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WETLAND RESTORATION

Performance of a floating treatment wetland for in-stream water amelioration in NE Italy

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Abstract Floating treatment wetlands are innovative systems and their processes are still scarcely known within the traditional methods of phytodepuration. To gain initial information on their performance and potential in removing pollutants, two experiments have been conducted in northeast Italy, in a Natural Park with resurgent water. Barriers formed by a new patented floating element were tested in real climatic and water flow conditions. One experiment was conducted in a channel receiving aquaculture effluents, while the other was set in two cleaner channels to test two installation designs (two barriers composed of two lines of elements—2 × 2 design and two composed of three lines of elements—2 × 3 design). Different macrophyte species were used (*Phragmites australis, Carex elata, Juncus effusus, Typha latifolia, Chrysopogon zizanioides, Sparganium erectum,* and *Dactylis glomerata*). The floating systems were easily installed and required few maintenance operations. Native plants grew successfully, developing roots 90–135 cm deep 1 year after planting. Conversely, *Chrysopogon zizanioides* showed scarce adaptation to local conditions. In the first experiment, median chemical oxygen demand (COD) in water passing through the floating wetland system was reduced by 66%, biochemical oxygen demand by 52%, and total phosphorus by 65%. In the second experiment, the 2 × 3 design had a slightly better performance than 2 × 2 in reducing COD (38 and 28% of removal, respectively). The two designs performed similarly on NO_3-N, reducing the incoming concentrations by 12% (2 × 3 design) and 14% (2 × 2). This form of nitrogen represents almost all the total nitrogen, which was abated by 13% by the 2 × 3 design and by 29% by 2 × 2 design.

Keywords Floating treatment wetland · River water treatment · Macrophytes · Aquaculture effluents

Introduction

Floating treatment wetlands (FTW) are innovative within the traditional methods of phytodepuration. These systems employ rooted, emergent plants growing as a floating mat on the water surface rather than in the sediments (Headley & Tanner, 2006). This technique complements natural floating wetlands, defined by Sasser et al. (1991) as a marsh of vascular vegetation having a significant mat of live and dead roots, peat and detritus, that floats over a layer of free

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water. Due to the fact that the system can float, plants are not affected by fluctuations in water levels, so FTW have several applications and are used especially in ponds or rivers. It is possible to use nonfloating plants highly efficient in terms of water purification, with a well-developed rooting system and impossible for plants to escape from the area allocated for treatment and colonize space in the water body. Furthermore, FTW can operate at greater water depth than conventional wetlands, and are thus able to achieve a higher level of treatment.

In nature, floating wetlands exist that consist of a floating organic mat supporting plant growth, where the self-buoyancy is made possible by the entrapment within the matrix of gases generated by anaerobic metabolism and the presence of air spaces in the roots of certain plant species (Hogg & Wein, 1988).

Floating treatment wetlands are artificially created systems using various ways to trap macrophytes in self-buoyant mats. They may sustain suitable plants, which are able to extend their roots in the water column, in still or running waters, and perform the typical functions: physical filtering of the water flow, dissolved nutrients uptake and support for microorganisms. Vegetation absorbs nutrients transformed into simple elements dissolved in water column. This action is performed by bacterial communities which grow on the root system and that live in symbiosis with plants. It is thus important to use different botanical species so that different bacterial colonies develop that will help organic macromolecules' degradation. Purification efficiencies of phytodepuration systems depend on the types of plants used, local climate conditions, the type of system adopted, maintenance performed and several other technical, ecological, and microbiological factors.

Floating systems developed around the world have performed well in pollution control (removing suspended solids (SS), nitrogen (N), phosphorus (P), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and metals in particular) and in the creation of new water environments. The main applications in terms of water quality improvement are for storm water, sewage, acid mine drainage, piggery effluent, poultry processing wastewater, and water supply reservoirs (Headley & Tanner, 2006). A famous system for storm water runoff treatment has been operating at Heathrow Airport since 1994, to remove mainly glycol and associated BOD. The treatment system consists of different components and the floating reed-beds achieved a BOD removal efficiency of 43% (Revitt et al., 2001). Van Acker et al. (2005) describe a floating system in Belgium for treatment of combined sewer overflows and give these pollutant removal results: COD 33–68%, SS 66–95%, total P 61% and a variable total N removal due probably to the anaerobic condition of the water beneath the floating island. Another example of this kind of depuration is the work of Van de Moortel (2008) conducted at Ghent University, Belgium; the results of treatment performance in percentages were: total N 44%, ammonia N 34%, total P 31%, and COD 49%. Dealing with acid mine drainage, the problem is the huge amount of metals (copper and zinc) and sulfates; Smith & Kalin (2000) provide data of some applications in Canada. Hubbard et al. (2004) used a floating system for treatment of swine lagoon wastewater and the calculated percentages of nutrients removed from the root zone by the floating mats were: total N 43–52%, total P 34–41%, K 127–160% (Calculations of percent nutrient removal were made assuming a set rooting zone depths, where is greater than 100 natural mixing of nutrients within the experiment tank would have provided nutrients in addition (Hubbard et al., 2004).) An example of river treatment from wastewater comes from China, on the Pearl River in Guangzhou. The parameters measured before and after the floating wetland gave the following data in depuration efficiency: total N removal was 50%, ammonia nitrogen oxidation 100%, nitrate nitrogen removal 22%, and COD removal 95% in 5 days of retention (Lianpeng et al., 2009). Constructed wetland to remove aquaculture effluents has been also investigated (Ying Feng et al., 2002; Schulz et al., 2003). Nakamura & Shimatani (1997) report on the entire ecosystem created around the installation of a floating island on Lake Kasumigaura in Japan, where they found new bird and fish species and other aquatic animals, and noted landscape improvement.

Different materials are used to set up the floating structures, which need to have some important features such as buoyancy, durability, anchoring, flexibility, environmental sensitivity, easy installation, and affordability. The structures that guarantee buoyancy can be sealed polyvinyl chloride or polypropylene pipes, polystyrene sheets, bamboo, inflatable vinyl pillows, polystyrene foam in a polyester matrix, and the internal structure can be filled with coconut fiber, bamboo reed net, or other material. It is possible to have frames that support a growth medium for the plants, but in others these are planted directly into the floating mats without additional planting media (Hoeger, 1988; Smith & Kalin, 2000; Hubbard et al., 2004).

The choice of vegetation species used for floating treatment wetlands is fundamental for good results from these phytodepuration systems. Many international studies state that botanical species utilized for phytodepuration must have a high capacity to absorb nutrients. The most suitable species are emergent macrophytes. These are aquatic plants growing in wetlands, shallow lakes, and streams and that are either emergent, submergent, or floating. They include the aquatic angiosperms (flowering plants), pteridophytes (ferns), and bryophytes (mosses, hornworts, and liverworts). It is recommended to select native species that occur locally and exhibit vigorous growth in polluted waters under local climatic conditions (Headley & Tanner, 2006). The most common species used for floating treatment wetlands are *Phragmites australis* (common reed), *Typha latifolia* (cattail), *Juncus effusus* (soft rush), *Iris pseudacorus* (yellow flag), *Carex* spp., *Glyceria maxima* (sweet mannagrass), *Canna indica* (Indian shot, canna), and *Chrysopogon zizanioides* (vetiver grass), but a broad range of plants are suitable for these purposes.

The above review shows that the FTW is a promising solution for improving the quality of surface water bodies, but local conditions can strongly affect the performances. Since this system has never been applied in Italy, two experiments were conducted during 2005–2008 to test a patented floating element in river stream conditions by evaluating plant adaptation and depuration efficiency, monitoring N, P forms and COD.

Materials and methods

Floating element

The floating structure used in these studies was developed as a prototype in 2004 and upgraded after a test period; in 2006 the patent was applied for at the Italian Patent Office (Tech-IA®). The single self-floating element of Tech-IA® (Fig. 1) is produced in ethylene vinyl acetate (EVA), rectangular (50 × 90 cm), with eight windows each of which has grids to sustain plants. The mass is 1.7 kg supporting a load capacity up to 20 kg. Two matched elements give 1 m^2 of raft. The presence of six holes in its frame means that the single elements can be easily connected to each other and to the riverbanks. The elements can be easily installed in different designs to fit the shape of the water body and intercept the pollutant flow.

The most important features of these structure are the high mechanical resistance of the material associated with biological, chemical, and weather resistance. His internal structure not allows to absorb water, moreover these elements are easy to install and manage and are made of recyclable material.

The floating element can be vegetated with herbaceous species with colorful flowers and these

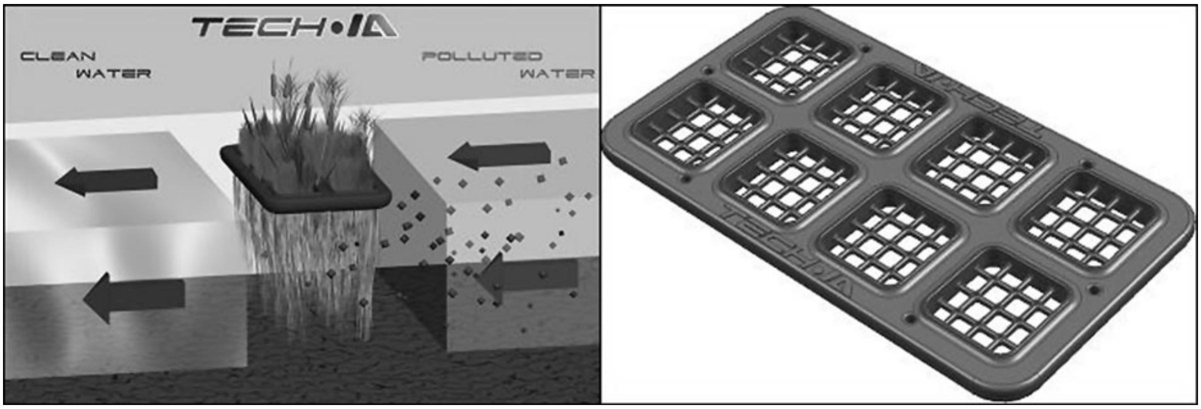

Fig. 1 Tech-IA system single element and scheme of treatment process

can be distributed to bloom at different seasons, it can be used for ornamental purposes and become a perfect element of urban fittings. The structure was created to be a support in phytodepuration for nonfloating plants, but it can be used in several other sectors. It could become a vegetated island for natural and faunal purposes, floating vegetated or nonvegetated barriers used for delimitation or signaling. But, it can be used also as a decorative island in a natural, artificial, private, or public water body, a support for plants growing in hydroponic culture, creation of buoyant platforms, and as a support for fish-farming environments.

Vegetation

The species used in the experiments are aquatic emergent or sub-emergent plants, chosen among those that can survive in the environmental conditions of northeast Italy.

Phragmites australis (Cav.) Trin ex Steud (common reed)

Herbaceous perennial plant, erect stems rise from underground rhizome. The stems are 2–3 m tall, green in the growing season, and pale brown in winter. Blooms in summer with flowers at the top of the stems, prefers sunny environment, and is fast-growing and rapidly colonizes the land around the original rhizome. This plant has been widely used around the world for phytodepuration purposes and is known to perform well in treatment wetlands (Headley & Tanner, 2006).

Carex elata All. (tufted sedge)

Commonly used in floating treatment wetlands (Van Acker et al., 2005), this species is a herbaceous plant, evergreen, 0.5–1.2 m tall, flowering in spring with flowers at the top of the green stems, and is adapted to shady or sunny environments. Fully grown plants form compact bushes.

Juncus effusus L. (soft rush)

Herbaceous perennial plant, evergreen, found worldwide in wetlands and running waters. The stems are cylindrical and flexible, 0.8–1.5 m tall, dark green; the small flowers appear at the top of the stems in summer. Prefers sunny places, and withstands complete flooding.

Typha latifolia L. (broadleaf cattail)

Another species already tested in floating treatment wetlands around the world (Smith & Kalin, 2000; Hubbard et al., 2004). A herbaceous perennial plant with rhizomes. The leaves and flowering stems rise from the underground rhizome network, the stems may reach 3 m tall. The long leaves are linear and dark brown. The mature flowers are brown and in a sausage-shaped spike. Suited to living in many different climatic conditions.

Chrysopogon zizanioides (L.) Roberty (vetiver grass)

A herbaceous perennial plant, with deep and resistant root system and fast growth. The height is 0.5–1.5 m. The leaves are erected and rather stiff. Vetiver grass is an "ecological-climax" species. It withstands drought and high levels of flooding. It is tolerant to high levels of pesticides and herbicides and also to a wide range of toxic and heavy metals and high level of tolerance to soil salinity (Maffei, 2002). Used in a floating system in Australia for sewage treatment (Ash & Troung, 2003).

Sparganium erectum L. (bur reed)

Herbaceous perennial plant recommended as a species in floating wetland applications to remove nutrients from water (Lakatos, 1998). Its height is 0.4–0.8 m, and it is common in Europe.

Dactylis glomerata L. (orchardgrass)

A common herbaceous perennial species worldwide. It is caespitose, has stems of 0.2–1.2 m tall, compressed at the base. It has a deep root system and it is frost, heat, and drought resistant. This species grows in sunny environments but tolerates shade very well (Pignatti, 1997).

Experimental design

The two experiments were carried out in sites at a short distance from one to another in the upper reaches of the Sile River, which is the longest resurgence river in Italy.

The first experiment was conducted in an aquaculture farm in the Sile River Natural Park, Veneto Region from May 2005 to March 2006. The farm uses groundwater to rear rainbow trout and discharges the outflow directly into the Sile River. The FTW is a single barrier composed of three lines of floating vegetated elements, 1.5 m wide and perpendicular to the water flow (velocity 0.09 m s^{-1}), and was installed in the final basin between the farm channel (8.0 m wide) and the Sile River (Fig. 2). No trees are growing on the riverbanks, so the vegetation of the barrier is well exposed to the sun. The FTW also intercepted the effluent coming from an activated sludge treatment plant that was used by the fish farm.

The floating system was initially planted with 100 plants of *Chrysopogon zizanioides* (16 plants per m^2) and later some of them were replaced with *Typha latifolia* and *Sparganium erectum* uprooted from the river banks; *Dactilis glomerata* colonized spontaneously.

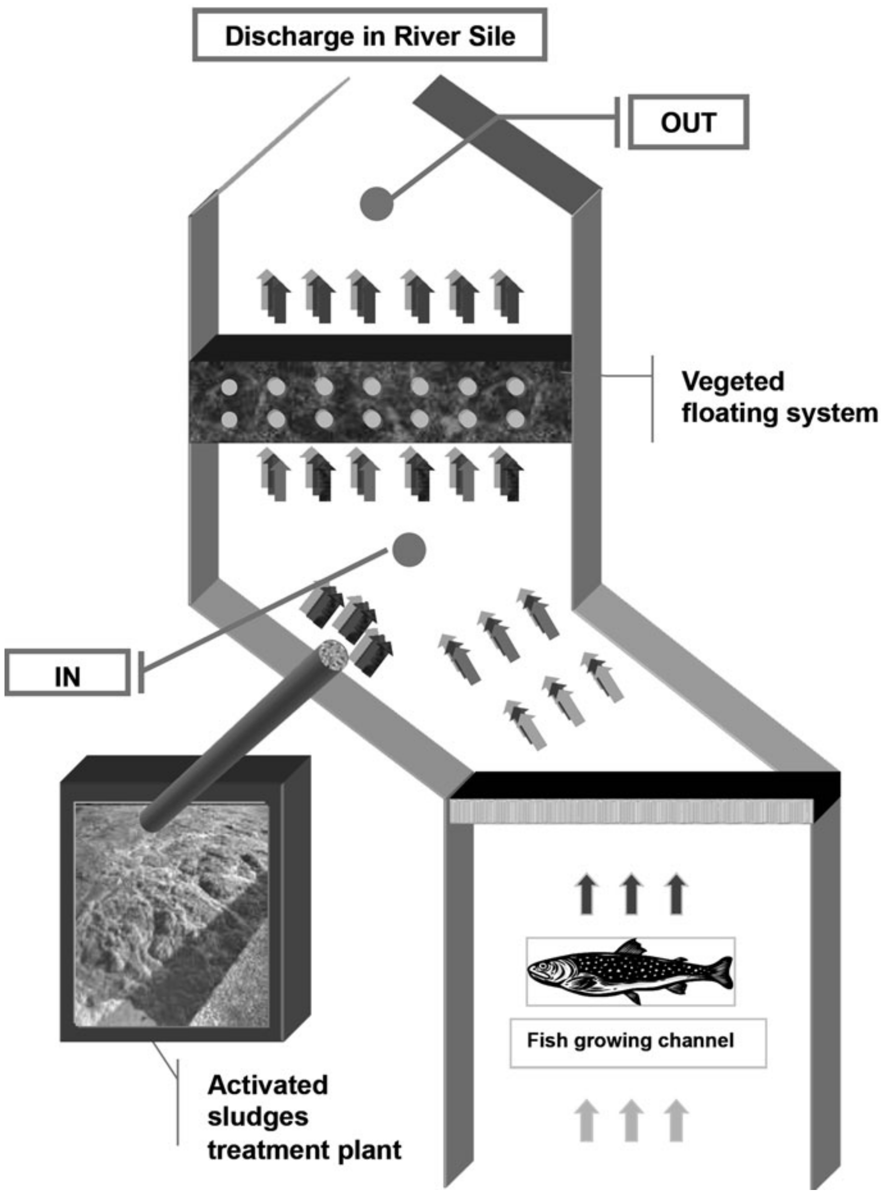

Fig. 2 First experiment layout

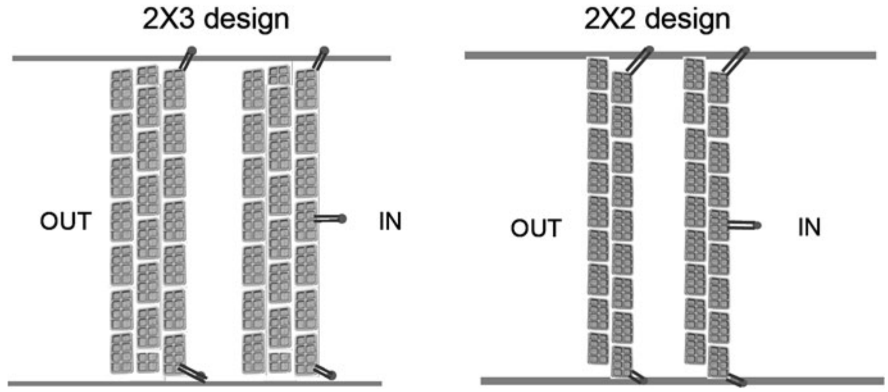

Fig. 3 Second experiment layout

Water analyses were conducted before and after the phytodepuration system and water samples were collected every 2 weeks, for a total of 24 samplings. Plants growth, roots development, and system surface colonization were also evaluated during the study period. The specific objective was to gain the first indications on the efficiency of the FTW in terms of water amelioration, plant adaptation, and ease of management.

The second experiment was carried out from September 2006 till June 2008 in a Nature Reserve, called Oasi di Cervara in the Sile River Natural Park, to ameliorate water ecosystems characterized by unusual and protected flora and fauna. Barriers were installed in two channels called Rosta and Piovega (Fig. 3). In Rosta channel, two barriers 6.5 m long composed of three lines of Tech-IA elements (2 × 3 design) were set leaving a space of 3 m between them. In Piovega channel, there were two barriers 8 m long, each composed of two lines of elements (2 × 2 design); the barriers were 4 m apart. In both cases, the barriers were installed from bank to bank of the channel.

A total of 624 plants of *Carex elata, Dactilis glomerata, Juncus effusus,* and *Phragmites australis* were used in the two experiments. Trees are growing on the river banks at both sites, giving shade to the barriers.

Monitoring consisted of nine samplings during the project, collecting 31 water samples; during each sampling, water was collected before, after, and sometime between the barriers. The depth of sampled water was 10 cm. For every sample, nine parameters were evaluated (Table 1) for a total of 279 analyses. This experiment aimed to obtain information on the effect of different barrier designs in treating water with similar chemical characteristics.

Table 1 Parameters monitored in the two experiments

Parameter	Experiment 1	Experiment 2
pH	x	x
Temperature	x	x
Electrical conductivity	x	x
Dissolved oxygen		x
Chemical oxygen demand	x	x
Biological oxygen demand	x	
Total nitrogen	x	x
Total Kjeldahl nitrogen	x	
Ammonia nitrogen		x
Nitrate nitrogen	x	x
Total phosphorus	x	x
Soluble phosphorus	x	
Total suspended solids	x	

Monitoring activities and data elaboration

In both the experiments, the chemical and physical parameters of water listed in Table 1 were measured. Samples were collected, frozen, and then analyzed within a few days. COD, total P, soluble P (PO_4-P), total N, ammonia nitrogen, and nitrate nitrogen were analyzed with the spectrophotometer (spectrophotometer DR2008 Hach-Lange and specific couvettes test for each parameters). BOD_5 was determined with the standard method for water analysis (Mecella, 2001). The physical parameters, electrical conductivity, dissolved oxygen, and pH were measured with a Hach-Lange HQD 40d portable digital instrument according to standard methods (APHA, 1992). Observations on plants were made periodically, with particular attention paid to establishment and root development.

The data series of the parameters did not follow normal distribution even after transformations. Thus, statistical analyses were carried out with the non-parametric test of Kruskal–Wallis and Box and Whiskers were used to display the variability.

Results

Experiment 1

Sile River is a resurgence river and this feature leads to particular environmental conditions. One important feature, as suggested by the analysis (Fig. 4), is that water temperature was quite steady at around 14°C throughout summer and autumn, then decreased to 10–11°C; conversely the average air temperature presented wide variability. Air temperature was 8–10°C higher than water during summer, then had similar values in September until October and was 8–10°C lower in winter. This situation permitted aquatic plants growth even in the winter season, without stress due to temperature variations, especially for root systems.

Regarding vegetation, vetiver was not very successful, because its establishment was slow and the average depth of roots was 20 cm 1 month after installation; in the following 5 months the root growth was modest, reaching an average length of 34 cm at the end of the summer. On the contrary, *Typha latifolia* and in particular *Dactylis glomerata* gave the best performances in terms of roots development. One month after set up *Typha latifolia* had elongated its roots to a depth of 30 cm. *Dactylis glomerata,* at the end of establishment, had an average root depth of 35 cm; only 2 months later the roots reached 75 cm and at the end of experiment the length was 115 cm.

A general amelioration of the water quality was attained when water flowed across the FTW. The greatest effects were on COD and BOD, which showed a reduction in the median and the variability (Fig. 5). In particular, median values were reduced from 15 to 5 mg l^{-1} (66% removal) for COD and from 4.2 to 2 (52% removal) for BOD. It is important to stress that the removal rate was higher in the presence of the highest values entering the FTW system. Concerning nutrients, different trends are detectable for N and P. In the former the median values remained unvaried before and after the barriers, but the dispersion was modified. In fact, before the barriers the data distribution was more dispersed in the field of values higher than the median, while after the barriers distribution was the opposite. Considering the two analyzed forms of N, total N, and NO_3-N, the latter was predominant and that more subjected to amelioration. The median of total P was reduced from 0.55 mg l^{-1} before the barrier to 0.19 mg l^{-1} after (65% removal), while the distribution around the median was not modified. Soluble phosphorus (ortho P) had very low values, not always detectable (molybdate reactive phosphate method, detection limit 0.02 mg l^{-1} (Murphy & Riley, 1962)).

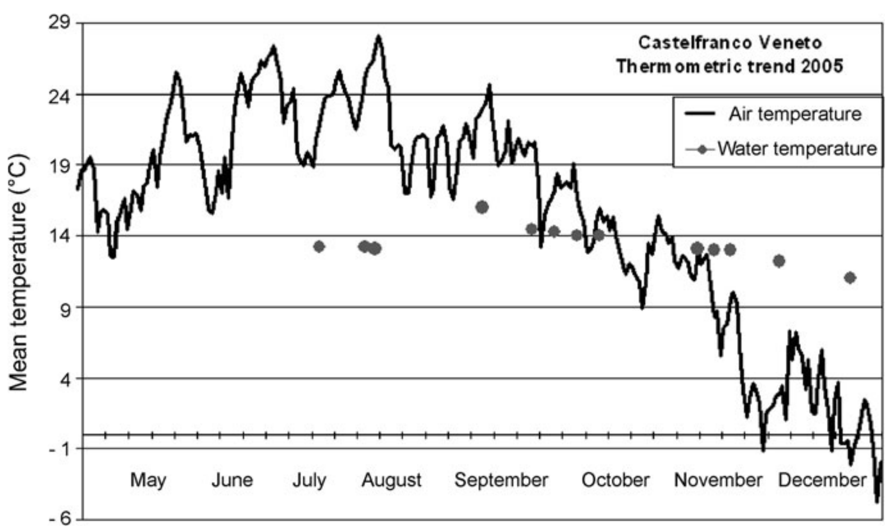

Fig. 4 First experiment: water and air temperature recorded from May to December 2005

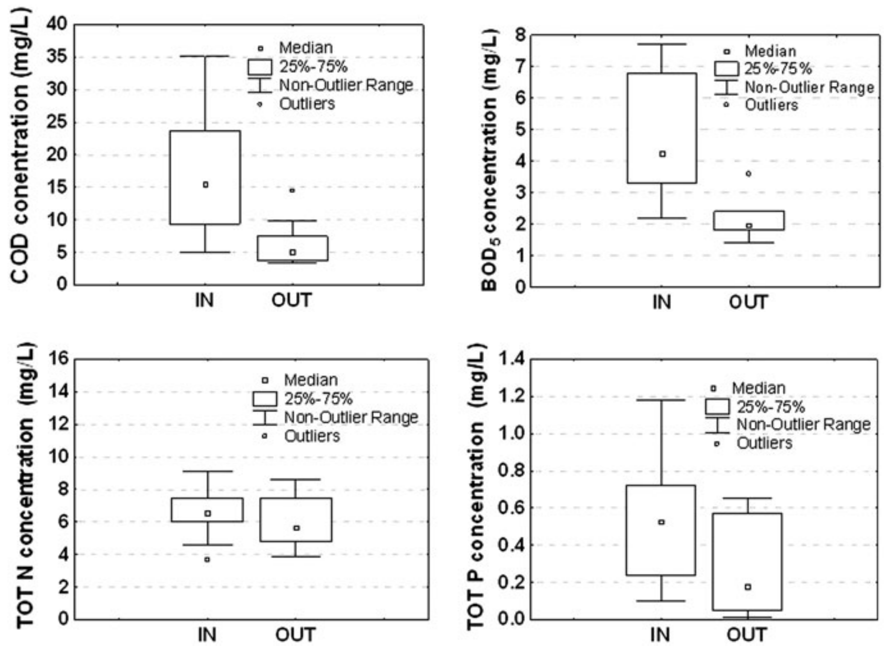

Fig. 5 First experiment: Box-plot diagrams of chemical oxygen demand (COD), biological oxygen demand (BOD), concentrations of total nitrogen (tot N) and total phosphorus (tot P) before (=in) and after (=out) the floating treatment wetland systems

Table 2 First experiment: selected parameters measured before (=in) and after (=out) the floating treatment wetland systems

Parameters (%)	Suspended solids		Electrical conductivity (μS cm^{-1})		pH	
	In	Out	In	Out	In	Out
25	323	320	635	640	7.2	7.1
50	350	320	645	645	7.3	7.2
75	390	348	730	650	7.4	7.2

Values are given as percentiles

The passage through the rooted filter also involved a slight but significant decrease in suspended solids, that is visible considering the median and the 75th percentile (Table 2); the electrical conductivity of water was reduced only at higher values, while pH values were reduced considering the 25th, 50th, and 75th percentiles.

Experiment 2

The species used (*Carex elata, Dactilis glomerata, Juncus effusus,* and *Phragmites australis*) showed a good adaptation to local conditions. At the time of installation plants were at a very early stage of development, but after 1 month the length of the root systems was already 20 cm. In August 2007, almost 1 year from the start of the project, the roots were 90 cm long. A slight decrease in numbers of plants was recorded in the barriers of both channels, probably due to the shading by the trees living on the banks and due to the competition from submergent macrophytes living in the water, especially in the 2 × 2 site.

The more interesting effects of FTWs on water characteristics have been observed for COD, total N, and NO_3-N (Fig. 6).

The 2 × 3 design gave a slightly better performance than the 2 × 2 in reducing COD concentration, with the median values being abated from 13.9 to 8.7 mg l^{-1} (38% removal) in the former and from 12.5 to 9.0 mg l^{-1} (28%) in the latter. The 2 × 3 design was also able to compact the dispersion of data around the medians.

The two designs performed similarly on NO_3-N, reducing the incoming concentrations by 12% (2 × 3 design) and 14% (2 × 2). This inorganic N

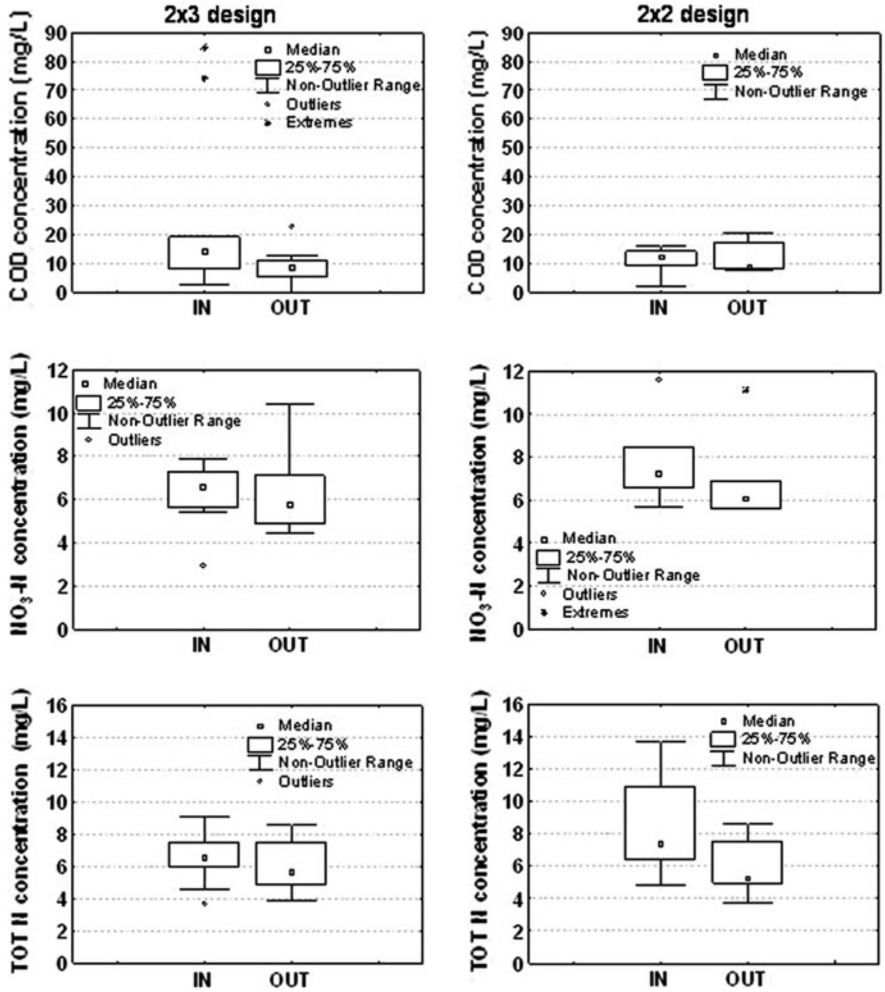

Fig. 6 Second experiment: Box-plot diagrams of chemical oxygen demand (COD), concentrations of total nitrogen (tot N) and nitrate N (NO_3-N) before (=in) and after (=out) the 2 × 3 and 2 × 2 floating treatment wetland systems

represented almost all the total N, which was abated by 13% by the 2 × 3 design and by 29% by the 2 × 2 design.

At the Rosta site (2 × 3 installation) pH values were all close to 7 and dissolved oxygen had a median of 8.7 mg l^{-1}, while at Piovega medians of pH and dissolved oxygen were 7.3 and 5.5 mg l^{-1}, respectively. In both cases, the values were not significantly affected by the FTWs.

Discussion

The two experiments were conducted in the upper reaches of the Sile River, a resurgence river that showed similar chemical conditions in the experimental sites and years. The water quality in the river was generally good, with low COD and NO_3-N concentration that met the EU threshold for drinking water (50 mg l^{-1} for NO_3-). Both sites are located inside the Sile River Natural Park and this stimulated the desire to test the FTWs to achieve a further amelioration of the water in a very fragile environment. In fact, there is intensive human activity in the area with severe risks of compromising water quality and aquatic life, leading to the implementation of protection measures. In particular, many aquaculture farms are located in the area, given the favorable features of the resurgence water (almost steady conditions of flow, composition and temperature through the year that favor trout growth). In this scenario, the FTWs might represent a feasible solution to mitigate the environmental impact of this activity.

The correct selection and installation of vegetation is a key factor to guarantee rapid establishment and root development, which is essential for the prompt functioning of the system. The attempt to use vetiver grass, a nonnative species, was justified by its highly promising features to be used for depuration purposes, but was not successful in terms of establishment and development. This species is known for its wide capacity to adapt to various water regime conditions, but probably its temperature requirements were not fully satisfied, limiting growth and competitive capacity. Better performances have been achieved with native species, well adapted to the environment, such as common reed, cattail, sedges, and bur reed. Surprising but promising results have been obtained with orchardgrass, a species commonly used for pasture but not known for phytodepuration purposes. Indeed, it was able to rapidly develop a deep and diffused root system even living directly in water. This was not expected because orchardgrass is known to be sensitive to water-logging. In the first experiment, it spontaneously colonized the floating system probably because the good natural oxygen availability of the water was not limiting for root growth. This positive response suggested using the species also in the second experiment, which confirmed its validity.

In the experiments the concentrations of pollutants were low and the residence time in the FTWs was reduced, given the velocity of the water flow. Nonetheless, the barriers gave interesting performances in terms of pollutant abatement. The higher removal was observed on COD (together with BOD in the first experiment), suggesting that a combined action of filtering and biological degradation takes place in the root environment. Comparing the depuration efficiency on COD observed in first experiment (removal of 66%) with the values we find in bibliography (removal from 37% to 95%), it stands around the average, but for the second experiment values are lower (removal of 29–38%). For BOD, mean removal values of 52% in the first experiment, was higher in comparison with those found by Revitt et al. (2001) and Billore et al. (2008), which stands from 37 to 45%. The effects on nitrogen were less evident but still significant, with removal mainly of the nitrate fraction. This can be the combined result of plant-microbes uptake and some denitrification. Total N removal was actually lower than the values we can find in bibliography, while nitrate removal is closer to them (Lianpeng et al., 2009).

Lower and contrasting results between the two experiments have been obtained for P. Important removal (65%) was only detected in the first experiment, probably because the median content in the water was one order of magnitude higher than in the second one. In other works, we found the removal was lower (Hubbard et al., 2004; Van Acker et al., 2005; Van de Moortel, 2008).

Conclusions

This study evaluated the potential of floating wetland systems to work in running water conditions. Although the systems were monitored only during the first year after installation, a good development of roots and significant effects on pollutant removal were detected in both experiments. The highest depuration efficiency was attained on COD (66% in the first experiment, 29–38% in the second) and BOD, but also N (particularly nitrate form) and total P (in the presence of the higher entering concentration) were abated. Regarding the second experiment, the settings with 2 barriers formed by 2 lines versus 2 barriers of 3 lines of floating elements gave slightly contrasting results, since the first scheme was more efficient in treating nitrogen, the second in treating COD.

The Tech-IA floating system was very easy to install and manage and did not give any problems as plants grew in flowing water conditions. It also performed very well in terms of buoyancy and stability even when single elements were joined together to form multi-line barriers. In spite of severe weather events during the project no damage to the systems was observed. A floating wetland system may be used as an in-stream water treatment that is easy to install and manage and effective in controlling pollutants if suitable vegetation is chosen and planted.

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