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Nutrient storage in urban wetlands

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Abstract A pond in Sydney's Centennial Park is fed by stormwater from a 120 ha catchment that has predominantly residential land use. Over a period of several months the pond inflow and outflow were monitored to observe flow rate, suspended solids and total phosphorus concentration. In all runoff events, the inflows were characterized by rapid increases in the concentration of both suspended solids and phosphorus. It appears that significant amounts of phosphorus and sediment accumulate in the pond during the small, more frequent rainfall events. In most small to medium size winter flood events, 60% of phosphorous and 80% of suspended sediments were deposited in the pond. The implication for use of ponds for stormwater treatment would appear to be that ponds can be effective in arresting the downstream movement of sediment, but may not significantly reduce the downstream movement of phosphorus.

INTRODUCTION

Nutrient pollution is a major problem in many of our waterways, and phosphorus or nitrogen is generally the growth limiting nutrient (Golterman, 1995). Much recent research has focused on the use of constructed wetlands or ponds for the treatment of nonpoint source pollution. Constructed wetlands have a high potential for the removal of sediment and nitrogen, however a significant limitation to their use is their restricted capacity to permanently immobilize phosphorus (CRC, 1993). Furthermore, natural systems tend to have a much lower capacity to remove phosphorus than constructed systems (Johengen & LaRock, 1993).

It is well known that phosphorus adsorbs onto oxidized sediments (Mortimer, 1941), and the number of studies investigating sediment phosphorus release has increased considerably in recent times. It seems that the key to permanent immobilization of phosphorus is burial in the sediments (Klump *et al.*, 1997; Johengen & LaRock, 1993).

Phosphorus removal occurs through processes such as adsorption, precipitation, and biological uptake. Iron, aluminium, and calcium all have a strong affinity for phosphorus, which will tend to bind with these minerals if they are present in the sediment (Faulkner & Richardson, 1989). Ramm & Scheps (1997) stated that a high Fe:P ratio in a sediment generally characterizes good capacity for a sediment to permanently bind phosphorus. However, anaerobic conditions or high pH may cause phosphorus to be remobilized from sediments back into the overlying water. It was stated by Kleeberg & Kozerski (1997) that phosphorus release from aerobic sediments is possible following the formation of anoxic microlayers at the sediment-water interface.

Mixing and circulation in a water body affect sedimentation and resuspension of sediments, and diffusion of phosphorus from pore water in the sediments to overlying water (Jensen & Andersen, 1992). These factors are likely to have a significant impact on ponds or similar natural systems, particularly with poorly stabilized bed sediments, and regular flushing by stormwater inflow.

This paper examines the behaviour of an urban pond under stormwater loading, using phosphorus and suspended solids data collected at the pond inflow and outflow points during storm events. The main objective of this study was to assess the ability of the pond to arrest the downstream movement of phosphorus, by studying its balance of phosphorus and sediment under stormwater loading.

The study was carried out on Musgrave Pond in Sydney's Centennial Park. The poly-eutrophic Musgrave Pond is one of ten ponds in the Centennial Park pond system, located in the upper catchment of the Botany Basin. The 0.46 ha pond has an average depth of 0.40 m (Preston, 1995), and receives stormwater directly from a 120 ha urban catchment. Stormwater enters the pond via a concrete and brick lined channel, and exits through a weir structure into the ponds downstream.

METHODS

Stormwater inflows and pond outflows were sampled during seven rainfall events between June and September 1997. Water samples were analysed for total phosphorus, TP (measured in mg l^{-1} as phosphorus), total suspended solids, TSS (mg l^{-1}), and volatile suspended solids, VSS (mg l^{-1}), concentrations. Inflow and outflow rates were also observed. Rainfalls were measured using three tipping bucket rain gauges located in or near the catchment.

The behaviour of the pond under stormwater loading was observed using flow rates, and phosphorus and suspended solids concentrations measured at the pond inflow and outflow points. These data were then used to calculate phosphorus and suspended solids loads and balances for each rainfall event. Total phosphorous and suspended solids concentrations were measured according to the procedures set out in APHA (1992). Inflow rates were measured using a stage-discharge curve developed for the stormwater channel by the Hydrology Department at the University of New South Wales. Outflow rates were measured using equation (1) (after King *et al.*, 1996):

$$Q = CLH^{3/2} \quad (1)$$

where Q = flow rate, C = coefficient, L = weir length and H = height of water above the weir crest measured just upstream of the weir.

RESULTS

Pond inflow and outflow behaviour under stormwater loading

Stormwater inflows were characterized by rapid increases in phosphorus and suspended solids concentrations during the first flush for each rainfall event. Typical peak total phosphorus (TP) concentrations were 0.5–1.0mg l^{-1}, with a single concentration of 3.50 mg l^{-1} recorded. Typical peak total suspended solids concentrations were 200 mg l^{-1} with readings up to 1600 mg l^{-1} recorded. Following the first flush, TP concentrations quickly returned to a baseflow concentration of about 0.10 mg l^{-1}. The rainfall event on 20 August 1997, shown in Fig. 1, illustrates the typical behaviour of the pond inflow and outflow during a storm.

Pond outflows were characterized by a near constant phosphorus concentration of about 0.10 mg l^{-1}, followed by a slight increase in concentration after the peak in the outflow hydrograph. The phosphorus concentrations remained elevated for a period before falling back down to the constant concentration of 0.10 mg l^{-1}. (These effects can be seen in Fig. 4 for the event on 20 August 1997.)

During a rainfall event, most of the phosphorus load is deposited in a short period of time during the first flush. The shape of the phosphorus concentration plot for the outflow (Fig. 2) shows that a portion of this phosphorus load seems to move through the pond as a discrete parcel or plug. There is a definite period of elevated phosphorus concentration at the outflow as the "plug" exits the pond. These observations imply a flow regime in the pond with limited mixing during storm flows.

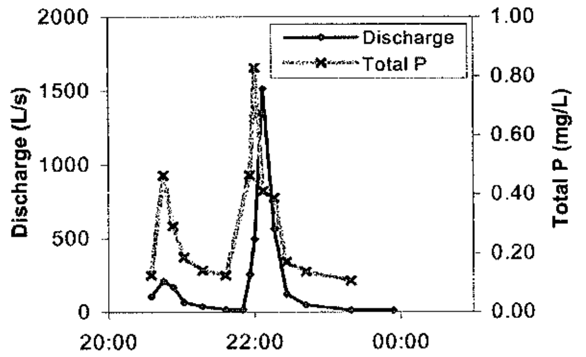

Fig. 1 Discharge and phosphorus concentration at inflow for event on 20 August 1997.

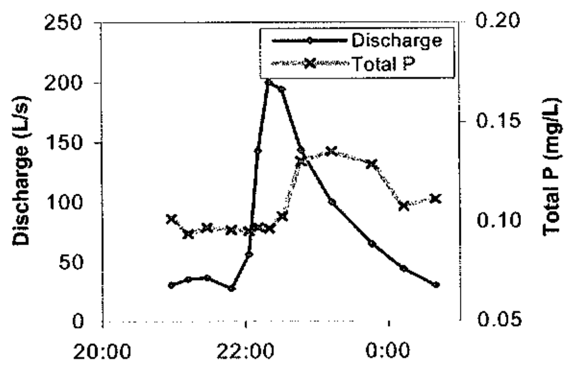

Fig. 2 Discharge and phosphorus concentration at outflow for event on 20 August 1997.

Figures 3 and 4 show that the suspended solids concentrations are closely related to the phosphorus concentrations at the inflow and outflow.

Over the seven flood events the peak TP concentrations at the outflow varied between 0.11 mg l^{-1} and 0.23 mg l^{-1}. The magnitude of the outflow peak TP concentrations was generally dependent on the magnitude of the inflow peak TP concentrations.

Total suspended solids concentrations at the outflow varied between 3 mg l^{-1} and 44 mg l^{-1}. For a given rainfall event, the peak outflow suspended solids concentrations proved to be much more closely related to the outflow discharge rate than the inflow concentrations. Higher outflow rates indicate a faster flow of water through the pond, and the increased suspended solids concentrations are due to reduced sedimentation efficiency from shorter detention times, and possibly the resuspension of pond bed sediments.

During periods of low flow, the inflow and outflow phosphorus concentrations were the same at roughly 0.1 mg l^{-1}.

Phosphorus and sediment balance

All rainfall events sampled showed an accumulation of phosphorus in the pond. Influent TP loads varied between 0.1 kg and 0.9 kg, and the proportion of the load that

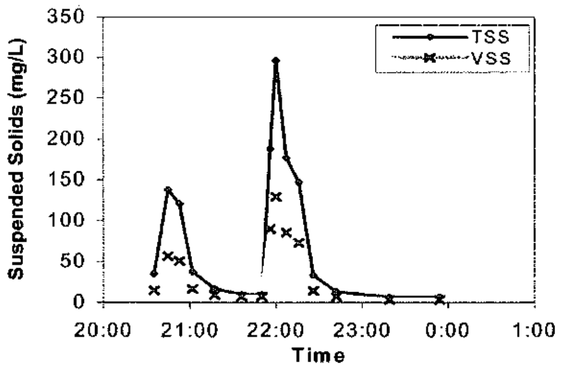

Fig. 3 Total and volatile suspended solids concentrations at inflow for event on 20 August 1997.

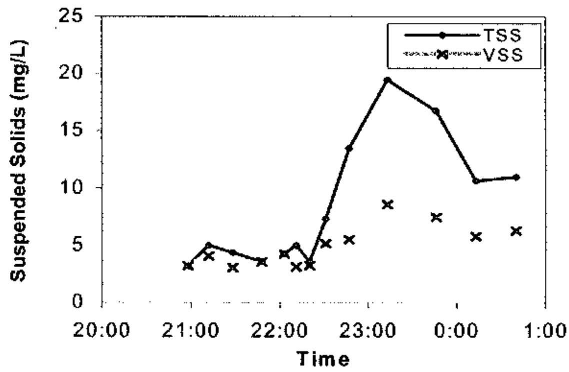

Fig. 4 Total and volatile suspended solids concentrations at outflow for event on 20 August 1997.

remained in the pond varied between 6% and 96%. Inflow and outflow phosphorus loads for six of the sampled events are shown in Fig. 5. Sediment loads for the same events are shown in Fig. 6.

Sediment loads entering the pond during storm events varied between 26 kg and 351 kg. All storms except for one resulted in an accumulation of sediment, with typically 80–99% of the influent load remaining in the pond. However, an 8 mm rainfall event on 4 August 1997 which was characterized by frequent light showers and low influent suspended solids concentrations, imported 26 kg of sediment while it exported 38 kg. This is possibly due to resuspension of fine sediments from the pond bed. Another possibility is that fine sediments, which remain suspended in the water column from previous rainfalls, are flushed out when relatively clean stormwater enters the pond. In this case, the cleaner stormwater, resulting from a clean catchment, displaces the more turbid pond water, causing a net export of sediment. During the same event, inflow and outflow TP loads were almost identical, with 0.28 kg of TP entering the pond, and 0.26 kg leaving the pond.

Influent phosphorus loads were increased by larger runoff events, longer dry spells preceding the storm, and higher rainfall intensity. Since the outflow phosphorus

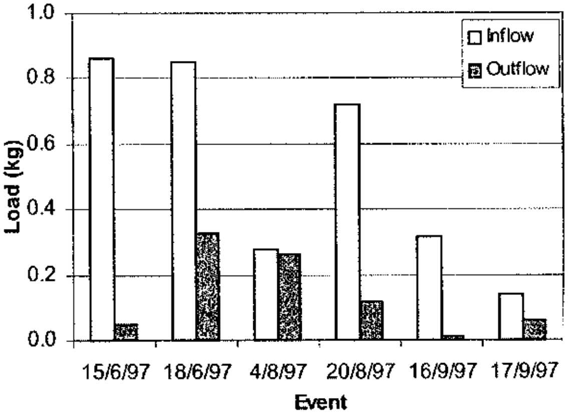

Fig. 5 Inflow and outflow total phosphorus loads.

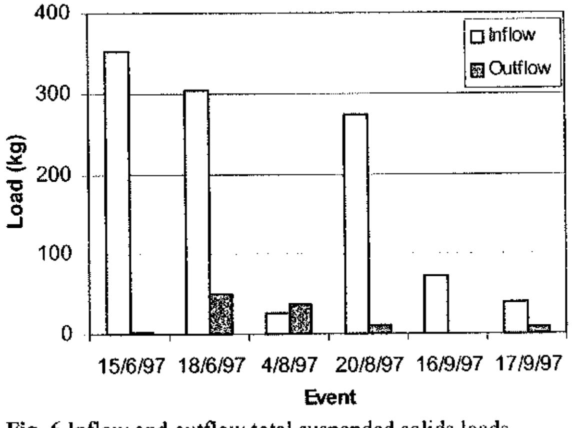

Fig. 6 Inflow and outflow total suspended solids loads.

concentrations showed a relatively small variation during an event (typically a range of 0.10–0.15 mg l^{-1}), outflow loads were most dependent on the outflow volume. Evapotranspiration and infiltration caused the pond water level to drop below the crest of the outflow weir a couple of days after a rainfall event. Thus, for small rainfalls, outflow volumes were often significantly less than the inflow volumes if the previous rainfall was more than a few days earlier, usually resulting in significant phosphorus accumulation in the pond. Dry weather inflow rates were approximately 5 l s^{-1}, with typical TP and TSS concentrations of 0.1 mg l^{-1} and 10 mg l^{-1} respectively. Outflow rates ultimately reduced to zero after rainfall. Based on these assumptions, a transmission rate in g s^{-1} can be calculated for TP and TSS. Thus, dry weather flows deposit annually about 16 kg of phosphorus and 1.6 t of sediment in the pond. Preston (1995) showed that wet weather flows deposited roughly 100 kg of TP and 30 t of sediment per year into the pond.

DISCUSSION

This study showed that there was significant accumulation of phosphorus and sediments in the pond during most rainfall events, with more than 60% of phosphorous and 80% of sediment being trapped in the pond during typical medium sized storm events. However, the pond's ability to remove phosphorus during large, infrequent events was untested.

The Centennial Park Ponds have recently suffered many blooms of blue-green algae. Musgrave Pond has suffered occasional small blooms of green and blue-green algae, and the large downstream ponds have supported very large blue-green algal blooms (Preston, 1995). Regular accumulation of nutrients in Musgrave Pond from stormwater inflows results in nutrient enriched water and sediments. Despite this, algal blooms have been small because regular flushing of the pond provides less than favourable conditions for the growth of blue-green algae, which prefer calm water (Batten, 1993). Large algal blooms in the lower ponds are most likely due to the flushing downstream of nutrient and algal enriched waters over time from the upper ponds (such as Musgrave Pond), and conditions favourable for algal growth. These observations do not indicate whether the major nutrient sink lies in the upper or lower ponds, however they do imply that large quantities of nutrients are being flushed from the upper ponds into the lower ponds.

The mechanisms involved in internal phosphorus cycling are complex and results indicate it is likely that some of the bed sediments are resuspended during large flows. Preston (1995) showed that bed sediments in the Centennial Park Ponds were relatively enriched in phosphorus. Furthermore, if the top layer of sediment was resuspended, substantial amounts of phosphorus would be released into the overlying water. It was estimated that if the top 10 cm of sediment in the pond system were resuspended at any one time, approximately 0.2 t of phosphorus would be released into pond water.

The storm on 4 August 1997 showed a net export of sediment from the pond, possibly due to the resuspension of bed sediments. If this is the case, then the internal phosphorus and sediment loads exported from the pond would be much larger during very high flows.

Musgrave Pond has limited coverage of submerged macrophytes (Preston, 1995) which help to bind sediments and reduce flow velocities at the pond bed. Since the pond is shallow (average depth 0.40 m), it is likely that high flows will produce flow velocities fast enough to stir up bed sediments in some areas of the pond. The implication of this is that phosphorus stored in the sediments may be released into the overlying water, and flushed out of the pond.

Another mechanism of phosphorus release from sediments is through diffusion. Diffusion rates from pore water in the sediments to overlying water are increased by circulation of water over the sediments and warm water temperatures. The results showed that a rainfall of 5 mm produced a runoff volume approximately equal to the volume of the pond. Continuous flow data collected by Preston (1995) at the pond inflow suggests that the annual stormwater inflow volume is more than 200 times the volume of the pond. This regular flushing will increase phosphorus diffusion rates and wash phosphorus enriched waters downstream. Furthermore, diffusion rates will be greater in summer due to warm water, with temperatures up to 30°C recorded by Preston (1995) in some of the Centennial Park Ponds.

Recent studies have highlighted the fact that phosphorus cycling in shallow lakes and wetlands is very susceptible to seasonal variation (e.g. Ramm & Scheps, 1997). Internal phosphorus loading is usually much greater in summer, and it is not uncommon for a water body to be a sink for phosphorus in winter, and a source in summer. Summer is the growing season, and much of the phosphorus utilized during the growing season is recycled from the sediments (CRC, 1993). Warmer waters in summer increase microbial activity, which can lead to anaerobic conditions accompanied by anaerobic release of phosphorus. Data for this study were collected in winter and show a substantial accumulation of phosphorus in the pond during most of the events sampled. However, increased internal loading in summer will probably result in significantly larger exports of phosphorus with each rainfall than suggested by the results here.

Twenty-four hour monitoring of oxygen levels by Preston (1995) in three large ponds in Centennial Park showed that aerobic conditions were generally maintained in these ponds, and stratification was broken down by night-time mixing. Musgrave Pond is the shallowest pond in the park, and is mixed regularly by stormwater inflows. Therefore, based on observations in other ponds, it is reasonable to assume that any stratification in Musgrave Pond has minimal impact on dissolved oxygen levels, and that aerobic conditions are maintained. Phosphorus release due to anaerobic conditions is therefore probably not a major mechanism in the cycling of phosphorus in Musgrave Pond.

CRC (1993) stated that the permanent phosphorus immobilization rate in natural wetland sediments was about 0.05–2.4 kg ha^{-1} $year^{-1}$. At the upper limit of this range, Musgrave Pond could immobilize about 1 kg of phosphorus per year, which is 1% of the estimated annual stormwater inflow load. If this figure is close to the true figure, most of the phosphorus accumulating in the pond with each runoff event is not permanently immobilized in the sediments. Ultimately this phosphorus may be washed downstream due to frequent flushing of the pond.

CRC (1993) also found that constructed wetland systems with annual phosphorus and hydraulic loading rates similar to Musgrave Pond retained on average about

37 kg P ha^{-1} $year^{-1}$. With the differences between Musgrave Pond and a constructed wetland aside, applying the latter figure to the pond yields an average phosphorus retention of 17 kg $year^{-1}$, or 17% of the estimated annual inflow load. Musgrave Pond is subject to sporadic, high flows rather than continuous hydraulic loading as is the case in most constructed wetlands. The pond would generally not be expected to perform as effectively as such constructed systems.

Preston (1995) estimated that the annual inflow loads of total phosphorus, total nitrogen and sediment into the pond system as a whole were 0.2 t, 1.7 t, and 50 t respectively. Preston (1995) also estimated that over 70% of the phosphorus and sediment loads and 50% of the nitrogen load were retained in the pond system each year. Based on these figures, the average phosphorus retention rate for the whole pond system is roughly 7 kg ha^{-1} $year^{-1}$.

It appears that, in the short term, the pond is effective in removing phosphorus and sediment from influent stormwater, with the major phosphorus sink most likely to be in the sediments. In the long term however, most of the influent phosphorus is probably flushed downstream. Using the average annual phosphorus retention rate for the pond system of 7 kg ha^{-1} $year^{-1}$, Musgrave Pond would retain only 3% of the annual influent phosphorus load.

CONCLUSIONS

The study showed that Musgrave Pond can effectively remove substantial amounts of phosphorus and suspended solids from influent stormwater during most rainfall events. The pond was able to remove 60–95% of influent phosphorus loads, and 80–99% of influent suspended solids loads during typical winter rainfalls.

It is likely that high flows are able to resuspend bed sediments. Preston (1995) showed that bed sediments in the Centennial Park pond system are a rich source of phosphorus, and that large amounts of phosphorus would be released into the overlying water if the top layer of sediment was resuspended. The internal load of phosphorus exported from the pond due to sediment resuspension appears to be small compared to the loads washed into the pond during most rainfalls. Thus, it is likely that the small, more frequent events result in continuous accumulation of phosphorus, while large, rare rainfall events cause scouring of the sediments, flushing stored phosphorus out of the pond. Phosphorus release from sediments in summer is also likely to contribute significantly to the flushing downstream of phosphorus.

The study led to the conclusion that, in the long term, ponds cannot effectively arrest the downstream movement of phosphorus. However, greater amounts of phosphorus could be permanently immobilized by taking measures to stabilize bed sediments, such as establishing appropriate communities of rooted macrophytes.

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