2.7 Influence of limnological characteristics on culture-based fisheries in irrigation reservoirs of Sri Lanka

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Abstract

This study investigates the limnological variations in perennial reservoirs in Sri Lanka across monsoon seasons and their impact on nutrient dynamics, primary production and CBF harvest. Surface water and bottom sediment were sampled from 3 random locations of the limnetic zone of 48 reservoirs on a bimonthly basis from February 2023 to April 2024. Significant seasonal shifts in physicochemical and hydrological factors were observed, influencing nutrient availability, DO levels and overall reservoir productivity. The study highlights the role of sediments as both a nutrient sink and a source, with phosphorus and nitrogen dynamics varying between wet and dry seasons. Fish production was predominantly shaped by limnological conditions, rather than stocking densities alone. GFP yields were significantly correlated with reservoir elevation, alkalinity and sediment phosphorus content. Similarly, finfish harvest, particularly for GIFT tilapia, catla, rohu and mrigal, was strongly influenced by key water quality parameters such as alkalinity, hardness and chlorophyll-a levels. The findings suggest that optimal fish yields require balanced water chemistry and reservoir morphometry, rather than increased stocking efforts. This study underscores the necessity of integrating seasonal limnological variations into fisheries management strategies to enhance fisheries production and maintain ecological stability in irrigation reservoirs. Future research should focus on the long-term impacts of climate change and anthropogenic activities on reservoir limnology and sustainability of fisheries.

Keywords: *culture-based fisheries, limnology, nutrient dynamics, fish production, Giant Freshwater Prawn*

Introduction

Aquatic foods play an important role in global food supply ensuring both physical and economic access to basic nutrition for the continuously increasing world population (Godfray et al. 2010; Golden et al. 2021; Worldometer 2024). These foods contribute significantly to food security and improve nutritional levels on a global scale, providing over 50% of the animal protein consumed in Asian and African countries (Boyd et al. 2022; FAO 2024).

Aquaculture and capture fishery are the 2 primary approaches for producing aquatic foods. While aquaculture involves farming aquatic organisms, capture fisheries focus on harvesting naturally available wild fish stocks (FAO 2022). CBF have been identified as stock enhancement practices associated with low cost and higher production, mainly in developing nations (De Silva 2003). Whether in aquaculture or fisheries, habitat quality is crucial for the healthier production of inhabitant fish fauna. Therefore, understanding the relationship between the limnological conditions of inland water bodies can be instrumental for the better management of fisheries associated with these water bodies.

Culture-based fisheries

CBF involve both aquaculture and fisheries phases. Aquaculture, or 'farmed' phase, focuses on preparing seed stock material, while the fisheries phase involves capturing the released aquatic animals once they reach marketable size (Wijenayake et al. 2016). The goal is to enhance the total production or specific elements of production when natural processes fail to ensure sustainability (FAO 2010).

In common operations, inland water bodies with low natural recruitment are stocked with intended fish species at predetermined densities. Stocked fish use naturally available resources for their growth, survival and reproduction. The main difference is that CBF stocks are owned and managed by a specific organisation or individual, whereas stock enhancement supports wild populations without ownership. These organisations or individuals are responsible for water body preparation, obtaining seed stock, watching over and capturing fish at a marketable size. In perennial reservoirs, fish are intermittently captured using gillnets, cast nets or pole fishing. In contrast, non-perennial reservoirs are completely harvested during the dry season, when the water levels are minimal (De Silva et al. 2006).

CBF are less resource-intensive – they can utilise existing water resources as secondary users in a non-consumptive manner, they are less complicated than conventional aquaculture practices, they are a communal activity which benefits rural communities in the vicinity of the water body – and the government or organisations find CBF attractive due to their sustainable manner (De Silva 2003; Hudson et al. 2014). With these advantages, CBF are gaining popularity in Asian countries, and have proven to be an effective way to fight malnutrition, especially in developing nations (Wijenayake et al. 2016).

Culture-based fisheries in Sri Lanka

The Sri Lankan freshwater irrigation system in the dry climatic zone is an ancient iconic structure with more than 12,000 man-made reservoirs (De Silva et al. 2018; Panabokke et al. 2002). These reservoirs are approximately 2,000 years old and developed around the concept of 'village, temple, reservoir and pagoda'. Excavating the reservoir provided soil for the pagoda around which a temple was built, with the village forming around the temple. This structure fostered a self-sustaining ecosystem, where the reservoir played a crucial role in supporting agriculture and water needs, reflecting ancient society's integrated approach to sustainable resource management (Rathnayake 2023).

To support these rural communities, Mendis and Indrasena recognised reservoirs as good candidates for CBF activity in 1965 (Hudson et al. 2014). Since then, development of CBFs has consistently been supported by ongoing research and development efforts (Amarasinghe and Wijenayake 2015; Digamadulla et al. 2023; Jayasinghe et al. 2005a, 2005b, 2006; Jayasinghe et al. 2018; Jones et al. 2021; Kularatne et al. 2018; Nissanka et al. 2000; Pushpalatha and Chandrasoma 2010; Pushpalatha et al. 2020; Sanuja et al. 2024; Wijenayake et al. 2016; Wijenayake et al. 2005; Wijenayake et al. 2021). Although the marine fisheries production in Sri Lanka is declining (Fisheries 2023), inland fish production is thriving, with more than 90% of inputs from the seasonal and perennial reservoirs where CBF are operational (Jones et al. 2021). Thus, CBF can provide fish (a cheap source of animal protein) to rural communities with low incomes, thereby generating employment and supplementary income for farmers. Therefore, these reservoirs have great potential to increase the socioeconomic aspects of rural communities (Ekanayake et al. 2023; Pushpalatha and Chandrasoma 2010).

Each reservoir has a fisheries organisation which has the ownership of stocks and manages all CBF activities within the reservoir under the supervision of NAQDA, Sri Lanka. Fish production from these reservoirs mainly consists of exotic fish species, including Indian carps – rohu (*L. rohita*), mrigal (*C. mrigala*) and catla (*C. catla*); Chinese carps – grass carp (*C. Idella*), silver carp (*H. molitrix*), bighead carp (*H. nobilis*); and common carp (*C. carpio*) (Jones et al. 2021). The GFP (*M. rosenbergii*), recognised as a more valuable species compared to other cultured species, is also cultured in these reservoirs (Sanuja et al. 2024). Additionally, a self-recruiting species, GIFT, an improved strain of *O. niloticus*, represents the highest landing for CBF production (Athauda and Chandraratna 2020).

Factors influencing production

The GFP established recapture rate in CBF is still very low (<5%) (Pushpalatha and Chandrasoma 2010; Asoka 2015; Rajeevan et al. 2018; Jones et al. 2021). CBF activities can be significantly affected by changes in water quality as the cultured organisms may not have any chance to escape from the confined conditions (Bastian et al. 2025). According to the NAQDA database, CBF production of reservoirs in Sri Lanka is drastically varying throughout the year. In some studies, reservoir surface area has been used to understand the production variations (Digamadulla et al. 2023; Jayasinghe et al. 2006). According to Sugunan (2000), wind-induced turbulence, vertical stratification of pH, DO, total alkalinity and specific conductivity are important factors related to the production of reservoirs in India, whereas mean depth and low nutrient levels do not affect the changes in production.

Although several numbers of studies are available about CBF in non-perennial reservoirs in Sri Lanka (Jayasinghe et al. 2005a, 2005b, 2006; Pushpalatha and Chandrasoma 2010; Wijenayake et al. 2005), CBF in perennial reservoirs have not been well studied yet. Furthermore, productivity of reservoirs depends upon geochemical, meteorological, morphometric and hydrographic variables. Further investigations of reservoir morphometry, sediment organic matter and other limnological factors have been suggested by Jones et al. (2021) for the perennial reservoirs in Sri Lanka.

Objectives of this research

The aim of the study is to explore how limnological characteristics affect CBF production by studying perennial reservoirs of varying sizes and conditions, incorporating water quality, sediment quality, reservoir morphometry and meteorological data. The hypothesis to be tested is that limnological characteristics are significant factors influencing the production performance of CBF in perennial reservoirs of Sri Lanka.

Specific objectives are to:

1. identify the major seasonal limnological gradients in reservoirs
2. assess the seasonal variability in nutrient dynamics of reservoirs
3. determine important environmental parameters and their limitations affecting species-wise production
4. identify the reservoir with the highest and lowest potential for each CBF species.

Materials and methods

The present study was carried out in 48 perennial reservoirs utilised for CBF in the dry zone of Sri Lanka. Sampling locations are shown in Figure 2.7.1 and the relevant details are shown in Table 2.7.1.

Surface water and bottom sediment were sampled from 3 random locations of the lacustrine region of each reservoir on a bimonthly basis from February 2023 to April 2024. The majority of water quality and sediment quality parameters were collected in situ during field sampling, and the remaining parameters were measured in the laboratory. Water and sediment samples were collected, preserved and transported to the laboratory for the analysis. All the laboratory analyses were performed by author at the Department of Limnology and Water Technology, Faculty of Fisheries and Marine Sciences & Technology, University of Ruhuna, Sri Lanka.

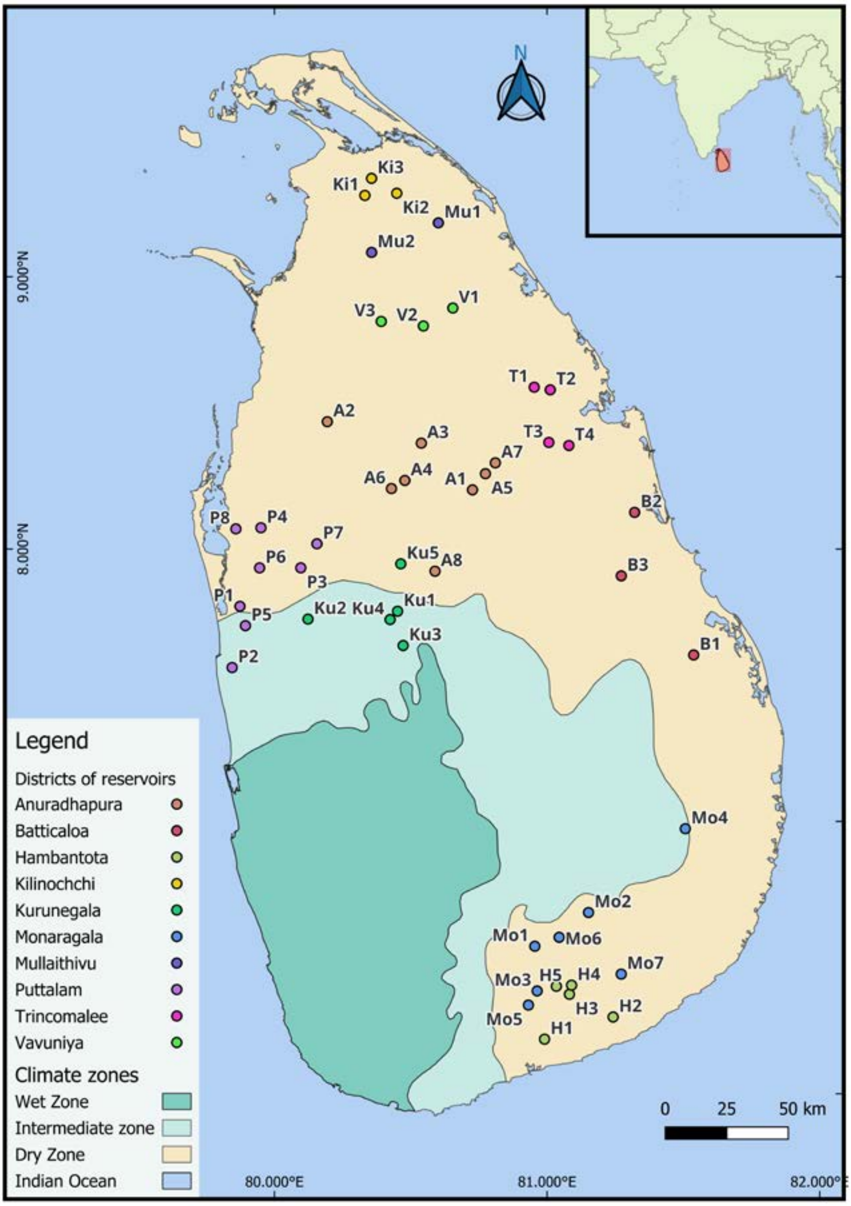

Figure 2.7.1: Distribution of reservoirs selected for the study across the country

Table 2.7.1: Description of selected reservoirs with their locations

District	Name of reservoir	Code	Latitude	Longitude	Area (ha)
Anuradhapura	Hurulu wewa	A1	8.211 180°	80.726 887°	1,198
	Maha wilachchiya	A2	8.466 018°	80.199 686°	1,189
	Mahakanadarawa	A3	8.387 917°	80.543 948°	1,287
	Nachchaduwa	A4	8.252 547°	80.481 158°	1,517
	Aluthdiulwewa	A5	8.276 868°	80.775 253°	206
	Thuruwila	A6	8.220 648°	80.430 154°	337
	Kiulekada	A7	8.321 877°	80.807 084°	252
	Ranawa	A8	7.918 079°	80.589 373°	59
Batticaloa	Unnichchai	B1	7.609 435°	81.540 600°	1,145
	Kaddumurivu	B2	8.131 919°	81.319 971°	242
	Vadamunai	B3	7.902 815°	81.271 569°	250
Hambantota	Ridiyagama	H1	6.206 802°	80.986 333°	876
	Weerawila Wewa	H2	6.287 436°	81.238 285°	406
	Maha Aluthgam ara	H3	6.365 208°	81.086 881°	82
	Maha wewa	H4	6.398 522°	81.094 304°	50
	Mahagal wewa	H5	6.395 397°	81.037 610°	168
Kilinochchi	Akkarayankulam	Ki1	9.297 348°	80.327 640°	801
	Iranamadu	Ki2	9.317 675°	80.449 785°	2,220
	Pudumurippu kulam	Ki3	9.361 711°	80.354 326°	299
Kurunegala	Hakwatunaoya	Ku1	7.772 887°	80.461 248°	362
	Magalla wewa	Ku2	7.743 964°	80.125 216°	218
	Kimbulwanaoya	Ku3	7.640 269°	80.484 219°	196
	Maeliya	Ku4	7.741 792°	80.425 194°	44
	Siyambalangamuwa	Ku5	7.943 953°	80.463 618°	79
Monaragala	Hambegamuwa	Mo1	6.541 986°	80.956 525°	149
	Handapanagala	Mo2	6.665 547°	81.151 660°	264
	Kiribban wewa	Mo3	6.375 799°	80.970 030°	324
	Muthukandiya	Mo4	6.979 702°	81.503 215°	608
	Urusita wewa	Mo5	6.332 615°	80.933 658°	141
	Balaharuwa wewa	Mo6	6.574 274°	81.044 326°	68
	Gestupana wewa	Mo7	6.437 688°	81.273 191°	36
Mullaitivu	Muthiyankaddu	Mu1	9.201 521°	80.607 541°	1,088
	Vavunikulam	Mu2	9.089 970°	80.351 369°	1,040
Puttalam	Devalahandiya	P1	7.787 486°	79.879 212°	195
	Karavita wewa	P2	7.568 043°	79.848 560°	102
	Mahauswewa	P3	7.926 054°	80.096 962°	188

(Continues on next page)

District	Name of reservoir	Code	Latitude	Longitude	Area (ha)
	Tabbowa	P4	8.072 554°	79.955 442°	537
	Vijayakatupotha	P5	7.720 039°	79.895 142°	162
	Kottukachchiya	P6	7.930 162°	79.945 732°	105
	Maha Andarawewa	P7	8.017 970°	80.155 109°	103
	Viluka wewa	P8	8.074 776°	79.856 607°	120
Trincomalee	Mahadiulwewa	T1	8.599 225°	80.953 527°	603
	Morawewa	T2	8.590 722°	81.010 197°	652
	Wendrasan wewa	T3	8.390 288°	81.007 964°	376
	Wanela	T4	8.381 168°	81.081 127°	107
Vavuniya	Bogaswewa	V1	6.637 291°	80.909 609°	77
	Mamaduwa	V2	8.818 677°	80.547 824°	132
	Kalmadu	V3	8.838 036°	80.391 005°	72

Limnological data

Water temperature (°C), DO saturation (%), DO (mg L^{-1}), specific conductivity (µS cm^{-1}), electrical conductivity (µS cm^{-1}), resistance (kΩ cm^{-1}), total dissolved solids (mg L^{-1}), salinity (PSU), pH, oxidation reduction potential (ORP) (mV), and atmospheric pressure (psi) were measured in situ using a multipara water quality meter (YSI Inc., Yellow Springs, OH, USA). SDD was measured in centimetres using a standard 20 cm Secchi disc. The colour of water (Pt-Co) and total suspended solids (TSS) (mg L^{-1}) were measured using a Hach DR 1900 portable spectrophotometer (Hach®, Loveland, CO, USA). TSS was calibrated with the American Public Health Association (APHA) standard method 2540-D (APHA 2017). Turbidity (FAU) was measured using Lovibond MD 600 colorimeter (Tintometer GmbH, Dortmund, Germany). Alkalinity of water was determined using 2 consecutive titrations: phenolphthalein alkalinity (mg L^{-1} as $CaCO_3$) and total alkalinity (mg L^{-1} as $CaCO_3$) using methyl orange in titration (Dhoke 2023). Water hardness (mg L^{-1} as $CaCO_3$) was determined using the EDTA titrimetric method according to the APHA standard method 2340-C (APHA 2017).

Laboratory analyses were performed for the following parameters: chlorophyll-a (µg L^{-1}) amount in the surface water (0 to 3 ft) of reservoirs was determined using the standard acetone method 10200-H (APHA 2017). Total phosphorus (TP) (mg L^{-1}) in water was quantified with acidic digestion with potassium persulfate and ascorbic acid method 4500-P E (APHA 2017). For the total nitrogen (TN) (mg L^{-1}) in water, samples were digested with potassium persulfate (APHA 2017; Studt et al., 2020) and quantified using the sodium salicylate method (Monteiro et al. 2003; Yang et al. 1998).

In situ sediment quality parameters were recorded parallel to the water quality data collection. Sediment samples were obtained using a standard (6×6”) Wildco® Ekman bottom grab (Wildlife Supply Company®, FL, USA); the top layer (<1 cm) was collected. pH and ORP were measured using the multipara water quality meter. The sediment colour spectrum was measured following CIE Lab standards using Miniscan EZ 4500L colorimeter (HunterLab, Reston, VA, USA). Collected sediment samples were transported to the laboratory in ice and were frozen at -18 °C until further analysis. For the analysis, samples were dried approximately at 105 °C for 8 hours, and ground using a mortar and a pestle.

Sediment TP was determined using the ascorbic acid method, followed by acid-persulfate digestion (Nelson 1987). Sediment TN was determined using an alkaline-persulfate digestion (Smart et al. 1983) and quantified using the sodium salicylate method (Monteiro et al. 2003; Yang et al. 1998). 'Loss on ignition' was used to determine the organic matter percentage 2540-E (APHA 2017).

Reservoir morphometry

The QGIS software (version: 3.34.4 LTR) was used to delineate watershed boundaries using a prepared Digital Elevation Model (DEM), which was based on Sentinel-1 Synthetic Aperture Radar (SAR), Interferometric Wide Swath (IW) and Single Look Complex (SLC) Level-1 images (Qin 2018). These images were acquired during the dry season from the Copernicus Data Space Ecosystem for the study area. The images were pre-processed to clean and convert the phase information into elevation using SNAP (version: 9.0.0) software. The generated DEM was used to delineate and calculate the watershed areas of each reservoir using PCRaster Tools (0.3.0) in QGIS (Karssenberg et al. 2010).

Sentinel-1 Ground Range Detected (GRD), Level 1 SAR images of the study area for each exact or possible nearest sampling date were pre-processed using SNAP software (ESA 2019). Then the shorelines of reservoirs were extracted using QGIS software by visually confirming with the same temporal Sentinel-2 and L2A images.

Harvest data

For each reservoir, monthly cumulative harvest in kilograms was collected from the logbooks from each fisheries society and the cumulative catch per month in kilograms of GFP and finfish was recorded separately.

Data analysis

Average values of environmental parameters obtained from bimonthly sampling in reservoirs were analysed using multivariate statistics and machine learning techniques. Major environmental parameters were selected based on their correlations, variance within the dataset, and theoretical and practical importance. Parameters with highly skewed data distributions were log-transformed. All parameters were scaled and used for dimensionality reduction through PCA. Selected morphometric parameters were superimposed on the PCA plot using ordisurf where necessary.

Hierarchical clustering (using Euclidean distance and Ward's linkage) was performed to identify distinct clusters within the sample distributions. The identified clusters were visualised in the PCA plot to determine the corresponding limnological gradients and associated seasonal variations.

Tree-based machine learning models, including Random Forest, Gradient Boosting and Adaboost were applied to identify key parameters influencing fish harvest of each species. The selected parameters were then used in tuned regression (decision) trees to cluster the samples. Decision trees were then constructed using both post- and pre-pruning methods to assess the natural boundaries of the selected parameters. The clustered groups in the tree leaves were subjected to analysis of variance (ANOVA) based on their harvest.

These analyses were conducted using the Orange data mining software (version 3.38.1) and RStudio (version 2024.12.0+46). Maps were created using QGIS Desktop (version 3.34.13).

Results

Major limnological gradients

The PCA plot of the first 2 principal components with selected parameters revealed that the first 5 principal components (PCs) accounted for 94% of the variation within the samples, with the first 2 being particularly important, explaining 53% of the environmental variation (Figure 2.7.2). Two major groups of correlated parameters were identified using the PCA plot:

- Dissolved oxygen in water (DO), sediment total nitrogen (sediment TN), and sediment total phosphorus (sediment TP) were positively correlated with each other and loaded positively on the PC1 axis.
- Total nitrogen in water (water TN), total phosphorus in water (water TP), and chlorophyll-a were highly correlated with dissolved ions in water, and these parameters were negatively loaded on the PC1 axis.

A clear negative linear relationship was observed between dissolved ions, chlorophyll-a, water nutrients, and the surface area of the reservoirs.

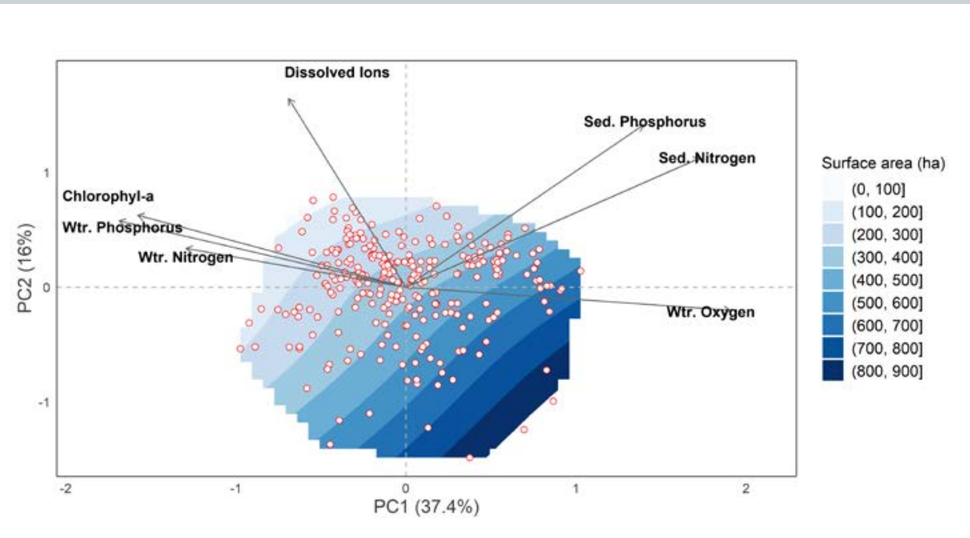

Figure 2.7.2: Two-dimensional PCA score plot using the first two principal components to ordinate reservoir samples, showing parameter loadings and the reservoir surface-area gradient

Note: The arrows represent the magnitude and direction of the contribution of each parameter to ordination. The surface area of the reservoirs representing the samples was laid in the background as blue colour gradient using the ordisurf function.

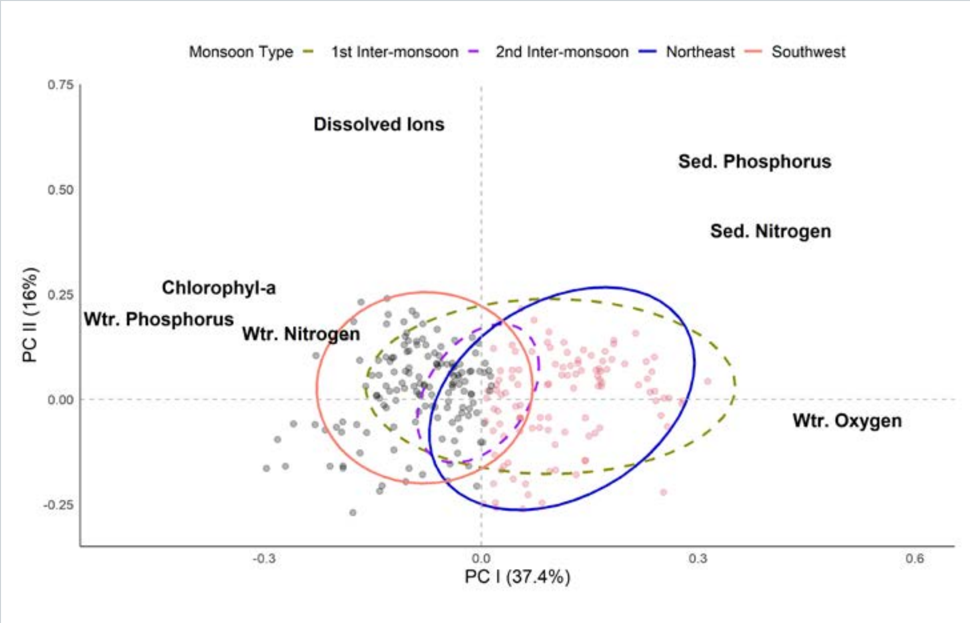

Figure 2.7.3: Two-dimensional PCA score plot using the first two principal components to ordinate reservoir samples, highlighting k-means clusters and seasonal (monsoon) groupings

Note: Samples were coloured (black and pink) according to the 2 identified clusters using the k-means method. Bigger circles represent the 2 monsoons (solid line) and 2 inter-monsoon periods (dotted line) in which 95% confidence interval of the samples were taken.

The 2 unsupervised clusters resulted by k-means method were clearly distinguishable along the PCI axis and samples grouped according to their monsoon period are shown in Figure 2.7.3. The pink cluster clearly deviated toward the positive side of the PC 1 axis, which was loaded with sediment nutrients and DO in water. The black cluster clearly deviated toward the negative side of the PC 1 axis, which was loaded with water nutrients, primary production and dissolved ions in water.

According to Figure 2.7.4, more than 96% of the south-west samples were associated with the black cluster and 92% of the north-east monsoon samples were clearly associated with the pink cluster in the PCA plot. While 80% of the first inter-monsoon samples were classified as more related to the north-east monsoon than south-west, second inter-monsoon is not explained clearly. Classified temporal sampling points according to k-means clusters are shown in Figure 2.7.5.

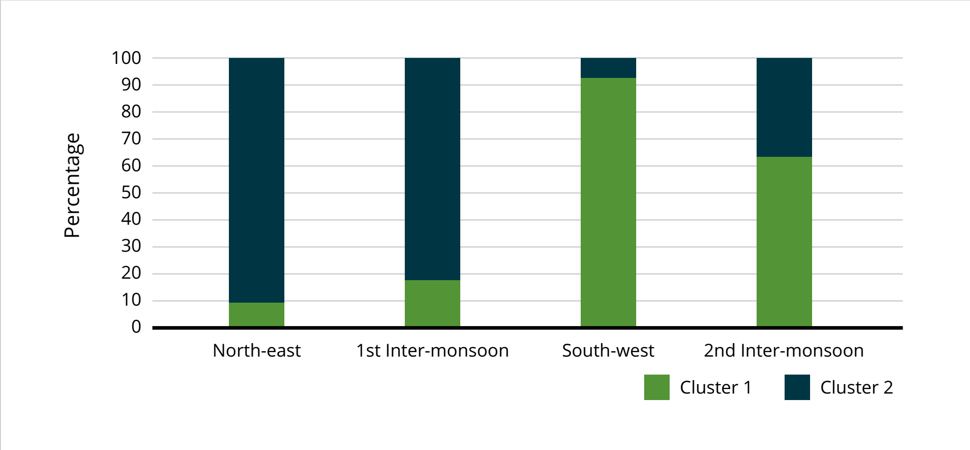

Figure 2.7.4: Percentage of each monsoon sample separated by hierarchical clustering tool using k-means clustering

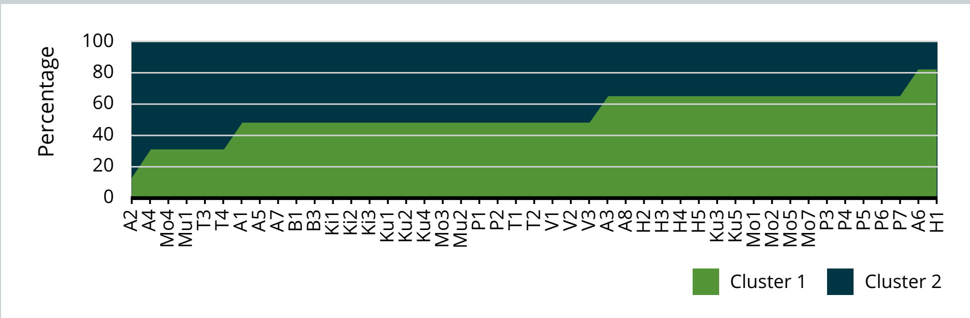

Figure 2.7.5: Percentage distribution of samples of each reservoir in clusters indicated in the PCA

The temporal trend of TP and primary production in reservoirs is shown in Figure 2.7.6. During the dry season, TP in water gradually increases while sediment TP decreases. Conversely, during the rainy season, sediment TP gradually increases and water TP decreases drastically. Figure 2.7.7 illustrates the temporal trends of TN and primary production in reservoirs. During the dry season, TN in water fluctuates, increasing and decreasing alongside spikes in chlorophyll-a, while sediment TN remains relatively stable. In contrast, sediment TN steadily increases during the rainy season. Additionally, a spike in chlorophyll-a was observed just before the onset of the rainy season in both Figure 2.7.6 and Figure 2.7.6.

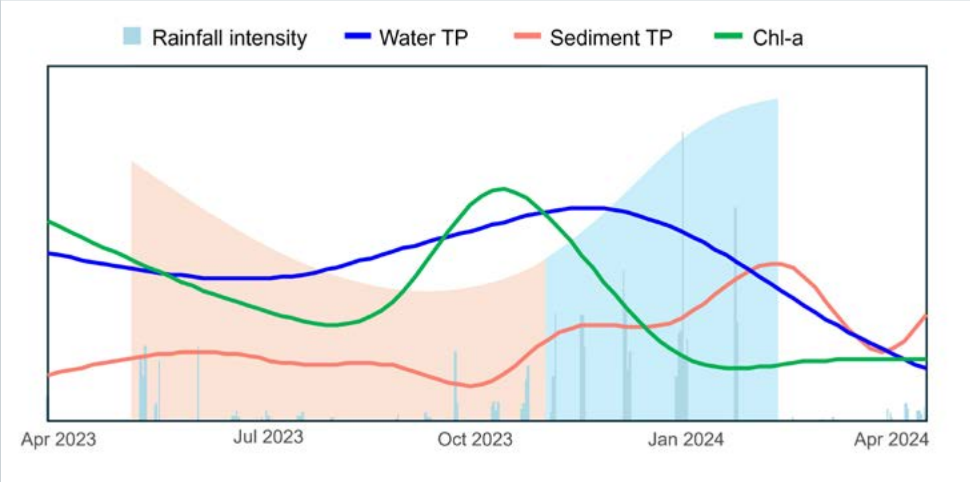

Figure 2.7.6: Temporal trends of scaled parameters: sediment TP, water TP, chlorophyll-a as lines and rainfall intensity laid at back as shades of columns in light blue

Note: Background colours: orange represents the dry period and blue represents the wet period. The white band cutting through the background shading represents the percentage change of reservoir surface area compared to the full supply level.

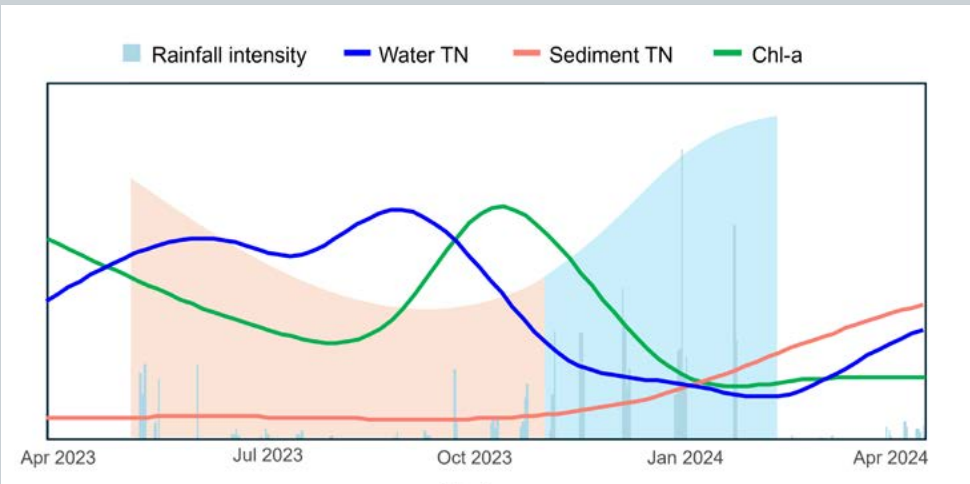

Figure 2.7.7: Temporal trends of scaled parameters: sediment TN, water TN, chlorophyll-a as lines and rainfall intensity laid at back as shades of columns in light blue

Note: Background colours: orange represents the dry period and blue represents the wet period. The white band cutting through the background shading represents the percentage change of reservoir surface area compared to the full supply level.

Fish production in reservoirs

Reported total fish production including GFP and finfish from the reservoirs was 11,428 mt for the study period from February 2023 to April 2024. Cross comparison of species-wise harvest was unable to proceed because of practical issues; fishers tend to record only total finfish harvest and GFP harvest separately rather than recording all species.

Giant freshwater prawn harvest

According to tree-based machine learning models (Figure 2.7.8) and generalised additive models (GAM) (Figure 2.7.9), reservoir elevation was the primary factor that significantly influenced the non-linear pattern of GFP harvest. Suggesting a negative relationship, GFP harvest was significantly higher where tank elevation was below 77 ft ($p<0.05$) and significantly

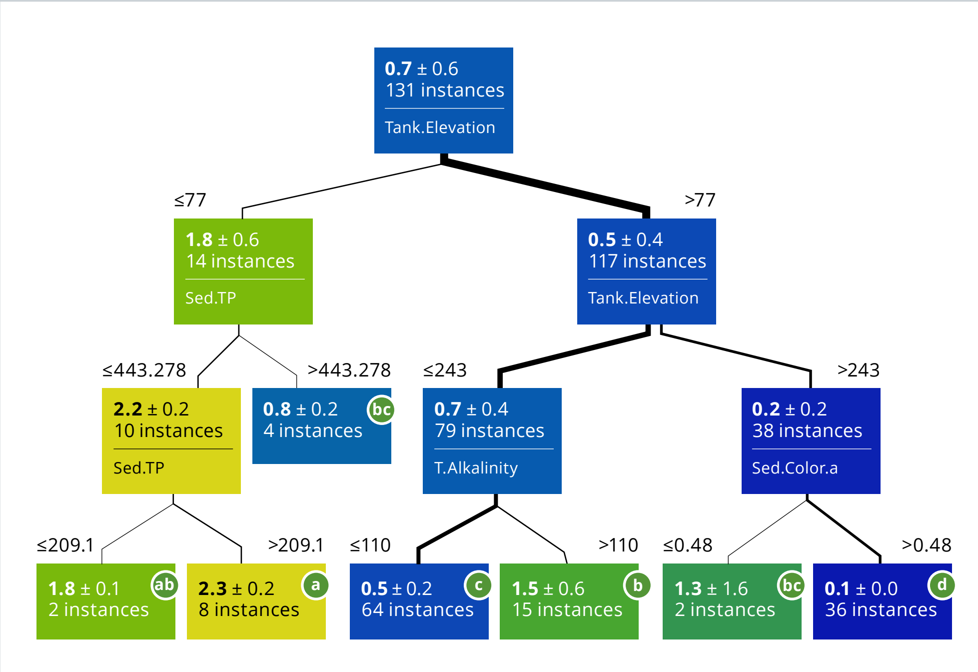

Figure 2.7.8: A single decision tree (R^2 = 64%) developed using the most important parameters for GFP harvest, identified through tuned Random Forest (RF) and Gradient Boosting (GB) machine learning techniques

Notes: Each square contains information on the mean monthly harvest (bold text±SE) at the top, the number of samples in the middle, and the parameter used for the next split at the bottom. The squares are connected by lines of varying thickness, representing the fraction of data in each branch. The value at the end of the branch is the cutoff value of parameter. The colours of the squares follow a gradient from dark blue to bright yellow, indicating an increasing trend in harvest. Lower case letters indicate significantly different groups, with harvest levels increasing alphabetically.

lower when elevation was above 243 ft ($p<0.001$). Furthermore, the reddish colour of sediment (Sed.Color.a), total alkalinity and sediment TP were relatively more important in identifying underlying patterns compared to other parameters. GFP stocking was not a significant parameter. Reservoirs expected to exhibit significant performance are shown in Table 2.7.2. However, Maeliya, Hakwatunaoya, Mamaduwa, Hambegamuwa, Kimbulwanaoya, Mahakanadarawa, Kiulekada and Muthukandiya did not fall within the optimal range of limnological parameters for maximum GFP harvest.

A significantly higher GFP harvest was observed under the following combined situations:

- tank elevation is 77 ft or below, with sediment TP lower than 443 mg kg^{-1}
- tank elevation is between 77 ft and 243 ft, with total alkalinity exceeding 110 mg L^{-1}.

It was significantly lower when:

- tank elevation is between 77 ft and 243 ft, with total alkalinity lower than 110 mg L^{-1}
- tank elevation is between 77 ft and 243 ft, with a reddish colour in sediment >0.48.

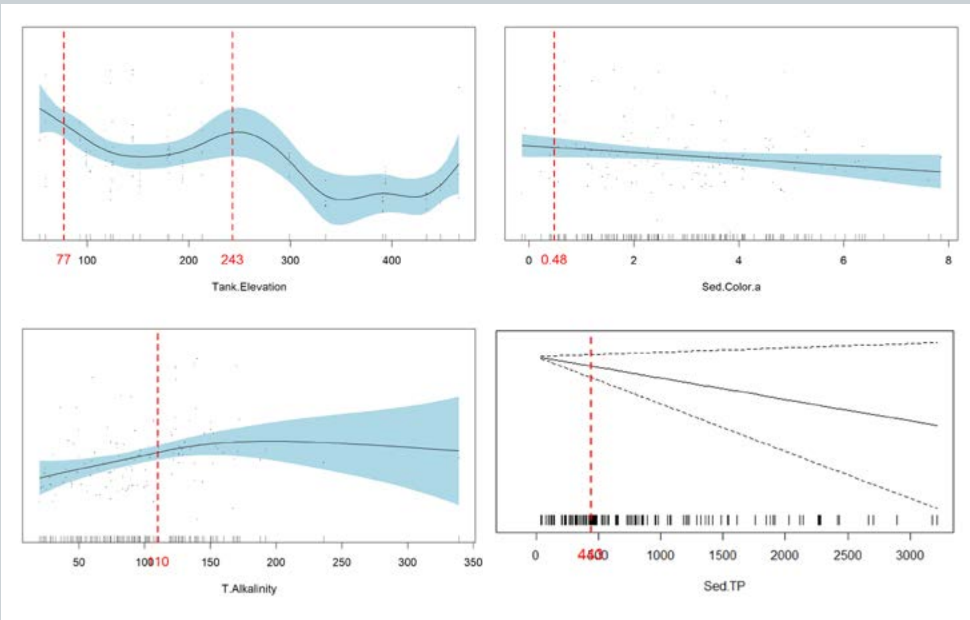

Figure 2.7.9: Multivariate GAMs showing the GFP harvest variation in y axis with the error in its smooth term and selected major factors in x axis with its original scale values (variance explained = 42%)

Table 2.7.2: List of reservoirs within the limit of significant environmental parameters (mean±SD) for expected higher GFP harvests based on the decision tree model

Name	Code	Elevation (ft)	T Alkalinity (mg L^{-1})	Sediment TP (mg L^{-1})
Maha wilachchiya	A2	181	186.8±29.2	1074.1±504.3
Ridiyagama*	H1	59	140.5±21.5	704.6±391.8
Weerawila Wewa*	H2	73	162±54.3	450.1±250.2
Maha Aluthgam ara	H3	191	128.6±39.8	792.6±587.8
Maha wewa	H4	230	122.4±38	1249.1±821.4
Mahagal wewa	H5	243	151±38.5	1367±1275.8
Pudumurippu kulam**	Ki3	77	64.3±24.2	251.7±60.6
Magalla wewa	Ku2	168	123.1±6.7	257.2±97.7
Urusita wewa	Mo5	145	141.6±42.9	1326.1±979
Gestupana wewa	Mo7	181	132.4±48.1	753.1±543.3
Devalahandiya*	P1	53	100.6±17.7	643.3±221.8
Karavita wewa*	P2	39	54.7±18.1	746.3±742.8
Mahauswewa	P3	179	125.9±34.3	480.4±221.7
Tabbowa*	P4	66	157.9±36	619.6±410.4
Vijayakatupotha*	P5	53	99.5±28.1	606.9±573.7
Kottukachchiya	P6	123	112.4±25.3	474.1±238
Wendrasan wewa	T3	181	82.7±22.2	1404.3±785.2
Wanela*	T4	72	130.2±42.2	858.4±526.8
Bogaswewa	V1	197	134.7±62.6	555.3±117.9
Kalmadu	V3	235	188.3±67.7	538.5±172.3

Notes: * Significantly preferred environmental conditions at least one time, ** Significantly preferred environmental conditions in all the samples.

GIFT tilapia harvest

Water hardness was identified as the primary driver of tilapia harvest, exhibiting a significant positive relationship. Yields were notably higher when water hardness exceeded 88 mg L⁻¹ ($p<0.05$). Stocking had not appeared as a major parameter in the analysis. Additionally, organic matter percentage, total alkalinity and electrical conductance were important compared to other parameters. Several different nodes in the decision tree confirmed that tilapia production was positively related to hardness (Figure 2.7.10).

Significantly higher tilapia harvest was observed where:

- hardness was higher than 140 mg L^{-1}, with total alkalinity higher than 90 mg L^{-1}.

It was significantly lower when:

- hardness was lower than 88 mg L^{-1} with mostly total alkalinity lower than 90 mg L^{-1}.

Reservoirs within the limit of significant environmental parameters are shown in Table 2.7.3. Based on the decision tree model, Karavita wewa, Wendrasan wewa, Unnichchai tank, Akkarayankulam, Kiribban wewa and Muthukandiya exhibit hardness and sediment TP levels do not fall within the optimal range of limnological parameters.

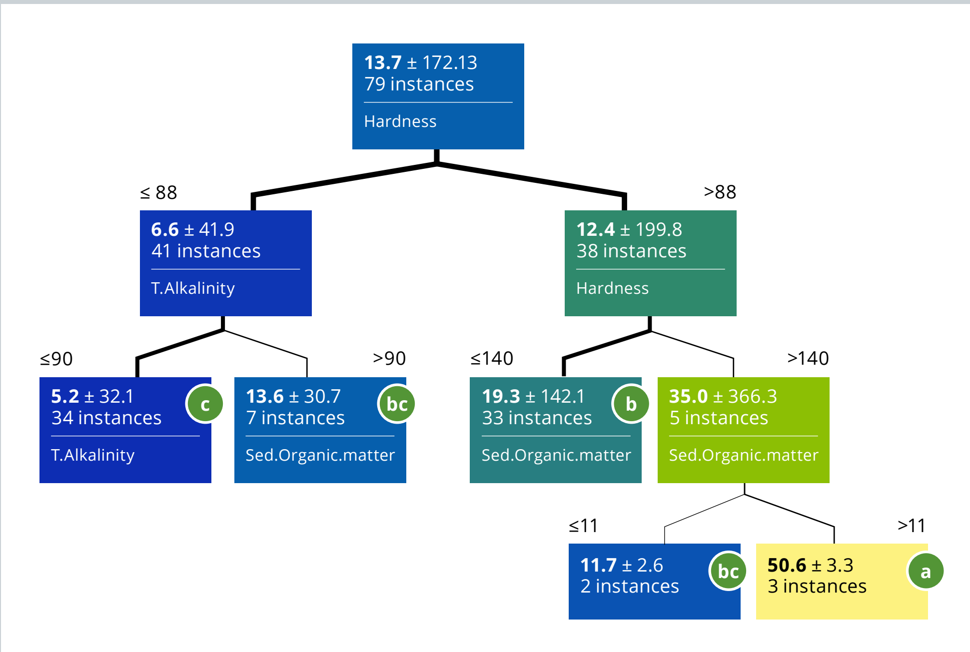

Figure 2.7.10: Single decision tree (R^2 = 63%) prepared using the most important parameters for GIFT tilapia production which identified using tuned RF-tree and GB-tree machine learning techniques

Note: Lower case letters indicate significantly different groups, with harvest levels increasing alphabetically.

Table 2.7.3: List of reservoirs within the limit of significant environmental parameters (mean±SD) for expected higher tilapia harvests based on the decision tree model

Name	Code	Hardness (mg L^{-1})	Sediment TP (mg kg^{-1})	T Alkalinity (mg L^{-1})
Ridiyagama*	H1	133±6.6	704.6±391.8	140.5±21.5
Tabbowa*	P4	163.5±32.7	619.6±410.4	157.9±36
Wanela	T4	114.4±28.8	858.4±526.8	130.2±42.2
Weerawila Wewa	H2	131.9±20.2	450.1±250.2	162±54.3
Devalahandiya	P1	189.7±77.1	643.3±221.8	100.6±17.7
Vijayakatupotha	P5	133.5±42.3	606.9±573.7	99.5±28.1
Kottukachchiya	P6	203.2±95.3	474.1±238	112.4±25.3
Bogaswewa	V1	157.7±67.6	555.3±117.9	134.7±62.6
Maha wilachchiya	A2	151.8±39.1	1074.1±504.3	186.8±29.2
Kalmadu	V3	217.3±68.5	538.5±172.3	188.3±67.7
Mahauswewa	P3	132.1±33.8	480.4±221.7	125.9±34.3
Maha wewa	H4	138.4±44.5	1249.1±821.4	122.4±38
Mahagal wewa	H5	126.6±36.4	1367±1275.8	151±38.5
Siyambalangamuwa	Ku5	142.5±38.9	819.5±834.8	154.2±46.6
Thuruwila	A6	128.9±26.2	571.9±565.3	152.5±32.2
Nachchaduwa	A4	132.1±39.8	956.2±475	129.7±36.6
Maha_Andarawewa	P7	163.1±72.6	698.8±360	85.8±23.5
Hakwatunaoya	Ku1	124.4±22.3	914.6±583.8	165±32.2
Mahakanadarawa	A3	144.3±33.7	797.2±553.7	165.2±41.2
Mamaduwa	V2	130.3±56	418.8±81.1	96.5±33.9

Note: * Significantly preferred environmental conditions at least one time.

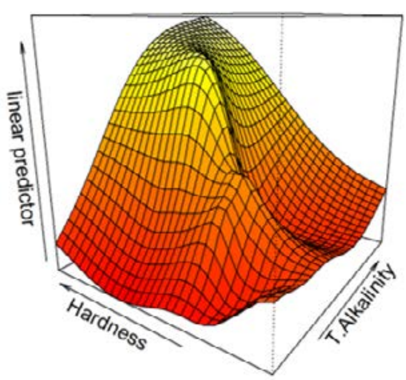

Figure 2.7.11: Multivariate generalised additive significant model showing the tilapia harvest as linear predictor with the interaction term of hardness and total alkalinity (variance explained = 56%)

Catla fish harvest

According to the decision tree model, stocking of catla fingerling was the most significant factor (R^2 = 0.68) instead of limnological parameters. While the analysis suggests that a stocking density above ~1,300 fingerlings ha^{-1} can lead to significantly higher production ($p<0.05$), only 6 out of 74 samples support this finding. Furthermore, GAM showed that the maximum harvest can be obtained using ~1,800 fingerlings ha^{-1} as the stocking density, and increasing beyond that is unnecessary. Therefore, excluding stocking, total alkalinity is the most important factor, followed by tank elevation as the second most important. Catla production tends to be significantly higher ($p<0.001$) when total alkalinity exceeds 106 mg L^{-1}, with tank elevation less than 145 ft (Figure 2.7.12 and Figure 2.7.13). Additionally, lower elevations (<145 ft) result in significantly higher production ($p<0.001$). Reservoirs within the limit of significant environmental parameters are shown in Table 2.7.4. According to the decision tree model, Iranamadu tank, Vavunikulam, Muthiyankaddu, Vadamunai, Pudumurippu kulam, Karavita wewa, Unnichchai and Akkarayankulam are expected to result in significantly lower yield of catla harvests.

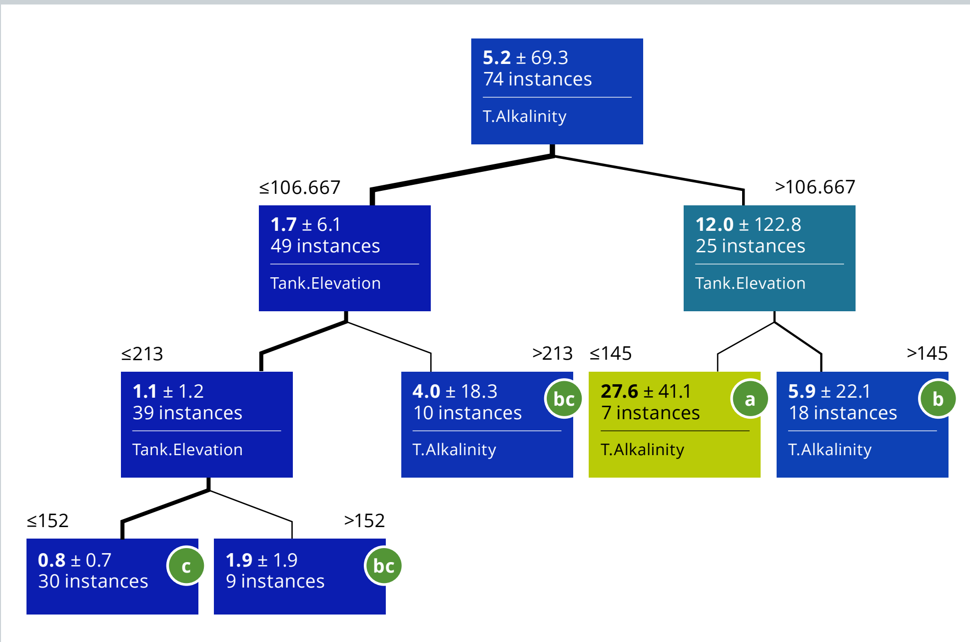

Figure 2.7.12: Single decision tree (R^2 = 95%) prepared using the most important parameters for catla harvest which identified using tuned RF-tree and GB-tree machine learning techniques

Note: Lower case letters indicate significantly different groups, with harvest levels increasing alphabetically.

Table 2.7.4: List of reservoirs within the limit of significant environmental parameters (mean±SD) for expected higher catla harvests based on the decision tree model

Name	Code	T Alkalinity (mg L^{-1})	Elevation (ft)
Tabbowa*	P4	157.9±36	66
Devalahandiya	P1	100.6±17.7	53
Kottukachchiya	P6	112.4±25.3	123
Vijayakatupotha	P5	99.5±28.1	53
Ridiyagama*	H1	140.5±21.5	59
Wanela	T4	130.2±42.2	72
Weerawila Wewa	H2	162±54.3	73
Urusita_wewa*	Mo5	141.6±42.9	145

Note: * Significantly preferred environmental conditions in all the samples.

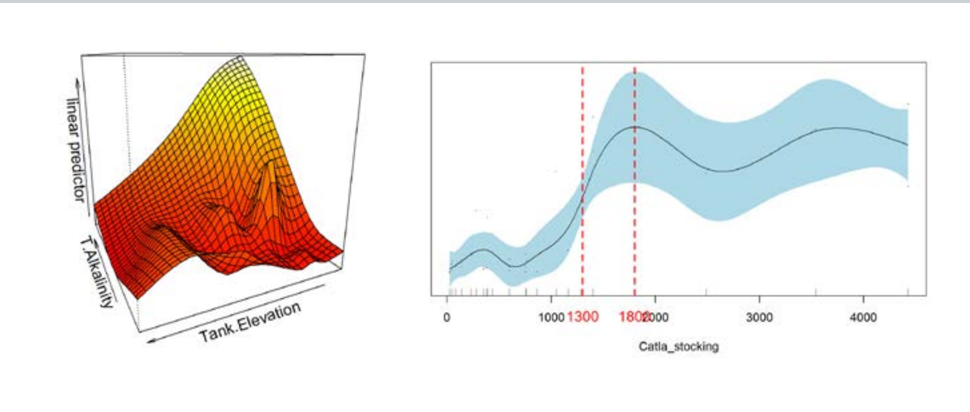

Figure 2.7.13: Multivariate GAM illustrating catla harvest as a linear predictor

Note: The left panel shows the interaction between total alkalinity and tank elevation, while the right panel depicts the variation of catla harvest with stocking density. The model explains 99.8% of the variance with stocking density included and 90.9% without it.

Rohu harvest

According to the decision tree models (Figure 2.7.14), stocking of rohu fingerlings is the most significant factor ($R^2 = 0.84$) instead of limnological parameters. While the analysis suggests that a stocking density above ~1,800 fingerlings ha^{-1} can lead to significantly higher production ($p<0.05$), only 11 out of 68 samples support this finding. According to the GAM (Figure 2.7.15), total alkalinity and stocking is significant and production had peaked around 5,200 fingerlings ha^{-1}. However, excluding stocking, total alkalinity is the most influential factor among all parameters. Indicating a positive relationship at multiple nodes in the decision tree, rohu harvest is significantly higher when total alkalinity exceeds 106 mg L^{-1} ($p<0.01$).

Significantly higher rohu harvest was observed, where:

- rohu fingerling stocking is between 1,800 and 5,200 fingerlings ha^{-1}
- total alkalinity is higher than 107 mg L^{-1}, with tank elevation lower than 145 ft.

It was a significantly lower harvest when:

- total alkalinity is lower than 107 mg L^{-1}.

According to the decision tree model, Ridiyagama, Tabbowa, Urusita Wewa, Weerawila Wewa, Dewalahandiya Wewa and Wanela are expected to yield higher rohu harvests.

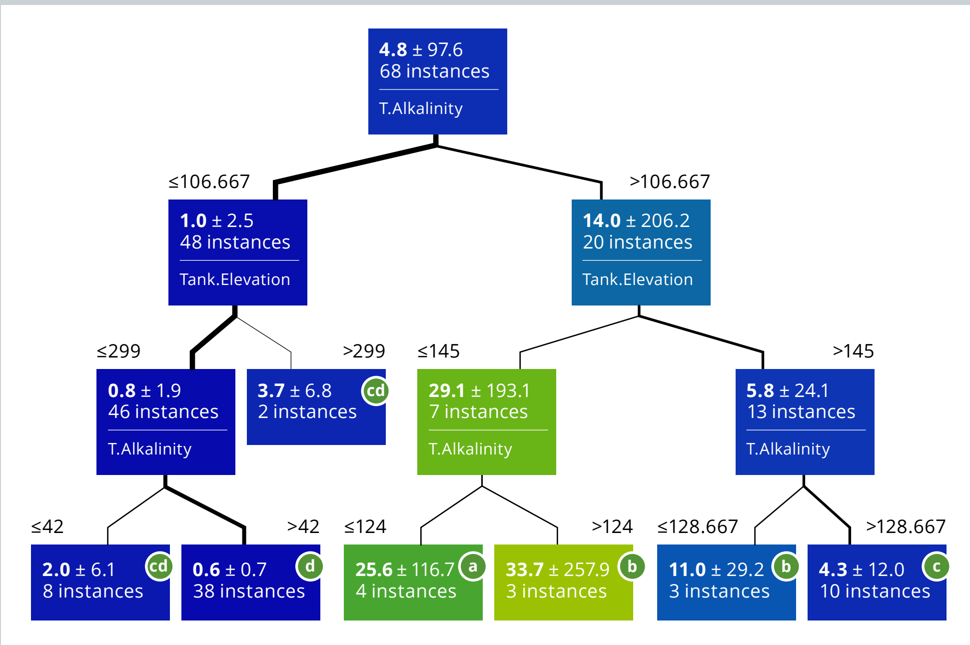

Figure 2.7.14: Single decision tree (R^2 = 77%) prepared using the most important parameters for rohu harvest which were identified using tuned RF-tree and GB-tree machine learning techniques

Note: Lower case letters indicate significantly different groups, with harvest levels increasing alphabetically.

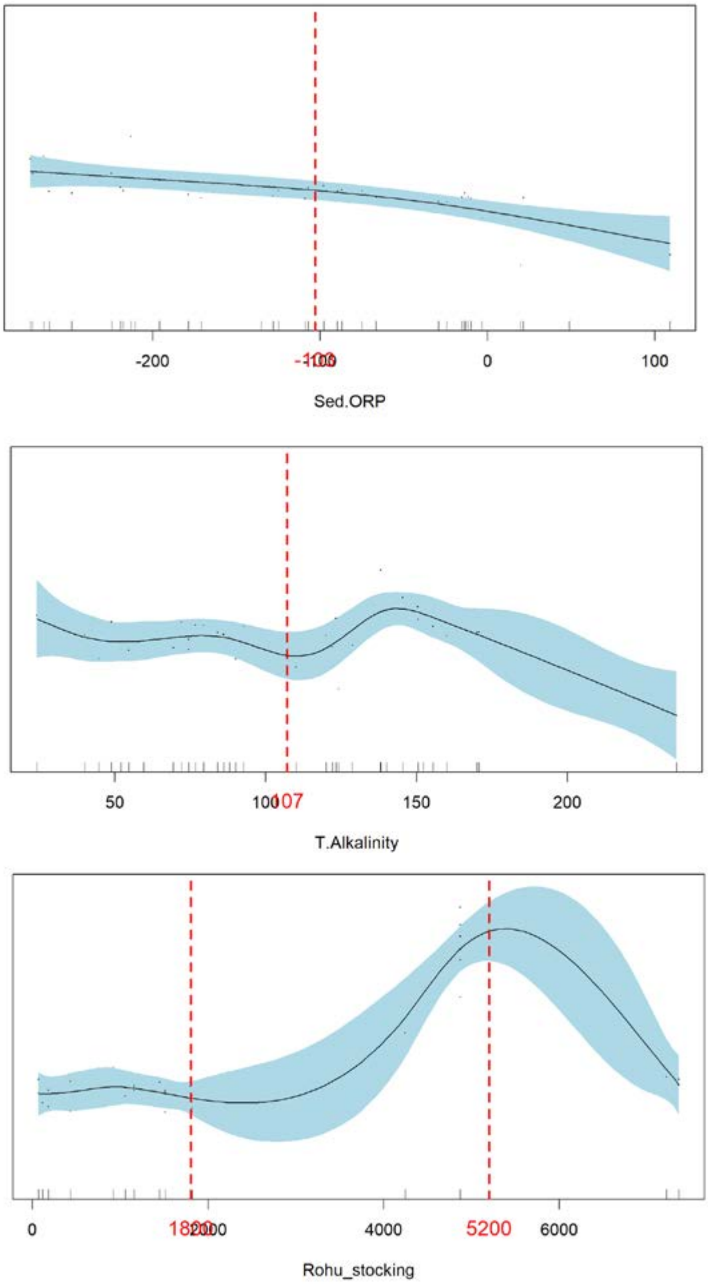

Figure 2.7.15: Multivariate GAM showing the rohu harvest variation in y axis with error in its smooth term and selected major factors in x axis with its original scale values (explained variation was 81%)

Mrigal harvest

RF suggests that the stocking density of mrigal fingerlings as the most important factor instead of limnological parameters. However, only 54% of the variance has been explained, and the divided samples were not significant. Figure 2.7.16 considers only the limnological conditions since GAM (Figure 2.7.17) also is not detecting the stocking density as a significant predictor. Therefore, excluding stocking density, chlorophyll-a is the most important factor. Mrigal production is significantly higher ($p<0.05$) when chlorophyll-a concentration exceeds 14.4 μg L^{-1} and the reservoir's maximum depth is less than 23 ft; otherwise, it is significantly lower (Figure 2.7.16). Reservoirs within the limits of significant environmental parameters are shown in Table 2.7.5. Nachchaduwa, Ranawa, Weerawila wewa, Muthukandiya. Maha Andarawewa and Kalmadu reservoirs did not fall within the optimal range of limnological parameters.

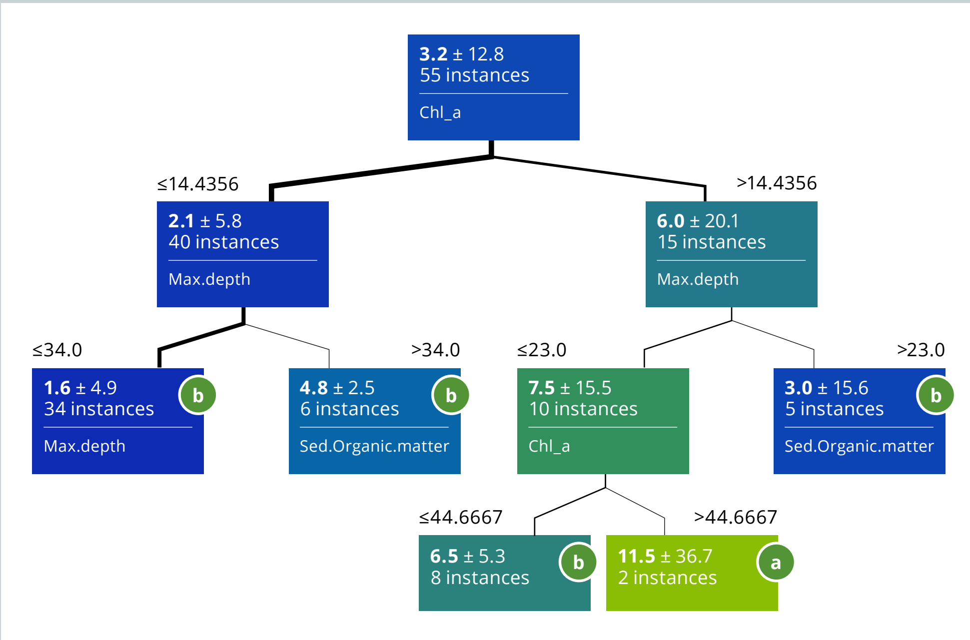

Figure 2.7.16: Single decision tree (R^2 = 59%) prepared using the most important parameters for mrigal harvest which were identified using tuned RF-tree and GB-tree machine learning techniques

Note: Lower case letters indicate significantly different groups, with harvest levels increasing alphabetically.

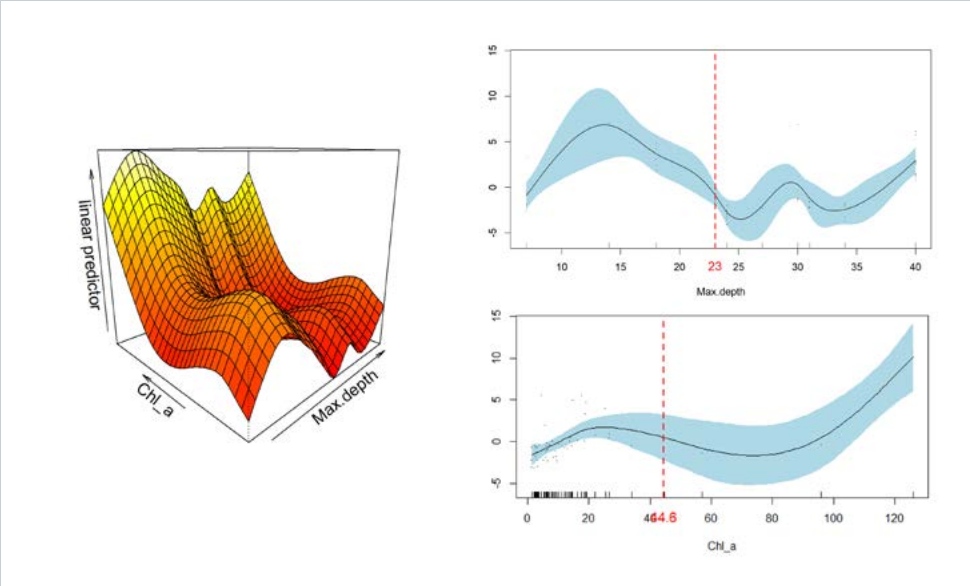

Figure 2.7.17: Multivariate GAM illustrating mrigal harvest as a linear predictor

Note: The left panel shows a 3d surface of maximum depth and chlorophyll-a, while the right panel depicts the variation in the mrigal harvest with each parameter. The model explained 78.9% of the variance without stocking density.

Table 2.7.5: List of reservoirs within the limit of significant environmental parameters (mean±SD) for expected higher mrigal harvests based on the decision tree model

Name	Code	Chlorophyll–a (μg L^{-1})	Max depth (ft)	Sed. organic matter %
Aluthdiulwewa	A5	17.1±15.5	20	18.7±2.7
Vadamunai	B3	28.8±16.2	20	16.8±3.5
Maha Aluthgam ara	H3	20.2±27.5	12	13.4±9.3
Kimbulwanaoya	Ku3	18.2±16.5	17	13.8±5.2
Maeliya	Ku4	27.4±17.7	18	19.8±3.9
Siyambalangamuwa	Ku5	32.6±31.4	18	17.9±4.2
Hambegamuwa	Mo1	42.1±41.5	18	16.1±2.6

Considering all the important parameters for CBF species, the mean values of total alkalinity, tank elevation, sediment TP, organic matter percentage, hardness and chlorophyll-a are spatially represented using the two-dimensional GAM model in Figure 2.7.18.

Discussion

The present study revealed substantial limnological variations among reservoirs across the main classes of variables, including reservoir morphometry, nutrients, primary production, DO and dissolved ions in water during 2 major monsoon periods. The measured limnological factors correlated and displayed distinct gradients and seasonal fluctuations. Additionally, reservoir elevation and several other limnological factors were identified as being correlated with reported GFP and species-wise finfish harvest variations.

Heavy rains associated with the north-east monsoon contribute to increased nutrient input from run-off, which is deposited in the sediments at reservoir bottoms, and increasing water inflow increases the water volume in reservoirs. Concurrently, rising

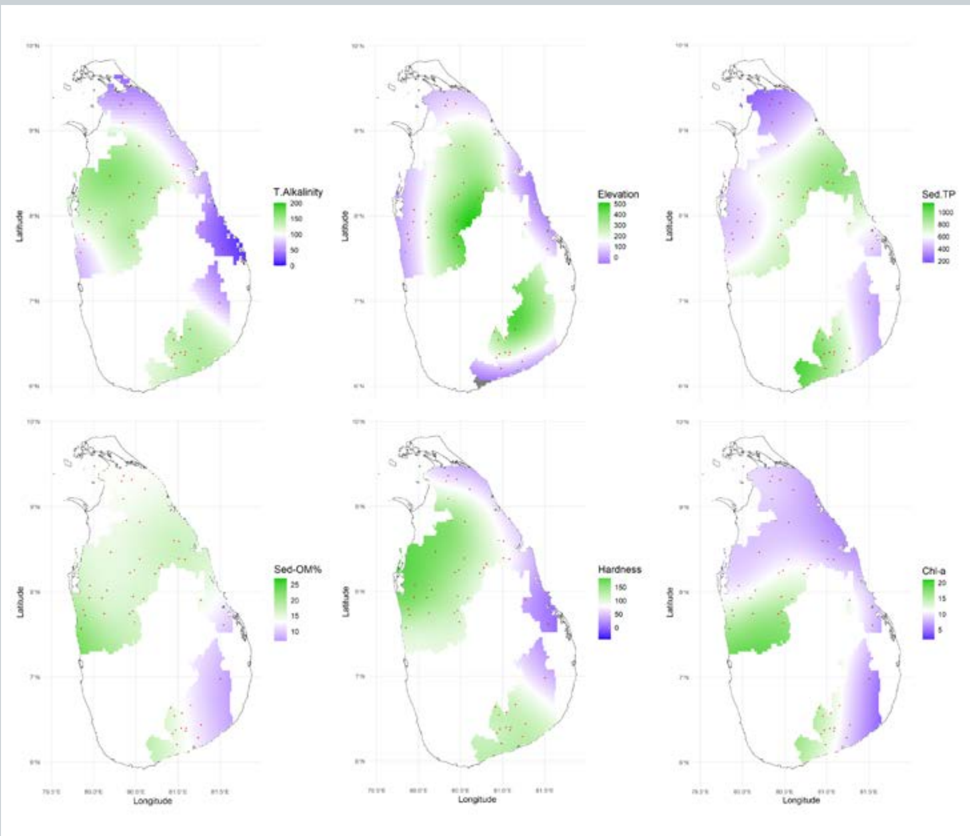

Figure 2.7.18: Spatial distribution of major limnological factors within the Sri Lankan map

water levels result in a dilution effect that reduces dissolved ion concentrations in the water column, whereas enhanced mixing increases DO levels. As the monsoon transitions into the south-west phase, rainfall intensity decreases, leading to a gradual increase in dissolved ions, including hardness, conductivity, salinity and nutrients. Nutrients previously deposited during run-off events are progressively released into the water column, fostering increased primary production. This process is evidenced by reduced sediment nutrient levels, increased dissolved nutrient levels, and chlorophyll-a in the water.

Another interesting pattern was observed because of the variations in rainfall intensity during the monsoon seasons. During the dry season, a phosphorus balance between the water and sediment phases was observed; the TP concentration in water gradually increased, while it decreased in the sediment. This may be mainly due to the release of phosphorus from the sediment into the water. Wang et al. (2019) indicated that the sediment can act as a phosphorus source during summer by transforming phosphorus from sediment to water. Iron can trap phosphate under oxygen-rich conditions and release it back into the water under anoxic conditions (Bakker et al. 2016). Furthermore, the increased evaporation of water may have concentrated phosphate in water. During the rainy season, nutrient-rich storm flow conditions may replenish the sediment TP. Water TP further decreased with spillover and deposition in the sediment phase during the north-east monsoon. Similarly, Mihiranga et al. (2025) indicated that organic phosphorus is transported to reservoirs via surface and soil water run-off, mainly as dissolved organic phosphates, during wet seasons. Furthermore, Wang et al. (2019) found that sediment can act as a sink during the winter and spring.

TN in the water may decrease primarily due to assimilation by phytoplankton, which is driven by the spiked primary production during the dry season. This indicates that the reduction in nitrogen is more influenced by biological processes than spillover, which is in contrast to the behaviour of TP in the same period. According to Han et al. (2014), under anaerobic conditions, sediment can produce ammonia through the mineralisation of organic matter. Because nitrification is suppressed by the unavailability of oxygen, ammonia nitrogen can be concentrated within the water. Therefore, sediments can act as a nitrogen source during the dry season. Theoretically, primary producers can assimilate more nitrogen than phosphorus (Karpowicz et al. 2019) and the typical Carbon:Nitrogen:Phosphorus ratio is 106:16:1 according to the Redfield ratio (Tyrrell 2001).

Interestingly, stocking was not identified as a significant parameter in the tree-based regression model, suggesting that environmental conditions, rather than stocking density, primarily drive the GFP harvest. This finding implies that increasing stocking efforts may not yield better harvests unless the optimal limnological conditions are met.

According to both univariate GAM and regression tree-based models, reservoirs with elevations below 243 m may provide more favourable environmental conditions for GFP productivity, possibly because of their inherent biological instinct to adapt to environmental conditions closer to the ocean as suitable for their reproductive migration behaviour. According to FAO (2009), GFP naturally found in 'tropical and subtropical freshwater environments influenced by adjacent brackish water areas' because they spend their larval stage in brackish water, and post larvae migrate to freshwater for growth. Next, mating occurs in freshwater, and egg-bearing females migrate to brackish water areas where egg hatching and larval development occur. According to this life cycle, they may require lower elevations for better survival and growth. Most of the sampled reservoirs were not directly connected with each other through a perennial cascade system; therefore, it is not possible to assume that GFP migrated through the sluice-released water into the reservoirs at lower elevations.

Alkalinity in water is important for buffering pH levels, mainly during the rainy season. Raindrops can dissolve more carbon dioxide while travelling through the air from clouds to the ground (Radha et al. 2022; Silva and Manuweera 2004). Dissolving CO_2 can produce carbonic acid, which drives sudden pH changes in natural water, leading to respiratory failure with ionic imbalances between the water and gills of fish (Chen et al. 2023). This impact can be reduced if ionic compounds or complexes are available within the water to buffer incoming foreign acids or bases. Furthermore, the calcareous outer shell of GFP can be dissolved because of the low pH, where alkalinity has lower values; hence, there is no control over pH changes. According to the results, the alkalinity higher than 110 mg L^{-1} (as $CaCO_3$) was significantly better. However, increasing it to more than 150 mg L^{-1} resulted in a slight reduction in harvest but with a higher standard error. This suggests that alkalinity levels between 110–150 mg L^{-1} (as $CaCO_3$) in reservoirs are beneficial for GFP production. Similarly, Adhikari et al. (2007) found that 100 mg L^{-1} was associated with the highest survival rate and growth.

Lower sediment total, which is associated with higher production, may be explained by bioturbation. GFP is a benthic feeder that can disturb benthic sediments by releasing phosphorus into the water column. Therefore, a phosphorus content below 443 mg kg^{-1} in sediment can be an indicator of a higher abundance of GFP in the reservoir.

Reddish colour in sediment calculated as CIE Lab color value a* can mainly occur due to iron oxides in sediment (Wang et al. 2022). The iron in water, mainly Fe^{3+}, can reduce the amount of bioavailable phosphate by forming complexes with phosphorus in the presence of oxygen (Bakker et al. 2016). Hence, primary production can be retarded, resulting in a cascade of effects on the entire food web of the reservoir. Eventually, a decrease in the growth of omnivorous GFP may have occurred. In addition, higher ferric concentrations can affect the survival of GFP because these particulate iron oxides can clog the gills and cause irritation in the gills due to their highly oxidative nature. However, lower levels of iron can increase primary production (Keller et al. 2012). Hence, lower levels of red colour in the sediment seem to be beneficial for GFP harvest.

The finfish harvest results suggest that a simple increase in stocking density may not yield better harvests unless the optimal limnological conditions are met. Tilapia is a self-recruiting species which can reproduce in Sri Lankan reservoirs (Athauda 2010). Hardness and total alkalinity have been identified as the major limnological factors that influence tilapia production. The hardness was calculated using the total ion concentrations of magnesium and calcium in water. While magnesium is mainly important for primary production because it is the central atom in chlorophyll-a, calcium is crucial for osmoregulation in aquatic animals and is a constituent of the exoskeleton and bones (Wurts and Durborow 1992).

Although tilapia do not possess any calcareous outer layers such as GFP to be dissolved under low pH conditions, their gill tissues are susceptible to sudden pH changes (Wurts and Durborow 1992). According to the results, the combination of alkalinity and hardness performed well, rather than as individual factors. An alkalinity higher than 90 mg L^{-1} and hardness higher than 140 mg L^{-1} yielded better results. However, the highest hardness value recorded in this study was 202.7 mg L^{-1}; therefore, configuring an upper limit was not possible here. According to Cavalcante et al. (2014), the alkalinity:hardness ratio is important, and a 1:1 ratio has a significant influence on production. Tilapia (2025) reported that a hardness between 50–150 mg L^{-1} is preferred for the culture of tilapia and most other finfish species.

Although stocking densities between 1,300 and 1,800 fingerlings ha^{-1} are suggested for significantly higher catla production, the limited number of samples makes this recommendation uncertain. The model may have been overfitted. However, stocking in reservoirs where alkalinity is higher than 106 mg L^{-1} and elevation is lower than 145 ft will lead to a significantly higher harvest. According to Jena (2009), 25–32 °C is the preferred temperature for *C. catla*. Lower elevations are often associated with higher water temperature and biodiversity (Vijverberg et al. 2012). This can increase the metabolic activity of fish, allowing them to grow faster.

The rohu yield suggests that stocking density should be maintained between 1,800–5,200 fingerlings ha^{-1} to obtain the maximum yield. Other than the stocking density, a total alkalinity higher than 106.6 mg L^{-1}, lower tank elevation less than 145 ft and sediment oxidation reduction potential (ORP) less than -103 mV can result a significantly higher harvest. As discussed before, alkalinity is important for pH buffering to reduce damage to fish, and a lower elevation will increase the metabolic rate of fish, enabling faster growth. Lower and negative sediment ORP are associated with reducing or anoxic conditions in the sediment (Godoi et al. 2012). If the sediment is anoxic, the lower water column might also be anoxic, causing fish to move into the upper layers, where oxygen is sufficient for their survival. Eventually, they can be entangled by passive gillnets deployed in the upper water column to increase the harvest. Alternatively, as discussed before, anoxic conditions can release trapped phosphorus into the water column, making it bioavailable to phytoplankton for assimilation. Since rohu mainly depends on phytoplankton as their main meal, this will also drive rohu fish into the euphotic zone, where preferred light intensities are available for higher abundance of phytoplankton.

Stocking density is not significant for mrigal harvest, although chlorophyll-a and maximum depth of the reservoir are considered major influential factors. The maximum depth was less than 23 ft, and chlorophyll-a was higher than 44.6 μg L^{-1}, which resulted in higher yields compared to other environmental conditions. Chhanda et al. (2019) have reported that mrigal fish prefer up to 9 ft of water depth, however in that study, they did not increase the depth beyond 9 ft to check the survival rate of fish. As shown by this study, 23 ft might be a possible maximum depth to survive because Towers (2009) stated that adult mrigal fish are bottom dwellers, and their main diet consists of detritus and decayed vegetation supplemented by phytoplankton and zooplankton. For such a variety of diets, mrigal should move frequently from the surface to the bottom. Accordingly, higher chlorophyll-a levels can increase the growth and harvest of mrigal fish. When they are attracted to abundant planktonic communities in the upper water layers, they can become entangled in the gillnets.

Conclusion

This study highlights significant limnological variations among reservoirs across different monsoon seasons, emphasising the influence of hydrological and physicochemical changes on nutrient dynamics, primary production and fish productivity. Seasonal fluctuations in nutrient concentrations, particularly phosphorus and nitrogen, were evident, with sediment playing a crucial role as both a sink and source of nutrients. The observed shifts in nutrient availability and primary production underscore the importance of seasonal hydrological processes in shaping reservoir productivity.

Fish production was strongly influenced by limnological factors rather than stocking density alone, suggesting that environmental conditions play a significant role in shaping harvest outcomes. GFP productivity was linked to reservoir elevation, alkalinity levels and sediment phosphorus content, indicating the significance of both water chemistry and sediment characteristics in supporting optimal growth conditions. Finfish harvest, particularly for GIFT tilapia, catla, mrigal and rohu, was driven by key water quality parameters such as alkalinity, hardness and chlorophyll-a levels. These findings underscore the importance of maintaining a balanced water chemistry and reservoir morphometry to sustain optimal fish yields.

Overall, this research emphasises that successful fisheries management in reservoirs requires a comprehensive understanding of the seasonal limnological dynamics. Strategies focusing on water quality variations, nutrient balance and ecosystem stability can enhance fish productivity and ensure sustainable CBF in irrigational reservoirs. Future studies should further explore the long-term implications of climate variability and anthropogenic influences on reservoir productivity to refine management practices.

References

Adhikari S, Chaurasia VS, Naqvi AA and Pillai B (2007) 'Survival and growth of Macrobrachium rosenbergii (de Man) juvenile in relation to calcium hardness and bicarbonate alkalinity', *Turkish Journal of Fisheries and Aquatic Sciences*, 7:23–26.

Amarasinghe US and Wijenayake WMHK (2015) 'Results of a decade of R&D efforts on culture-based fisheries in Sri Lanka', *Perspectives on culture-based fisheries developments in Asia*, 59–71.

APHA (2017) *Standard Methods for the Examination of Water and Wastewater* (23 ed.). American Public Health Association, doi:10.2105/SMWW.2882.216.

Asoka JM, Chandraratne PN and Amarasinghe US (2015) *Production performance of Macrobrachium rosenbergii in culture based fisheries in perennial reservoirs*.

Athauda S (2010) 'Is tilapia becoming an invasive fish in Sri Lanka' in Marambe B, Silva P, Wijesundara S and Atapattu N (eds), *Invasive Alien Species in Sri Lanka – Strengthening Capacity to Control Their Introduction and Spread* (127–130), Biodiversity Secretariat of the Ministry of Environment, Sri Lanka.

Athauda S and Chandraratna N (2020). 'Fisheries Sector Contribution for Sustainable Food System: Past, Present, and Future' in Marambe B, Weerahewa J and Dandeniya

WS (eds), *Agricultural Research for Sustainable Food Systems in Sri Lanka: Volume 1: A Historical Perspective* (333–349), Springer Singapore, doi:10.1007/978-981-15-2152-2_14.

Bakker ES, Van Donk E and Immers AK (2016) 'Lake restoration by in-lake iron addition: a synopsis of iron impact on aquatic organisms and shallow lake ecosystems', *Aquatic Ecology*, 50(1):121–135, doi:10.1007/s10452-015-9552-1.

Bastian A, Mardiana A, Koswara E and Rifqi M (2025) 'Assessing The Impact of Water Quality on Freshwater Aquaculture: A Systematic Literature Review', *International Journal of applied information systems and informatics*, doi:10.37058/jaisi.v3i1.14180.

Boyd CE, McNevin AA and Davis RP (2022) 'The contribution of fisheries and aquaculture to the global protein supply', *Food Security*, 14(3):805–827, doi:10.1007/s12571-021-01246-9.

Cavalcante D, Caldini N, Lucinda J, Lima F and Carmo-e-Sá M (2014) 'Imbalances in the hardness/alkalinity ratio of water and Nile tilapia's growth performance', *Acta Scientiarum - Technology*, 36:49–54, doi:10.4025/actascitechnol.v36i1.18995.

Chen X, Liu S, Ding Q, Teame T, Yang Y, Ran C, Zhang Z and Zhou Z (2023) 'Research advances in the structure, function, and regulation of the gill barrier in teleost fish', *Water Biology and Security*, 2(2):100139, doi:10.1016/j.watbs.2023.100139.

Chhanda M, Hosen MH, Sarker K and Gupta N (2019) 'Effects of water depth on growth performance of Indian major carps at a poly culture system in Bangladesh', *International Journal of Aquaculture and Fishery Sciences,* 5:014–021, doi:10.17352/2455-8400.000046.

De Silva S, Aheeyar M, Arulingam I and Manthrithilake H (2018) 'The New Water: Opportunities and Challenges of the Rise to Prominence of Groundwater in Sri Lanka in the Face of Socioeconomic and Climatic Change' in Mukherjee A (ed), *Groundwater of South Asia* (759–799), Springer Singapore, doi:10.1007/978-981-10-3889-1_44.

De Silva SS (2003) 'Culture-based fisheries: an underutilised opportunity in aquaculture development', *Aquaculture*, 221(1-4):221–243, doi:10.1016/s0044-8486(02)00657-9.

De Silva SS, Amarasinghe US, Jayasinghe UAD, Wijenayake WMHK, Nguyen TTT, Sim Y, Nguyen S and Murray F (2006) *Better Practice Approach for Culture-based Fisheries Development in Asia*.

Dhoke SK (2023) 'Determination of alkalinity in the water sample: a theoretical approach', *Chemistry Teacher International*, 5(3):283–290.

Digamadulla DS, Asoka JM, Jones C, Jayasinghe-Mudalige UK, Wijenayake WMHK, Amarasinghe US and De Croos MDST (2023) 'Appraisal of culture-based fisheries of giant freshwater prawn (Macrobrachium rosenbergii, De Man, 1879) in reservoirs of Sri Lanka', *Aquaculture, Fish and Fisheries*, 3(1):81–95, doi:10.1002/aff2.94.

Ekanayake DNB, Kularatne MG, Kanchana RAC and Paranamana GP (2023) *Advancing livelihood benefits in culture-based fisheries in Sri Lanka: a SWOT analysis*.

ESA (2019) SENTINEL-1 Flood mapping tutorial, *Skywatch* (February), 1–9.

FAO (2009) Macrobrachium rosenbergii, *Cultured Aquatic Species Fact Sheets*.

FAO (2010) *FAO EXPERT CONSULTATION ON THE DEVELOPMENT OF GUIDELINES FOR THE ECOLABELLING OF FISH AND FISHERY PRODUCTS FROM INLAND CAPTURE FISHERIES*, FFa Aquaculture.

FAO (2022) *FAO Fisheries and Aquaculture Division,* doi:10.4060/cb8609en.

FAO (2024) *The State of World Fisheries and Aquaculture 2024*, doi:10.4060/cd0683en.

Fisheries Mo (2023) *PROGRESS REPORT 2023*.

Godfray HC, Crute IR, Haddad L, Lawrence D, Muir JF, Nisbett N, Pretty J, Robinson S, Toulmin C and Whiteley R (2010) 'The future of the global food system', *Philosophical Transactions of the Royal Society B Biological Sciences*, 365(1554):2769–2777, doi:10.1098/rstb.2010.0180.

Godoi RHM, Hirata P, Bitterncourt A, Godoi A, Miguel J, Santos F, Bini R, Zara L, Cunha C, Soares A, Gobbi E, Potgieter-Vermaak

S, Ferreira da Costa Gardolinski JE, Neto J, Rotondo G and Van Grieken R (2012) ‘Geochemical Assessment of a Subtropical Reservoir: A Case Study in Curitiba, Southern Brazil’, *CLEAN - Soil Air Water*, 40, doi:10.1002/clen.201000610.

Golden CD, Koehn JZ, Shepon A, Passarelli S, Free CM, Viana DF, Matthey H, Eurich JG, Gephart JA, Fluet-Chouinard E, Nyboer EA, Lynch AJ, Kjellevold M, Bromage S, Charlebois P, Barange M, Vannuccini S, Cao L, Kleisner KM … Thilsted SH (2021) ‘Aquatic foods to nourish nations’, *Nature*, 598(7880):315–320, doi:10.1038/s41586-021-03917-1.

Han H, Lu X, Burger DF, Joshi UM and Zhang L (2014) ‘Nitrogen dynamics at the sediment–water interface in a tropical reservoir’, *Ecological Engineering*, 73:146–153, doi:10.1016/j.ecoleng.2014.09.016.

Hudson LN, Newbold T, Contu S, Hill SLL, Lysenko I, De Palma A, Phillips HRP, Senior RA, Bennett DJ, Booth H, Choimes A, Correia DLP, Day J, Echeverría-Londoño S, Garon M, Harrison MLK, Ingram DJ, Jung M, Kemp V … Purvis A (2014) ‘The PREDICTS database: a global database of how local terrestrial biodiversity responds to human impacts’, *Ecology and Evolution*, 4(24):4701–4735, doi:10.1002/ece3.1303.

Jayasinghe UAD, Amarasinghe US and De Silva SS (2005a) ‘Limnology and culture-based fisheries in non-perennial reservoirs in Sri Lanka’, *Lakes & Reservoirs: Research & Management*, 10:157–166, doi:10.1111/j.1440-1770.2005.00271.x.

Jayasinghe UAD, Amarasinghe US and De Silva SS (2005b) ‘Trophic classification of non-perennial reservoirs utilized for the development of culture-based fisheries, Sri Lanka’, *International Review of Hydrobiology*, 90(2):209–222, doi:10.1002/iroh.200410753.

Jayasinghe UAD, Amarasinghe US and De Silva SS (2006) ‘Culture-based fisheries in non-perennial reservoirs of Sri Lanka: influence of reservoir morphometry and stocking density on yield’, *Fisheries Management and Ecology*, 13(3):157–164, doi:10.1111/j.1365-2400.2006.00488.x.

Jayasinghe UAD, Athula JA, De Silva SS and Amarasinghe US (2018) ‘Cattle and water buffalo densities wading into small village reservoirs of Sri Lanka impact on yields on the culture-based fisheries thereof’, *Sri Lanka Journal of Aquatic Sciences*, 23:67, doi:10.4038/sljas.v23i1.7547.

Jena JK (2009) Catla catla, *Cultured Aquatic Species Fact Sheets*.

Jones C, Amarasinghe US, De Croos MDST, Digamadulla DS, Jayasinghe UAD, Yomal GATK and Deepananda KHMA (2021) *Assessing production of giant freshwater prawns in reservoirs in Sri Lanka* (978-1-922635-26-6), Australian Centre for International Agricultural Research (ACIAR).

Karpowicz M, Feniova I, Gladyshev MI, Ejsmont-Karabin J, Górniak A, Zieliński P, Dawidowicz P, Kolmakova AA and Dzialowski AR (2019) ‘The stoichiometric ratios (C:N:P) in a pelagic food web under experimental conditions’, *Limnologica*, 77:125690, doi:10.1016/j.limno.2019.125690.

Karssenberg D, Schmitz O, Salamon P, de Jong K and Bierkens MFP (2010) ‘A software framework for construction of process-based stochastic spatio-temporal models and data assimilation’, *Environmental Modelling and Software*, 25(4):489–502, doi:10.1016/j.envsoft.2009.10.004.

Keller AA, Garner K, Miller RJ and Lenihan HS (2012) ‘Toxicity of Nano-Zero Valent Iron to Freshwater and Marine Organisms’, *PLOS ONE*, 7(8):e43983, doi:10.1371/journal.pone.0043983.

Kularatne MG, Pascoe S, Wilson C and Robinson T (2018) ‘Efficiency of culture-based fisheries production in village irrigation systems of Sri Lanka’, *Aquaculture Economics & Management*, 23(1):65–85, doi:10.1080/13657305.2018.1497104.

Mihiranga HKM, Jiang Y, Sathsarani MGS and Li XY (2025) ‘Dissolved phosphorous through dry-wet-dry transitions in a small-dammed river basin: integrated understanding on transport patterns, export controls, and fate’, *Environmental science - processes and impacts,* doi:10.1039/d4em00686k.

Monteiro MIC, Ferreira FN, Oliveira NMMD and Ávila AK (2003) 'Simplified version of the sodium salicylate method for analysis of nitrate in drinking waters', *Analytica Chimica Acta*, 477(1):125–129.

Nelson NS (1987) 'An acid-persulfate digestion procedure for determination of phosphorus in sediments', *Communications in Soil Science and Plant Analysis*, 18(4):359–369, doi:10.1080/00103628709367826.

Nissanka C, Amarasinghe US and De Silva SS (2000) 'Yield predictive models for Sri Lankan reservoir fisheries', *Fisheries Management and Ecology*, 7(5):425–436.

Panabokke CR, Sakthivadivel R and Weerasinghe AD (2002) *Evolution, present status and issues concerning small tank systems in Sri Lanka*.

Pushpalatha KBC and Chandrasoma J (2010) 'Culture-based fisheries in minor perennial reservoirs in Sri Lanka: variability in production, stocked species and yield implications', *Journal of Applied Ichthyology*, 26(1):98–103, doi:10.1111/j.1439-0426.2009.01361.x.

Pushpalatha KBC, Kularatne MG, Chandrasoma J and Amarasinghe US (2020) 'Production trends and technical efficiencies of culture-based fisheries in five tropical irrigation reservoirs: A case study from Sri Lanka', *Fisheries Management and Ecology*, 28(2):112–125, doi:10.1111/fme.12460.

Qin Y (2018) *Sentinel-1 Wide Swath Interferometry: Processing Techniques and Applications* (December), 132–132.

Radha SVVD, Sabarathinam C, Al-Ayyadhi N, Al-Ajeel FK, Al-Qallaf H and Akber A (2022) 'Spatial and temporal variation of dissolved CO2 in rainwater from an arid region with special focus on its association with DIC and pCO2', *Environmental Earth Sciences*, 81(4):113, doi:10.1007/s12665-022-10176-4.

Rajeevan R, Edirisinghe U (2017) 'Emerging culture based fisheries of *Macrobrachium rosenbergii* (de man, 1879) in puthumurippu medium perennial reservoir, kilinochchi district, Sri Lanka', *3rd International Conference on Dry Zone Agriculture 2017*, Faculty of Agriculture, University of Jaffna, Sri Lanka.

Rathnayake Z (2023) *The ancient Sri Lankan 'tank cascades' tackling drought*, BBC, accessed October 2024.

Sanuja RG, Jayasinghe UAD, Lakshman PLN and Deepananda KHMA (2024) 'The trophic state of the reservoir influences the allometric coefficient and condition factor of Giant Freshwater Prawn (Macrobrachium rosenbergii) cultured in perennial reservoirs of Sri Lanka', *Davao Research Journal*, 15(1):69–82, doi:10.59120/drj.v15i1.155.

Silva EIL and Manuweera L (2004) 'Surface and Rainwater Chemistry in Sri Lanka A Risk of Acidification', *AJWEP*, 2(1), doi:10.3233/ajw-2004-1_1-2_10.

Smart MM, Rada RG and Donnermeyer GN (1983) 'Determination of Total Nitrogen in Sediments and Plants Using Persulfate Digestion', *Water Research*, 17(9):1207–1211.

Studt JL, Campbell ER, Westrick D, Kinnunen-Skidmore T, Marceau AH and Campbell WH (2020) 'Non-toxic total nitrogen determination using a low alkaline persulfate digestion', *MethodsX*, 7 (October 2019):100791–100791, doi:10.1016/j.mex.2020.100791.

Sugunan VV (2000) 'Ecology and fishery management of reservoirs in India', *Hydrobiologia*, 430(1/3):121–147, doi:10.1023/a:1004081316185.

Tilapia L (2025) *How to Raise Tilapia*.

Towers L (2009) *FAO Cultured Aquatic Species Information Programme provides information on farming mrigal carp (Cirrhinus mrigala)*, accessed 18 February 2025.

Tyrrell T (2001) 'Redfield Ratio' in Steele JH (ed) *Encyclopedia of Ocean Sciences* (2377–2387), Academic Press, doi:10.1006/rwos.2001.0271.

Vijverberg J, Dejen E, Getahun A and Nagelkerke L (2012) 'The composition of fish communities of nine Ethiopian lakes along a north-south gradient: Threats and possible solutions', *Animal Biology,* 62:315–335, doi:10.1163/157075611X618246.

Wang H, Yang Z, Du H, Hu J, Zhang K, Hou W and Li H (2022) 'Micro-Mechanisms and Implications of Continental Red Beds', *Minerals*, 12:934, doi:10.3390/min12080934.

Wang M, Xu X, Wu Z, Zhang X, Sun P, Wen Y, Wang Z, Lu X, Zhang W, Wang X and Tong Y (2019) 'Seasonal Pattern of Nutrient Limitation in a Eutrophic Lake and Quantitative Analysis of the Impacts from Internal Nutrient Cycling', *Environmental Science & Technology*, 53(23):13675–13686, doi:10.1021/acs.est.9b04266.

Wijenayake WMHK, Amarasinghe US and De Silva SS (2016) 'Application of a multiple-criteria decision making approach for selecting non-perennial reservoirs for culture-based fishery development: Case study from Sri Lanka', *Aquaculture*, 459:26–35, doi:10.1016/j.aquaculture.2016.03.019.

Wijenayake WMHK, Jayasinghe UAD, Amarasinghe US, Athula JA, Pushpalatha KBC and De Silva SS (2005) 'Culture-based fisheries in non-perennial reservoirs in Sri Lanka: Production and relative performance of stocked species', *Fisheries Management and Ecology*, 12(4):249–258, doi:10.1111/j.1365-2400.2005.00447.x.

Wijenayake WMHK, Najim MMM and Amarasinghe US (2021) 'Constraints in culture-based fisheries of Sri Lanka and strategies for future development', *Sri Lanka Journal of Aquatic Sciences*, 26(2):81–95, doi:10.4038/sljas.v26i2.7589.

Worldometer (2024) *World Population Projections,* accessed 22 June 2024.

Wurts WA and Durborow RM (1992) *Interactions of pH, Carbon Dioxide, Alkalinity and Hardness in Fishponds* (SRAC Publication No. 464).

Yang JE, Kim JJ, Skogley EO and Schaff BE (1998) 'A Simple Spectrophotometric Determination of Nitrate in Water, Resin, and Soil Extracts', *Soil Science Society of America Journal*, 62(4):1108–1115, doi:10.2136/sssaj1998.03615995006200040036x.