visits from technical officers and DNCWS, while SDS and CBO monitoring occurred moderately. These findings underscore the need for strengthened post-project institutional support and proactive community engagement.

About 73.1% of schools achieved good sustainability of their AWFS, while 26.9% experienced poor sustainability. Statistically significant associations ($p<0.05$) were found between sustainability and student population, non-academic staff availability, and system capacity. Schools with more than 500 students, presence of support staff, and systems with higher capacity (>2500 L/day) demonstrated better sustainability. Additionally, schools with expired warranties or lacking frequent water quality testing exhibited lower sustainability. Finding of the study also showed a significant relationship with recorded water quality issues ($p=0.021$). External support mechanisms and institutional capacity may play a more crucial role in long-term functionality.

The Spearman's correlation analysis between the overall operation and maintenance (O&M) of AWFS and its overall sustainability yielded a mild positive correlation ($r = 0.229$) with a p- value of 0.103, indicating no statistically significant association at the 0.05 level. This suggests that while better O&M practices may contribute to improved sustainability outcomes, other external or institutional factors likely have a stronger influence. The decision to use Spearman's test was justified by the non-normal distribution of the sustainability data (skewness = -1.867). These findings align with earlier results, emphasizing that beyond operational standards, stakeholder engagement, resource support, and system capacity play a critical role in sustaining AWFS functionality in dry zone schools. Maintenance support was timely in 92.3% of cases. However, only 65.4% had formal agreements with service providers, and just 32.7% had backup agreements with DNCWS.

Conclusion

the post-sustainability remains a concern: 40.4% of systems were not officially handed over and only 53.8% of schools-maintained logbooks. Systems ≤2500 L/day showedbetter performance (91.7%) than larger ones (67.9%). Significant correlations were found between performance and year of installation (2021 > 2024), training ($p<0.05$), and testing frequency (3-monthly > yearly). Compared to RWHSs, AWFSs demonstrated better institutional accountability but similar post-project risks.

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Assessing the economic impact of improved land use practices in the upper catchment of minor tanks: a cost-benefit analysis approach

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Introduction

In many developing countries, determining whether the benefits of development projects outweigh the costs is a critical concern, particularly in the context of agricultural and water management initiatives (Campbell and Brown 2022). In the Dry Zone, people often rely on tank-cascade systems, a traditional water management method vital for sustaining agriculture and livelihoods.

These systems are increasingly vulnerable due to population growth, climate change, and inefficient land use. Improved land use practices under the Climate Resilient Integrated Water Management Project (CRIWMP) deviated from conventional VIS rehabilitation and introduced an integrated approach where VIS were upgraded together with the associated ecosystem. By revitalizing water resources and enhancing agricultural productivity, these measures have the potential to boost rural economies. Evaluating the economic impact of these practices is essential for guiding investment in sustainable land and water management.

This research problem is particularly pertinent to small-scale irrigation tank systems in rural Sri Lanka, where resource constraints necessitate efficient use of funds. In the Kapugama tank within the *Palugaswewa* cascade, where agricultural productivity and water availability fluctuate significantly, questions remain about the cost-effectiveness of adopting CRIWMP-supported practices. Therefore, this study examined whether the economic returns from improved land use practices justify the investment costs, contributing valuable insights for rural development strategies.

Methodology

Research Site

The study focuses on the Kapugama tank, a critical part of the Palugaswewa tank cascade in the Anuradhapura district of Sri Lanka. This region is characterized by a network of

interconnected tanks supporting agricultural livelihoods and water security for local communities. The area's dependence on rainfall and seasonal water availability presents both a challenge and an opportunity for improving land use through sustainable practices (Wijeratne and Piyadasa 2014). *Kapugama* village, being a small-scale irrigation tank-dependent community, serves as a suitable case for assessing the socio-economic impacts of CRIWMP interventions on rural farming systems and water resource management (Warnakulasooriya et al. 2024).

Data and Statistical Model

This study employs a Cost-Benefit Analysis (CBA) framework to assess the economic viability of improved land use practices in the upper catchment of the tank cascade system in 2020. The methodology integrates primary and secondary data collection to estimate both costs and economic benefits associated with interventions such as home gardens, perennial crops, runoff water harvesting tanks, and groundwater recharging pits.

Primary data will be collected through structured household surveys, focus group discussions, and key informant interviews with farmers, community leaders, and CRIWMP officials. These surveys will capture information on agricultural productivity, household income, water usage patterns, and cost components before and after intervention. Secondary data sources, including project reports, government statistics, and prior research studies, will supplement the analysis by providing baseline information on land use and hydrological conditions.

Cost-Benefit Analysis (CBA)

The CBA approach involves estimating both direct and indirect costs related to project implementation, such as infrastructure development, maintenance, labour, and input costs (Rouwendal 2012). Economic benefits will be assessed by analysing increased agricultural yields, improved water availability, and income changes among beneficiary households, specifically from upland areas and home gardens, excluding the irrigated command area, which focuses on evaluating the economic viability of CRIWMP interventions in the upper catchment of the tank cascade system (He et al. 2021). The financial feasibility of interventions will be determined using Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR), which provide a quantitative basis for evaluating long-term sustainability (Boardman et al. 2020) Sensitivity analysis will also be conducted to assess the impact of variable cost and benefit assumptions on overall project outcomes

Results and Discussion

To evaluate the financial feasibility of CRIWMP interventions in the Kapugama tank village, key economic indicators were calculated. The Net Present Value (NPV) of the project was estimated at LKR 2,788,775.51, indicating a substantial surplus of benefits over costs in present terms. The Benefit-Cost Ratio (BCR) was 1.29, suggesting that for every rupee invested, a return of 1.29 rupees was generated. Furthermore, the Internal Rate of Return (IRR) was computed at 22.05%, exceeding conventional thresholds for development

projects. The payback period - the time required to recover the initial investment—was found to be approximately 2.5 years, demonstrating a relatively quick return on investment. These results collectively demonstrate that the improved land use practices supported under CRIWMP are economically viable and hold strong potential for replication in similar tank-cascade systems. The cost estimation and benefit assessment of improved practices are presented in Tables 1 and 2, respectively.

Table 1. Cost Estimation of Improved Land Use Practices in the Upper Catchment of Tank Cascades in 2020

Cost Component	Description	Unit Cost (LKR)*	Total Units	Total Cost (LKR)
Initial Setup Costs (Investment)				
Infrastructure Development	Construction of lock and spill, Soil Bunds and Recharging Pits, Planting Pits	1,500.00	75	112,500.00
Immediate upper catchment development (Perennial crops)	Mango	250.00	380	95,000.00
	Coconut	150.00	560	84,000.00
	Lime	55.00	40	2,200.00
Seeds	Other field crops FC, Green Gram	1,250.00	36	45,000.00
Irrigation Systems	Sprinkler	130,000.00	5	650,000.00
	Storage tanks	30,000.00	2	60,000.00
Animal Husbandry	Coops	100,900.00	2	201,800.00
	Chicks	450.00	44	19,800.00
Total Investment				**1,270,300.00**

Source: CRIWMP (2020); 1 US$ = approx. 300 LKR

It is important to note that no crop or livestock yields were recorded in the years 2020, 2021, and 2022. This was primarily due to disruptions caused by the COVID-19 pandemic and the concurrent economic crisis, which halted cultivation activities during this period. The mango plantation, though established earlier, only began yielding harvests in 2023. Similarly, poultry farming activities commenced in mid-2022, resulting in meaningful egg production being recorded from 2023 onwards. Therefore, the benefit assessment reflects post-intervention outcomes beginning in 2023, aligning with the recovery and operationalization of project activities.

The Climate Resilient Integrated Water Management Project (CRIWMP) has delivered significant non-monetary benefits that enhance rural sustainability and resilience. Unlike conventional rehabilitation efforts that primarily focus on irrigation infrastructure and benefits limited to the command area, CRIWMP adopts a holistic, integrated approach that includes upland interventions such as home gardens, perennial crops, and water harvesting systems. This broader focus has not only improved year-round water availability in drought-prone areas—boosting both agricultural productivity and household

water security—but also lowered irrigation costs through efficient water systems and groundwater recharge.

Table 2. Benefit Assessment of Improved Land Use Practices in the Upper Catchment of Tank Cascades

Benefit Category	Indicator	Net Benefit				
		2020	2021	2022	2023	2024
Agricultural Yield Increase (Green Gram, Chili, Big Onion)	Crop yield per year (kg/acre)	0.00	0.00	0.00	701,900.00	483,000.00
Perennials Yield (Mango)		0.00	0.00	0.00	280,500.00	253,000.00
Seeds Production (Green Gram/ Big Onion)	Seed Produced per year (kg/acre)	0.00	0.00	0.00	293,000.00	295,000.00
Animal Husbandry	Egg Production per year (unit/farmer)	0.00	0.00	0.00	102,000.00	106,500.00
Total Benefits		**0.00**	**0.00**	**0.00**	**2,079,300.00**	**1,620,500.00**

Source: CRIWMP (2020); 1 US$ = approx. 300 LKR

Furthermore, the project supports soil conservation by reducing erosion and preserving topsoil, which ensures long-term land productivity. Biodiversity has been enhanced through reforestation and sustainable land use practices, promoting ecological balance. Most importantly, CRIWMP strengthens climate resilience by improving water retention and promoting sustainable agriculture, enabling communities to better cope with droughts and erratic weather.

In addition, there are several unquantified benefits that further enhance the value of CRIWMP interventions. These include the reduction in desilting costs due to minimized soil erosion, reduced evaporation losses from improved vegetative cover and water retention structures, and the preservation of flood mitigation potential through improved tank storage capacity. While these benefits were not included in the financial estimates of this study, their inclusion in future analyses could reveal an even higher economic return, further supporting the viability and replicability of integrated land and water management approaches for upgrading Village Irrigation Systems (VIS).

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The Ancient Tank Cascade System of Sri Lanka: A climate-resilient agro-ecological heritage

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Introduction

Climate change has amplified the vulnerability of dry-zone agriculture in Sri Lanka, manifesting through prolonged droughts, erratic rainfall, floods, and soil degradation. In this context, the ancient tank cascade system (*Ellanga*), designated as a Globally Important Agricultural Heritage System (GIAHS) by FAO (2018), stands as a living testimony to indigenous climate-smart water management. Developed over two millennia, this integrated landscape ensured equitable water sharing, soil conservation, biodiversity protection, and community resilience. While modern irrigation projects often overlook ecological complexity, the cascade system represents a sustainable alternative. Yet, despite its global recognition, systematic understanding of its ecological and socio-cultural functions remains underutilized in contemporary climate adaptation strategies. This study reviews the structural and functional components of the cascade system, highlighting their role in climate resilience and sustainable agriculture.

Methodology

This study adopted a qualitative review methodology, synthesizing historical records, ecological surveys, and ethnographic documentation of Sri Lanka's dry-zone landscapes. The analysis is structured around the major components of the cascade system as identified in traditional knowledge repositories. Each element is evaluated in terms of hydrological regulation, biodiversity conservation, socio-cultural services, and climate resilience functions. The findings are compared with modern water management approaches to assess lessons for future climate action.

Results and Discussion

The cascade integrates upper tanks, forest tanks, water holes, grass filters, and tree belts, which trap sediments, recharge groundwater, and minimize evaporation losses. Features such as *Yathuru Wala* and interceptor lands prevent saline seepage into paddy fields, ensuring long-term soil fertility. Drainage canals and traditional sluices (*keta sorowwa*,

mada sorowwa) provided controlled distribution of irrigation water, preventing both scarcity and excess. Collectively, these ensured year-round water availability, even under erratic rainfall.

At the heart of the cascade, paddy fields (*liyadi*, *kanati*, *niyara*) were supported by a precisely engineered irrigation network. Seasonal crop diversification improved food security. Pest control strategies, such as reserving *Kurulupaluwa* for birds, illustrate an early form of ecosystem-based pest management.

The cascade landscape maintained high levels of faunal and floral diversity. Shrublands, tree belts, and hamlet buffers provided habitats for birds, pollinators, and medicinal plants. This mosaic of land uses enhanced resilience by safeguarding ecological services such as pollination, pest control, and nutrient cycling.

The system was more than engineering—it was community governance. Villagers collectively managed water distribution structures, chena cultivation, and hamlet buffers through customary rules and leadership of Vel Vidane councils. These traditions ensured fairness, minimized conflict, and embedded ecological stewardship in rural culture. The cascade system demonstrates multiple nature-based solutions: water security, soil and salinity control, renewable resources, and community resilience. Integrating these principles into modern adaptation strategies offers pathways to sustainable irrigation, biodiversity protection, and rural livelihoods in the face of climate change.

Conclusion

The Sri Lankan tank cascade system exemplifies a holistic response to water scarcity and climate variability. By blending engineering, ecology, and culture, it sustained dry-zone communities for centuries. Contemporary climate policies can greatly benefit from reviving and adapting these time-tested practices. Scaling up cascade restoration could provide a low-cost, community-driven climate solution aligned with global frameworks such as the Paris Agreement and the UN Sustainable Development Goals.

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The authors acknowledge traditional knowledge holders of Sri Lanka's dry zone communities and archival sources that preserved details of the cascade system.

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Challenges in Survey and Demarcation of Village Irrigation Systems in Cascades

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Introduction

In Sri Lanka, Tank Cascade Systems (TCS) were established and developed by ancient kings during the Rajarata hydraulic civilization as a rainwater conservation strategy to optimize water utilization for irrigation in the dry zone (Bandara 1985). The Village Tank Cascade Systems (VTCSs) operate on the principle of recycling and re-use of water through networks of small to large scale tanks, supporting not only irrigation and villagers' water needs but also flood control, groundwater recharge, and biodiversity conservation (Bebermeier et al. 2017; Panabokke et al. 2002). These cascade systems are considered an adaptation strategy to overcome threats from long-term climate change impacts (Withanachchi et al. 2014), having demonstrated remarkable resilience with tanks that were managed in a decentralized manner remains functional even after periods of socio-economic instability and increased climatic fluctuations (Bebermeier et al. 2017). However, VTCSs are increasingly subjected to external pressures and global environmental change such as climate change, population growth, and land use pattern dynamics (Wickramasinghe et al. 2022), resulting in continued degradation of ecological well-being and hydro-socio-ecological condition significant for rural agricultural society livelihood and food security (Ratnayake et al. 2021).

Accordingly, due to the absence of clearly defined and legally recognized boundaries, VISs face various challenges which is leading to huge encroachment and misuse of resources that threatens both physical infrastructure and ecological functions (Geekiyanage et al. 2023). This study addresses the critical challenges faced during the surveying and demarcating components of VIS, with the objective of supporting sustainable planning and management through informed boundary demarcation and legal clarity.

Methodology

A participatory methodology was used to ascertain accuracy, inclusion, and workability while emphasizing the significance of traditional knowledge and technological requirements (Perera 2017). The research framework integrated multiple data collection approaches and stakeholder engagement strategies to develop unified demarcation guidelines for Village Irrigation Systems (VIS) within cascade environments.

Large-scale stakeholder consultations with farmers, farmer organizations, villagers, *Grama Niladhari* (GN) officers, Community-based Organizations (CBO), and regulative bodies like Divisional Secretariats (DSs), Forest Department (FD), Department of Wildlife Conservation (DWC), Department of Archaeology, and VIS management authorities were conducted. Traditional knowledge regarding boundaries, opinions of the stakeholders, and expectations were recorded while encouraging community involvement during demarcation.

Technical and historical data were collected from key government institutions. Control surveys, statutory surveys, and reservation area maps were obtained from the Survey department (SD); Land Commissioner's department and DSs provided land tenure records and historic land allocation data; FD and DWC provided protected area maps and conservation policies; while Irrigation Department (ID), Provincial Irrigation Department (PID), and Mahaweli Authority of Sri Lanka (MASL) provided operating records, maintenance processes, and up-to-date demarcation criteria of VIS.

Field surveys were conducted over a number of cascade systems (Figure 1) to validate existing boundaries, identify patterns of encroachment, and note existing land use practices GPS surveys mapped the elements of VIS, while ground truthing verified institutional records against actual field conditions.

Collaborative meetings with relevant agencies led to formulation of harmonized demarcation guidelines tailored to VIS. Stakeholder collaboration facilitated field implementation through awareness programs educating participants on demarcation processes, technical criteria, and ecological significance of buffer zones. Reservation boundaries were demarcated according to unified guidelines, with marked points validated through comparison with historical survey records and government permits, ensuring accuracy and minimizing conflicts with existing land users. A detailed comparative review of existing reservation guidelines of SD, DAD, ID, and MASL was conducted. In addition to that, field observations and land use characteristics—such as contour levels, high flood levels (HFL), and sluice spill levels—were examined.

Results and Discussion

Comparative Analysis of Institutional Guidelines

The study revealed significant variations in reservation guidelines across institutions, creating confusion and implementation challenges in the field (Table 1).

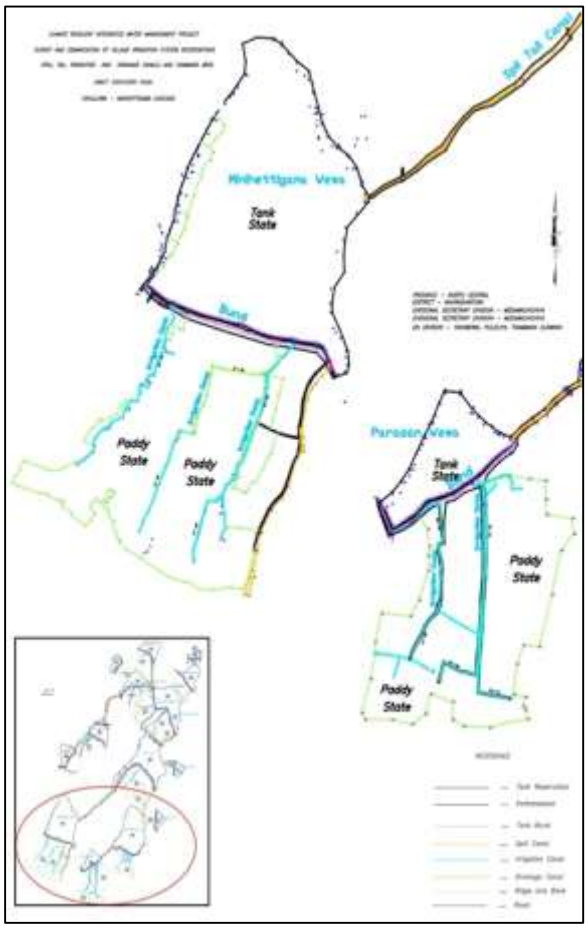

Figure 1. Study Area Map

Challenges in Survey and Demarcation

Although a structured methodology and comprehensive stakeholder engagement were adapted, during the field implementation stage several significant challenges encountered that impacted to demarcation effectiveness. The unavailability of legally recognized standard VIS boundary system developed as the most critical challenge. While traditional knowledge provides valuable information, its undocumented and region-specific variability leads to mis-interpretations. These challenges are compounded by the lack of legally binding reservation limits, and also jurisdictional overlaps among major institutions, leading to paralysis of enforcement. Inefficient inter-institutional coordination also subverts legal action and limits effective action against violations.

Massive encroachment by agricultural and urban activities has transformed natural boundaries and resulted in ecological imbalance. Illegitimate land allotments, often supported by politically influential persons, have created massive ecological belt degradation. Encroachment has created complex issues and made boundary restoration much more complex.

Table 1. Comparison of Reservation Guidelines for VIS Components

Village Irrigation System (VIS) Component	**Mahaweli Authority of Sri Lanka (MASL)**	**Survey Department (DS)**	**Irrigation Department (ID)**	**Department of Agrarian Development (DAD)**	**Recommendation for VIS in CC/ NRCIRD**
Tank Bed	Bottom Top Level (BTL) or 7 m from HFL	5 m from High Flood Level (HFL)	BTL contour or minimum 7m from HFL	Not specified	Contour +5 m or 5 m from Spill Crest Level + 30 cm
Tank Bund	7X maximum bund height from centerline	15X maximum bund height from centerline	7X maximum bund height from centerline	7X height from base of bund	5X height from bund base, minimum 10m
Drainage Canal	5m on both sides	10m on O&M road side	Not specified	5m both sides; 10 m on O&M road side	3m width to allow maintenance access
Spill Tail Canal	BW ≤ 3 m: 5 m both sides BW > 3 m: 10 m both sides	Not Specified	3m corridor on land side for maintenance (as needed)	3 m corridor on land side if needed	Same as ID: 3 m corridor if needed
Main/ Distribution/ Irrigation Canals	4 m on both sides	3 m/8 m/15 m depending on canal type	Minimum m for Main Canals	7m on O&M road side; 2 m – 3 m for distribution	1.5 m (below 3m width); 3m and above: both sides
Anicut	50 m from both banks	5X height of embankment from centerline	5X height of abutment from centerline	Reservations for stream as required	5 – 60 m based on stream width

Rapid infrastructure expansion, particularly road construction and etc, frequently encroaches upon reserved areas, disrupting natural water flow patterns and fragmenting ecosystems. These activities significantly complicate demarcation efforts when original cascade components have been permanently altered or removed.

Community resistance presented additional implementation challenges. During the stakeholder consultations, people verbally support for boundary demarcation initiatives as a community, but at individual-level resistance emerged from economically or politically influential stakeholders facing potential resource access losses. Propaganda and ignorance of eventual environmental, economic, and social benefits fueled further opposition towards successful boundary demarcation. These interconnected issues highlight the multidimensional socio-political and technical character of demarcation in cascade systems, requiring comprehensive solutions in terms of legal, institutional, community, and technical aspects simultaneously.

Strategic Implementation Framework

The development of integrated legal and technical standards represents the foundational strategy, incorporating traditional knowledge and scientific parameters into legally binding definitions. Integration into national policies ensures institutional consistency and enforceability while harmonizing existing guidelines to optimize ecological and land use outcomes.

Technology-enhanced demarcation through GNSS surveys, drone mapping, and GIS systems significantly improves boundary identification precision and monitoring capabilities. Participatory mapping incorporates local knowledge while centralized digital databases facilitate inter-agency coordination and enforcement. This approach provides accurate, legally defensible documentation while maintaining community involvement.

Community-driven governance promotes sustained awareness activities with emphasis on cascade preservation benefits through community representatives. In addition, transparent consultations and grievance mechanisms increase local acceptance and reduce resistance while ensuring participatory decision-making mechanisms that address community concerns.

Institutional coordination requires joint task forces comprising SD, ID, Land Commissioner's Department, FD, and DSs to streamline coordination and reduce jurisdictional conflicts. Clear role definitions enhance accountability while centralized dispute resolution improves implementation efficiency. Field investigations revealed widespread farmer cultivation extending to Full Supply Level (FSL) due to ecological misconceptions, necessitating targeted awareness programs and clear physical demarcation markers. Practical solutions include fair compensation mechanisms for affected farmers and involving them in reservation zone stewardship to reframe demarcation as collaborative conservation.

Buffer zone management in productive and effective way, through environmentally friendly activities such as controlled grazing, fodder cultivation, native species planting are ecologically serves and fulfil community needs while addressing human-wildlife conflict. Legal penalties need to be imposed for reservation land encroaches and that should combine with regular boundary monitoring and community-based reporting mechanisms. That is ensure sustainability and effectiveness of mechanisms and it can be further strength by introducing incentive-based approaches fostering stewardship and compliance.

Conclusion

Boundary demarcation is an essential task for conserve the cascade systems and remain in function. Although boundary demarcation is a challenging process due to the unclear criteria, encroachments, legal gaps, and community resistance, those challenges can be effectively addressed through a integrated approach of legally enforceable guidelines, advanced technologies, and participatory engagement strategies. Further, adaptation of multi-stakeholder approaches helps to balance conservation with livelihood needs through inclusive governance. Both technical and socio-political dimensions are address in the

proposed framework. This is crucial to sustained institutional commitment and community engagement to ensure these traditional systems serve future generations.

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Community Acceptance of Legal Demarcation of Tanks Cascade Systems in Sri Lanka's Dry Zone

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Introduction

The dry zone of Sri Lanka is home to the Village Tank Cascade Systems (VTCSs), an ancient model of integrated network of small, interlinked tanks developed over two millennia to sustainably manage water for agriculture and biodiversity (Madduma Bandara 1985; Panabokke et al. 2002). These systems include a range of features such as *kiul ela* for drainage, *gangoda* for settlements, and *liyadi* for cultivation, with ecological zones like *kattakaduwa*, *gasgommana*, and *perahana* that enhance water purification and habitat conservation (Dharmasena 2010). Functional components such as *yathuru wala* and *mada sorowwa* ensure efficient water regulation, while *kulu wewa* and chena lands support forest and wildlife integration. The VTCS model demonstrates a holistic approach to water management, blending ecological resilience with traditional knowledge and communal governance. Panabokke et al. (2002) underscore that communities not only constructed these systems but also managed inter-tank water transfers and land use through locally recognized norms. Acknowledging their global significance, the FAO declared VTCSs a Globally Important Agricultural Heritage System (GIAHS) in 2017 (FAO, 2017).

However, in recent decades, these systems have deteriorated due to anthropogenic pressures including land encroachment, deforestation, poor land use practices, and inadequate institutional management (Panabokke et al. 2002). These challenges undermine the VTCSs' capacity to support agriculture, maintain hydrological balance, and buffer climate shocks, putting both environment and rural livelihoods at risk (Dharmasena 2010). This decline is partly attributed to the absence of formal legal frameworks defining their boundaries, ownership, and governance responsibilities. Efforts to restore and manage these tanks have often overlooked the role of traditional institutions and the cultural embeddedness of water governance, resulting in mixed outcomes.

To address these issues, the Climate Resilient Integrated Water Management Project (CRIWMP), led by the Ministry of Irrigation and funded by the Green Climate Fund (GCF), allocated LKR 6,000 million to rehabilitate 325 tanks across 20 major cascades (UNDP 2019). In response, CRIWMP identified the demarcation of tank boundaries as a critical conservation strategy. Two distinct approaches were adopted, (a) Social demarcation, which involves community participation and consensus and (b) Legal demarcation, which follows formal procedures in line with government regulations.

This study focuses on the legal demarcation process outlines its key features are (1) All demarcation activities are carried out under the supervision of the Department of Survey and conducted by licensed surveyors, (2) The project does not aim to displace existing land users or encroachers, (3) Coordination is ensured with all relevant stakeholders from the outset, (4) Government rules and regulations are strictly applied throughout the process, (5) Valid grievances are addressed amicably through established procedures, (6) In cases of disagreement, affected individuals can file complaints with the Divisional Secretariat (DS), which then initiates a structured dialogue process to seek resolution. These procedures are designed to reduce conflicts and are officially recognized, allowing all government institutions to use it as a legal reference.

Despite the growing emphasis on tank restoration under initiatives like CRIWMP, there is limited empirical research on how communities perceive legal demarcation, especially in Sri Lanka. Factors such as institutional trust, awareness, participation, and livelihood impact are thought to shape acceptance, as emphasized in Ostrom's (1990) Commons Theory and Ajzen's (1991) Theory of Planned Behavior. Yet these frameworks are rarely applied in VTCS studies. This study addresses that gap by exploring community-level responses to legal demarcation, focusing on the governance, social, and institutional elements that influence acceptance—factors essential to ensuring long-term sustainability of VTCSs.

Methodology

Study Area, Population and Sampling

The research was conducted in 20 tank cascades across six districts within Sri Lanka's Dry Zone - Anuradhapura, Kurunegala, Trincomalee, Puttalam, Vavuniya, and Mannar, where the Climate Resilient Integrated Water Management Project (CRIWMP) has implemented legal demarcation initiatives. The study targeted households located in or near the demarcated VTCSs. A total of 200 household respondents were selected through stratified random sampling to ensure balanced representation across geographic and administrative contexts.

Research Design

This study adopted a quantitative explanatory research design to investigate factors influencing community acceptance of legal tank demarcation. Using structured questionnaires and statistical analysis, the design enabled identification of significant relationships between socio-demographic, institutional, and perceptual variables providing a data-driven understanding of patterns within the target population.

Data Collection Methods and Analysis

Primary data were collected using a structured, pre-tested questionnaire featuring Likert-scale items on perceptions and attitudes toward legal demarcation outcomes.
Data analysis involved SPSS 27. Descriptive statistics summarized distributions, while binary logistic regression modelled the probability of acceptance (Y=1).

The model specification is presented as Equations 1, 2 and 3;

General Logistic Model: $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots\cdots + \beta_m X_m + \varepsilon$ …… (Eq. 1)

Logit Function: $\ln\left(\frac{P(Y=1)}{1-P(Y=1)}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots\cdots + \beta_7 X_7 + \varepsilon$ …… (Eq. 2)

where P = Probability of acceptance; X1 to X6 = explanatory variables; β = coefficients; ε = error term.

Odds Ratio: Odds = $\frac{p}{(1-p)}$ …… (Eq. 3)

Variables were checked for multicollinearity and coded for regression. Statistical significance was assessed at $p < 0.05$.

This study has several limitations. Respondent bias may have occurred due to participants' affiliation with or awareness of the CRIWMP project, potentially influencing their responses. Additionally, the findings are primarily applicable to dry zone cascade communities involved in the CRIWMP intervention, limiting generalizability to other regions or contexts.

Results and Discussion

Socio-Demographic Profile of Respondents

The socio-demographic composition of the 200 respondents highlighted a predominantly male (61%) and agriculture-based community (83.5%). The average age of participants is approximately 50.6 years (SD = 11.41), indicating a middle-aged population, ranging from 25 to 75 years. Educational attainment was relatively modest, with the majority (59.5%) having completed secondary education. Residency patterns indicate long-term settlement, with 76.5% residing in the village for over 20 years. No new settlers (less than 5 years) were recorded. Land ownership near tanks was high (93%), and 66% lived within 500 meters of the tank. This demographic profile reflects a long-term, agricultural-dependent community with strong geographical and economic ties to tank cascade systems. The distribution of these variables is summarized in Table 1.

Table 1. Demographic data distribution.

Variable	Category	Frequency (n = 200)	Percentage (%)
Gender	Male	122	61
	Female	78	39
Occupation	Agriculture	167	83.5
	Government	27	13.5
	Non-Government	6	3
Education Level	No Formal Schooling	7	3.5
	Primary Education	69	34.5
	Secondary Education	119	59.5
	Higher Education	5	2.5

Years in Village	5 – 20 Years	47	23.5
	More than 20 Years	153	76.5
Own Land Near Tank	Yes	186	93
	No	14	7
Distance to Tank	Less than 500 m	132	66
	500 m – 1000 m	62	31
	More than 1000 m	6	3

Determinants Influencing Community Acceptance of Legal Tank Demarcation

The binary logistic regression model predicting the factors influencing the decision to accept the legal demarcation of tank cascade initiative under the CRIWMP project is give as Equation 4:

$$\ln\left(\frac{P(Y=Yes)}{P(Y=No)}\right) = -0.939 - 2.39 * F1 - 3.14 * F2 + 5.53 * F3 + 1.51 * F4 - 1.917 * F5 - 3.67 * F6 \quad \text{(Eq. 4)}$$

This model estimates the log odds of accepting the legal tank demarcation initiative (Y=Yes) based on six predictors (F1–F6). According to the results, satisfaction with the opportunity to participate in the process of demarcation (F3) (β = 5.53), strongly increased the likelihood of supporting the initiative. This highlights the importance of involvement of communities in a fair and inclusive way to build trust and acceptance (Tyler, 2006). Belief that demarcation contributes to ecological sustainability (F4), also had a positive effect (β = 1.51) suggesting that people who recognize the environmental benefits of the initiatives are more likely to accept it. This aligns with previous research showing that strong environmental values often lead to greater acceptance of conservation efforts (Pretty 2003). Meanwhile, perceived need for more transparency (F5) (β = -1.917) and having experienced problems due to demarcation (F6) (β = -3.67) both reduce the acceptance, highlighting the role of trust in the process and people's direct experiences play a key role in shaping their acceptance. This aligns with the concerns raised by Ostrom (1990) transparent and responsive institutions are crucial for gaining community support in managing shared natural resources.

Long-term residence in the community (F1) was found to negatively affect acceptance (β = -2.39), suggesting that individuals who have lived in the village for over 20 years may resist formal demarcation. This is due to the stronger reliance on traditional tenure systems and informal land claims. This finding is consistent with Cleaver and Franks (2005), who noted that such communities often manage land through customary norms that do not align with formalized interventions. Surprisingly, involvement in any demarcation-related activities (F2) showed a significant negative effect (β = -3.14), implying that individuals who participated directly in the process may have encountered procedural flaws, unmet expectations, or unresolved tensions, leading to reduce acceptance which aligns with the findings by Ratner et al. (2013), which emphasized that poorly managed participation can

lead to disillusionment, especially when community engagement lacks transparency, inclusiveness, or tangible outcomes.

Overall, the model reveals that acceptance of legal tank demarcation under the CRIWMP project is strongly influenced by perceived environmental benefits and participatory satisfaction foster support, while negative experiences and mistrust in the process deter acceptance. These findings highlight the critical need for the CRIWMP project to strengthen participatory mechanisms, enhance procedural transparency, and address community grievances to foster lasting support for formal demarcation efforts.

Community Perceptions and Attitudes Toward Legal Demarcation Process and Outcomes

Results of the perception of the community towards the legal demarcation process and outcomes indicated a strong community agreement (Table 2).

Table 2. The percentage of the frequencies for perceptions on legal tank demarcation

Perception	Code	SD	D	N	A	SA
Tank demarcation contributes to the sustainability of the tank	P1	1%	28%	9%	50%	13%
Tank demarcation in necessary to protect water bodies.	P2	1%	29%	8%	50%	13%
Tank demarcation will help reduce conflicts over land and water usage.	P3	1%	25%	11%	51%	14%
Demarcation boundaries should be visibly marked.	P4	1%	22%	15%	49%	15%
Demarcation boundaries should be clearly accessible to the community.	P5	1%	22%	15%	48%	15%
I am concerned that tank demarcation may limit my traditional land use rights.	P6	1%	20%	17%	49%	14%
Educational materials on tank demarcation should be shared with the community.	P7	1%	22%	13%	52%	14%
Awareness programs about tank demarcation should be held regularly in community.	P8	1%	21%	16%	48%	16%
More transparency is needed in how decisions about tank demarcation are made.	P9	1%	21%	13%	49%	17%
I trust the authorities involved in the demarcation process.	P10	1%	24%	11%	49%	16%
The community should be more involved in future demarcation processes.	P11	1%	24%	14%	48%	15%

Over 60% agreed that it promotes tank sustainability (62.5%), reduces land-water conflicts (64.5%), and requires regular awareness programs (63%). A majority (65%) endorsed visible boundary marking and transparency while 62.5% expressed potential limitations on land use, reflecting tensions between legal frameworks and customary claims. Additionally, 63.5% favored community involvement in future demarcation processes, reinforcing the

need for participatory governance. The 11-item perception scale showed excellent reliability (Cronbach's Alpha = 0.976) and strong sampling adequacy (KMO = 0.954). Principal Factor Analysis revealed a single factor explaining 80.7% of the total variance, supporting the construction of a unified perception score using the mean of all 11 items. The constructed perception variable showed a moderately positive tendency (Mean = 3.53; Median = 4.00; SD = 0.92), indicating that respondents generally viewed the legal tank demarcation process (Table 2) and the outcomes favorably, although some variation in perception was observed.

The study found that community acceptance of legal demarcation under the CRIWMP is shaped by both social and institutional factors. Institutional trust, transparency and the perceived fairness of the demarcation process emerged as critical determinants of acceptance. Active participation in meetings and consultations was found to significantly enhance both understanding and acceptance among community members. In contrast, when the process was perceived as a threat to land ownership or livelihoods, support declined, highlighting the need to address these concerns through transparent communication and inclusive engagement strategies. Trust building played a significant role, as villages with strong relationships and regular interaction with local officers demonstrated higher levels of acceptance. Additionally, effective conflict resolution mechanisms, especially those involving local dialogue, were associated with increased community support, emphasizing the value of participatory and transparent approaches.

Implications for Policy and Practice

This study suggests several important lessons for improving the legal demarcation process, including, (1) Improve legal literacy: Communication tools must be adapted for varying literacy levels using visual aids, and participatory learning using local languages, especially for people with limited formal education, (2) Foster Institutional Trust: Building trust requires consistent, face-to-face interaction with local officers. Institutions must operate transparently through regular dialogue. Strengthening community relationships and local support networks is important, and (3) Adapt to local contexts: One uniform approach won't work everywhere. Legal demarcation must respect traditional land-use systems and cultural practices. A more adaptive model that blends formal laws with local customs will be more successful and sustainable.'

Conclusion

Legal demarcation, when effectively implemented, holds considerable promise for enhancing the sustainability and resilience of Sri Lanka's tank cascade systems. However, the findings make clear that acceptance is mediated by socio-cultural alignment, institutional behavior, and alignment with community values. Formal legal recognition alone cannot guarantee compliance unless grounded in participatory, inclusive, and culturally appropriate processes. As CRIWMP and similar initiatives evolve, incorporating these social dimensions will be crucial. Empowering communities through transparent engagement, legal clarity, and livelihood-sensitive governance will ensure that legal tank demarcation moves from being a contested intervention to a collaborative opportunity for

ecological stewardship, rural empowerment and water management tool to ensure the resilience of Sri Lanka's tank cascade heritage.

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The relevance of transformative adaptation and polycentric governance to the Tank cascade management

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Introduction

A polycentric system is a mechanism enabling several governing authorities, operating at different scales and independently of each other, to engage in collective action (Ostrom 2010). Polycentric governance—a system where multiple, overlapping decision-making centers collaborate—is critically relevant for managing complex natural resources systems.

The poor performance of some climate change adaptation measures and concerns about their sustainability have resulted in a demand by governments, donors, and civil society for a systemic change in those measures. This need has now been recognized by institutions such as the International Panel on Climate Change (IPCC) (Filho et al. 2020). Furthermore, the need to address the root causes of vulnerability has been emphasized, and transformative adaptation is described as a strategy serving that purpose. While it is agreed that the term could have differing interpretations according to the time scales of changes and the goals of the interventions, etc., basically, the term implies fundamental changes in the systems and the society (United Nations 2024).

Sri Lanka's tank cascade systems, comprising hydrologically connected village irrigation systems (VIS) including tanks and anicuts, are facing numerous challenges due to climate change. Inadequate governance mechanisms have been identified as a root cause of cascades' vulnerability (Imbulana and Aheeyar, forthcoming). The Climate Resilient Integrated Water Management Project (CRIWMP) and a few other projects moved beyond incremental fixes to systemic redesign of tank cascade governance to address this situation.

The objective of this paper is to study the relevance of transformative adaptation and polycentric governance for the sustainable management of tank cascade systems and recommend measures to incorporate those principles into future tank cascade-based development projects.

Methodology

This study employed a mixed-methods approach. A literature survey to examine the issues relevant to unsustainable governance in tank cascade systems before the CRIWMP, and assess how transformative adaptation measures and polycentric governance in the CRIWMP addressed these unsustainable issues in tank cascade systems. Obtaining

community perceptions to strengthen CRIWMP interventions to generate systemic impacts using a questionnaire survey.

Results and Discussion

Literature survey

Sri Lanka's tank cascades are facing unprecedented threats from climate change-intensified droughts, erratic rainfalls, and extreme floods. Conventional adaptation (e.g, incremental repairs to individual tanks) has proven insufficient. For example, it is noted that rehabilitation works in the Anuradhapura District have not significantly improved cropping intensity, and there are suggestions to reexamine the strategies used in such interventions (Dharmasena 2020). Similarly, post-evaluations of some rehabilitation projects have raised doubts about the sustainability of the benefits, due to poor post-project operation and maintenance (O&M) (Abeyratne 1990). The ecosystem, which has a major role in the sustainability of the tank cascades, has substantially deteriorated now (Imbulana et al. 2023), and conventional rehabilitation does not pay sufficient attention to restoring or managing these ecosystems.

Imbulana et al. (2023) noted that they provided a variety of services for the community in the past. Different tanks in a cascade performed a variety of social, economic, and environmental functions. There were also agreed-upon principles for water use and responsibilities for the maintenance of irrigation infrastructure. Sustaining these services and characteristics for a long period indicates the existence of well-established governance arrangements. In ancient times, these systems functioned as self-sustaining entities not heavily influenced by governance arrangements at different scales.

However, the current situation of the tank cascade is different. An institutional mapping conducted on selected CRIWMP interventions identified 19 government institutions involved in the planning and implementation of the project. These institutions function at the national, provincial, district, and divisional levels. In addition, the private sector and civil society organizations are involved in the development and management activities at the cascade level (Imbulana et al. 2023). Thus, various services required by the community in a tank cascade are provided by numerous sectoral organizations with little coordination.

Furthermore, current governance arrangements in cascades consist of farmer organizations (FO) focused on irrigated agriculture and other community organizations (CO) focusing on drinking water, fisheries, etc., where the FOs and COs' spatial scale of authority is either the village or the area commanded by an individual tank. As such, the governance arrangements are both sector-wise and spatially disaggregated. Quite often, women and youth are not included in the governing mechanisms. Therefore, although the cascades are hydrologically integrated, current governance arrangements do not support bringing in the full spectrum of stakeholders to achieve the development potential of a cascade.

Based on the literature survey, the main reasons for the unsustainability of tank cascade systems are summarized as (a) Operation and maintenance (O&M) of irrigation systems and maintenance of ecosystems are inadequate, and therefore, physical improvements to the

system are not sustainable., and (b) There is no mechanism to engage the full spectrum of beneficiaries and the service providers of the cascade in the management of the system and the maintenance of irrigation infrastructure and the ecosystems. Therefore, the potential of the cascade to deliver a variety of functions is not achieved.

This situation calls for a new governance mechanism based on polycentric principles to bring different government sectors (irrigation, agriculture, forest, wildlife, extension), the private sector, and the communities to a common forum for cascade management. The CRIWMP designed a development and governance model having the key components, (a) A cascade management plan integrating the uses such as agricultural, domestic, fisheries, and environmental, and resources such as irrigation infrastructure, surface water, groundwater, and land within the cascade, and (b) An institutional arrangement to bring in the relevant actors, including the government, private sector, and communities, to a common forum called the Cascade Management Committee (CMC)

The sectoral measures to improve sustainability introduced by the CRIWMP included (a) Upgrading village irrigation systems (VISs) and restoring the associated ecosystem to be resilient against climate change, (b) Introduction of improved operation and maintenance (O&M) plans covering the irrigation system and the ecosystem, with clear responsibilities assigned, (c) Adoption of Climate Smart Agricultural (CSA) practices, including improved on-farm water management, (d) Drinking water solutions, and (e) Disaster risk reduction (DRR) and weather and water management advisories. These sectoral measures, when individually considered, were interventions tried out in previous development projects, and the CRIWMP introduced innovative elements into them. The services resulting from these measures in individual tanks were integrated by the cascade management plan.

The CMC comprises all the government institutions and community organizations involved in implementing the cascade management plan. The government institutions included those dealing with agriculture, irrigation, agrarian services, and environmental conservation. The community organizations included farmer organizations (FO), fisheries societies, women's FOs, drinking water-related COs etc.

Community survey

The project carried out an internal assessment of the effectiveness of CMCs in 2025, as well. While the results were encouraging, they also revealed the way forward and the constraints to be addressed. The summary of findings from Mottapetthawa, Kadawala, and Sivalakulama cascades are presented in Table 1.

Table 1. Summary of the findings of the community survey

The objective of the CMC was clear to most of the farmers. Overall rating given by the farmers was 97% across three cascades
The participation of the community organizations (82%) and the relevant government agencies (100%) was given very high ratings by the community. However, the rating for the community organizations' participation in Sivalakulama was comparatively low (67%)

The Community agreed that they had a say in the management of their resources (87% rating with only a small variation across cascades)
The water sharing arrangements between users in the same VIS and the involvement of women and youth in water management decision-making were somewhat satisfactory, with ratings of 83% and 77% from the community
Water sharing arrangements between different VISs were very poor, with a rating of 17%.
Land resources-sharing arrangements for different uses, such as grazing lands, were not satisfactory, with an average rating of 33%. However, there was a substantial variation among the cascades, with 0% in Mottapetthawa to 80% in Kadawala.
When the ability of the CMC to resolve community problems were evaluated, a similar variation was observed, from Sivalakulama (0%) to Kadawala (100%).
The high scores received for understanding the objective of the CMCs and the participation of both community organizations and government institutions are encouraging, and indicate the effectiveness of community mobilization by the project. These results support the relevance of polycentric governance for enabling wider participation of women and youth in local resource management.
For several generations, the community did not have formal land and water sharing arrangements between different VISs. Introducing such concepts and the needed attitude changes requires time. Moreover, there are very few structural facilities to share water among VISs, and the future structural designs should incorporate such facilities.
As noted above, the success of the CMC as a problem-solving mechanism had a high variation. In the Sivaakulama cascade, where the rating was the lowest, there was a low participation of community organizations in the CMC, and women and youth did not have a strong role in decision-making. Similarly, the decisions taken at the CMC appear to be rarely implemented in Sivalakulama.

Table 2 indicates the factors affecting effectiveness of CMCs in different cascades.

Table 2. Factors affecting CMC's effectiveness in different cascades

Factors affecting CMC's effectiveness	**Ratings**		
	Mottapothawa	**Kadawala**	**Sivalakulama**
Clarity of the objective of forming the CMC	90%	100%	100%
Participation of Community Organizations	80%	100%	67%
Participation of Government agencies	100%	100%	100%
Having water sharing arrangements between VISs	0%	0%	50%
Water sharing among users of the same VIS	50%	100%	100%
Improved community engagement in the management of their resources	80%	80%	100%
Whether women and youth have a say in decisions (including as office bearers)	80%	100%	50%
Land resources re-allocation (grazing lands etc.,)	0%	80%	20%
CMC as as a problem-solving mechanism	40%	100%	0%
Are the decisions of CMCs implemented?	50%	80%	0%

Conclusion

Considering the ability of tank cascades to effectively minimize the impacts of droughts and floods, it can be seen that development and management of tank cascades are crucial to climate change adaptation. However, conventional approaches do not seem to cater for achieving the full potential of these systems.

Transformation adaptation is essential because, (a) The root causes of unsustainable adaptation, such as inadequate O&M of irrigation infrastructure and the ecosystem, need to be addressed, (b) Women and youth need to be engaged in the management of local resources, but conventional governance arrangements do not allow it, (c) Isolated sectoral interventions (such as in irrigation system rehabilitation, improved agricultural practices, improved drinking water solutions, improved weather information) need to be integrated for optimum impact on climate resilience. The cascade is a suitable unit for this integration because the water resources are already hydrologically integrated in the cascade.

Therefore, the CRIWMP's development and governance model described above is conducive to transformative adaptation in the tank cascade. Strategies such as physical, ecological, and institutional restorations, women-led agro-ecological initiatives, and water management considering the whole cascade support the transformative approach and have yielded promising outcomes, increasing the sustainability of the interventions and household incomes.

Considering the clarity of CMC's objective and high level of participation by stakeholders, the CMC has the potential to transform the tank cascade management, provided the generated momentum continues post-project. For this to be achieved, the existing community organizations need to be transformed into business-oriented organizations, and they need to be represented in CMCs. The constraints to the effective functioning of the CMC highlighted in the community survey appear to be cascade-specific and they and to be resolved with the government intervention and legal support, at their initial stages.

However, the governance challenges persist. In all CMCs, FOs still play the dominant role in decision-making. These findings align with critical institutionalism's emphasis on various power structures that influence the participatory framework. Yet their scalability was often hindered by systemic barriers, including FOs' dominance in decision-making and a top-down funding model. Without addressing power asymmetries, even the most technically sound transformative adaptation interventions risk replicating the very vulnerabilities they aim to resolve.

Considering the above, a four-pronged strategy is proposed to address issues affecting the sustainability of this transformative adaptation model, such as (a) Develop a business plan for the cascade accommodating all the production components (irrigation command, uplands, home gardens, livestock, fisheries, etc.). Such plans will incorporate high-value crops with advanced irrigation techniques, (b) Gradually transform existing community organizations into business entities such as farmer companies and engage them in the CMC for coordination and technical support, (c) Continue the CMC as a governance entity,

providing technical support, agrarian services, and legal backup, as required, and (d) The sustainability of tank cascade systems will be further enhanced by incorporating cascade management plans into river basin development and management plans, and the government's rural development plans.

These interventions need to be supported by government policies and legislation. Therefore, amending the existing policies and legislation, such as the Agrarian Development Act, is essential.

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Community-based Approach to Protect Water Sources through Nature-Based Solutions and Policy Implementation in the Central Province of Sri Lanka: Challenges and lessons learned

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Introduction

Central Province of Sri Lanka serves as the primary watershed for most of the country, since many of the rivers of country originate from the central region. In ancient times, most of the hilly part of the Central Province was protected as a catchment area without cultivation.

However, after the introduction of the plantation economy, many natural sources of water have been utilized by the local communities for agriculture and other development activities. The Central Province is extremely susceptible to the effects of climate change, such as rising temperatures, severe weather, and altered precipitation patterns. During the dry season, there has been evidence of water source depletion in certain locations. The primary problems brought on by landslides and flash floods are high turbidity and contaminated water.

In 2022, UNICEF and the provincial land department launched a climate resilience project in the province to lessen the consequences of climate change. The initiative used a community-based participatory approach to safeguard water sources from other anthropogenic risk factors and found nature-based solutions to lessen the effects of climate change. To improve the execution of the policies at the local level, additional regulatory instruments have been developed.

Methodology

This study is participatory action research. A systematic and reflective approach was used to identify challenges, best practices, and areas for improvement, mainly on the role of the community in policy implementation to protect water sources. For this study, the following components related to the conservation and protection of water sources in Sri Lanka have been taken into account.

As a part of this participatory action research, the community members were empowered to find solutions by themselves to protect their water sources and bridge the communication and coordination gaps between government administrative authorities. As a result, the communities were involved in the implementation of nature-based solutions and policy measures. Among them identification of high-risk water sources, establishment

of village-level society or committee on matters related to the environment, climate change, and water resource protection, implementation a long-term participatory action plan for each identified high-risk water sources, prevention of illegal human intrusion and occupations in catchment areas and reassessing of risks are significant.

This initiative was further streamlined by strengthening the local-level legal framework through the development of a provincial-level policy on regularization, protection, conservation, and management of watersheds, water sources, and reserves in the Central Province of Sri Lanka. A gazette notification was made in the central province to make adequate provision to the Pradeshiya Sabha to streamline the water distribution strategies including the water sources within the authority area of the *Pradeshiya Sabha* for the sustainable maintenance of drinking water safety so that the public of the Central Province can safely use drinking water.

This study explored how the inclusion of the community in the process of policy implementation has contributed to enhancing community awareness of the policy and empowerment to implement community-led actions. Community engagement plays a vital role in enhancing transparency within planning and decision-making processes, hence fostering increased responsiveness. This study will provide recommendations for further research on community engagement in policy implementation that can broaden the understanding of issues related to the topic.

Initially, the water sources were mapped and prioritized based on the vulnerability assessment by the provincial land commission. Risk categorization has been developed based on different risk levels, which were identified by giving a wide range of risk factors. CAPs with local solutions were developed by members of the Village Development Committees (VDC), with the support of land officers who were trained on the effects of climate change on water resources and relevant policy implementation (Provincial-level policy on regularization, protection, conservation, and management of watersheds, water sources, and reserves in the Central Province) at the local level. High-risk water sources were selected to implement the CAP, through community participation. Community-based mechanisms were developed to monitor the implementation of CAP and the protection of water sources from illegal actions. Focus group discussions were held with VDCs and government officers to understand the effectiveness of using NBS to protect water sources and implement relevant policies at the community level.

Results and Discussion

The community-led participatory approach was assessed against the implementation of policies on water source protection at local levels and the implementation of nature-based solutions. Community engagement is defined as a dynamic process with the involvement of individuals, community collectives, and civic entities in the formulation and execution of plans and decision-making procedures that have an impact on their daily existence (Head 2007). The below subsection describes community-led nature-based solutions designed

and implemented by communities coordinating with grassroots-level government administrators who represent land, water, youth, and social protection.

Community participation in nature-based solutions to protect water sources

IUCN (2020) recognized Nature-Based Solutions as actions taken to address societal challenges through the protection, sustainable management, and restoration of ecosystems, benefiting both biodiversity and human well-being. The NBS proposed in this study through community participation are presented in Table 1.

Table 1. Nature-based Solutions to protect water resources

✓	Demarcate the water conservation area by the provincial survey department with the support of the Village Development Committee (VDC), and plant the arecanut (*Puvak*) tree belt alone as the demarcation line
✓	Plant Gliricidia (*Wetamara*/*Ladappa*) branches and develops the life fence around the water sources, and this life fence demarcates the legal boundary of the water sources
✓	Plant indigenous trees inside the water catchment areas.[1]
✓	Develop green areas consisting of local indigenous trees near the water source
✓	Provide bee boxes to people inhabiting the water catchment area with awareness and promote the pollination of trees
✓	Enhance the diversity of the ecosystem of the water system by planting different varieties of local indigenous plans
✓	Plant trees with economic value to support the food production of local communities (e.g., Jack trees, Palmyra trees, etc.).
✓	Each plant was assigned to a family or member of the Village Development Committee (VDC) to water and maintain the plant until it grew healthy
✓	Develop water diversion drains and contours towards the water sources to prevent flooding and promote groundwater recharge
✓	Ecosystem management, protection, and restoration have been proposed for buffering societies to reduce the adverse impact of climate-related extremes due to anthropogenic climate change (Holden et al. 2022). Similarly, this study revealed that nature-based solutions are sustainable and implementable to mitigate anthropogenic climate change when they are originated by local communities that have local knowledge about ecosystems such as suitable local plant varieties, planting methods and traditional water conservation and pest control practices. When community-based participatory approaches are used as appropriate mechanisms to implement nature-based solutions, a sense of ownership and sustainability is built up within local communities. Nature-based solutions are more sustainable when they are instrumental in relevant local policies\
✓	The community-based participatory approach has been used for the implementation of Nature-Based Solutions, and they have been included in the Community Action Plan (CAP)

[1] A water catchment is an area of land and the water that collects and moves through it. It is often bordered by hills or mountains, and the water enters via precipitation (rain or snow) and then moves across the surface or subsurface (as groundwater) until it drains into a stream or river.

Community participation in the policy implementation:

Training was conducted for the divisional secretaries, assistant divisional secretaries, and other decision-making officers of the Divisional Secretariats to understand climate change, the resilience of impact, protection of water sources, participatory planning, implementation, monitoring, evaluation, and budgeting were the key topics of this training program. The objective of this training program was to make the decision-making officers aware at the divisional level of the importance of water source protection with community involvement. Land Officers, Development Officers, Youth Service Officers, social service officers, and Land Use Officers were trained as trainers to conduct the village-level training programs for the communities and youth groups in each selected village with high-risk water sources. These trained officers conducted village-level training programs for the selected village development committees and community youth groups in 20 identified villages.

These training programs were planned as a two-day training program in the same villages. The first day was allocated for conducting theoretical sessions and the second day was allocated to prepare a participatory action plan (PAP) to protect the water sources by communities. At the end of these two days of training sessions in each village, long-term conservation and protection plans for each water source were developed. These conservation plans consisted of low-cost and no-cost activities which are implemented through community participation. The Provincial Land Commissioner's Department with the participation of the provincial land commissioner, planning director of the provincial council, and relevant field officers, a review was conducted to allocate funds for water source conservation.

Youth officers, land officers, and social work officers in the province have been trained on climate change-related topics and youth participation to get their community involvement led and youth-led activities. The feedback received from the youth was presented to the government partners of the Provincial Council to be considered for the draft policy on water source protection.

The government should establish and maintain effective participatory mechanisms, such as advocacy groups, discussion forums, and working groups that represent various segments of society (children's groups, youth groups, schools, and the elderly population). These mechanisms must be open and inclusive to ensure that all voices are heard and considered.

Challenges and Lessons Learnt

Development concepts like community development, empowerment, and participatory techniques are not taught to grassroots government officials and policymakers, and consequently, the implementation of the participatory approach were the key challenges. The difficulties of coordinating multiple agencies are a common challenge faced in policy development and implementation processes.

Figure 1. Development of the CAP by VDC

To improve young leadership as future leaders, development partners and the government need to encourage youth involvement in community development initiatives and their active participation in policy-making processes. Then the Youth are inspired and given the chance to become future leaders as a result.

Governments may build solid and reliable partnerships with communities by actively include them in decision-making processes. In addition to preventing disputes. This strategy improves interaction in order to successfully address challenging challenges such as human intrusion, man-made pollution, and malpractices, which impose threats to water source protection.

Conclusion

Communities and young people need to be empowered with the knowledge, skills, and opportunities to take actions in their communities to address the issues in water source protection. Community-level social networks and grassroots-level leadership are crucial to take action to protect their water sources. Policymakers and decision-makers understood

the importance of meaningful community participation in policy development and implementation. Engaging communities in the implementation of policies and programs enhances accountability and improves implementation quality. Participatory approach enables communities to offer valuable feedback for further enhancement. Grass root-level officers play a critical role in translating local policies into actions at the community level with the participation of people. The inclusion of many perspectives of communities that are directly impacted facilitates the identification and resolution of issues that may be imperceptible or disregarded by the government.

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Living with the Water: What Sri Lanka can learn from the Netherlands' Coastal Adaptation Experience

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Introduction

Sri Lanka, a small island developing state surrounded by the Indian Ocean, is highly vulnerable to the adverse effects of climate change, particularly in its coastal regions. Rising sea level, coastal erosion, salt water intrusion and severe flooding events pose significant threats to both livelihoods and infrastructure in low-lying coastal areas. Sea level rise is projected to rise by 10 cm in 2030 and 21 cm in 2060 (World Bank 2020). Furthermore, Sri Lanka is particularly vulnerable to the combined effects of sea level rise and storm surges (Dasgupta et al. 2011). Over the past years, Sri Lanka has increasingly experienced, these climate impacts, which are becoming more common and severe.

To address the impact posed by climate change, Sri Lanka's adaptation strategies have primarily focused on hard engineering solutions such as revetments, groins, sea walls, and gabion walls (Kodikara 2021). In addition to climate change, human activities like illegal sand mining, unregulated constructions, destruction of mangroves and coral reefs have further weakened the coastal natural defences. The ecological and social trade-offs of relying on hard infrastructure are evident in several areas across Sri Lanka, including erosion in Negombo, Kalutara, and Oluvil caused by dredging operation or poorly planned rigid construction. These "gray" operations, often disrupt natural sediment flows and vegetation cover (Diwyanjalee 2025). Therefore, there is a pressing need to shift toward more adaptive, nature-based, and community-centred approaches to climate resilience, especially at the ground level, where the impacts are felt most. Though the Netherlands is considered a developed country in a temperate climate, its history of flooding and sea-level rise makes it a significant comparative case for Sri Lanka (van Koningsveld et al. 2008). Despite differences in income and geography, both countries face same challenges in protecting coastal communities and infrastructure (Adger, Arnell & Tompkins, 2005). Sri Lanka can learn important lessons from the Dutch model while adapting them to its unique socio-economic and tropical circumstances (World Bank 2020).

In this context, Netherlands showcase a valuable case study. The country has long been susceptible to flooding, with a significant portion of its land situated below sea level. Rather than relying solely on walls and barriers, the Netherlands has adopted an innovative approach that embraces water as a part of life. Though sustainable and nature-based programs such as "Rooms for the River" (Verweij et al. 2021), sand dune reinforcement projects like Spanjaards Duin (Meulen et al. 2014) and wetland restoration initiatives (Schapendonk 2024), the Netherlands has become a global pioneer in blending

engineering with nature-based solutions and spatial planning. These strategies not only safeguard people from disasters but also enhance biodiversity, improve water quality and actively involve local communities in decision-making.

This extended abstract explores how Sri Lanka can learn from the Dutch experience through concepts such as "Living with Water". It prioritizes community resilience, eco-system-based strategies and practical solutions over national policy analysis. Specifically, it seeks to demonstrate how more comprehensive adaptation models for Sri Lanka's coastal zones can be inspired by the Dutch experience with nature-based infrastructures, adaptive land use and public engagement. Additionally, this study aims to identify practical lessons to guide future local adaptation efforts in Sri Lanka. These include the importance of making space for water, restoring and expanding mangroves and wetlands and integrating local communities in the climate resilience process. Ultimately, the goal is to fostering long-term resilience in ways that are sustainable, socially inclusive and ecologically sound.

Methodology

The study employed a qualitative, literature-based methodology to investigate how Sri Lanka can enhance its coastal adaptation strategies by learning from the Netherlands' experience. The research is entirely based on secondary data, analyzed through a review of relevant literature. Data was collected from a range of credible sources, including peer-reviewed journal articles, government publications, policy reports, international reports and documented case studies. Special attention was given to publications that emphasize coastal resilience, nature-based solutions and climate change adaptation in the contexts of both Sri Lanka and the Netherlands. Thematic analysis was used to examine the information gathered. Key themes such as embracing nature-based solutions, living with water and community engagement and local ownership were interpreted to explore how Dutch adaptation strategies can be applied in Sri Lankan's coastal regions. With a focus on relevance to Sri Lanka's socio- ecological context, this methodology aims to provide a grounded understanding of best practices and practical approaches to coastal resilience.

It is crucial to emphasize that, whereas the Dutch experience is based on extensive hydrological data and spatial modelling (Roth and Winnubst 2014), Sri Lanka's data collection is minimal due to fragmented monitoring and insufficient coastal mapping (Eriyagama and Smakhtin 2010). This gap underscores the necessity of simpler, community-based monitoring methods and incremental scaling when applying Dutch-inspired techniques.

Results and Discussion

Embracing Nature-Based Solutions

In the Dutch coast, erosion is the predominant threat. Previously, this was counteracted using hard engineering measures such as groynes. However, the government of the Netherlands has shifted towards a more sustainable approach and introduce a new policy called, "Building with Nature". This form of coastal management promotes the

development or restoration of areas by harnessing natural elements process intrinsic to the site or the region. It essentially works with natural forces such as wind, water and sediment transport. The goal is to restore or create ecosystem while also protecting the coast. A key example of this approach is the Spanjaards Duin project on the Delfland coast. In this project, approximately 35 hectares of new dune landscape was created as ecological compensation for port expansion. That process involved sand nourishment, followed by wind-driven sand distribution and natural colonization of vegetation (Van der Meulen et al. 2014).

Another notable strategy adopted by the Dutch government is the "Room for the River" programme, which also embraces nature-based solutions for sustainable flood risk management. Historically, the country relied heavily on hard-engineering structures such as dikes and levees. However, after the catastrophic floods of 1993 and 1995, the Netherlands introduced this new policy, "Room for the River" in 1999. This marked a significant shift by promoting the restoration of natural floodplains and allowing rivers to temporarily occupy designated areas during high flows (Chan et al. 2022). This strategy has proven effective in reducing flood hazards in a sustainable manner by connecting with natural process.

As outlined above, these two approaches hold a significant relevance to Sri Lanka as well. The country faces growing challenges such as coastal erosion and biodiversity loss. Adopting a, "Building with Nature" strategy tailored to Sri Lanka's geography-using soft-engineering techniques like dune restoration and regulated sand replenishment, could support ecological preservation and climate adaptation along its vulnerable coastlines. Similarly, the "Room for the River" model offers valuable insights for Sri Lanka, where urbanization and climate change have made flooding an increasingly serious issue. Resilience in flood-prone areas could enhanced by integrating ecological techniques align with community engagement. As Chan et.al argue, long-term climate adaptation in poorer coastal countries requires a shift away from traditional hard infrastructure solutions towards nature-based, participatory approaches. In Sri Lanka, over 50% of the population and critical economic sectors such as fishing and tourism are concentrated around the coast, making even small-scale flooding occurrences extremely disruptive (World Bank 2020). In contrast, the Netherlands, with 26% of its land below sea level and more than 60% flood-prone, has successfully integrated flood management into socio-economic development (Roth & Winnubst 2014). This comparison indicated that low-cost, community-driven, and ecosystem-based solutions are key to socioeconomic viability in Sri Lanka. For instance, ecosystem-based adaptation strategies like wetland protection, vegetative buffers and watershed restoration can regulate water supply, enhance water quality and lower the risk of flooding, while providing sustainable and affordable solutions for traditional grey infrastructure (Khaniya et al. 2021).

It is important to note that while the Netherlands and Sri Lanka differ significantly in geography and context, these solutions can still offer useful guidance. However, studies need to be done how these approaches can be adapted and implemented effectively in the Sri Lankan context.

Living with Water Adaptive Spatial Planning

"The Room for the River" initiative in the Netherlands is a strong example of how adaptive spatial planning can be used to actualize the concept of "Living in the Water". This innovative programme focused on the dual objectives of enhancing spatial quality and improving flood safety through 34 river basin projects, particularly along the Rhine and its branches. The Dutch approach was to accommodate floodwaters by moving dikes, depoldering, and excavating floodplains instead of resisting them, while simultaneously improving ecological resilience and landscape aesthetics. This reflects the fundamental idea of adaptive spatial planning, which is to enhance safety and livability by integrating land use and water flow (Verweij et al. 2021). A key success factor in the Dutch approach was the use of mix policy instruments, including participatory spatial design (Roth and Winnbust, 2014; Edelenbos et al. 2017), the involvement of landscape architects (Klijin et al. 2013; Van den Brink et al. 2019; Heeres et al. 2016), inclusive contracts (Lenferink et al. 2013; Feddes and Hinz 2013; PIANOo and Unie van Waterschappen 2016) and flexible project management (Verweij 2015; Van Meerkerk 2020). Spatial quality was evaluated based on three main criteria: utility, beauty and robustness (Klijn et al. 2013). The decentralized implementation allowed stakeholders and local authorities to influence design results.

Furthermore, by combining long-term innovation with adaptive spatial design, the Dutch Flood Protection Programme (DFPP) offers a modern example of the "Living with Water" Strategy. The Netherlands has shifted from a purely technical dike-based approach to a multi-layered, geographically integrated risk management strategy. The Flood Risk Management Pyramid (Figure 1) outlines this evolution across four progressive levels: understanding flood defence mechanisms, managing risks, enhancing environmental quality and building resilient systems. At the higher levels of pyramid, co-creation, spatial integration, and adaptability-key components of the "Living with the Water" philosophy are emphasized (Tromp et al. 2022).

Figure 1. The Pyramid of Flood Risk Management

From a Sri Lankan perspective, the Dutch approach provides valuable insights into integrating water into spatial planning, rather than merely managing it. This is especially relevant for a developing country like Sri Lanka, where urban flooding and coastal erosion worsening due to climate change and rapid urbanization. Inspired by the decentralized and participatory framework of the Netherlands, particularly the "Room for the River"

program, Sri Lanka could implement inclusive floodplain redevelopment plans that involve local governments, communities and multi- stakeholders' alliance. This approach ensure that flood resilience measures align with regional ecological and social contexts while also enhancing public ownership and policy acceptance. In vulnerable coastal and inland areas, institutional mechanisms such as safety nets and flexible planning cycles can help achieve long-term, sustainable results.

Sri Lanka's National Adaptation Plan (2016-2025) and Coastal Zone Management Plan (2018) serve as policy frameworks for resilience (Ministry of Mahaweli Development and Environment 2016; Coastal Conservation Department 2018). However, insufficient enforcement, fragmented institutional responsibilities and limited community engagement remain significant challenges (Kodikara 2021). Lessons from the Dutch decentralized and participatory planning model indicate that stronger local government involvement, policy coherence, and multi-stakeholder collaboration are required for Sri Lanka to achieve similar outcomes (Edelenbos et al. 2017; Van Her et al. 2015).

Community Engagement and Local Ownership

In 2021, the "Limburg floods" highlighted a turning point in the Netherlands' understanding of the importance of community engagement and local ownership in flood risk management. The crisis revealed that communities are active contributors to resilience, rather than passive recipients of aid, as demonstrated by citizen self-reliance and informal local initiatives.

Since then, Dutch flood policy discourse has evolved, leading to the introduction of new a new initiative called, "Layer 0- Water Awareness" as a key component of the multilayer safety framework. This new layer places strong emphasis on empowering local institutions, business and citizens by enhancing their knowledge water-related risks and enabling them to take preventive measures. The initiative promotes shared decision-making and encourages long-term behavioral change through realistic, community-driven strategies (Pot et al. 2024). Furthermore, participatory governance in water management underscores the importance of trust building, local knowledge and collaborative learning (Edelenbos et al. 2017; Van Herk. 2014).

Moreover, the importance of community engagement and local ownership was highlighted through the "Fresh Water Initiative", which was implemented in the 18th century in the Netherlands. In Amsterdam, this initiative addressed drinking water shortage by sourcing and disturbing clean water from the River Vecht. During winter time, the supply was often disrupted due to frozen water, forcing people to rely on polluted canal water. In response, local communities partnered with municipal authorities to ensure access to clean water-an effort that later inspired the formalization of water infrastructure (Maurik and d' Baar 1993; Bokma 1996). Although this method is now outdated, the core values such as local problem solving, public-private collaborations, and equitable access remain highly relevant today. Modern strategies like the, "Amsterdam Rainproof" programme, demonstrate how climate adaptation measures (green roofs, storm water harvesting) can decentralized resilience efforts through active community engagement. Similarly, initiatives such as the "Water and Energy Enterprise (WEE)" and

Waternet's waster-energy synergies highlight how co-benefit frameworks such as converting sewage sludge into energy can gain public support, especially when aligned with circular economy principles (Waternet 2018).

Sri Lanka is increasingly experiencing flooding, especially in urban areas. Through the Dutch experience, Sri Lanka can draw meaningful lessons. Key highlights from the Dutch approach such as raising public awareness, supporting grassroots networks, and fostering societal dialogue demonstrate how local ownership and resilience can be strengthened. Amsterdam's transition from small-scale community initiatives to integrated municipal structures illustrates the scaling up community actions. However, ensuring long term sustainability required integrating these initiatives into formal governance systems, as evidence by Amsterdam's evolved water management system. Dutch strategies need to be contextualized in order to be effective in Sri Lanka. Instead of expensive dike relocations, ecosystems-based adaptation measures such as wetland rehabilitation, vegetative buffer zones, and rainwater harvesting can provide natural flood protection while simultaneously supporting livelihoods (Khaniya 2021). Rooftop rainwater harvesting, permeable pavements and green roofs could be implemented in urban areas like Colombo using initiatives similar to Amsterdam's 'Rainproof' program (Gunawardena 2017; Van de Ven et al. 2016). These approaches are socio-economically sustainable and align with local ecological conditions, providing resilience pathways that connect global best practices with local adaptation needs.

In conclusion, as stated above Sri Lanka can learn from the adopted by the Netherlands to foster coastal resilience through nature-based solutions, adaptive spatial planning and community engagement. Tailoring these initiatives or similar ones to Sri Lanka's geographical context offers viable ways to protect infrastructure, ecosystems and livelihood from the escalating threats posed by climate change.

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