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Floating treatment wetland influences on the fate and removal performance of phosphorus in stormwater retention ponds

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ABSTRACT

A field trial comparing the fate and removal performance of phosphorus (P) in two parallel stormwater retention ponds, one retrofitted with a Floating Treatment Wetland (FTW) and one without any vegetation (a control), was carried out near Auckland, New Zealand. Results suggest that inclusion of a FTW would significantly improve P removal efficiency exhibiting 27% lower TP outlet event mean concentrations (EMCs) than a conventional retention pond. The low SRP inlet EMC did not allow the performance of either pond to be differentiated.

Inlet particulate bound P (PP) is thought to have been associated with particulate copper on fine particles like colloidal organic matter and/or clay and trapped into the sticky biofilm of the roots to subsequently settle on the bottom of the pond. The FTW pond induced a more neutral water column pH and higher organic release into the water column, likely promoting dissolved phosphorus sorption onto particles. Surprisingly, the reduced (low redox potential) sediment observed below the FTW did not induce P release probably due to the more neutral pH conditions allowing re-adsorption onto organics and/or clay minerals (e.g. Al-OH). This resulted in higher P sediment accumulation in the FTW pond. P uptake by plants is not thought to be a significant removal pathway. Sorption of dissolved P, physical entrapment of PP in roots and settlement are thought to be the main P removal pathways for ponds equipped with FTWs.

1. Introduction

Lawn fertilizing in residential areas, as well as agricultural activities contribute to increased phosphorus (P) concentration in stormwater runoff. Highways have also been identified as a potential source of P (Kennedy, 2003) with reported median runoff concentration of 0.25 mg/L (Pitt et al., 2004) and up to 0.55 mg/L recorded from highways in California (Caltrans, 2001). Untreated, P-laden stormwater runoff can contribute to eutrophication of surface waters and endanger aquatic life. Constructed wetlands and retention ponds are practices widely used to reduce the impact of nonpoint source pollution from stormwater runoff on the environment. Retention basins generally provide limited efficiency regarding dissolved contaminants, being more efficient at removing coarse, particulate-attached pollutants (Van Buren et al., 1996). On the other hand, wetland vegetation provides removal mechanisms for soluble pollutants and finer particles (Bavor et al., 2001) but usually require larger surface areas and show limited tolerance for extended periods of high water levels. A novel approach, the floating treatment wetland (FTW), offers a solution able to overcome these disadvantages.

A FTW is a vegetated device installed on the surface of a pond. It is comprised of a porous floating mat planted with emergent macrophytes. Plant roots grow through the fibrous matrix to reach the underside of the mat and hang into the water column. A FTW is suitable for new construction or retrofit installation.

There are limited published data on FTW applications in stormwater systems monitored at full scale under field conditions (Headley and Tanner, 2012). Previous studies have identified the capability of FTWs to remove nutrients (Chang et al., 2012; De Stefani et al., 2011; Hubbard, 2010; Stewart et al., 2008; Van De Moortel et al., 2010). These studies mainly reported the P removal efficiency for influent concentrations ranging from 0.5 to 30 mg/L total phosphorus (TP) which are representative of agricultural runoff or wastewater. These values are significantly higher than typical urban stormwater runoff concentrations (median of 0.27 mg/L TP across all urban lands reported (Pitt et al., 2004)). Two studies addressed P treatment for concentrations in the range of stormwater runoff. Tanner and Headley (2011) reported removal efficiencies of 26 and 28% after 7 days for soluble reactive

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phosphorus (SRP) and TP, respectively, in FTW mesocosm experiments using *Carex virgata* (plant species used in the present study). Winston et al. (2013) found significantly lower effluent concentrations after retrofitting a stormwater retention pond with FTWs covering 18% of the pond area. The median SRP and TP concentrations were reduced from 0.09 to 0.02 mg/L and 0.18 to 0.04 mg/L respectively, between the inlet and the outlet of the pond. In order to confirm the benefits of using FTWs as well as identify the removal processes of these new systems to improve their design, additional full scale experiments are needed.

This paper summarises the findings of a field study with side-by-side monitoring of two geometrically similar retention ponds, one of which contained a FTW with fully developed vegetation. During storm events, inflow and outflow event mean concentrations (EMCs) were quantified and used to assess the overall pollutant removal efficiency of each system. EMCs and factors such as flow ratio (runoff inflow volume/permanent pool volume of the pond), water column temperature, and antecedent dry days were investigated to try to identify common influences on P removal. The fate of P was identified by assessing where it accumulates. Sediment (both ponds) and plant tissue (FTW pond only) P concentrations were monitored over a 2-year period. Temperature, dissolved oxygen (DO), redox potential (Eh), and pH were monitored in both ponds to identify possible chemical reactions induced by the FTW.

2. Material and methods

2.1. Experimental site

The study site and instrumentation has been described elsewhere (Borne et al., 2013a). Briefly, the experimental site is a stormwater retention pond located north of Auckland, New Zealand, and collects runoff coming from a highway including shoulder and vegetated berms. The catchment is approximately 1.7 ha (75% impervious). The retention pond was bifurcated into two straight-walled parallel sections (~100 m^2 each) with a permanent water depth of 0.75 m, in order to allow a side by side study (Fig. 1). The sediments were dredged before allowing water into the ponds, leaving a thick clay layer at the bottom. An approximately 50 m^2 FTW, representing 50% surface area coverage, planted with *C. virgata* (~17 plants/m^2) was installed in December 2010 (summer in the Southern Hemisphere) in one partition (FTW pond, Fig. 2). The other partition remained as a conventional retention pond and served as a control (Control pond).

2.2. Storm event sampling and analysis

Inflow and outflow sampling began after six months of plant growth and lasted over a period of ~1 year (May 2011–June 2012), during which 17 storm events were sampled. Three ISCO 3700 automatic samplers, equipped with pressure transducers (PT) to measure the water level, were installed in the forebay and upstream of each outlet weir to collect storm event samples (Fig. 1). PT measurements coupled with the standard equation for a fully contracted sharp-crested 90° V-notch weir were used to calculate inflows at two minute intervals. Detailed methodology is presented in Borne et al. (2013a). Flow-weighted composite samples were made to determine event mean concentrations (EMCs) and the overall system mass pollutant removal efficiency. Samples were analysed by Watercare Ltd. (Auckland, New Zealand), an International Accreditation New Zealand (IANZ) certified laboratory. Samples for SRP analysis were filtered through a 0.45 μm pore size filter according to method 4500-P B (APHA, 2005). Samples for TP analysis were digested according to method 4500-P J (APHA, 2005) modified to digest samples for 15 min at 120 °C (recovery verified with comparison data). Element quantification was performed according to method 4500-P F (APHA, 2005) modified to analyse a second source calibration standard every 12 samples instead of 10. The method detection limit was 0.005 mg/L for SRP and TP.

The overall system efficiency was assessed for each individual storm event by (MRE) as per equation (1):

$$MRE(\%) = \frac{((V_{in} \times \mathrm{EMC}_{in} - (V_{out} \times \mathrm{EMC}_{out}))}{(V_{in} \times \mathrm{EMC}_{in}} \times 100\% \quad (1)$$

where V_{in} and V_{out} are volume of runoff in and out, respectively, and EMC_{in} and EMC_{out} are event mean concentrations of inlet and outlet samples, respectively. When EMCs were below the MDL (representing 27 and 0% of the samples for SRP and TP, respectively), the MRE was calculated using the MDL value.

2.3. Measurement of physico-chemical parameters

In order to assess the impact of the FTW on physico-chemical parameters and possible influences on P forms, DO, Eh, temperature and pH were measured over a 2-year period in both ponds. Continuous temperature and DO monitoring was carried out below the FTW (at 10 and 40 cm depth) and in the Control pond (at 40 cm depth) at 15 min intervals using a D-Opto logger (Zebra-Tech Ltd, Nelson, NZ). Additionally DO, Eh and pH were measured during dry weather in both ponds on 8 occasions: one week after the FTW was installed and then at approximately 3-monthly intervals (always at similar time in the morning). Detailed methodology and data are presented elsewhere (Borne et al., 2014, 2013a). Only parameters showing a noticeable impact on P forms are discussed in this paper.

2.4. Plant sampling and analysis

Plant biomass assessment and tissue sample collection were performed 8 times; these occurred the day the FTW was installed and then at approximately 3-monthly intervals. Eleven removable 30 x 30 cm squares of the planted mat inserted into an enamel coated aluminium frame were incorporated into the FTW to allow easy access to measure roots (Fig. 2). The purpose was to quantify the amount of P taken up by the plants. Detailed biomass measurement methodology and pollutant accumulation estimates are described elsewhere (Borne et al., 2013a,b). During the first nine months when plants were still establishing, only biomass measurements were performed. Six plants from the same batch as those originally planted on the FTW were analysed in December 2010 as a baseline. Plant tissues were dried overnight at 60 °C and sent to Landcare Research (Palmerston North, NZ), an IANZ accredited laboratory. Samples for P analysis were digested using a Kjeldahl wet oxidation process as described by Blakemore et al. (1987) followed by ascorbic acid reduction and flow injection analysis as described in Lachat Instruments (1998).

The term "root" used in this paper refers to the plant tissues growing below the FTW mat. Roots growing within the mat matrix were not analysed or measured.

2.5. Sediment sampling and analysis

In order to assess the impact of a FTW on phosphorus accumulation in the sediments, samples were collected in the Control and FTW ponds 6 times over a period of 2 years. Redox potential was measured in situ prior to sediment sample collection. A combined Platinum-Ag/AgCl ring electrode linked to a laboratory redox meter (826, Metrohm) (Hinchey and Schaffner, 2005; Rodríguez et al.,