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Modeling phosphorus removal in wet ponds with filter zones containing sand or crushed concrete

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ABSTRACT

Generally, wet ponds are constructed only to reduce the hydraulic load of downstream receiving water bodies. Often most particulate matter will be retained, whereas dissolved nutrients mostly will be unaffected by the pond due to short retention times. A suite of lab-experiments have demonstrated that crushed concrete has high affinity for dissolved phosphorus (TDP), and potentially could be an effective new measure to reduce discharge of phosphorus (P) to downstream located P-limited lakes and estuaries. To verify this potential we have developed a dynamic model for a combined sedimentation and infiltration pond in Denmark, using the software PowerSim. The model simulates retention of P and suspended particulate matter (SPM). It is possible to change the description of filter material in the model to either a traditional sand filter or a filter of crushed concrete, and thereby demonstrate the P-retention efficiency of the different materials. Two scenarios with changing wet volume and storage volume of the pond indicated that 400 and 50 m^3 pr. reduced hectare (red. ha), respectively, would be optimal for retention of particles. In combination with this result, the model showed a significant increase in TDP retention with a concrete filter (≈60%) compared to a traditional sand filter (≈10%). This only applies for water actually percolating through the filters and not for the overflow. Because concrete is an alkaline material, pH in the discharge to the receiving water body will be high (>9.5) for approximately 100 days and then decrease to neutral. If adequate precautions against high pH in the discharge are put in place, crushed concrete can reduce the discharge of TDP to sensitive receiving water bodies.

1. Introduction

Runoff from urban catchments makes up a significant amount of the total runoff diverted into sewers or surface waters (Kronvang et al., 2001). This is due to a combination of the increase in paved areas and the change in hydrological regime with increased volume of storm water runoff with higher peak flow rates and flood water levels (Barbosa and Hvidtved-Jacobsen, 2001). Additionally, nutrients and xenobiotics in urban runoff make up a significant amount of the total runoff, due to a reduction of other sources, by means of improved wastewater treatment and reduced discharge from agriculture (Göbel et al., 2007; Kronvang et al., 2001). Due to risk of eutrophication of e.g. lakes and estuaries, it can be necessary to reduce the discharge of phosphorous (P), deriving from sewer overflows, fertilization of areas in the catchment, atmospheric deposition and erosion of various surfaces (e.g. Egemose and Jensen, 2009).

Detention ponds have been used to prevent overflows from sewers and thereby reduce discharge to receiving water bodies after heavy rain events (Reinhardt et al., 2005). The ponds reduce the hydraulic load and ensure sedimentation of particles before discharge to the receiving water body, thereby preventing damages from erosion and deposition of sand (Persson et al., 1999). The design of ponds only ensures retention of large particles (and nutrients sorbed to these), while finer particles do not have the sufficient time to settle (Hvitved-Jacobsen et al., 2010; Muthukrishnan and Selvakumar, 2006). Unfortunately, these smaller particles are the most nutrient-rich (Stone and English, 1993). During late autumn, winter and spring, net accumulation of nutrients occurs in the ponds, due to decreasing water temperatures and slow mineralization processes. In the summer period, where the temperature in the ponds may reach 20–25 °C, mineralization processes are

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stimulated, and part of the settled particulate matter (SPM) may be degraded, and the associated nutrients will be released to the water body. Microbial degradation of the organic matter uses oxygen as terminal electron acceptor resulting in low or depleted oxygen levels in the ponds. Since most detention ponds are not designed to retain dissolved nutrients, the newly dissolved nutrients will either be taken up by the primary producers in the pond or be flushed out to the receiving water body by the next rain event (Hvitved-Jacobsen et al., 2010).

To achieve a better retention of both particulate and dissolved nutrients, a combined sedimentation and infiltration pond are recommended (Hvitved-Jacobsen et al., 2010). By diverting the water through a porous media (often a sand filter) a large proportion of particles are retained (Birch et al., 2005). But the deposition of particles gradually clogs the porous structure of the filter, thereby reducing the hydraulic conductivity resulting in less water percolating through the filter. Siriwardene et al. (2007) found that small silt particles (<6 μm) and a fluctuating water level accelerate the formation of the clogging layer. To ensure satisfying retention efficiency, the filter has to be renewed before it is completely clogged. Thus, the lifetime of a filter varies depending on particle loading and size distribution. Most filters are assumed to have a lifetime of about 15 years according to the Danish National Organization of water treatment DANVA (2005). Since the water periodically has a long contact time with the filter material, a minor part of the dissolved substances may be adsorbed to the material (Arias et al., 2001; Hvitved-Jacobsen et al., 2010). Despite this, the removal of dissolved nutrients in infiltration ponds is insignificant, compared to the removal of particulate nutrients. Besides, such ponds are generally designed to reduce the hydraulic load, and not the nutrient load.

A new alternative to the traditional sand filters are filters of crushed concrete (Egemose et al., 2012). It is a cheap residue (10 € per ton) from demolition of various constructions. Concrete is a very alkaline material due to the high content of calcium hydroxide ($Ca(OH)_2$), resulting in pH up to 12.5 during hardening (Herholdt et al., 1985). When concrete comes into contact with water, $Ca(OH)_2$ is redissolved and induces a pH increase in the surrounding water (Oguz et al., 2003; Berg et al., 2005). The high pH causes a binding of dissolved P (TDP) to concrete due to the content of calcium, iron and aluminum. As the concrete particles are covered with P, the calcium release is reduced and at a certain threshold the P binding capacity is reached. One of the binding mechanisms is believed to be adsorption, but it still needs to be confirmed. pH will gradually decline toward neutral over time due to decreasing release of $Ca(OH)_2$ (Berg et al., 2005).

By using crushed concrete as filter material, the removal capacity for P is increased (Egemose et al., 2012) compared to sand filters (Arias et al., 2001). Laboratory studies have shown that crushed concrete has a maximum adsorption capacity of 8.31 mg P g^{-1} concrete, as well as an effectiveness of 96.3% P-removal at pH > 9.5 and a smaller effectiveness of 40.3% at pH < 9.5 (Egemose et al., 2012). This is in agreement with Oguz et al. (2003) and Berg et al. (2005) who consider alkaline conditions to be an important factor for a high P adsorption.

To compare different filter materials, we have developed a dynamic model for a specific pond to handle a mixture of water from a separate sewer system and agricultural runoff with outlet to Lake Nordborg (Denmark) (Egemose and Jensen, 2009). The model simulates the total P (TP), TDP, particulate P (PP) and SPM-loading into a combined sedimentation and infiltration pond with respect to hydraulic conductivity and degree of clogging. More importantly, the model is used to create scenarios of possible P reduction with ordinary sand as filter material (with little or no P reduction) and with crushed concrete as filter material (with good P reduction).

2. Methodology

2.1. Site description and methods

The study was carried out in a pond situated in the town Nordborg in the southern part of Denmark. It is a combined sedimentation and infiltration pond with a catchment area of 375 ha consisting of approximately 81.4% agriculture (Egemose and Jensen, 2009) and 15.8% paved area. The pond receives most of its water as runoff from the paved area. The pond was built in autumn 2006, with the primary objective of reducing the external P loading to the eutrophic Lake Nordborg (Egemose et al., 2011). The pond is constructed with a sedimentation part (wet volume 7400 m^3, area 3900 m^2) discharging to the top of a sand filter (area 2050 m^2, depth 0.4 m), when a specific water level is reached. The water then percolates vertically through the sand filter into a drainage system below the filter. Here, the water is collected and discharged to Lake Nordborg through a small stream. The pond is constructed with an overflow 0.2 m above the water and filter surface, creating an additional volume of 1190 m^3 serving as storage capacity for the entire pond. The maximum volume of the pond is therefore 8590 m^3 (Reschat and Sibbesen, 2005). During heavy rain events the pond cannot always cope with the increased water volumes, and the excess water is instead let directly into Lake Nordborg trough overflow.

The filter clogged shortly after construction. Runoff caused erosion of clay from the pond banks that subsequently was washed into the pond and loaded the filter. In September 2007 the filter was renewed, but the level between filter surface and elevation of overflow was reduced to only 5 cm by the contractor. The new filter quickly lost its efficiency, but this time it was due to formation of small channels at the filter surface. Some water was flowing directly in these channels and into the overflow due to the reduced storage level. Besides, the filter beneath these channels was beginning to clog.

During the first year after construction the system were sampled once a month (Egemose and Jensen, 2009), but because of the filter problems in 2006 and 2007, only flow measurements from the inlet can be used for this period of time. These data is used for calibration of the inflow. Calibration and validation of the model (Fig. 1) is therefore performed with data from 2009 and 2011, respectively, with approximately 720 mm precipitation each year. The data available for both years was very limited, with 4–6 data points per parameter (flow, TDP, PP and SPM) in both inlet and outlet. But during calibration and validation the model shows to be quite robust even when using limited data.

Data series for local daily precipitation and evaporation has been obtained from the Meteorological Institute of Denmark, covering the period from construction in 2006 to the end of 2011. The precipitation and evaporation were measured at a standardized weather station positioned approximately 20 km away from the pond.

2.2. Conceptual description of the model

The model consists of 4 sub-models (water, TDP, PP and SPM) all affecting each other dynamically (Fig. 1). The sub-models were developed equally with recognizable state variables and processes, but with different content. In each sub-model there is an inlet to the sedimentation pond including a storage volume. Next is an outlet from the pond into the filter, followed by percolation through the filter and finally an outlet from the bottom of the filter to the receiving water body. Additionally, there is an overflow from the storage volume directly to the receiving water body (Fig. 1). The integrated model includes the most important processes in combined sedimentation and infiltration ponds. Since the model easily