Int. J. Aquat. Biol. (2020) 8(6): 434-446
ISSN: 2322-5270; P-ISSN: 2383-0956
Journal homepage: www.ij-aquaticbiology.com
© 2020 Iranian Society of Ichthyology

Original Article

Macrophytes as indicators of the ecological status of a tropical rehabilitated wetland ecosystem: Application of multivariate statistics and Ecological State Macrophyte Index (ESMI)

Dimuthu Wijeyaratne, Aravinda Bellanthudawa*

Department of Zoology and Environmental Management, University of Kelaniya, Sri Lanka.

Abstract: The present study used the Ecological State Macrophyte Index (ESMI) and the multivariate statistical methods to assess the ecological status and the variation of macrophytes in a tropical wetland system. Six sites were selected from rehabilitated and non-rehabilitated areas of an urban tropical wetland and the water quality parameters (water pH, temperature, conductivity, total dissolved solids (TDS), dissolved oxygen (DO), visibility, biological oxygen demand 5 days after incubation (BOD_5), chemical oxygen demand (COD), nitrate, chlorophyll-a and total phosphorus concentrations), sediment quality parameters (pH, organic matter content, percentage sand, silt and clay content) and abundance of aquatic macrophytes were measured. Shannon Weiner diversity index, percentage vegetation under anthropo-pressure, macrophyte settlement rate and ESMI were calculated. Significant variations in the water and sediment quality parameters were observed and ten species of aquatic macrophytes were recorded. *Salvinia melosta* and *Cypreus iria* were recorded only from the non-rehabilitated sites. Although there was no significant difference in the percentage anthropo-pressure among study sites, the rehabilitated sites were displayed low anthropo-pressure. The sites in the non-rehabilitated area showed a significantly lower macrophyte settlement rate. ESMI and macrophyte abundance showed significant correlations with water quality parameters. Based on the results, it can be recommended that applications based on ESMI and multivariate statistics can be used to assess the ecological status of tropical wetlands.

Article history:
Received 18 November 2019
Accepted 7 December 2020
Available online 25 December 2020

Keywords:
Anthropo-pressure
Macrophyte settlement rate
Sri Lanka
Tropical wetlands

Introduction

Aquatic macrophytes are important components of wetland ecosystems. They can grow as rooted emergent, rooted submerged or floating vegetation in wetlands and play a major role in wetland communities by performing direct and indirect ecological functions. Aquatic macrophytes are important in nutrient cycling, maintenance of water quality, prevention of sediment re-suspension and providing food and habitats for many other wetlands associated organisms (Gidudu et al., 2011). A healthy macrophyte community is an indicator of a healthy wetland ecosystem. As the rooted macrophytes are rooted in the soft muddy bottoms of wetland ecosystems, they are able to integrate long term changes in water and sediment quality, making them ideal indicators of assessing the changes in wetland environments for several seasons or several years (Murphy et al., 2003; Lee and McNaughton, 2004).

Several studies have been conducted to investigate effect of environmental characteristics on the changes in macrophyte community in various types of wetland ecosystems. These studies have shown that, the physical and chemical properties of the water and sediments can determine the composition of the aquatic macrophyte community, thereby influencing the health of the ecosystems (Lee and McNaughton, 2004; Lacoul and Freedman, 2006; Henry-Silva et al., 2008; Fu et al., 2014). Concentration of nutrients in both water and sediments and light penetration were recorded to be the strongest predictors of macrophyte distribution (Bini et al., 1999; Henry-Silva et al., 2008). In addition to these major predictors, variation of conductivity, Mg, Ca and Na concentrations,

*Correspondence: Dimuthu Wijeyaratne
E-mail: dimuthu.wijeyaratne@kln.ac.lk

DOI: https://doi.org/10.22034/ijab.v8i6.675

alkalinity, altitude, pH and depth can also have strong effects on abundance and distribution of macrophytes (Kunii, 1991). In addition to the physical and chemical factors, biological factors also play a key role in determining the abundance and distribution of macrophytes in the wetlands. Many studies have identified that primary and secondary succession, competitive interactions among plants, patterns of herbivory by invertebrates and vertebrates as major biological factors that control the composition and distribution of aquatic macrophytes in wetlands (Gidudu et al., 2011; Dar et al., 2014).

Biological monitoring is very important in predicting the stressors associated with wetland communities, as the biological community can have both direct and indirect effects due to natural and human induced changes in an ecosystem. Therefore, there should be reliable, predictable and cost-effective comprehensive studies on wetland biological communities (Birk et al., 2012; Lyche Solheim et al., 2013). However, the common biological indicators of wetland health assessment involve macrobenthos (Braccia and Vosell, 2006; Dahanayaka and Wijeyaratne, 2006; Brraich and Kaur, 2017; Wijeyaratne and Bellanthudawe, 2017; Wijeyaratne and Kalaotuwawe, 2017; Basu et al., 2018) and fish (Karr, 1981; Brousseau et al., 2011; Priyatharsini et al., 2018). Comparatively less priority is given to studies using aquatic macrophytes as bioindicators. Several studies on macrophyte indices in wetland health monitoring programmes have been used in Europe, but applications are rare in other regions of the world (Ciecierska, 2006; Birk et al., 2012; Lyche Solheim et al., 2013).

Aquatic macrophyte indices are also used as indicators in wetland health assessment in wetland management and rehabilitation programmes. These methodologies involve analysis of the spatial and structural distribution of aquatic macrophytes in a wetland ecosystem for a predetermined time period and their spatial and temporal arrangements are modeled to predict the wetland health (Ciecierska, 2006). Ecological State Macrophyte Index (ESMI) is a biological monitoring method to assess the ecological status of wetlands based on macrophyte abundance and diversity characteristics. This method involves development of a macrophyte index based on ratio of redundancy index and colonization index of aquatic macrophytes in wetland ecosystems (Ciecierska and Kolada, 2013). This method is applied in several studies in the Europian Union to study the ecological status of small lakes and wetland ecosystems (Willby et al., 2009; Søndergaard et al., 2010; Ciecierska and Kolada, 2013). However, applications of ESMI is very limited in the other parts of the world. Therefore, the present study was designed to apply ESMI to assess the ecological status of a tropical urban wetland system that is associated with wide array of diverse land-uses.

The present study was conducted in an urban wetland system located in the commercial capital of Sri Lanka, Diyawanna Wetland system. This wetland is identified as an important marshland in the area and IUCN Sri Lanka and Central Environment Authority of Sri Lanka have recognized the Diyawanna Oya Wetland, as the Colombo flood retention area and as a wetland system that is at a high level of risk. This wetland system contains both rehabilitated and non-rehabilitated areas. The rehabilitated areas are restored by wetland rehabilitation programme initiated by the Sri Lanka Department of land reclamation and highly contribute to the social well-being of the surrounding urban and sub-urban communities by facilitating income generation activities such as fishing and cattle grazing, and collecting reeds, rushes and fuel wood and serving as recreational area for family outings and water sports. The unmanaged (non-rehabilitated) areas are left as pristine habitats and are rich in indigenous fauna and flora. However, clearance of land, illegal reclamation and construction, dumping of garbage, and encroachments are taking place at some areas of the ecosystem and these environmental changes are affecting the health of the wetland.

The present study aims to use ESMI and mulitivariate analysis techniques to study the abundance and distribution of macrophytes in different parts of the Diyawanna Wetland ecosystem and to thereby characterize the ecological status of this wetland system, which will be very useful in planning and management of wetland development activities in future wetland restoration activities.

Materials and Methods

Study sites: Six study sites were selected from both rehabilitated and non-rehabilitated areas of the Diyawanna wetland system. A map showing the locations of the study sites is given in Figure 1. Site A (06°54'585"N, 079°54'722"E), site B (06°54'664"N, 079°54'633"E) and site C (06°54'609"N, 079°54'604") are located in non-rehabilitated areas. But sites B and C were in close proximity to the rehabilitated area compared to site A (Fig. 1). Site D (06°54'68"N, 079°54'610"E), Site E (06°54'751"N, 079°54'735"E) and Site F (06°54'741"N,079°54'525"E) are located in the rehabilitated area (Fig. 1).

Water and sediment quality parameters: From each site, water samples and shallow sediments samples (0-0.5 m depth) were collected in seven replicates for water and sediment quality analysis. Sampling was carried out once in 6 weeks for a period of 7 months from April to December in 2016. At each sampling site, water pH, temperature, conductivity, total dissolved solids (TDS) and salinity were measured in-situ using a calibrated digital multi parameter (YSI Environmental Model-556 MPS). Dissolved oxygen concentration (DO) was measured using DO meter (HQ 40b model-Hach). Visibility was recorded using a secchi disk. The biological oxygen demand 5 days after incubation (BOD_5), Chemical oxygen demand (COD), nitrate concentration, chlorophyll-a concentration and total phosphorus concentrations were measured using the methods described by APHA (1992). In addition, sediment pH was measured in-situ using the calibrated digital multiparameter (YSI Environmental Model-556 MPS). In the laboratory, sediment organic matter content was measured by the loss on ignition method and the percentage sand, silt and clay content of the sediments were measured using the sedimentation jar.

Macrophyte abundance and percentage coverage: Line-transect sampling described by Southwood and Henderson (2000) was followed to sample the

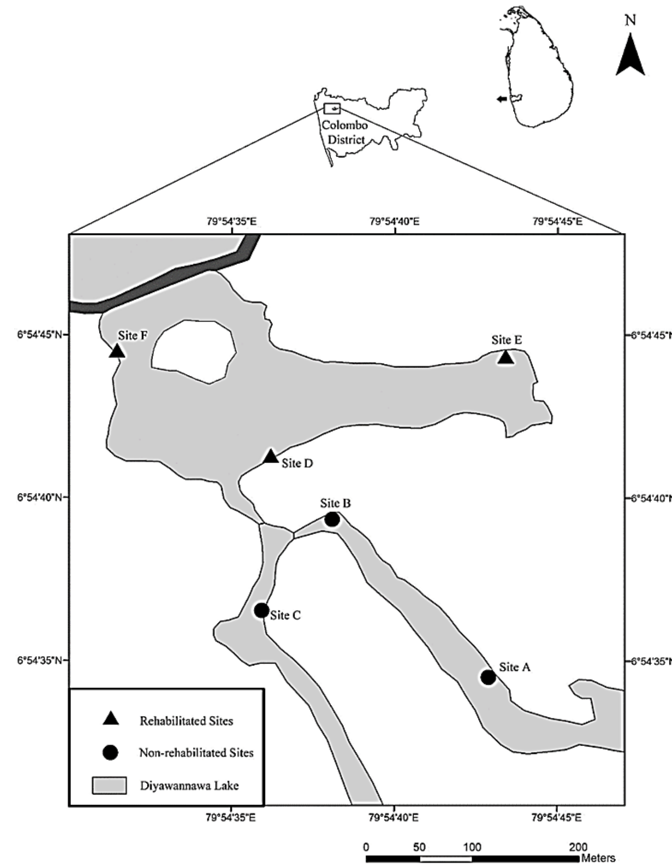

Figure 1. The study sites in the Diyawannawa wetland, Sri Lanka. The study sites A, B and C are located in the non – rehabilitated area and the sites D, E and F are located in the rehabilitated area.

macrophytes. A measuring tape was taken to mark approximately 5 m distance from bank to the middle of the wetland. Intervals of 0.5 m distance was marked off using colored tags. Each interval was treated as a separate unit of 5 m line transects. At each site, individual macrophytes were counted along the line transect at 0.5 m intervals started from bank to middle of wetland. Seven replicate transects were used at each site for macrophyte sampling. Identification of macrophytes to the lowest taxonomic level as possible was done using the photographic guide of aquatic plants prepared by the National Aquaculture Development Authority (NAQDA) and the Flora of Ceylon (Dassanayake and Fosberg, 1980-1991; Dassanayake et al., 1994-1995; Dassanayake and Clayton, 1996-2000). The identified samples were verified by comparison with the specimens from the specimen collection of Department of Botany, University of Kelaniya, Sri Lanka. The abundance of each species at each site were recorded. The percentage cover of macrophytes at each study site was determined by determining the proportion of locations where a particular species is present compared to the total number of sampled locations as described by Southwood and Henderson (2000). The macrophyte abundance data were used to calculate Ecological State Macrophyte Index (ESMI) for each site in the rehabilitated and non-rehabilitated areas of the wetland.

Determination of ESMI: ESMI was determined using the phytocoenotic diversification index (H), maximum phytocoenotic diversification index (H_{max}) and vegetation under anthropo-pressure (J). Phytocoenotic diversification index (H) was calculated from the Shannon-Wiener Index (Panek, 2001) as following:

$$H = -\sum_{i}^{i=100} \frac{n_i}{\mathrm{N}} * \ln \frac{n_i}{N}$$

Where, H = phytocenotic diversification index, n_i= area of specific plant community in the percentage of the total phytolittoral area and N = total area of phytolittoral area (100%). The maximum phytocoenotic diversification index (H max) was calculated as described by Ciecierska and Dynowska (2013) using the equation of $H_{max} = ln\, S$, where S is the total number of communities in the sampling site. The vegetation under anthropo-pressure (J) was calculated as described by Pielou (1966) using equation of J = H/H_{max}. The settlement rate of macrophytes was determined considering the relationship between the area actually occupied by the macrophytes (phytolittoral surface) and the surface potentially available to them, considered as the area of littoral zone where the water is shallower than 2.5 m (Ciecierska and Dynowska, 2013). For each site, the settlement rate of macrophytes was calculated using following equation (Ciecierska and Dynowska, 2013):

$$Z = \frac{N}{P - isob.2.5}$$

Where Z = Settlement rate of macrophytes, N = total area of phytolittoral zone in the site (m^2), P = the total surface area of the site (m^2) and isob.2.5 = area where the water is shallower than 2.5 m (m^2). Using the values calculated in above equations, ESMI for each site was calculated using following equation (Kolada and Soszka, 2004; Ciecierska 2008; Ciecierska et al., 2010):

$$ESMI = 1 - \exp[- \frac{H}{H_{max}} * Z * \exp\left(\frac{N}{P}\right)]$$

Where, H = phytocenotic diversification index (Shannon Weiner diversity index), H_{max} = the maximum phytocoenotic diversification index, Z = Settlement rate of macrophytes, N-total area of phytolittoral zone in the site (ha), and P = the total surface area of the site (ha). The calculated ESMI values were compared with the water quality classes established by Ciecierska and Kolada (2014).

Statistical Analysis: MINITAB 14 statistical software package was used in the statistical analysis. The data were tested for normality using Anderson Darling test. If the data were not normally distributed, data were Log 10 transformed before further analysis. However, the portioned variables, such as the percentage sand, silt, clay, TOC and percentage abundance were arcsine transformed before analysis. One-way ANOVA followed by Tukey's pairwise comparison was used to assess the spatial variation of water and sediment quality parameters and the abundance of macrophytes. The Shannon Weiner diversity index, maximum phytocenotic diversification index, the vegetation under anthropo-pressure, settlement rate of macrophytes and EMSI among the study sites were compared by One-way ANOVA followed by Tukey's pairwise comparison.

Principal Component Analysis (PCA) was used to determine water and sediment quality parameters and diversity and biotic indices that describes the distribution and abundance of macrophytes in this wetland system. Regression relationship of water and sediment quality parameters with the diversity of macrophytes were used to identify the influence of these parameters on the distribution of aquatic macrophytes.

Results

The spatial variation of mean±standard deviation of

Table 1. Spatial variation of mean±standard deviation of water quality parameters at each sampling site. For each parameter, mean values indicated by different superscript letters at each row are significantly different from each other (ANOVA, Tukey's pairwise comparison; n = 7).

Parameter	Non-rehabilitated area			Rehabilitated area		
	Site A	Site B	Site C	Site D	Site E	Site F
pH	6.98 ±0.3^{a}	7.54 ±0.2^{a}	7.63±0.3^{a}	7.78±0.2^{a}	7.38±0.2^{a}	8.05±0.3^{a}
visibility (cm)	42.7±4.0^{a}	40.2±4.4^{a}	37.7±1.5^{a}	43.3±2.6^{a}	40.8±1.7^{a}	43.76±1.2^{a}
temperature (ºC)	30.74±0.4^{a}	31.34± 0.3^{a}	31.44±0.3^{a}	31.54±0.4^{a}	31.75±0.5^{a}	32.14±0.3^{a}
conductivity (µs/cm)	345.5±10.5^{a}	253.7± 9.7^{b}	271.6±14.6^{b}	252.4±8.3^{b}	248.69±4.8^{b}	245.23±7.4^{b}
Water depth (cm)	85.5±3.2^{a}	118.6±9.5^{a}	98.9±5.9^{a}	119.4±2.5^{a}	85.7±6.2^{b}	62.7±6.8^{b}
TDS (mg/L)	166.25±5.0^{a}	121.68±4.7^{b}	129.98±7.1^{b}	120.47±4.0^{b}	109.90±5.3^{b}	116.84±3.6^{b}
DO (mg/L)	2.82±0.09^{a}	6.84±0.4^{b}	7.68±0.4^{b}	7.81±0.4^{b}	10.61±0.2^{c}	10.28±1.0^{c}
salinity (º/ₒₒ)	0.16±0.004^{a}	0.12±0.004^{a}	0.12±0.006^{a}	0.12±0.004^{a}	0.11±0.006^{a}	0.12±0.003^{a}
BOD_5 (mg/L)	1.20±0.5^{a}	3.13±0.5^{b}	3.85±0.3^{b}	3.79±0.3^{b}	6.56±0.3^{c}	5.13±0.3^{c}
total phosphate (mg/L)	0.02±0.004^{a}	0.02±0.003^{a}	0.02±0.004^{a}	0.03±0.005^{a}	0.03±0.006^{a}	0.04±0.008^{a}
Nitrate (mg/L)	0.01±0.001^{a}	0.02±0.001^{a}	0.02±0.002^{a}	0.02±0.003^{a}	0.037±0.004^{b}	0.04± .002^{b}
Chlorophyll-a (mg/dm^{3})	2.05±0.2^{a}	2.45±1.7^{b}	2.40± 0.6^{a}	11.61±0.5^{b}	12.13±2.6^{b}	12.42±0.9^{b}
COD (mg/L)	173.1 ± 36.4^{a}	305.3±44.7^{b}	285.5±46.9^{b}	384.9±38.8^{c}	387.5±38.2^{c}	454.8±0.1^{c}

Table 2. Spatial variation of mean±standard deviation of sediment quality parameters at each sampling site. For each parameter, mean values indicated by different superscript letters at each row are significantly different from each other (ANOVA, Tukey's pairwise comparison; n = 7).

Parameter	Non-rehabiliated area			Rehabiliated area		
	Site A	Site B	Site C	Site D	Site E	Site F
Sand content (%)	44.6±9.7^{a}	54.3±11.9^{a}	48.7±10.6^{a}	7.7±9.4^{b}	7.3±1.6^{b}	5.5±1.2^{b}
Silt content (%)	9.9±2.1^{a}	3.9±1.2^{a}	8.1±1.7^{a}	13.6±3.1^{b}	11.9±2.6^{b}	13.1±2.8^{b}
Clay content (%)	45.5±11.9^{a}	41.8±12.7^{a}	43.3±12.4^{a}	83.8±12.3^{b}	80.76±4.20^{b}	81.50±4.04^{b}
Total organic carbon (%)	12.42±0.01^{a}	12.34±0.02^{a}	12.36±0.03^{a}	12.35±0.02^{a}	12.48±0.03^{a}	12.48±0.03^{a}
conductivity (µs/cm)	47.98±0.6^{a}	43.80±0.7^{a}	70.87±2.5^{b}	74.49±2.4^{b}	77.05±1.5^{b}	91.44±1.2^{c}
pH	6.19±0.08^{a}	5.76±0.24^{a}	6.17±0.11^{a}	6.12±0.12^{a}	6.23±0.13^{a}	6.31±0.10^{a}

Table 3. Spatial variation of mean±standard deviation of percentage coverage of macrophytes at each sampling site. For each species, mean values indicated by different superscript letters at each row are significantly different from each other (ANOVA, Tukey's pairwise comparison; n = 7).

Species	Non-rehabilitated Area			Rehabilitated Area		
	Site A	Site B	Site C	Site D	Site E	Site F
Nymphaea ampla	63.3±3.39^{a}	12.5±3.67^{b}	18.33±5.03^{b}	-	-	8.33±0.83^{c}
Cryptocoryne wendtii	10.0±1.75^{a}	1.67±0.11^{b}	11.1±0.1^{a}	-	6.67±0.14^{c}	-
Annona glabra	10.8±1.94 ^{a}	-	4.17±0.15^{b}	1.67±0.14^{b}	-	-
Eichhornia crassipes	3.1±0.25^{a}	21.67±3.06^{b}	9.17±3.63^{a}	4.17±1.8^{a}	21.67±4.7^{b}	15.83±3.89^{ab}
Pistia stratiotes	2.2±1.08^{a}	15.83±2.63^{b}	9.17±2.30^{bc}	12.5±1.81^{b}	29.17±5.75^{c}	11.67±2.44^{b}
Hydrilla verticillata	6.3±035	-	6.67±2.26 ^{a}	7.5±3.08^{a}	7.67±0.17^{a}	7.5±0.2^{a}
Ceratophyllum demersum	5.9±1.2^{c}	-	-	11.67±2.64^{a}	10.15±3.89^{a}	8.33±0.83^{b}
Nymphaea rubra	2.1±0.5^{c}	-	29.17±0.62^{b}	-	-	52.5±3.59^{a}
Salvinia melosta	1.1±0.1	1.67±0.11^{a}	0.8±0.02	-	-	-
Cypreus iria	5.02±0.18^{a}	2.5±0.13^{a}	5.01±0.15^{a}		-	-

water quality parameters of the study sites are given in Table 1. Water pH, visibility, temperature, dissolved oxygen concentration (DO), salinity, total phosphate concentration (TP) did not show significant spatial variations (P>0.05). Site A of the non-rehabilitated area showed significantly high conductivity, TDS and significantly low BOD_5 and COD compared to other sites (P<0.05). Significantly high water depth, nitrate concentration, TDS and BOD_5 were recorded in sites E and F of the rehabilitated area, and significantly high COD and chlorophyll-a concentration were in all the rehabilitated sites compared (P<0.05) (Table 1).

The spatial variation of mean±standard deviation of sediment quality parameters of the study sites is given are Table 2. Total organic matter content and sediment pH did not show significant spatial variations between the studied sites (P>0.05). The sites in the rehabilitated area showed significantly high sand, clay and silt contents compared to the sites

Table 4. The mean±standard deviation values of Shannon-Weiner Diversity index (H`), Maximum phytocenotic diversification index, Percentage vegetation under anthropo-pressure, Settlement rate of macrophytes and Ecological State Macrophyte index (ESMI)in the study sites (n = 7). Different superscripts in each column indicate statistically significant differences (One-way ANOVA, Tukey's pairwise test; P<0.05). Sites A, B and C; non-rehabilitated area and sites D, E, and F; rehabilitated area.

Site	Shannon Wiener diversity index	Maximum phytocenotic diversification index	Vegetation under anthropo-pressure (%)	Settlement rate of macrophytes (per m^2)	(ESMI)
A	$1.09{\pm}0.02^{a}$	$1.09{\pm}0.02^{a}$	$100{\pm}1.2^{a}$	$3.50{\pm}0.1^{a}$	$0.30{\pm}0.01^{a}$
B	$1.72{\pm}0.01^{b}$	$1.8{\pm}0.01^{b}$	$95{\pm}3.6^{a}$	$3.25{\pm}0.2^{a}$	$0.29{\pm}0.01^{a}$
C	$2.01{\pm}0.01^{c}$	$2.2{\pm}0.01^{c}$	$91{\pm}1.6^{a}$	$3.75{\pm}0.2^{a}$	$0.32{\pm}0.02^{a}$
D	$1.61{\pm}0.02^{b}$	$1.8{\pm}0.02^{b}$	$89.4{\pm}2.6^{a}$	$4.5{\pm}0.5^{b}$	$0.72{\pm}0.02^{b}$
E	$1.33{\pm}0.02^{ab}$	$1.6{\pm}0.02^{ab}$	$83.1{\pm}4.6^{a}$	$4.5{\pm}0.3^{b}$	$0.80{\pm}0.02^{b}$
F	$1.54{\pm}0.02^{b}$	$1.8{\pm}0.02^{b}$	$85.5{\pm}1.6^{a}$	$4.5{\pm}0.3^{b}$	$0.76{\pm}0.1^{b}$

in the non-rehabilitated area (P<0.05). Significantly high sediment conductivity was recorded at site F of the rehabilitated area and significantly lower sediment conductivity was recorded at the sites A and B of the non-rehabilitated area (P<0.05) (Table 2).

The percentage cover of aquatic macrophytes at each study site is given in Table 3. Ten species of aquatic macrophytes namely, *Nymphaea ampla, Cryptocoryne wendtii, Annona glabra, Eichhornia crassipes, Pistia stratiotes, Hydrilla verticillata, Ceratophyllum demersum, Nymphaea rubra, Salvinia melosta* and *Cypreus iria* were recorded from the study sites. *Salvinia melosta* and *C. iria* were recorded only from the sites located in the non-rehabilitated area. Significantly higher percentage coverage of *N. ampla* (63.3%) and *A. glabra* (10.8%) were recorded from Site A of the non-rehabilitated area (P<0.05). Sites B and E showed significantly higher percentage coverage of *E. crassipes* (21.67%) and Site E showed significantly higher percentage coverage of *P. stratiotes* (29.17%) (P<0.05). Sites D (11.67%) and E (10.15%) of the rehabilitated area showed significantly high percentage coverage of *C. demersum* and Site F showed significantly high percentage coverage of *N. rubra* (52.5%) (P<0.05). *Hydrilla verticillata* was recorded from all the study sites except site B, and there was no significant difference of the percentage coverage between the studied sites (P>0.05) (Table 3).

The Shannon Wiener diversity index, maximum phytocenotic diversification index, the vegetation under anthropo-pressure, settlement rate of macrophytes and Ecological State Macrophyte index of the study sites are given in Table 4. The Shannon Wiener diversity index of the study sites ranged from 1.09 to 2.01 and ESMI ranged from 0.29 to 0.8. Comparatively high ESMI were recorded from the sites located in the rehabilitated area. The highest Shannon wiener diversity index was recorded from site C (2.01) and the lowest was from Site A (1.09) of the non-rehabilitated area (Table 4). Maximum phytocenotic diversification index ranged from 1.09 to 2.20 and the variation was similar to that of the Shannon wiener diversity index (Table 4). The percentage vegetation under anthropo-pressure ranged from 83.1 to 100%. Site A was having the highest anthropo-pressure (100%) and site E of the rehabilitated area was having the lowest anthropo-pressure (83.1%). Although there was no significant difference in the percentage anthropo-pressure among study sites, the rehabilitated sites were displaying comparatively low anthropo-pressure compared to the non-rehabilitated sites (Table 4). The sites in the non-rehabilitated area recorded a significantly lower macrophyte settlement rate compared to the sites in the rehabilitated area (P<0.05) (Table 3).

PCA score plot for variation of water and sediment quality parameters among the study sites in the Diyawannawa Wetland is given in Figure 2. The eigenvalues of the first two PCs, eigenvectors of the water and sediment quality variables and the principal component scores for the study sites are given in Table 5. Two PCs displaying a cumulative variance of 87.4% were obtained after applying PCA for 5 principal components. According to the PCA on water and sediment quality parameters, the sites C and B of

Table 5. Summary of the PCA of physico-chemical parameters of water and shallow sediments of the study sites at the Diyawannawa Wetland. Cumulative % variation of only the PC1 and PC2 are shown. A high cumulative percentage as high as 87.4 % of the total variation among physico-chemical parameters are explained by PC1 and PC2 axis. Sites A, B and C; non-rehabilitated area and sites D, E, and F; rehabilitated area.

Eigenvalues

PC	Eigenvalues	%Variation	Cum.%Variation
1	12.2	64.2	62.8
2	4.41	23.2	87.4
3	1.47	7.8	95.1
4	0.52	2.7	97.9
5	0.40	2.1	100.0

Eigenvectors **(Coefficients in the linear combinations of variables making up PC's)**

Variable	PC1	PC2	PC3	PC4	PC5
Water pH	0.218	-0.251	-0.182	-0.339	0.281
Temperature	0.280	-0.058	-0.041	-0.175	0.170
EC	-0.234	0.272	0.039	-0.029	-0.049
TDS	-0.245	0.232	0.013	-0.173	0.199
DO	0.263	-0.165	-0.089	-0.089	-0.232
BOD5	0.264	-0.025	-0.202	0.018	-0.466
COD	0.266	-0.148	-0.109	0.094	0.221
Nitrate	0.262	-0.100	0.267	-0.177	-0.023
Chlorophyll a	0.215	-0.171	0.348	0.451	0.246
Total Phosphorous	0.251	0.149	-0.080	0.208	0.495
Visibility	-0.245	-0.157	-0.248	0.361	-0.085
Depth	-0.142	-0.367	-0.236	0.369	-0.153
%TOC	0.172	0.346	0.238	0.165	-0.199
Sediment pH	0.122	0.389	-0.304	-0.113	-0.140
%sand	-0.247	-0.204	-0.199	-0.136	0.090
% Silt	0.130	0.305	-0.447	0.388	0.156
%clay	0.239	0.213	0.224	0.169	-0.203
Sediment conductivity	0.240	0.123	-0.383	-0.155	-0.003

Principal Component Scores

Sample	PC1	PC2	PC3	PC4	PC5
Site A	5.093	-2.819	-0.411	-0.218	-0.111
Site B	1.702	3.153	-1.532	0.009	-0.180
Site C	1.013	0.515	1.064	1.125	0.575
Site D	-0.047	1.171	1.811	-0.712	-0.514
Site E	-3.176	-0.529	-0.402	-0.717	0.938
Site F	-4.586	-1.492	-0.530	-0.513	0.707

Table 6. Summary of the PCA of the abundance of macrophytes in the study sites at the Diyawannawa wetland. Cumulative % variation of only the PC1 and PC2 are shown. A high cumulative percentage as high as 68.2 % of the total variation among macrophyte abundance are explained by PC1 and PC2 axis. Sites A, B and C; non-rehabilitated area and sites D, E, and F; rehabilitated area.

Eigenvalues

PC	Eigenvalues	%Variation	Cum.%Variation
1	4.13	41.3	41.3
2	2.69	26.9	68.2
3	1.63	16.3	84.5
4	1.24	12.4	96.9
5	0.31	3.1	100.0

Eigenvectors **(Coefficients in the linear combinations of variables making up PC's)**

Variable	PC1	PC2	PC3	PC4	PC5
Nymphaea ampla	0.489	-0.034	-0.043	0.086	-0.016
Cryptocoryne wendtii	0.342	-0.317	0.310	-0.239	-0.236
Annona glabra	0.478	0.121	0.048	-0.072	-0.168
Eichhornia crassipes	-0.338	-0.405	-0.114	0.159	-0.337
Pistia stratiotes	-0.378	-0.285	0.189	-0.235	-0.459
Hydrilla verticillata	-0.183	0.548	0.034	-0.167	-0.239
Ceratophyllum demersum	-0.299	0.076	0.542	-0.168	0.573
Nymphaea rubra	-0.112	0.191	0.067	0.822	-0.120
Salvinia melosta	-0.078	-0.318	-0.629	-0.086	0.388
Cypreus iria	-0.131	0.441	-0.395	-0.333	-0.201

Principal Component Scores

Sample	PC 1	PC 2	PC 3	PC 4	PC 5
Site A	4.025	-0.367	0.438	-0.124	-0.137
Site B	-0.656	-1.749	-2.098	-0.219	0.243
Site C	0.065	1.832	-0.861	0.376	-0.849
Site D	-1.063	1.960	0.320	-1.283	0.575
Site E	-1.354	-1.751	1.491	-0.713	-0.499
Site F	-1.017	0.076	0.710	1.963	0.393

the non-rehabilitated area and site D of the rehabilitated area grouped together. Sites E and F of the rehabilitated area were grouped together characterizing by high visibility, depth and percentage sand content. Site A of the non-rehabilitated area was separated from the other groups characterizing by high total phosphorous concentration, total organic carbon and percentage clay content of sediments (Fig. 2, Table 5).

PCA score plot based on abundance of macrophytes among the study sites in the Diyawannawa Wetland is given in Figure 3. The eigenvalues of the first two PCs, eigenvectors and the principal component scores for the study sites are given in Table 6. Two PCs display a cumulative variance of 68.2%. The results of the PCA on macrophyte abundance indicated that site A was grouped separately from other sites and was categorized by high abundance of *N. ampla.* Sites B and D were grouped together and they were characterized by high abundance of *E. crassipes*, *P. stratiotes* and *S. melosta*. Sites E and F were characterized by *H. verticillata* and *C. iria*, and Site C was characterized by *A. glabra* (Fig. 3, Table 6).

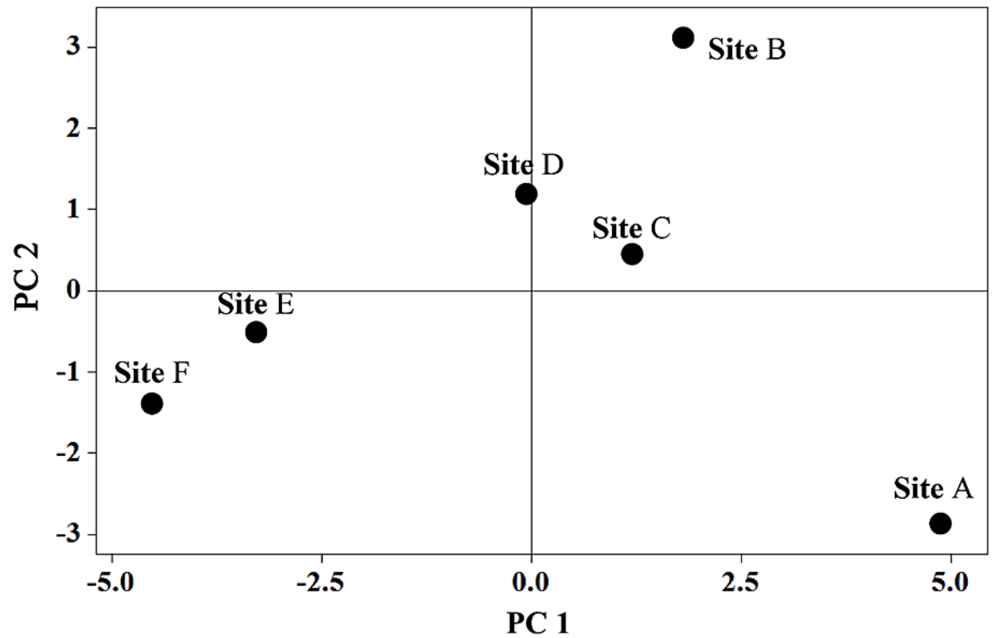

Figure 2. Ordination of the study sites based on PC1 and PC2 scores of PCA of the physico-chemical parameters of over lying water and sediments of the study sites in rehabilitated and non – rehabilitated areas in the Diyawannawa Wetland. The study sites A, B and C are located in the non – rehabilitated area and the sites D, E and F are located in the rehabilitated area.

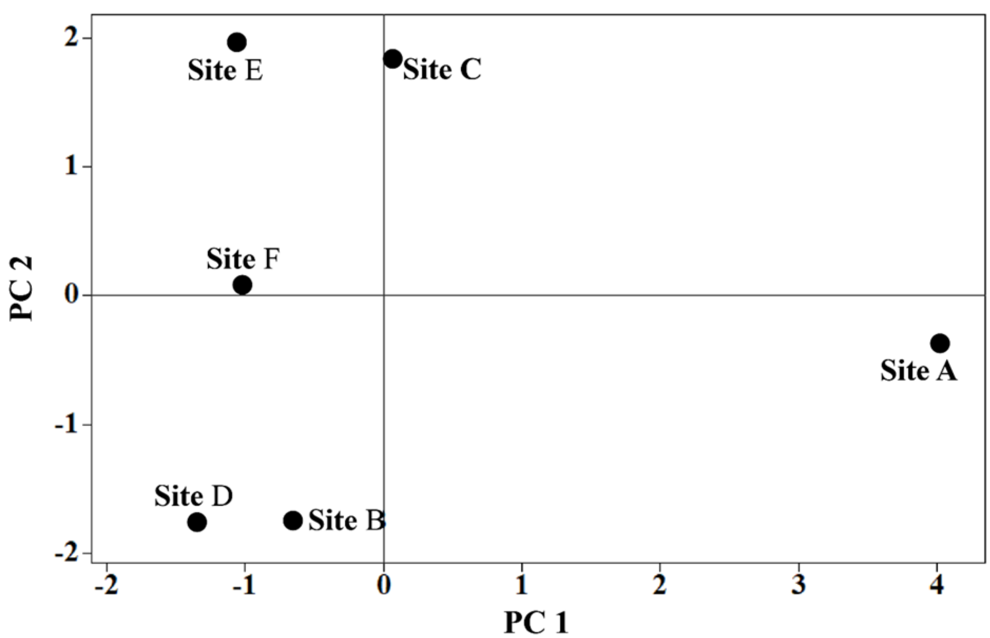

Figure 3. Ordination of the study sites based on PC1 and PC2 scores of PCA of the abundance of macrophytes in the study sites in rehabilitated and non – rehabilitated areas in the Diyawannawa wetland. The study sites A, B and C are located in the non – rehabilitated area and the sites D, E and F are located in the rehabilitated area.

The results of the linear regression analysis showed the coefficients of determination (R^2) being greater than 0.5 at 95 % level of significance indicated strong negative relationship of ESMI with PC1 score of water and sediment quality parameters (R^2 = 71.4, *P* = 0.034). PC1 score of the macrophyte abundance showed a strong negative correlation with the PC1 of water and sediment quality parameters (R^2 = 64.4, *P* = 0.025, Fig 4). However, Shannon Weiner diversity index (H) did not show a significant relationship with

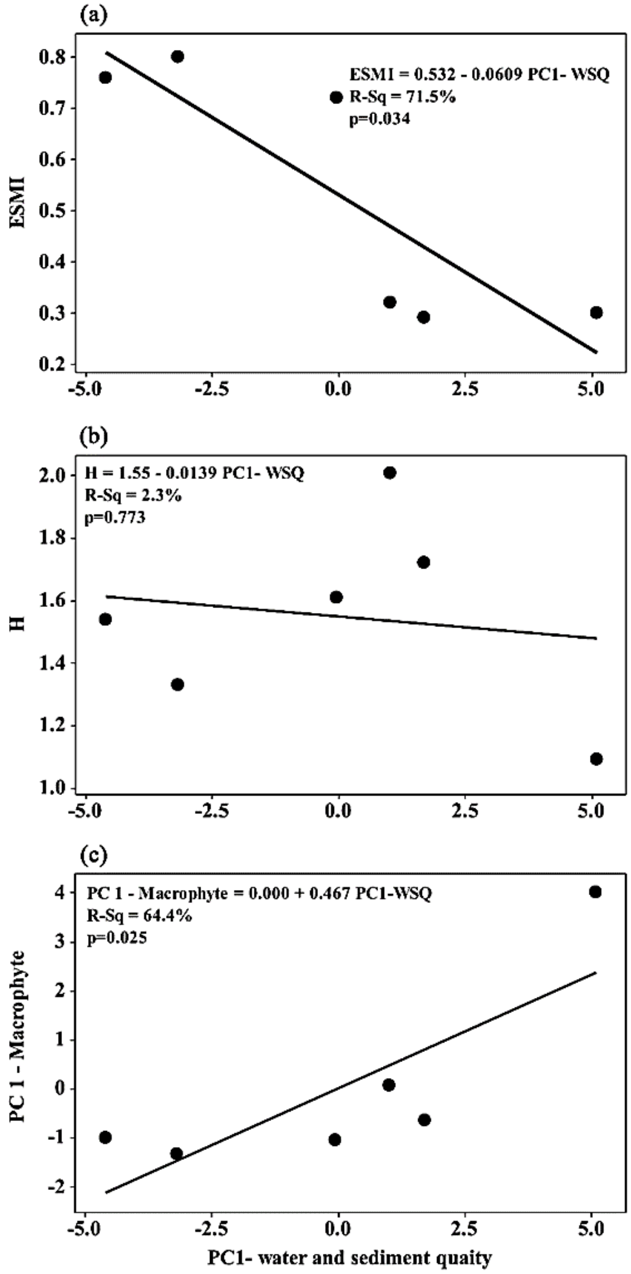

Figure 4. Linear regression against the PC1 score for physico-chemical parameters of the sediments and overlying water in the study sites. (a) Ecological State Macrophyte Index, (b) Shannon Wiener diversity index, (c) PC1 score for abundance of macrophytes in study sites.

the water and sediment quality parameters (Fig. 4).

Discussions

Macrophytes are important part of the wetland ecosystems as they serve as major primary producers, sediment stabilizers and habitat providers (Schaumburg et al., 2004). The results of the present study indicate that there is a significant variation in the abundance of macrophytes in the rehabilitated and non-rehabilitated areas in the wetland. Further, significantly high abundance of invasive alien species is recorded in the non-rehabilitated area compared to the rehabilitated area. The rehabilitated area is managed under the wetland management programmes and the management actions involve dredging to increase the depth of the wetland and continuously monitoring for the water quality, detecting occurrence of invasive alien species and removing them accordingly. This may have resulted in a significantly low number of invasive alien plants in the rehabilitated area.

However, high chlorophyll-a concentration, biochemical oxygen demand, chemical oxygen demand, nitrate and DO were recorded in some sites of the rehabilitated area. The increased water quality parameters in the rehabilitated area may be due to the presence of high concentrations of phytoplankton. When macrophytes are abundant, they can serve as nutrient sinks, utilizing much of the available phosphorus and nitrates (Jasser, 1995; Zimmer et al., 2011; Hilt, 2015). Therefore, in macrophyte abundant environments, less potential for high growth of phytoplankton can be expected as the nutrient availability for phytoplankton is low (Zimmer et al., 2011; Hilt, 2015). In the rehabilitated area, continuous removal of invasive macrophytes may have caused availability of nutrients to phytoplankton and resulted in high growth of phytoplankton, increasing chlorophyll-a concentration, DO, BOD_5 and COD.

Application of univariate to assess the variation of abundance of the biological communities are a commonly practiced methodology in ecological assessments. However, multivariate statistical techniques are more sensitive and accurate in studying environmental disturbance associated community changes in ecosystems (Warwick and Clarke, 1993). In Sri Lanka, few studies have been conducted using multivariate statistics to assess the variation of biological communities in relation to water and sediment quality parameters (Dahanayake and Wijeyaratne, 2006; Idroos and Manage, 2012; Wijeyaratne and Bellanthudawe, 2017). These studies have focused on variation of benthic macroinvertebrate communities in wetlands in relation to the water and sediment quality parameters. In the present study, the PCA was used to categorize the study sites based on water and sediment quality parameters and abundance of macrophytes. Based on the results, the sites A and B of the non-rehabilitated area and site D of the rehabilitated area were grouped together characterizing high visibility and high percentage sand content in the sediments. The sites A, B and D were located in close proximity to each other and this may have caused these sites to share common physical parameters. In the PCA on the abundance of macrophytes, sites B and D were grouped together and site A was separated from others. The results revealed that site A is characterized by *N. ampla* and high percentage of total phosphorous, high total organic carbon and high percentage clay content of sediments. *Nymphaea ampla* is considered as an invasive species that has originated in Caribbean and Central America and grows as a dense patch which is covering the water surface like a mat preventing light penetration and blocks the interface between air and water, decreasing DO in water (Maddy, 2009). The results of the present study also agree with Maddy (2009) regarding the site A with highest abundance of *N. ampla* has significantly lower DO. Maddy (2009) indicates that high abundance of *N. ampla* can cause nutrient release from the degenerating mats increasing the phosphorous and organic matter composition of the water and sediments. The results also agree with these findings regarding site A with highest abundance of *N. ampla* characterized by high total phosphorous in water and high total organic carbon in sediments.

Sites E and F of the rehabilitated area were grouped together characterizing by high visibility, depth and percentage of the sand content, and aquatic macrophytes of *H. verticillata* and *C. iria*. *Hydrilla* is identified as an important plant used in constructed wetlands to remove nutrients and to trap suspended solids (Langeland, 1996; Barko and james 1998; Knight et al., 2003; Tanaka et al., 2007). The results support the water purification ability of *Hydrilla* as the significantly high visibility recorded from two sites where *Hydrilla* is abundant.

Macrophyte based ecological quality assessment methods provide important information regarding the ecological status of the wetlands. However, absolute numbers such as the number of species recorded are less informative compared to the quantitative ratios of abundance of dominant species with relevance to the area of the wetland (Ciecierska and Kolada, 2014). In ESMI, a taxonomic composition is quantified using the phytocenotic diversity index (H) and the maximum theoretically possible H_{max}. If the anthropogenic or natural influences disturb the phytocenotic balance, vegetation patterns are simplified and extinction of some communities and dominance of other communities can result (Rejewski, 1981; Ciecierska et al., 2010). In the present study, the ESMI ranged from 0.29 to 0.80 with significantly lower values in the non-rehabilitated sites. However, there was no significant different of the Shannon Weiner diversity index (phytocenotic diversity index (H)) among the study sites. The percentage anthropo-pressure in the non–rehabilitated sites were comparatively higher. The rehabilitated sites of this wetland are carefully monitored and managed by the land reclamation department of Sri Lanka, which in turn provided less opportunities for people to engage in activities that disturbs the ecological functions of the wetland. However, in the non-rehabilitated area, it was observed that wetland associated animal farm management activities and waste deposition is prominently carried out. This may have resulted in the comparatively increased anthropo-pressure in the sites of the non-rehabilitated area. Further, the increased anthropo-pressure may have significant effects on the macrophyte resettlement rate. In the present study, the macrophyte resettlement rate in the rehabilitated sites were significantly higher than that of the non-rehabilitated sites. The weed removal, dredging and water quality monitoring activities conducted by the land reclamation department of Sri Lanka may be impose positive effects on the macrophyte resettlement rate in the rehabilitated portion of the Diyawanna Wetland.

According to boundary values of the ESMI index for classifying the ecological status in wetlands introduced by Ciecierska and Kolada (2014), ESMI values between 0.205-0.409 indicate moderate ecological status, 0.410-0.679 indicate good ecological status and values at or above 680 indicate high ecological status. In the present study, all the sites in the non-rehabilitated area were categorized into the moderate ecological status and all other sites are categorized as the high ecological status. Therefore, the present study proves that wetland rehabilitation programmes are successful in improving the ecological status of wetlands.

Further, the regression analysis between ESMI and the PC1 score based on water and sediment quality parameters indicated a significant positive association indicating that 71.5% of the variation of ESMI can be accounted due to variations in the water and sediment quality parameters. Therefore, the present study provides evidence of the suitability of adopting ESMI in ecological status classifications in the tropical wetland ecosystems. These macrophyte indices, together with multivariate statistical applications provide important information on the relationships between water quality, sediment quality and macrophyte indices which in turn can be used in long term wetland restoration and wetland management programmes.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Barko J.W., James W.F. (1998). Effects of submerged aquatic macrophytes on nutrient dynamics, sedimentation, and resuspension. In: E. Jeppesen, M. Sondergaard, M. Sondergaard, K. Christoffersen (Eds.). The Structuring Role of Submerged Macrophytes in Lakes. Ecological Studies (Analysis and Synthesis), vol 131. Springer, New York, NY. 427 p.

Basu A., Sarkar I., Datta S., Roy S. (2018). Community structure of benthic macroinvertebrate fauna of river Ichamati, India. Journal of Threatened Taxa, 10(8): 12044-12055.

Bini L.M., Thomaz S.M., Murphy K.J., Camargo A.F.M. (1999). Aquatic macrophyte distribution in relation to water and sediment conditions in the Itaipu Reservoir, Brazil. Hydrobiologia, 415: 147-154.

Birk S., Bonne W., Borja A., Brucet S., Courrat A., Poikane S. (2012). Three hundred ways to assess Europe’s surface waters: an almost complete overview of biological methods to implement the Water Framework Directive. Ecological Indicators, 18: 31-41.

Braccia A., Voshell J.R. (2006). Environmental factors accounting for benthic macroinvertebrate ssemblage structure at the sample scale in streams subjected to a gradient of cattle grazing. Hydrobiologia, 573: 55-73.

Brousseau C.M., Randall R.G., Hoyle J.A., Minns C.K. (2011). Fish community indices of ecosystem health: How does the Bay of Quinte compare to other coastal sites in Lake Ontario? Aquatic Ecosystem Health Management,14: 75-84.

Brraich O.S., Kaur R. (2017). Temporal composition and distribution of benthic macroinvertebrates in wetlands. Current Science, 112(1): 116-125.

Ciecierska H. (2006). Evaluation of the status of lakes located in the City of Olsztyn (Masurian Lake District, N-E Poland) by the macrophytoindication method (MPhI). Hydrobiologia, 570(1): 141-146.

Ciecierska H., Kolada A. (2013). ESMI: a macrophyte index for assessing the ecological status of lakes. Environmental Monitoring and Assessment, 86: 5501-5517.

Ciecierska H. (2008). Macrophyte based indices of the ecological state of lakes. Dissertations and Monographs. University of Warmia and Mazury in Olsztyn. 139 p. (In Polish with English summary)

Ciecierska H., Dynowska M. (2013). Biological methods for assessing the state of the environment. Volume 2. Water ecosystems. UMW, Olsztyn.

Ciecierska H., Kolada A., Soszka H., Gołub M. (2010). A method for macrophyte-based assessment of the ecological status of lakes, developed and implemented for the purpose of environmental protection in Poland. Proceedings of the 4th BALWOIS Conference on water observation and information system for decision support. Orchid, Republic of Macedonia. http://dewelopment.eu/p/Ciecierska_Macrophyte_method_BALWOIS2010.pdf Accessed 20 May 2019.

Dahanayaka D.D.G.L., Wijeyaratne M.J.S. (2006). Diversity of macrobenthic community in the Negombo estuary, Sri Lanka with special reference to environmental conditions. Sri Lanka Journal of Aquatic Sciences, 11: 43-61.

Dar N.S., Pandit A.K., Ganai B.A. (2014). Factors affecting the distribution patterns of aquatic macrophytes. Limnological Review, 14(2): 75-81.

Dassanayake M.D., Fosberg F.R. (1980-1991). A revised handbook to the flora of Ceylon. Vol. I–VII, Amerind Publishing Co. Pvt. Ltd. New Delhi, India.

Dassanayake M.D., Fosberg F.R., Clayton W.D. (1994-1995). A revised handbook to the flora of Ceylon. Vol. VIII–IX, Oxford & IBH Publishing Co. Pvt. Ltd., New Delhi, India.

Dassanayake M.D., Clayton W.D. (1996-2000). A revised handbook to the flora of Ceylon. Vol. X–XII, Amerind Publishing Co. Pvt. Ltd., New Delhi, India.

Fu H., Zhong J., Yuan G., Ni L., Xie P., Cao T. (2014). Functional traits composition predicts macrophytes community productivity along a water depth gradient in a freshwater lake. Ecology and Evolution, 4: 1516-1523.

Gidudu B., Copeland R.S., Wanda F., Ochaya H., Cuda J.P., Overholt W.A. (2011). Distribution, interspecific associations and abundance of aquatic plants in Lake Bisina, Uganda. Journal of Aquatic Plant Management, 49: 19-27.

Henry-Silva G.G., Camargo A.F.M., Pezzato M.M. (2008). Growth of free-floating aquatic macrophytes in different concentrations of nutrients. Hydrobiologia, 610: 153-160.

Hilt S. (2015). Regime shifts between macrophytes and phytoplankton – concepts beyond shallow lakes, unravelling stabilizing mechanisms and practical consequences. Limnetica, 34(2): 467-480.

Idroos F.S., Manage P.M. (2012). Aquatic life health quality assessment of the Bolgoda Canal and Waga Stream with respect to selected physico-chemical parameters and bioindicators. Journal of Tropical Forestry and Environment, 2(2): 13-26.

Jasser I. (1995). The influence of macrophytes on a phytoplankton community in experimental conditions. Hydrobiologia, 306(1): 21-32.

Karr J.R. (1981). Assessment of biotic integrity using fish communities. Fisheries, 6: 21-27.

Knight R.L., Gu.B., Clarke R.A., Newman J.M. (2003). Long-term phosphorus removal in Florida aquatic systems dominated by submerged aquatic vegetation. Ecological Engineering, 20(1): 45-63.

Kolada A., Soszka H., Cydzik D., Golub M. (2005). Abiotic typology of Polish lakes. Limnologica, 35: 145-150.

Kunii H. (1991). Aquatic macrophyte composition in relation to environmental factors of irrigation ponds around Lake Shinji, Shimane, Japan. Vegetatio, 97: 137-148.

Lacoul P., Freedman B. (2006). Environmental influences on aquatic plants in freshwater ecosystems. Environmental Reviews, 14: 89-136.

Langeland K.A. (1996). *Hydrilla varticillata* (L.F.) Royle (Hydrocharitaceae), The Perfect Wee. Castanea, 6(1): 293-304.

Lee P.F., McNaughton K.A. (2004). Macrophyte induced microchemical changes in the water column of a northern Boreal Lake. Hydrobiologia, 522: 207-220.

Lyche Solheim A., Feld C., Birk S., Phillips G., Carvalho L., Morabito G. (2013). Comparison of common metrics for phytoplankton, macrophytes, macro-invertebrates and fish for ecological status assessment of European lakes: a synthesis from the WISER project Module 3. Hydrobiologia, 704: 57-74.

Maddy F.A. (2009). A short review on some aquatic plants from Grenada. Sociètè d´Histoire Naturelle L´Herminier (Nantes, France). Technical Report. 31 p.

Murphy K.J., Dickinson G., Thomaz S.M., Bini L.M., Dick K., Greaves K. (2003). Aquatic plant communities and predictors of diversity in a sub-tropical river floodplain: the upper Rio Parana, Brazil. Aquatic Botany, 77: 257-276.

Panek P. (2001). Biotic indices used in Poland since the implementation of Water Framework Directive. Przegląd Przyrodniczy, 22(3): 111-123.

Priyatharsini P., Dhanalakshmi B., Veeramani T. (2018). Monitoring and assessment of water health in Relation to fish perception in Theroor wetland ecosystem, Tamil Nadu, India. International Journal of Recent Scientific Research, 9(5): 26708-26714.

Schaumburg J., Schranz C., Hofmann G., Stelzer D., Schneider S., Schmedtje U. (2004). Macrophytes and phytobenthos as indicators of ecological status in German lakes – a contribution to the implementation of the Water Framework Directive. Limnologica, 34: 302-314.

Søndergaard M., Johansson L.S., Lauridsen T.L., Jørgensen T.B., Liboriussen L., Jeppesen E. (2010). Submerged macrophytes as indicators of the ecological quality of lakes. Freshwater Biology, 55:

893-908.

Southwood T.R.E., Henderson P.A. (2000). Ecological Methods. Blackwell publishing. 593 p.

Tanaka N., Jinadasa K.B.S.N., Werellagama D.R.I.B., Mowjood M.I.M., Ng W.J. (2006). Constructed tropical wetlands with integrated submergent-emergent plants for sustainable water quality management. Journal of Environmental Science and Health, Part A, 41(10): 2221-2236.

Warwick R.M., Clarke K.R. (1993). Comparing the severity of disturbance: a meta-analysis of marine macrobenthic community data. Marine Ecology Progress Series, 92: 221-231.

Wijeyaratne W.M.D.N., Bellanthudawa B.K.A. (2017). Assessment of suitability of macrobenthic mollusc diversity to monitor water quality and shallow sediment quality in a tropical rehabilitated and non – rehabilitated wetland system. International Journal of Aquatic Biology, 5(2): 95-107.

Wijeyarate W.M.D.N., Kalaotuwawe K.M.B.P.P. (2017). Evaluation of the water and sediment quality of a lotic water-body in the western coastal region of Sri Lanka using Rapid Bioassessment Protocol II (RBP II) of benthic macroinvertebrates. Sri Lanka Journal of Aquatic Sciences, 22(2): 85-97.

Willby N., Pitt J.A., Phillips G. (2009). The ecological classification of UK lakes using aquatic macrophytes. Stirling: UK Environment Agency, University of Stirling. 221 p.

Zimmer K.D., Hanson M.A., Butler M.G. (2011). Relationships among nutrients, phytoplankton, macrophytes, and fish in prairie wetlands. Canadian Journal of Fisheries and Aquatic Sciences, 60(6): 721-730.