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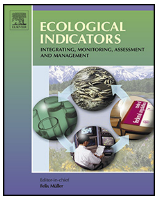

Original Articles

Development of submerged macrophyte and epiphyton in a flow-through system: Assessment and modelling predictions in interconnected reservoirs

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ABSTRACT

Every approach to lake restoration requires the reestablishment of submerged macrophytes. However, macrophyte overgrowth in shallow lakes may lead to deterioration and a consequent necessity for restoration treatments. We assumed that a major threat to the increased trophic level in the Jankovac flow-through system arises from the sediment, where the accumulation of deciduous leaf litter and decayed macrophyte fragments could generate anoxic conditions. The integrated Water Quality Model (WQM) and the Submerged Aquatic Vegetation Model (SAVM) were combined in the Jankovac Model (JanM) and applied during the vegetated season in 2008 and 2014, with the aim to offer a possible approach to the maintenance of good water quality. The impacts of flow velocity and epiphyton growth on submerged macrophyte coverage and biomass were simulated. Biocenotic analyses suggested that epiphyton growth was more extensive in 2014 in comparison to 2008. The results of JanM indicated that increased flow velocities enhanced macrophyte growth and dissolved oxygen concentrations concurrently with the decline of epiphyton biomass. Furthermore, results suggested that epiphyton growth rate of $0.4\,d^{-1}$ maintained macrophyte coverage and biomass at a satisfactory level of 70% reservoir coverage. Considering the proposed scenarios hydraulic treatment could be applied to regulate submerged macrophytes in shallow reservoirs, as an efficient and less invasive approach than sediment removal, especially in sensitive karst areas.

1. Introduction

Ratio among primary producers, macrophytes (i.e. charophytes, bryophytes and angiosperms): phytoplankton: periphytic algae, is crucial in maintaining a favourable transparent state in lakes (Scheffer, 1998). Macrophyte stands have exceptional ability to alter environmental conditions, nutrient cycling, biocoenosis assemblages and biotic interactions. Their impact on ecosystem functioning is related to the complexity of macrophyte stems and their physiology (Kuczyńska-Kippen and Nagengast, 2006; Chaparro et al., 2014). Complex submerged macrophytes achieve their best results in the suppression of algal bloom through the competition for nutrient uptake (Jeppesen et al., 1997; Lau and Lane, 2002) or by the production of allelopathic substances to mitigate algal growth (van Donk and van de Bund, 2002). Floating-leaved macrophytes increase shading, reduce algal photosynthetic oxygen production and reject zooplankters (Compte et al., 2011), whilst emergent macrophytes prevent coastal erosion (Horppila and Nurminen, 2005). Besides numerous zooplankters (Kuczyńska-Kippen and Nagengast, 2006; Špoljar et al., 2012b), macrophyte stands host many epiphytic organisms, i.e., algae, protozoans and meiofauna (Kralj et al., 2006; Špoljar et al., 2012c; Dražina et al., 2013). Epiphytic biomass and diversity depend on multiple abiotic (light supplies, nutrients, flow velocity, water residence time) and biotic (macrophyte architecture, abundance of grazers) factors.

Interactions among macrophytes, illumination, epiphyton, grazers and fish may reflect the trophic state of the hydrosystem (Beresford and Jones, 2010; Špoljar et al., 2011). Epiphyton biomass

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is generally higher in eutrophic lakes, but also, due to better illumination, its ratio can be higher in oligotrophic lakes (Laugaste and Reunanen, 2005). The same authors studied epiphyton on 22 macrophyte species during the summer in the hypertrophic stratified Verevi Lake (Estonia), and concluded that substrate complexity may affect epiphyton biomass. For instance, chlorophyll *a* amounted to 117–200 μg g DM^{-1} on floating-leaved plants, 330–360 μg g DM^{-1} on emergent plants, and the highest values, 820–920 μg g DM^{-1} on submerged plants. From biotic components, epiphyton-feeding snails as known grazers, have a significant impact on the biomass and species composition in the epiphyton, by reducing and removing old and recovering new epiphyton strata (Brönmark, 1989; Zębek and Szymańska, 2014).

A shift between a transparent *vs*. turbid state is largely due to macrophyte presence *vs*. absence. For instance, Scharmützelsee Lake (SE of Berlin, Germany) was characterized by turbid water until 2003. Thereafter, increased water transparency together with a rapid submerged macrophyte colonization, up to 5 m depth corresponded to the light supply of 3 E m^{-2} d^{-1} (Hilt et al., 2010). The authors recorded that an upgrowth of submerged macrophyte stands to approximately 24% coverage in 2005–2006, dominated by rootless *Nitellopsis obtusa* and *Ceratophyllum demersum*, contributed to the stabilization of the water transparency. Dense macrophyte stands may also cause low bottom oxygen concentration, release P from the sediment and suppress mineralisation (Stephen et al., 1997; Søndergaard et al., 2003). These conditions indicate a higher trophic level and may transform the lake from a transparent to a turbid state, in accordance with the known chemical process clearly described by Søndergaard et al. (2003): In oxidised conditions, phosphorus is sorbed to iron (III) compounds, while in anoxia iron (III) is reduced to iron (II) and subsequently both iron and sorbed phosphate returned into solution. In two reservoirs of the Parana basin (South America) Chiba de Castro et al. (2013) observed the negative effects of dense macrophyte stands (80–100% coverage) where a decline in the redox potential was caused by oxygen depletion. In the study of Caraco and Cole (2002) it was established that in the River Hudson (the stretch from New York to Albany, USA) the alien aquatic macrophyte (*Trapa natans*) may extremely decrease dissolved oxygen concentration to values below 2.5 mg l^{-1}, while within macrophyte stands dominated by a native species (*Vallisneria americana*) dissolved oxygen did not decrease below 5 mg l^{-1} during the summer growing season. In the restoration of overgrown lakes important ecological goals are to create diverse macrophyte stands with an open water and mosaic of different, preferably submerged, macrophytes (Moss et al., 1997). A mosaic community of macrophytes will increase habitat heterogeneity between macrophyte stands and the open water and enhance biocoenotic diversity and life styles (food preferences, migrations, nesting, moulting), facilitate succession of organisms and remove water pollutants and nutrients (Björk, 1994; Wang et al., 2009). Macrophyte diversity provides stands less sensitive to physical disturbances, i.e.waves, bioturbations and herbivores, suppress algal production and reduce losses of total phosphorus (Engelhardt and Ritchie, 2001; Hilt et al., 2006).

Predictions of ecosystem functioning are often requested and can prove to be of great value in protected areas with peculiar karst phenomenon, as in the Papuk Nature Park (Croatia). After sediment-drainage of the Jankovac reservoirs (Papuk Nature Park) in 2003 we analysed invertebrates in plankton, epiphyton and benthos as well as macrophyte coverage, and environmental parameters in 2008 and 2014. According to obtained data (Špoljar et al., 2012a,b,d, 2015) macrophytes tend to overwhelm both reservoirs and thus the eutrophication process could be triggered. We assumed that the increased trophic level in the Jankovac reservoirs originated from the sediment, where the accumulation of deciduous leaf litter and decayed macrophyte fragments probably generate anoxic conditions. In such cases aeration methods for water column (Verner, 1994) and sediment (Hilt et al., 2006) are frequently applied in lake restorations. Flow velocity also plays an important role in flow-through systems affecting macrophyte stands (Wilby et al., 1998), epiphyton (Špoljar et al., 2012a), planktonic (Špoljar et al., 2012b) and benthic (Sertić-Perić et al., 2011) organisms. For instance, low to medium flow velocities sustain the diversity and density of macrophyte stands (Madsen et al., 2001; Franklin et al., 2008). The same authors recorded that higher flow velocities negatively impact macrophyte stands, while Asaeda and Son (2000) and Horner et al. (2011) noted an increased epiphyton flushing rate. Recently, many modelling efforts have offered solutions for eutrophication reduction (Jin and Ji, 2015; Zhang et al., 2015, 2016). In the present study we considered flow velocity and dissolved oxygen concentrations as the main drivers in the balance between macrophyte coverage and epiphyton biomass and conducted them through a modelling design. The main objectives of this study were: (1) using a model simulation to analyse the influence of the flow velocity and epiphyton on macrophyte coverage and biomass; (2) to analyse environmental properties for sustainable growth of macrophytes and (3) to present an assemblage of zooepiphyton, protozoans and meiofauna, under impact of environmental conditions in the Jankovac flow-through system. The overall aim of this study is to present a hydraulic control strategy in the regulation of submerged macrophytes within shallow reservoirs.

2. Material and methods

2.1. Study area

Jankovac Stream (45°31′07″N, 17°41′11″E, Fig. 1, Table 1) is a small approximately 700 m long hydrosystem, in a submountain area at 475 m asl., situated on sedimentary karst rocks in the Papuk Nature Park, NE Croatia, and is described in detail in our previous studies (Špoljar et al., 2012a,b,d). Most of the stream was anthropogenically modified in two reservoirs (lentic parts), while lotic parts occur as rheocrene spring (JS) and the Skakavac Waterfall over the tufa barrier (JW). The two reservoirs (R1 and R2) exist as an interconnected flow-through system separated by a bank, and water flows through a connection between reservoirs. Across the longitudinal profile, the stream is mostly surrounded by deciduous forest, dominated by beech (*Fagus sylvatica* L.), followed by common ash (*Fraxinus excelsior* L.), maple (*Acer pseudoplatanus* L., *A. obtusatum* (Waldst. et Kit. ex Willd.)) and wych elm (*Ulmus glabra* Huds.). The reservoir banks are slightly inclined. The bottom is covered with organic mud, which consists of a thick layer (0.5 m) in the littoral zone of mostly fine particulated organic matter, originating from macrophyte decay and deciduous leaf litter.

Both reservoirs were subjected to the sediment-drainage method in September of 2003 in an attempt to increase the water level. Water is transparent through the whole column and thus favours the growth of submerged macrophytes, *Hippuris vulgaris* as dominant and accompanying *Potamogeton natans*. Emergent macrophytes, *Carex* sp., *Scirpus* sp., *Iris pseudacorus* and *Typha latifolia*, constitute a discontinuous narrow belt around both reservoirs.

2.2. Assessment of zooepiphyton, environmental parameters and their interactions

Samples were collected in triplicate in July and the first half of September of 2008 and 2014 (Fig. 1). Within both reservoirs two habitats were identified: nonvegetated habitats, with pelagial (R1N, R2N), inflow (R1I) and outflow (R1O, R2O) parts of reservoirs; and vegetated habitats with *H. vulgaris* (R1H, R2H). Epiphyton