Influence of hydraulic retention time and amplitude of water level fluctuations on water quality in irrigation reservoirs of the Kala Oya river basin, Sri Lanka

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Abstract Management of reservoir water quality is a global challenge due to the natural process of eutrophication and anthropogenic aggravation. In Sri Lanka, irrigation reservoirs support several secondary uses such as fish production, livestock farming, and many communal uses including drinking water supply. In the present study, basic limnological parameters of ten irrigation reservoirs of Sri Lanka were investigated from June 2013 to February 2016, with a view to identifying influence of hydrological regimes on reservoir water quality. Spatio-temporal similarities of water quality parameters were studied employing the self-organizing map (SOM) routine of the artificial neural network application. The sample vectors, classified on the SOM lattice, indicated 6 clusters at 50% similarity level. When reservoir that were categorized according to hydraulic retention time (HRT) and relative reservoir level fluctuation (RRWL; defined as the ratio of the mean reservoir level amplitude to mean depth), were compared with dominant water quality parameters in SOM lattice, it was evident that some productivity-related water quality parameters were influenced HRT and RRWL. The results of the study revealed that HRT and RRWL can essentially be controlled through management of hydrological regimes in irrigation reservoirs, thus, close dialogue between irrigation authorities and other users of reservoir water resources are needed to ensure desired water quality of the reservoirs.

Keywords: artificial neural network, nutrient loading, reservoir limnology, self-organizing maps, tropical reservoirs

INTRODUCTION

Sri Lanka is endowed with rich reservoir resources and the cumulative extent of reservoirs is about 206,000 ha (Jayasinghe and Amarasinghe 2018). This is perhaps the highest density of reservoirs in the world, which is worked out to be about 3.1 ha of reservoir area per every km² of the island (Fernando 1993). The total extent of reservoirs in the country consists of ancient reservoirs constructed irrigating agricultural lands and, recently constructed upland reservoirs are used for hydroelectricity generation several other purposes. Apart from these primary uses, reservoir resources support several secondary uses such as fish production, livestock farming, and

communal uses such as bathing, drinking water supply etc. Eutrophication in aquatic ecosystems is one of the major widespread problems worldwide. This natural process is often aggravated due to anthropogenic activities due to accelerated runoff of materials from the land surface to water bodies (Rast and Holland 1988). Therefore, monitoring and managing lakes and reservoirs would be important to have desired water quality in lakes and reservoirs and also to prevent or limit eutrophication (Wagner and Erickson 2017).

Reservoirs with longer a hydraulic retention time (HRT) may exhibit conditions prevailing in natural lakes and are generally characterized by prolonged nutrient retention (Kennedy 2005). In irrigation

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reservoirs, due to regular water releases to the agricultural lands, HRT is expected to be lower than in other lentic water bodies where outflowing water is minimal (Kawara *et al.* 1998). Further, the magnitude of reservoir drawdown had a significant positive influence on fish yield in a Sri Lankan reservoir (De Silva 1985). Kolding and van Zwieten (2006, 2102) have also shown that amplitudes of reservoir level had positive influences on fish yield. Similar positive influences of reservoir level amplitude on fish yields in Sri Lankan reservoirs were reported by Amarasinghe and De Silva (2015).

HRT and fluctuations in the reservoir water level are essential hydrological features, which are mainly related to water releases from reservoirs. Thus, understanding of their influences on reservoir water quality would provide important management implications. In the present paper, an attempt was made to investigate, employing a multivariate statistical approach, the spatio-temporal patterns of water quality in ten irrigation reservoirs of Sri

Lanka in relation to hydraulic retention time and amplitude of water level fluctuations. This study is therefore aimed at understanding importance managing hydrological regimes in the water quality management of irrigation reservoirs.

MATERIALS AND METHODS

Data collection

Ten irrigation reservoirs of Kala Oya river basin in Sri Lanka were selected for the present study. Geographic locations of the reservoirs are shown in Figure 1 and some morphometric characteristics of these reservoirs are given in Table 1. Hydrological data including reservoir volume and annual outflow volume of the reservoirs were obtained from the Irrigation Department and Mahaweli Authority of Sri Lanka.

Fig. 1 Map of the study area with reservoirs of Kala Oya river basin. Reservoirs; An - Angamuwa; Bw - Balaluwewa; Dw - Dewahuwa; Ib - Ibbankatuwa; Kw - Kalawewa; Kn - Kandalama; Kt - Katiyawa; Rj - Rajanganaya; Sg - Siyambalangamuwa; Us - Usgala Siyambalangamuwa.

Table 1 Morphometric characteristics of ten irrigation reservoirs selected for the present study. (Sources: Irrigation Department; Mahaweli Authority of Sri Lanka). Abb. – Abbreviation of reservoir name. FSL – full supply level; MSL – mean sea level; MCM – million cubic metres

Reservoir	Abb.	The extent at FSL (ha)	Capacity at FSL (MCM)	FSL (m) above MSL	Catchment area (km ²)
Angamuwa	An	792	15.79	64.3	129.5
Balaluwewa	Bw	934	41.42	120.0	269.8
Dewahuwa	Dw	433	13.56	182.9	67.3
Ibbankatuwa	Ib	405	11.72	162.2	169.0
Kalawewa	Kw	1980	87.81	129.2	572.0
Kandalama	Kn	736	33.74	176.2	98.0
Katiyawa	Kt	257	5.55	94.3	86.7
Rajanganaya	Rj	1599	100.37	68.3	1611.0
Siyambalangamuwa	Sg	146	2.6	36.3	46.6
Usgala Siyambalangamuwa	Us	769	26.72	86.8	184.6

Each reservoir was visited approximately once in two months from June 2013 to February 2016 and three predetermined sampling sites were used to collect water samples to determine physico-chemical and biological parameters. All the samples were taken at the 0.5 metre depth from the surface. Water temperature, pH, conductivity, dissolved oxygen, total alkalinity and, Secchi depth, were measured at the site itself. Water samples were kept in ice box during transportation and total phosphorus and nitrate were analysed using the

standard spectrophotometric methods (Table 2). For determination of chlorophyll-a and seston weight, water samples were filtered *in situ* using nitro-cellulose membrane filters (pore size - 0.45 µm; diameter - 47 mm) by a hand-held filter set-up and the filter papers were wrapped with aluminium foil, kept in an ice box until bringing to the laboratory for further analysis. The methods of determination of physico-chemical and biological parameters in the present study are given in Table 2.

Table 2 The water quality parameters investigated and the procedures employed.

Parameter	Abbreviation	Procedure
Alkalinity	Alk	Standard titrimetric method, Mixed bromocresol green-methyl red indicator solution, 0.1 N standard HCl (APHA 2012)
Chlorophyll-a	Chl-a	Spectrophotometric method with acetone extraction (Carlson & Simpson 1996; APHA 2012)
Electrical conductivity	EC	Electric conductivity meter (Hanna; HI86303)
Dissolved oxygen	DO	Winkler method (APHA 2012)
Nitrate	NO ₃ ⁻	Cadmium reduction method (APHA 2012)
pH	pH	Membrane pH meter (Cyberscane; pH300)
Secchi disc depth	SDD	20-cm diameter, alternate black-and-white segment Secchi disc
Water temperature	Temp	Mercury thermometer
Total Phosphorus	TP	Ascorbic acid method, following persulphate digestion (APHA 2012)
Seston weight	SW	Drying filtered particles on nitro-cellulose filter at 80°C in oven with fan (Wetzel 2001)

Data analysis

Underpinning patterns similarity and dissimilarity of water quality parameters in 10 reservoirs were investigated using the self-organizing map (SOM) routine of Artificial Neural Network (ANN) application (Kohonen 2001). This unsupervised algorithm of ANN application is an artificial intelligence approach for analyzing, clustering and modeling of multiple variables, and is thought to be appropriate for the present study because it allows analysis of complex data sets (Lek et al. 2005; Suryanarayana et al. 2008). The output of SOM is displayed as a hexagonal lattice and classifies the sample vectors (SVs), described by a set of descriptors on the map according to the similarities between the descriptors (*i.e.*, water quality parameters). During the learning process, two SVs with similar descriptors are classified in the same or neighboring cells, whereas two different SVs are classified in separated cells that could be distant from each other. The number of map units (C) or neurons for the output layer (*i.e.*, map size) was determined as $C = 5 \cdot \sqrt{n}$, where n is the number of samples (SVs), as proposed by the Laboratory of Computer and Information Science, Helsinki University of Technology (Kohonen, 1982; Tudesque et al., 2008). As the number of samples in the present study was 164, estimated C was 64, and consequently the map size of 8×8 output neurons was defined. The hierarchical cluster analysis (Euclidean distance), as articulated in ANN software, was also employed to illustrate the levels of similarity between clusters. The Artificial Neural Network Toolbox V.4 operating in Matlab environment was used for developing ANN and SOM (Vesanto 2000; Yu et al. 2011).

To investigate spatial patterns of reservoir water quality, percentage samples corresponding to each reservoir was determined in each cluster resulted from SOM analysis. The dominance of each reservoir in the SOM clusters was then compared with the dominant water quality parameters in

different SOM clusters that are illustrated in the component plan of each water quality parameter in the SOM.

Hydraulic retention time (HRT in yrs) of each reservoir was determined by the following equation (Dillon 1975).

$$\text{HRT} = \frac{\text{Reservoir volume in MCM}}{\text{Annual outflow (MCM/yr)}}$$

Reservoirs that were grouped into four categories based on the values of HRT as <25%, 25%-50%, 50%-75% and, >75%. Mean annual relative reservoir level fluctuation (RRLF) in each reservoir was calculated as follows (Kolding and van Zwieten 2006):

$$\text{RRLF} = \frac{\text{WL}_{\text{Max}} - \text{WL}_{\text{Min}}}{\text{Mean Depth}} \times 100$$

where, WL_{Max} = Maximum water level in m, WL_{Min} = Minimum water level in m, and mean depth is in m. Based on the values of RRLF, reservoirs were again grouped into three categories as $\text{RRLF} < 100$; 100-200 and > 200 .

The dominant water quality parameters in reservoirs, that could be determined from the component plan of each water quality parameter in the SOM, in relation to categories of HRT and RRWL, were then determined. To substantiate the findings of these analyses, dominant water quality parameters were related to HRT and RRWL.

RESULTS

Water quality parameters measured in the 10 reservoirs showed appreciable variations between reservoirs (Fig. 2). Of these water quality parameters, chlorophyll-a content showed the greatest variation. In Ibbankaruwa reservoir, where hydraulic retention time is the lowest (Fig. 3), the highest nitrate concentration (5.48 mg l^{-1}), lowest pH (7.68), lowest Secchi depth (0.69 m), and lowest water temperature (27.0°C), were recorded (Fig. 2).

Fig. 2 Water quality parameters (mean±SE) in 10 irrigation reservoirs. Abbreviations of reservoir names are as given in Table 1. Abbreviations of water quality parameters are as given in Table 2.

The Hydraulic Retention Time (HRT) of the 10 reservoirs studied, varied greatly between each reservoir (Fig. 3A). According to the results of the HRT, Angamuwa, Balaluwewa, Ibbankatuwa, Kandalama and Katiyawa belong to the category of HRT of <0.5 yrs, Rajanganaya and Siyambalangamuwa to the category of HRT of 0.5-1.0 yrs, Usgala Siyambalangamuwa to the HRT of 1.0-1.5 yrs and Dewahuwa to the category of the

highest HRT (>1.5 yrs). Based on Relative Reservoir Water Level fluctuations (RRWL), Kandalama and Rajanganaya registered low (<100) RRWL, Angamuwa, Balaluwewa, Katiyawa, Kalawewa and Usgala Siyambalangamuwa were characterized as intermediate (100-200) RRWL, and Dewahuwa, Ibbankatuwa and Siyambalangamuwa high (>200) RRWL (Fig. 3B).

Fig. 3 Hydraulic retention time (HRT) and Relative Reservoir Water Level fluctuations (RRWL) in the 10 reservoirs studied. (A) Horizontal broken lines indicate arbitrary categorization of reservoirs based on HRT (<0.5 yrs, 0.5-1.0 yrs, 1.0-1.5 yrs, and >1.5 yrs) and (B) horizontal broken lines are the arbitrary categorization of reservoirs based on RRWL (<100 , 100-200, and >200). Abbreviations of reservoir names are as given in Table 1.

The sample vectors (observations) in the present study, classified on the SOM lattice (Figure 4A) indicate that there were 6 clusters and in the similarity dendrogram (Figure 4B), these six clusters could be found at about 50% similarity level. Based on the samples that were represented by each cluster (Table 2), percentage samples of the 10 reservoirs in the six clusters were determined (Figure 5). From these plots, it is evident that Dewahuwa and Siyambalangamuwa had higher proportions of samples in cluster I, Balaluwewa in clusters II and V, Usgala Siyambalangamuwa and Rajanganaya in cluster III, Angamuwa and

Katiyawa in cluster IV, Kandalama and Kalawewa in cluster V, and Ibbankatuwa in cluster VI.

When the component plans of water quality parameters on the SOM lattice (Figure 6) are compared with the proportions of samples of reservoirs in the six clusters, spatial variations of water quality parameters could be identified.

The reservoirs, grouped according to HRT and RRWL (Figure 3), and characterized by dominant water quality parameters were then identified from the component plans of SOM lattice (Figure 6). The results are summarized in Table 4.

Fig. 4 Results of the SOM analysis. (A) Classification of sample vectors based on water quality parameters; and (B) Dendrogram of the SOM output, showing six clusters of sample vectors with similar water quality parameters. Definition of symbols is given in the caption of Table 3.

Table 3 The number of samples in the six clusters of SOM analysis. Sample codes represent sampling visit month and reservoir name (e.g., 10DJDw represents 10 sampling visit in December-January to Dewahuwa). Abbreviations of reservoir names are as given in Table 1.

Cluster	Samples
I	10DJDw, 12AMDw, 11FMDw, 13JJDw, 10DJUs, 16DJUs, 16DJKw, 11FMKw, 10DJKw, 16DJKt, 10DJKt, 17FMSg, 11FMSg, 1JJSg, 12AMSG, 1JJKn, 11FMKn, 10DJBw, 9ONUs
II	10DJAn, 9ONAn, 16DJAn, 12AMBw, 16DJBw, 14AsBw, 6AMBw, 12AMKw, 16DJRj, 9ONRj, 15ONRj, 17FMKn, 12AMKn, 13JJKn, 9ONKt, 11FMKt, 13JJSg, 15ONSG, 9ONSG, 1JJUs, 6AMUs
III	11FMAn, 15ONAn, 1JJAn, 12AMKt, 14ASKt, 1JJKt, 12AMRj, 6AMRj, 10DJRj, 5FMRj, 11FMRj, 13JJRj, 1JJRj, 14ASDw, 15ONDw, 5FMSg, 12AMUs, 14ASUs, 15ONUs, 11FMUs, 13JJUs, 5FMib, 6AMib
IV	12AMAn, 14AsAn, 5FMAn, 6AMAn, 13JJAn, 8ASAn, 7JJAn, 2ASAn, 3ONAn, 4DJAn, 14ASRj, 7JJRj, 8ASRj, 4DJRj, 2ASRj, 3ONRj, 14ASSg, 6AMSG, 8ASSg, 3ONSG, 4DJSg, 6AMKn, 15ONKn, 6AMKt, 5FMKt, 7JJKt, 4DJKt, 2ASKt, 3ONKt, 13JJKt, 5FMUs, 8ASUs, 7JJUs, 2ASUs, 3ONUs, 4DJUs, 5FMDw, 6AMDw
V	7JJSg, 2ASSg, 14KSKw, 6AMKw, 5FMKw, 8ASKw, 1JJKw, 7JJKw, 2ASKw, 3ONKw, 4DJKw, 7JJDw, 9ONDw, 4DJDw, 2ASDw, 3ONDw, 5FMKn, 14ASKn, 7JJKn, 8ASKn, 3ONKn, 9ONKn, 2ASKn, 4DJKn, 13JJBw, 5FMBw, 7JJBw, 1JJBw, 8ASBw, 4DJBw, 2ASBw, 3ONBw, 8ASKt, 2ASib, 7JJIb, 3ONIb, 4DJIb
VI	12AMIb, 13JJIb, 16DJIb, 9ONIb, 10DJIb, 11FMIb, 17FMIb, 15ONIb, 14ASIb, 1JJIb, 8ASIb, 15ONKt, 11FMBw, 15ONBw, 9ONBw, 10DJKn, 16DJKn, 10DJSg, 16DJSg, 15ONKw, 9ONKw, 13JJKw, 16DJDw, 17FMDw, 8ASDw

Figure 5. Histograms showing the proportion of samples in each reservoir in the six clusters. Abbreviations of reservoir names are as given in Table 1.

Figure 6. Visualization of the component plan of each water quality parameter in the SOM. The colour codes ranging from the low value (blue) to high value (red) indicate the relative importance of each parameter in the six clusters shown in Figure 4(A).

Table 4 Dominant water quality parameters in the reservoirs of different categories of hydraulic retention time (HRT) and Relative Reservoir Water level fluctuations (RRWL). Most dominant water quality parameters are indicated in bold phase. Abbreviations of water quality parameters are as given in Table 2.

Reservoir	HRT category	RRWL category	Dominant water quality parameters
Angamuwa	<0.5 yrs	100-200	Alk, SW , Temp, pH, SDD
Balaluwewa	<0.5 yrs	100-200	pH, TP , DO, Chl-a, SDD, Alk, SW, Temp
Dewahuwa	>1.5 yrs	>200	SDD , Alk, pH, DO, Chl-a, NO_3^- , SW, Temp
Ibbankatuwa	<0.5 yrs*	>200	NO_3^- , SW, Temp, Alk, pH, DO, Chl-a
Kalawewa	<0.5 yrs	100-200	pH, TP , DO, Chl-a, SDD, Alk, NO_3^- , SDD
Kandalama	<0.5 yrs	<100	pH, TP , DO, Chl-a, SDD, Alk, NO_3^- , SW, Temp
Katiyawa	<0.5 yrs	100-200	Alk , SW, Temp, pH, SDD, NO_3^- , DO, Chl-a
Rajanganaya	0.5-1.0 yrs	<100	SW, Alk , Temp, pH, SDD
Siyambalangamuwa	0.5-1.0 yrs	>200	SDD, Alk, SW , Temp, pH, NO_3^- , DO, Chl-a
Usgala	1.0-1.5 yrs	100-200	SW , Temp, Alk, SDD, pH
Siyambalangamuwa			

Although there was no clear pattern of water quality parameters in relation to HRT and RRWL, a high NO_3^- content was reported in Ibbankatuwa reservoir having the lowest HRT and the highest RRWL, whereas higher alkalinity was recorded in Angamuwa reservoir where intermediate RRWL was registered (Figure 3; Table 4). These findings are substantiated by the interrelationships of some water quality parameters with HRT and RRWL (Figure 7).

DISCUSSION

In many applications of assessment and management of water quality in aquatic ecosystems, univariate statistical approaches are often employed but it is evident that there is no general model that can be appropriate for all situations (Telebbeydokhti et al. 2017). Approaches pertaining to water quality indices (WQI) in which the aspects of multiple-attributes of water quality can be resolved into a single score sometimes does not provide sufficient information for decision makers (Abbasi and Abbasi 2012). Many WQIs are potentially useful in the planning of water resource protection, improvement, and utilization, whereas some WQIs

have been specifically developed to aid in environmental planning and decision making. Several authors have shown that multivariate statistical approaches are more appropriate to understand the underpinning patterns of water quality parameters, especially due to their interdependence (e.g., Sheela et al., 2012; Avakul and Jutagate 2012).

The multivariate statistical approach employed in the present study has shown considerable variations of water quality among irrigation reservoirs studied, which are possibly associated with hydrological regimes. These multivariate approaches have been proven to be more suitable for the analysis of complex data and understand the underlying patterns in a simple manner (Lek and Guegan 2000; Li et al. 2009; Aguilera et al. 2001; Mahagamage et al. 2014; Mahagamage and Manage 2014). The Self-Organizing Map (SOM) approach adopted in the present analysis belongs to the category of competitive learning networks. The SOM, which is one of the artificial neural network models, is based on unsupervised learning without human intervention and little needs to be known about the characteristics of the input data.

Figure 7. Relationships of some water quality parameters with HRT and RRWL in the 10 reservoirs studied.

In environmental assessment, it is imperative that methodologies which summarize complex environmental data into a simple visual format be employed especially for assisting decision makers. The present study indicates that the SOM approach is appropriate for the purpose because it provides an insight into how anthropogenic factors (in the present case HRT and RRWL) impact on the water quality of irrigation reservoirs. The present study was, however based on a few water quality parameters, which were important for planning fisheries management strategies in a parallel study. Nevertheless, this analysis has shown that HRT and RRWL influenced nutrient-related water quality parameters such as nitrate and alkalinity.

Furthermore, from the present analysis, it was evident that total phosphorous was not significantly influenced by either HRT or RRWL. Yatigammana & Cumming (2016) also mentioned that Sri Lankan reservoirs could be categorized as phosphate-limited systems.

The practical utility of the present analysis is that the desired levels of water quality, which are in accordance with the water quality management criteria, can be achieved through control of HRT and RRWL. In the developing countries, reservoir management is generally aimed at increasing food fish production and as such, eutrophy is favoured (Welcomme and Bartley 1998). On the other hand, reservoir trophy may lead to the proliferation of

toxigenic algae such as *Micocystis* (Jayatissa et al. 2006; Sethunga and Manage 2010; Manage et al 2010; Manage and Premathilaka 2011; Hettiarachchi and Manage 2014). Furthermore, the presence of toxigenic algae in some Sri Lankan reservoirs of drinking water supply due to eutrophic conditions has also been reported (Sethunga and Manage 2010). As such, strategies for the management of reservoir water quality should be viewed as a trade-off between the trophic levels favouring biological production and preventing eutrophication which may bring about the proliferation of toxigenic algae. As HRT and RRWL can essentially be controlled through management of hydrological regimes in irrigation reservoirs, close dialogue between irrigation authorities and other users of reservoir water resources might be useful to ensure desired water quality.

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