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Spatial and Temporal Variation of Irrigation Water Quality of a Small Tank Cascade System in Up-stream of Malala Oya River Basin, Thanamalwila, Sri Lanka

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ABSTRACT

Limited attempts were made using Canadian Council of Ministers of the Environment (CCME) water quality index (WQI) to interpret irrigation water quality conditions of tank cascade systems (TCS) in Sri Lanka. The present study attempts (i) to investigate the temporal and spatial variations of the irrigation water quality of a small TCS in Malala oya basin in Thanamalwila catchment, Monaragala district and (ii) to determine the WQI recommended by CCME. Representative tanks of TCS for upper (Sinhalayagama wewa and Podi wewa), middle (Maha wewa) and lower (Bagmuwa wewa) locations were selected to understand the nutrient dynamics along the cascade during Maha (wet) and Yala (dry) seasons. Hydrochemical parameters of pH, electrical conductivity (EC), Total Dissolved Solids (TDS), NO_3^-—N and NH_4^+—N, PO_4^{3-}, CO_3^- and Cl^- were determined applying standard analytical methods. The results reveal that the levels of pH and salinity have been increased in the middle and tail tanks of TCS in both dry and wet seasons. The Bagamuwa wewa possessed the highest values in EC, TDS, Cl^-, NO_3^-—N and NH_4^+—N, indicating the unsuitability for irrigation. Further, Bagamuwa wewa and Podi wewa discovered extraordinary high values for PO_4^{3-} in the dry spell beyond the permissible limits of 0-2 mg/L. The normalized values of CCME WQI for each tank in the cascade showed fair and good water quality conditions in upper cascade tanks while marginal conditions in middle and lower cascade tanks. The Bagamuwa wewa obtained the lowest CCME value indicating the marginal use for irrigation in both seasons. Accordingly, it was clear that the irrigation water quality decreases along the cascade where a temporal and spatial variation was clearly identified. Therefore, CCME WQI can be used to understand the temporal and spatial variations of water quality as an effective tool for a small TCS.

1. Introduction

During the ancient era Sri Lanka had an extraordinary irrigation system, which utilized different management strategies for its sustainability. Evidence appears since 500 B.C. for such systems and the tank cascade systems (TCS) were identified within the constructions. An interconnected tank network, which belongs to a particular micro-catchment to optimum usage of water for irrigation and to store, convey and utilize water from first order ephemeral stream or second order inland valley [1], is named as a TCS. The TCS play a major role in irrigation in the Dry zone, as an important and most efficient water conveyance technology. It comprises of an interconnected tank network within respective micro-catchment, which are located in a single meso-catchment.

Itakura and Abernethy (1993) [2] explain this as a chain of tanks, which are constructed using a watercourse. It is believed to be the most efficient and the oldest water management systems invented by the ancient people effectively developed on catchment ecosystems. Therefore, the hydrological endowment of a TCS depends on spatial and temporal rainfall distribution, surface and groundwater potentials, the form (linear or branched), the size (small, medium, large or very large) and the distributed characters of the cascade [2]. The storage volume of a tank depends on the tank capacity and the water amount received from the catchment. The four parameters which determine the quantity of surface water available to an individual tank of a particular cascade are mentioned as rainfall, rainfall runoff, return flow of drainage and spill water from upper tank [3].

A TCS consists of 4 to 10 tanks creating its own micro-catchment, and are located in a single meso-catchment [4]. In TCSs, the potential of reusability of spilled water from the head tanks for middle and tail tanks creates a high risk to transport many pollutants and sediments in remarkable amounts, which threatens the crop cultivation, aquaculture, and health conditions of human being. The risk is becoming severe as majority of the farmers use inorganic fertilizers excessively in dry zone and argued to be the main cause for chronic kidney disease [5]. The water pollution of tanks will also depend on the cropping intensity (CI). CI indicates the ratio of area irrigated/cultivated by an individual tank to its total command area [3]. Therefore, the tanks with higher CI can pollute the water in the tank by leaching the agro-pollutants to the tank. Eventually, the polluted water may harm the cultivated crops, fish, environment and ultimately the human being.

The kidney ailments such as CKDu in dry zone of Sri Lanka suspected to materialize due to polluted water by agro-chemicals [6]. The CKDu incidences have increased in several provinces in dry zone in Sri Lanka in past few years [7]. Most of the people in this CKDu prevalence area utilize groundwater from shallow wells for irrigation and drinking uses [6]. Recently, the CKDu incidences are increasing at an alarming rate in Thanamalwila, Monaragala District. The surface water is mostly popularized among the farmers in Monaragala district. However, tank water is mostly used for irrigation uses and rarely used for drinking and other domestic uses in this area. The shallow wells are the popular source for drinking water. Based on the purpose, the water quality should be determined and it is essential to ensure that the water has met its basic required quality to overcome the health hazards. The tanks in the area serve to recharge these shallow wells in the dry season. Further, aquaculture in these tanks provides fish for human consumption. Therefore, maintaining the quality of the tank water is of vital importance. Also, it is important to monitor the water quality in particular tanks in cascade systems to envisage the pollution and variations in chemical concentrations in water. Hence, the present study focuses the water quality by considering selected water quality parameters in a small tank cascade system in Thanamalwila catchment in the up-stream of Malala oya basin.

However, a large set of water quality data may be difficult to envisage the water quality, therefore a single value of water quality index has been used by many researchers [8]. Further, this eliminates the complexity of analysis of large amounts of data and easy to compliance with the quality standards [9].

Among many types of water quality indices, which has been used to express the overall water quality, the Canadian Council of Ministers of the Environment water quality index (CCME WQI) is a promising WQI [10]. Comparatively, this method is less complicated than the WQI, which uses relative weights and with many calculations. The problems encountered by limited usage in various geographically different locations have been addressed by this index and thereby convenient in summarizing the data. The CCME IWQI provides a numerical value between 0 to 100 assigning 0 for the worst quality and 100 for the best quality. The index differentiates three elements namely, scope, frequency and amplitude. It has proved that values that are more reliable could be obtained preferably by eight parameters [10]. It is applicable based on parameter type, number of parameters assessed, the time and type of water resource (river, stream, lake etc.) the quality guidelines according to the user requirements. However, these should be defined according to the objectives before calculating the index. The comparison between sampling locations are less reliable, if the water quality parameters and water quality guidelines which used in the index are vary among the sampling sites.

Although many studies have been conducted regarding water quality in surface water in Sri Lanka, only limited attempts were made using CCME WQI to interpret water quality conditions which are understandable to the general public. Also the up-stream of Malala oya basin is used to cultivate a large area of paddy in Maha season and vegetable crops in Yala season. Therefore, it is important to assess the water quality parameters and identify the suitability of water for irrigation in the particular TCS to aware the general public regarding the proper usage of fertilizers and rehabilitation of the tank cascade system and its water quality condition. Hence, the present study attempts to assess the temporal and spatial variations of the irrigation water quality of a small TCS in Malalaoya basin in Thanamalwila catchment, Monaragala district and to determine the WQI recommended by CCME. The water quality parameters were compared with the Food and Agriculture Organization (FAO) irrigation water quality guidelines [11].

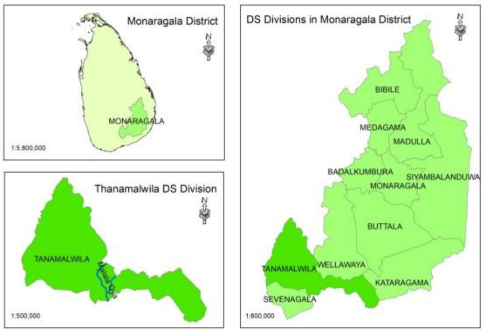

Figure 1: Up-stream of Malala oya in Thanamalwila catchment

2. Material and Methods

2.1 Experimental site

The tank density of Monaragala district is 20.2 km^2, which means one tank per 20 km^2 area. The up-stream of Malala oya belongs to Monaragala District and situated in the Thanamalwila and Wellawaya DS divisions (Figure 1). The boundaries of Malala oya basin are Walawa river basin and Kirindi oya basin. The down-stream of the basin belongs to Hambantota District. The up-stream of Malala oya s a small tank cascade system in Thanamalwila catchment, which consists of several tanks (Sinhalayagama wewa, Maha wewa, Podi wewa and Bagamuwa wewa). It is situated in the DL1b agro-ecological region of Sri Lanka. The mean annual rainfall is less than 1750 mm. The Maha season receives the highest rainfall (474.9 mm) in the region and continues from October to April. The Yala season is the drier season, which receives only 156.3 mm rainfall. The major cropping season is the Maha season, which utilizes the tank water for the paddy cultivation.

2.2 Sampling

Tanks were selected based on their locations i.e. head, middle and tail of the cascade system in up-stream of the basin, which belongs to Thanamalwila catchment. Four tanks from the cascade system namely, Sinhalayagama wewa (head), Podi wewa (head), Maha wewa (middle), and Bagamuwa wewa (tail) were selected (Figure 2). Sinhalayagama wewa is the upper tank in the Malala oya basin.

The size of command of Sinhalayagama wewa, Maha wewa and Bagamuwa wewa is 70 acres (0.28 km^2), 120 acres (0.49 km^2) and 89 acres (0.36 km^2), respectively. Podi wewa is a small tank of the system located at the upper catchment which has a low cropping intensity compared to the other tanks in the system. The land use of the cascade is mosty consists of paddy lands, forests, homestead and residential lands (Figure 3). Sampling was conducted in January/2020, February/2020 in Maha season (wet) and June/2020, July/2020 in Yala season (dry) to estimate water quality parameters.

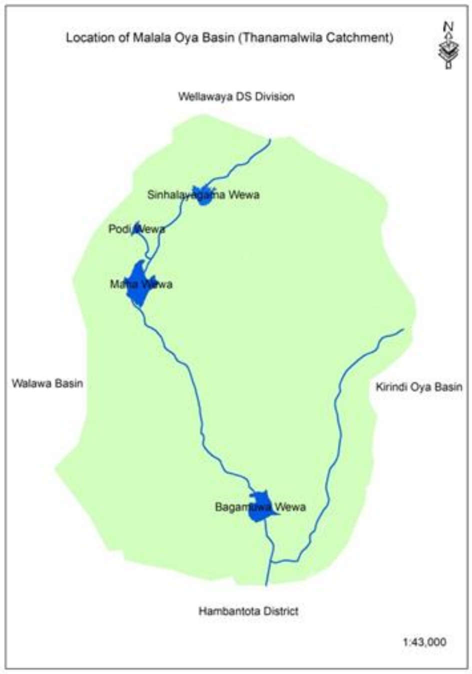

Figure 2: Selected small tank cascade system in Thanamalwila catchment of upper Malala oya basin

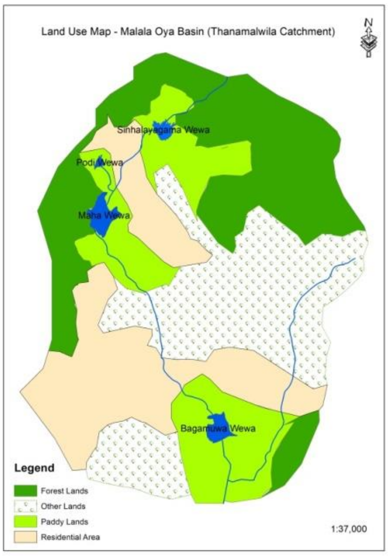

Figure 3: Land use map of the Thanamalwila catchment of Malala oya basin

2.3 Physico-chemical analysis

At the time of sampling, electrical conductivity (EC), pH, Total Dissolved Solids (TDS) were measured on site using a portable photometer (HANNA HI 83099). The collected water samples were transported to the soil science laboratory of the Department of Soil Science Faculty of Agriculture, University of Ruhuna and stored in 4 ^oC until analysis. NO_3—N, NH_4^+—N, PO_4^{3-} and Alkalinity concentrations were measured using the colourimetric methods as procedures explained in APHA guidelines [12]. Nitrate Nitrogen and ammonium nitrate were analysed using UV visible spectrophotometer (Shimadzu UV160 UV-vis). Phosphates, chlorides, and cabonates were determined using a photometer (HANNA HI 83099).

2.4 Statistical Analysis

Descriptive statistics was used by box and whisker plot charts as explanatory data analysis.

2.5 CCME WQI

The process of CCME WQI consists of 2 steps namely sampling and reporting (Figure 4). After sample analysis the index should be calculated according to the selected guidelines.

Sampling		
Set aims of the study	Collect samples	Assess parameters using standard methods
↓		
Reporting		
Set Guidelines	Calculate CCME WQI	Results verification and interpretation

Figure 4: CCME WQI calculation process [13]

The CCME conceptual model of the index is based on 3 factors viz. Scope (parameters count where the objective guidelines are not fulfilled), Frequency (the frequency in which the objective guidelines are not fulfilled) and Amplitude (value in which the guidelines are not fulfilled). The summative value of these 3 factors will provide a single index between 0-100 which describes the water quality of the particular sample (Figure 5). The FAO guidelines for irrigation water quality was fed into the index.

The CCME WQI was mathematically calculated for the relevant sample relative to the selected water quality standard with specific objectives (Table 1). For that, F1 (scope), F2 (Frequency) and F3 (Amplitude) were calculated. Amplitude (F3) was calculated in three steps. After calculating all 3 factors, the index was calculated by summing the 3 factors.

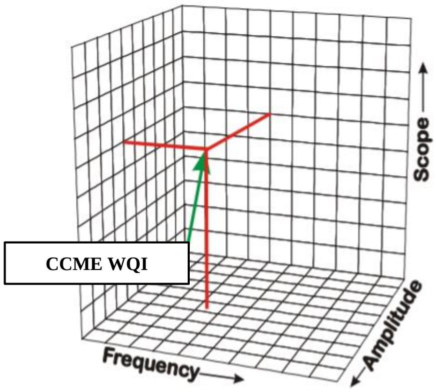

Figure 5: conceptual model of the CCME WQI [14]

The water quality classes have been created by CCME are based on the water quality index as excellent (95-100), good (80-94), fair (65-79), marginal (45-64) and poor (0-44).

Table 1: Calculation procedures of CCME WQI

Factor CCME	Equation	Description
Scope (F1)	$F_1 = \left(\frac{Number\ of\ failed\ variables}{Total\ number\ of\ variables}\right) x100$	Percentage of variables that do not meet the objective guideline (failed variables)
Frequency (F2)	$F_2 = \left(\frac{Number\ of\ failed\ tests}{Total\ number\ of\ tests}\right) x100$	Percentage of individual test which do not meet the objective guideline (failed tests)
Amplitude (F3)	I. $Excursion_i = \left(\frac{Failed\ test\ value_i}{Objective\ Guideline_i}\right) - 1$ or $Excursion_i = \left(\frac{Objective\ Guideline_i}{Failed\ test\ value_i}\right) - 1$	Number of times a sample concentration is deviate with the objective guideline (greater than/less than)
	II. $nse = \frac{\sum_{i=1}^{n} Excursion_i}{Number\ of\ tests}$	The normalized sum of excursions (*nse*) is the summation of individual tests which meet objective guidelines
	III. $F_3 = \left(\frac{nse}{0.01\ nse + 0.01}\right)$	calculated by an asymptotic function that scales the normalized sum of the excursions from objectives (nse)
CCME WQI	$CCME\ WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right)$	The 1.732 normalises the final values between 0 - 100

3. Results and Discussion

Most of the assessed water quality parameters indicated an increasing trend from upper cascade to lower cascade tanks (Table 2). The pH value is an important parameter for irrigation water quality as it affects the carbonate equilibrium, dissolution of heavy metals and the relative balance of nitrogenous elements, which in turn influence soil quality and plant growth. All the tanks had alkaline water ranging from 7.86-10.13 during the study period. Sinhalayagama wewa, which is the head tank, showed lesser pH in Maha and Yala (8.82±0.32 and 8.51±0.62, respectively) than the pH in both seasons of the tail tank. According to the Figure 6, pH has shown a higher alkalinity in tanks in the dry spell (Yala season) than in wet season (Maha season). Alkaline waters may accumulate carbonates but able to provide several nutrients to plants. Except Podi wewa in Yala season all the other tanks had pH levels above the permissible limit (6.5-8.5) for irrigation water according to the FAO guidelines.

When considering the individual tanks, it was clearly found that the EC level of majority of the tanks in the cascade was above 750 µS/cm (Table 2). Bagamuwa wewa, which was in the tail of the cascade system had the highest EC of 1800.5±6.36 µScm-1 in Maha season. The classification of salinity hazard by Wilcox (1955) [15], irrigation water quality has been grouped as Excellent (100-250 µS/cm), Good (250-750 µS/cm), Doubtful (750-2250 µS/cm) and Unsuitable (>2250 µS/cm). Accordingly, most of the tanks showed doubtful to unsuitable conditions of salinity hazard. The EC showed temporal variations in Maha season and Yala season (Figure 6). The highest EC was observed in Maha season. The reason may be the runoff of excess fertilizers and other agro-chemicals to the tanks from the cropping lands in the vicinity. The primary effect of high EC in irrigation water on crop productivity is the inability of the plant to compete with ions in the soil solution for water, which leads to less water availability to plants [16].

A higher level of nitrate nitrogen was observed with slight to moderate pollution of nitrate in some tanks of the TCS. According to Ayers and Westcot (1985) [11], restriction of nitrate nitrogen content for irrigation water can be categorized as 0-5 mg/L (no restriction), 5-30 mg/L (slight to moderate) and >30 mg/L (severe). Bagamuwa wewa showed the highest level of Nitrate-N concentration in both Maha and Yala sesons as it lies in the tail of the TCS and the pollutants may concentrate in the tank by runoff and leaching effects. The nitrate N and ammonium N levels were higher in Maha season but the permissible levels were not exceeded (Figure 6).

All the tanks showed higher concentrations of phosphate in Yala season exceeding the recommended level of 0-2 mg/l (Table 5). Figure 6 showed that the phosphate concentration in tank water was exceptionally higher during the dry period showing very high phosphate pollution. Thus, this situation will lead to eutrophication effects in the tank.

The chloride concentration in irrigation water plays an essential role in crop performance although the required amount is low. Sometimes it may create toxic effects to plants. Chloride values in irrigation water of below 140 mg/l are considered good quality irrigation waters [16]. Further, excess chloride amount in water can increase the TDS which decrease the plant uptake of essential nutrients from the soils. Except Podi wewa, all the tanks showed higher chloride concentrations in both seasons (Table 2). The maximum amounts of chloride content were observed in Maha and Yala seasons as 497.2 ppm and 463.9 ppm, respectively.

Carbonates and bicarbonates are responsible for the alkalinity (pH above 8.5) of irrigation water. Higher levels of carbonates may produce insoluble calcium and magnesium forms leaving sodium ions dominated in water. Thus, it will create adverse conditions to plants and soil, which might ultimately cause sodic soils. All the tanks except Podi wewa obtained higher values of carbonate content than the permissible level (Table 2). Higher carbonate concentration was observed in Maha season with maximum value of 138 ppm (Figure 6).

Total dissolved solids (TDS) include dissolved organic and inorganic materials in water. TDS in all the tanks in both seasons are less than the maximum desirable value of 2000 ppm and some tanks showed slight to moderate level exceeding 450 ppm. The maximum values of 900.2 ppm and 832.5 ppm were observed in Bagamuwa wewa in Maha and Yala, respectively.

3.1 CCME WQI

The comparison of water quality was done using CCME WQI for the small TCS by applying the assessed parameters. Except the podi wewa in the cascade, all the other tanks in TCS were categorized into fair and marginal water quality in Maha season and marginal in Yala season (Table 2). The leaching of agrochemicals in cropping season (Maha) may accumulate in lower tanks of the cascade creating unsuitability of water for irrigation uses. In Yala season, most of the tanks have limited water with high ion concentrations.

Thus, the water quality in Yala season is in marginal conditions to use for any purposes.

Table 2: Water quality parameter values and the CCME WQI of the tanks in the study area

		Sinhalayagama wawa		***Podi wawa***		***Maha wawa***		***Bagamuwa wawa***	
		Maha	*Yala*	*Maha*	*Yala*	*Maha*	*Yala*	*Maha*	*Yala*
pH	Average	8.82	8.51	8.64	8.11	9.02	9.40	9.00	8.99
	SD	0.32	0.62	0.23	0.35	0.25	1.04	0.22	0.08
EC (µS/cm)	Average	977	1040	334.50	386.50	601	1143	1800.5	1664.50
	SD	90.51	130.11	10.61	171.83	231.93	391.74	6.36	1106.62
TDS (ppm)	Average	489.00	543.50	167.50	193.00	410.00	571.50	900.5	832.50
	SD	45.25	31.82	4.95	86.27	38.18	195.87	3.54	553.66
Cl^- (ppm)	Average	266.67	297.22	86.11	102.78	219.44	311.11	497.22	463.89
	SD	23.57	19.64	3.93	43.21	19.64	109.99	3.93	318.20
NH_4^+—N (ppm)	Average	1.26	0.23	0.48	1.31	0.48	1.25	3.66	1.84
	SD	1.46	0.04	0.26	0.27	0.31	0.04	4.82	1.05
NO_3^-—N (ppm)	Average	1.85	1.55	0.95	3.20	1.70	2.20	3.75	3.55
	SD	0.07	1.34	0.21	2.69	1.41	1.84	4.03	3.18
PO_4^{-3} (ppm)	Average	0.55	2.25	1.20	9.60	0.40	3.80	0.55	6.75
	SD	0.49	2.47	0.85	10.47	0.14	4.24	0.07	7.99
CO_3^{-2} (ppm)	Average	97.50	109.50	43.50	7.50	97.50	63	138	102
	SD	23.33	90.51	10.61	2.12	10.61	42.43	0.00	16.97
CCME WQI		65.23	58.65	81.68	78.79	65.78	57.62	53.83	52.69
Condition		Fair	Marginal	Good	Good	Fair	Marginal	Marginal	Marginal

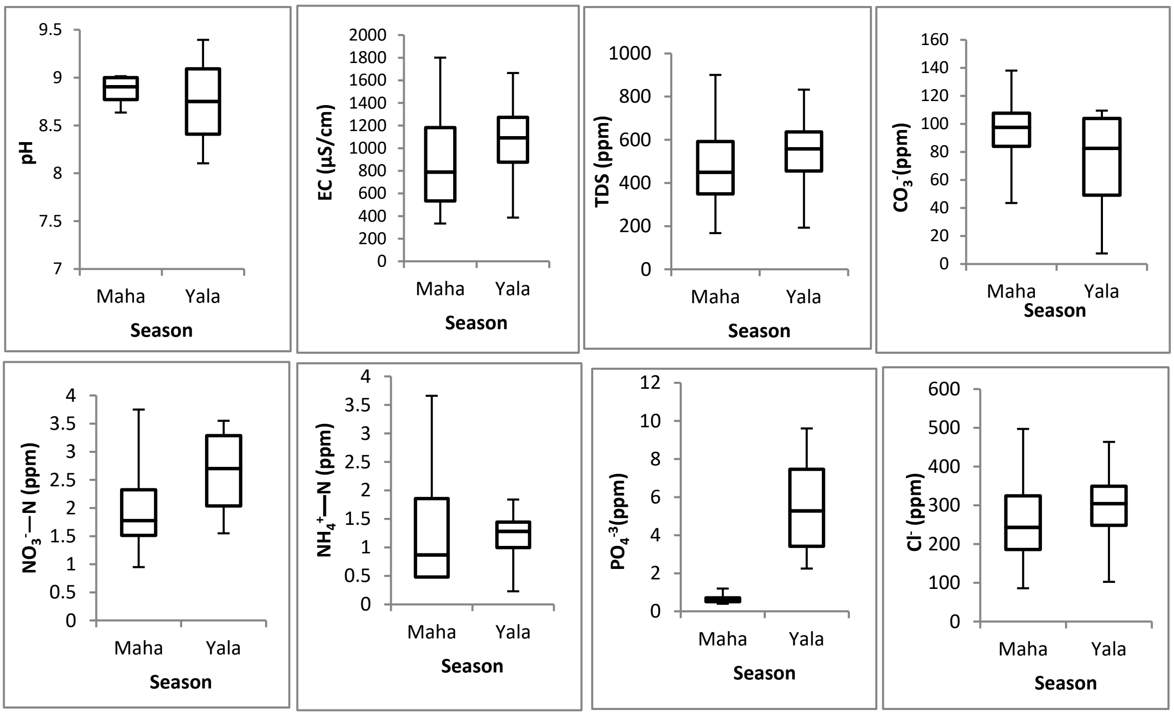

Figure 6: Temporal variation of water quality parameters

4. Conclusion

It was clearly visible that the pH, EC, TDS, ammonium-nitrogen, nitrate-nitrogen, and Chlorides of irrigation water increased from upper to lower in the TCS. This may be due to accumulation of chemicals along the cascade by anthropogenic activities, leaching from fertilizers, over usage of inorganic fertilizers. A temporal variation of irrigation water quality was observed in the tanks of the cascade indicating higher concentrations in Maha season, which is the major cultivating season in this area. However, the Phosphate concentration was remarkably high in the dry season. Therefore, there is a possibility to generate eutrophication in tanks especially in the tail parts of the cascade system due to higher concentrations of nitrates and phosphates. The normalized values of CCME WQI for tanks in the cascade showed fair, good and marginal conditions of water for irrigation in Maha (wet) season but most of them showed marginal conditions in Yala (dry) season. The tail tank obtained the lowest CCME value indicating the marginal condition for irrigation in both seasons. Hence, CCME WQI can be used to understand the temporal and spatial variations of water quality in a small TCS. A smart fertilizer management system is essential to circumvent the adverse effects of excessive chemical usage. Further, site-specific fertilizer recommendations based on the availability of nitrogen, phosphorus in irrigation water is essential to prevent any unfavorable effect of excessive nutrient concentrations such as eutrophic conditions.

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