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Monitoring the startup of a wet detention pond equipped with sand filters and sorption filters

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ABSTRACT

The startup of a wet retention pond designed for extended stormwater treatment was monitored by more than one year of continual measurement of hydraulic parameters, nutrients and quality parameters in the pond itself (pH, temperature, dissolved oxygen, turbidity). The data revealed that photosynthesis played an important role for dissolved oxygen and pH for most of the year. Another important observation was that the pond behaved more like a completely mixed reactor than like a plug flow reactor—even though the length to width ratio was as high as 4.5:1. The pond was equipped with sand filters and sorption filters whereby very good nutrient removal efficiencies were achieved.

Key words | colloidal pollutants, continuous monitoring, retention pond, stormwater

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INTRODUCTION

Stormwater runoff from urban surfaces, highways and roads contain numerous pollutants that cause harm in the aquatic environment. Many of the discharged organic and inorganic micropollutants have the potential to accumulate in the ecosystem, causing long term effects on the aquatic fauna. Other pollutants, e.g. phosphorus, cause more direct harm in terms of eutrophication of lakes and coastal waters and must therefore be removed to prevent deterioration of the receiving water bodies. The type and amount of pollutants entrapped in stormwater runoff depends on

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land use, such as traffic intensities, industries, building materials, etc.

In contrast to discharges of urban wastewater, urban stormwater runoff is discharged through a large number of separate outlets. Many small facilities are therefore needed when treating stormwater runoff. For this reason as well as the intermittent nature of the runoff process, technologies for treatment of stormwater runoff must be simple, robust, dependable and easy to operate. In addition hereto, the technologies must be appropriate to treat rather dilute pollutants as they occur in stormwater runoff. For facilities treating such runoff, today's technologies successfully manage pollutants associated with particulate matter, whereas soluble and colloidal pollutants typically are managed with less success. Among the commonly applied technologies, wet basins and constructed wetlands are cost-effective with respect to removal of particles. Wet basins have a lower requirement for land compared to constructed wetlands, and are therefore in most cases the technology chosen for stormwater treatment.

Wet ponds for stormwater treatment perform excellently with respect to particulate matter removal. However, removal of dissolved and colloidal pollutants is comparatively low (Marsalek *et al.* 1999; Semadeni-Davies 2006; Tuccillo 2006; Vollertsen *et al.* 2007). Unfortunately, pollutants on dissolved form or associated with colloids are more mobile in the aquatic ecosystem and more available for biological uptake. They consequently have a higher potential for causing ecotoxic impacts on the receiving water bodies.

It is therefore an environmental issue to remove dissolved and colloidal pollutants in stormwater. The technologies are in principle available, and numerous laboratory studies and field studies have proven the effect of a large array of methods for removal of such pollutants. Furthermore, extensive knowledge on lake restoration can be transferred for application on stormwater treatment ponds. An EU LIFE Environment demonstration project–TREASURE–implements such technologies in full-scale stormwater treatment ponds. In the context of that project, 3 full-scale wet retention ponds are constructed. Each pond consists of a silt trap, a vegetated pond, sand filters and a technology for sorption of dissolved and colloidal pollutants. The sorption technologies differ between the facilities, namely:

- Fixed media sorption in a separate filter unit
- Precipitation and sorption in the bulk water by continuous addition of aluminium salts
- Sorption to iron oxide enriched pond sediments

The facilities are constructed with monitoring in mind, and contain equipment for continuous measuring of flow and water quality parameters as well as flow proportional water sampling. It is the objective of this paper to present the treatment facility that applies fixed media sorption in a separate filter unit. The layout of and concept behind the facility is presented together with on-line monitoring results as well as results on the removal of nitrogen and phosphorus.

MATERIALS AND METHODS

The catchment

The facility is located in a recreational area in the southern part of Odense, Denmark. The catchment contains light industry and covers 27.4 ha of which 11.4 ha are impervious. The annual precipitation in the area has over the last 26 years been determined to 657 mm year^{-1}, and the annual average runoff from the catchment is estimated to 55.500 m^3. A permanent rain gauge from the Danish SVK system is located a few kilometres from facility.

The layout of the facility

The stormwater is piped to the facility by two 800 mm concrete pipes. The facility contains a grit chamber, a wet retention pond, sand filters and fixed media sorption filters (Figure 1). The sand filter unit is constructed as 3 separate filters and the sorption filter unit consists of 1 large filter and 3 smaller test filters. Green plants are furthermore integrated to enhance treatment as well as for aesthetic purposes. Flow is measured at the inlet and after the sand filters. Stormwater samples are collected at the inlet, in the pond, after the sand filters and after the sorption filters. DO, pH, temperature, and turbidity are measured continuously in the pond water. Measurement was initiated primo 2008.

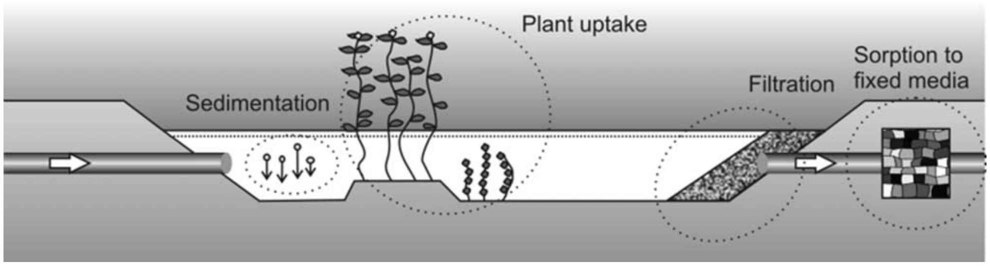

Figure 1 | Schematics of the facility with sorption in fixed media filters.

Wet pond

The retention volume of the wet pond is 1,992 m^3 with a surface area of 2,064 m^2 and a maximum depth of 1.45 m. The detention volume is 1,310 m^3 with a maximum surface area of 1,689 m^2. The maximum outflow from the facility is 25 $L\,s^{-1}$. The permanent pond volume per impermeable catchment area is 186 $m^3\,m^{-2}$ and the total pond volume per impermeable catchment area is 296 $m^3\,m^{-2}$–i.e. in the range of values recommended by e.g. Hvitved-Jacobsen *et al.* (1994), Pettersson *et al.* (1999) and Vollertsen *et al.* (2007).

Sand filters

Sand filters are prone to clogging from particles depositing on the filter surface, creating a colmation layer. This layer will typically have a much lower hydraulic conductivity than the filter medium, controlling the overall filter capacity. The limiting parameter for the filter capacity consequently becomes the depth and hydraulic conductivity of the colmation layer, which again is governed by parameters like filter loading, growth on the filters and drying out between storm events. Different filter layouts are consequently expected to behave differently with respect to long-term capacity.

In the scope of the LIFE Treasure project, three different sand filter layouts are tested (Figure 2):

- A horizontal filter placed in level with the permanent water level.
- A sloping filter placed in the embankment. The filter area starts in level with the permanent water level and goes up to the maximum level of the storage volume.
- A vertical filter placed in the pond. The filter area starts in level with the permanent water level and goes up to the maximum level of the storage volume.

The sand filters were designed based on a leakage factor approach as e.g. applied by Vollertsen & Hvitved-Jacobsen (2003) for exfiltration of wastewater from sewers. Assuming the colmation layer to be homogenous with a well defined depth and the conductivity of the layer much lower than the conductivity of the underlying filter material, the flow through the colmation layer occurs as saturated flow and can as a first estimation be described by Darcy's law, ignoring the underlying soil (e.g. Rauch & Stegner 1994). i.e. the flow through the colmation layer can be described by Equation (1).

$$Q_{out} = A_{out} \Delta h \, L_{out} \quad (1)$$

where Q_{out} is the filter capacity [$m^3\,s^{-1}$], A_{out} is the area through which water is filtered [m^2], Δh is the water pressure on the filter [m] and L_{out} is the leakage factor [s^{-1}]–i.e. the hydraulic conductivity of the colmation layer [$m\,s^{-1}$] divided by the colmation layer depth [m].

The reported hydraulic conductivities of colmation layers from wastewater infiltration and river beds lead to

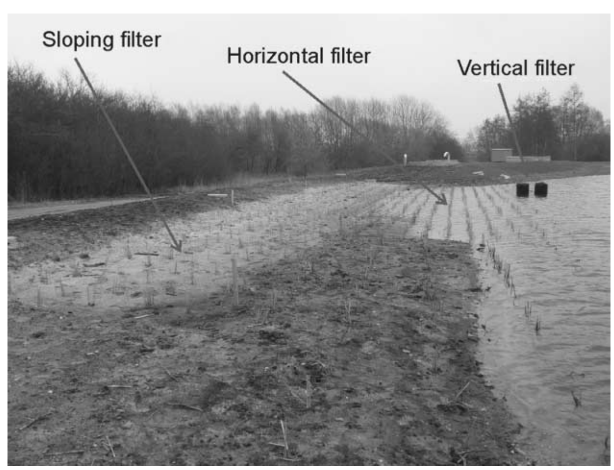

Figure 2 | Sand filters.

the conclusion that the hydraulic conductivity of a colmation layer formed under a permanent water level is likely to be at least $10^{-7}\,m\,s^{-1}$, with a likely value 1–2 decades higher (Houston *et al.* 1999; Calver 2001; Vollertsen & Hvitved-Jacobsen 2003; Reed *et al.* 2006). Dechesne *et al.* (2005) report stormwater infiltration field measurements for 4 infiltration basins that had been in operation between 10 and 21 years. For the basin with the lowest infiltration capacity, they report an infiltration rate of around $1.1 \times 10^{-4}\,m^3\,m^{-2}\,s^{-1}$ at 0.5 m of water depth, i.e. a leakage factor of $2.2 \times 10^{-4}\,s^{-1}$. For stormwater infiltration through a filter with intermittent loading, a design leakage factor of around $10^{-4}\,s^{-1}$ therefore seemed a conservative choice. The horizontal sand filter was assumed to develop the deepest colmation layer, followed by the sloping filter and the vertical filter. The filter sizes were chosen based here on: 1 filter of 20 m length and 5 m width; 1 filter of 30 m length, 3 m width and slope 1:5; 4 filters of 0.5 m diameter and 0.55 m height (Figure 2).

Sorption filters

Materials containing calcite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$) like limestone, marble, dolomite rock and different types of fossil shells are efficient in retaining phosphorus (Brix *et al.* 2001; Vohla *et al.* 2005; Westholm 2006). When it comes to the control of heavy metals, materials containing alumina and iron have proven efficient (Genc-Fuhrman *et al.* 2007). Designing sorption filters, it is essential that the selected filter media has a high sorption capacity at the rather low pollutant concentration levels characteristic of stormwater runoff, allowing for efficient long-term use of the filter media. In order to reduce the required contact time, the kinetics of the sorption process must be rapid. Furthermore must the sorption material be commercially available at an affordable price/effect ratio. The sorption materials applied in the present project have been chosen taking the mentioned aspects into account. The filter medium must furthermore have a good hydraulic conductivity and clogging of the material must be avoided. Prior to treatment by the sorption filter, the stormwater is therefore pre-treated by the sand filters.

The sorption filters are divided into 1 large filter and 3 smaller test filters. The larger filter is rectangular with a footprint of $24\,m^2$ and holds $55\,m^3$ of Oyta Shells, type OYTA 0 (Oytaco Ltd, Denmark), a natural product obtained from deposits of fossil oyster shells in the shallow waters of the North Sea. The size of the material is 0.5–2 mm and consists to 96% of $CaCO_3$ and $MgCO_3$ with a Calcium content of 38%. The water runs through the filter by gravitation.

The smaller test filters are circular with a surface area of $1.23\,m^2$. One filter holds $2.5\,m^3$ of Oyta Shells, another holds $2.5\,m^3$ of granulated olivine (Filtersil 2749 from North Cape Minerals, Norway). The last filter is built as a sandwich filter with $0.5\,m^3$ of Oyta Shells as the bottom layer, followed by $0.5\,m^3$ of iron oxide coated olivine (Filtersil TOC from North Cape Minerals, Norway) and $1.5\,m^3$ of Oyta Shells as the top layer. The 3 test filters are fed by intermittent pumping in order to precisely control the flow rate and pattern through the filters.

Monitoring and sampling

Inlet flow measurement consists of 2 full flowing magnetic flow meters coupled in series together with a rectangular weir coupled in parallel with the two magnetic flow meters. The flow meters are protected against silting by a grit chamber of $26\,m^3$. The magnetic flow meters are of type Krone Optiflux, DN 150 mm and DN 500 mm, respectively. The resulting measurement accuracy is better than 1% for flow rates between $5\,L\,s^{-1}$ and approximately $1\,m^3\,s^{-1}$, at which flow rate the rectangular weir starts to convey part of the flow. The flow over the weir is metered by a pressure gauge located in the middle of the silt trap and a preliminary flow rate is calculated from a weir equation.

The flow from each of the 3 sand filters is measured by a full flowing magnetic flow meter of type Krone Optiflux, DN 80 mm with accuracy better than 1% for flow rates above $1.5\,L\,s^{-1}$.

Flow proportional water samples are collected by automated water samplers of type Maxx TP IV, holding 24 one-litre bottles. Water is sampled from the inlet, the downstream part of the pond, after the sand filters and after the sorption filters. The sampler at the inlet is controlled by the combined measurement of the inlet flow whereas the other samplers are controlled by the combined measurement of the flow out of the sand filters.

DO, turbidity, pH, temperature and water level are continuously measured and registered. DO is measured by an optical device of type FDO 700 from WTW with a nominal accuracy of 0.1 mg L^{-1}. Turbidity is measured by a VisoTurb 700 meter from WTW with a nominal accuracy of 0.05 FNU. Both the FDO 700 probe and the VisoTurb 700 probe are supplied with compressed air cleaning heads. The pH is measured by a SensoLyt SEA probe from WTW and temperature is registered through the NTC temperature probe build into the pH-meter. The water level is metered by a Hydrobar I pressure transducer from Klay-Instruments with an accuracy of 1 cm.

The instruments are placed on a movable frame to facilitate maintenance of the probes. The frame is placed in the pond at approximately 1 m of water, ensuring 0.5–0.7 m of water coverage over the sensors. The pressure transducer is fixed at the bottom of the pond by means of a concrete slab.

RESULTS AND DISCUSSION

Figure 3 shows the result of continued water quality measurement in the pond for the period February 12, 2008 till April 5, 2009. The total inflow to the pond in this period was 79,900 m^3, corresponding to an average residence time of the stormwater of approximately 10 days.

The variability in pH and DO during spring, summer and autumn were large compared to the variability during winter. During much of the summer the DO was above 20 g m^{-3}–i.e. more than 200% of oxygen saturation–whereas it at other times fell to zero, albeit only for short durations. The DO supersaturation was most likely caused by suspended algae as the rooted plants were newly planted and only covered the brinks of the pond. Low oxygen levels occurred mainly during night and early morning and could have been caused by algae as well as bacteria in the pond sediments. The periodic oxygen supersaturation began middle of April and lasted till middle of November. In other words, photosynthesis played a significant role from early spring till late autumn.

Stormwater inflow events caused rapid changes in oxygen, pH and turbidity. As an example hereof, Figure 4 shows data from April 14 to May 14, 2008. The first and the second inflow event caused pH to drop approximately one pH unit–the larger inflow event causing the larger pH-drop. At the first event, the DO concentration dropped by approximately 7 g m^{-3}, the cause being that the pond water was supersaturated with oxygen prior to this event whereas the stormwater probably was saturated. At the second inflow event, the DO was only slightly affected, as DO in the pond was close to saturation.

The turbidity of the pond water increased upon these events, and slowly decreased during the following dry weather periods with a rate that was approximately exponential (Figure 4). Whether the increase in turbidity during storm events was caused by the incoming stormwater, by resuspension of bottom sediments or by a combination is not clear.

From the beginning of May, the pond water turbidity showed diurnal variations during dry weather (Figure 4). Turbidity increased during the day and decreased during the night. Similarly, DO exhibited clear diurnal variation with variations as high as 5–8 g m^{-3}. Some days of July, DO fell overnight from supersaturation to nearly zero (Figure 3). Bulk water pH varied over the day with as much 1 pH unit. All three parameters peaked in the late part of the day. Such variability is typical for photosynthesis, but also bacterial activity could have played a role.

The pond water temperature varied with daily amplitudes up to 3°C. The lowest temperature occurred in the morning and the highest temperature in late afternoon. The temperature variations in the pond were only insignificantly affected by even the largest of the storm events, indicating that the incoming stormwater was of a temperature similar to the pond water.

Scrutinizing the turbidity of the pond water in comparison with the inflow to the pond, increases in turbidity were often seen to occur within 1–2 hours of the onset of inflow. The response time of the turbidity on the incoming stormwater tended to decrease with increasing inflow rates. Similarly, changes in pH and DO due to inflowing stormwater occurred within hours of the onset of a storm event. The average retention time of stormwater from individual events was significantly larger than the time until the turbidity, DO and pH in the middle of the pond was affected, meaning that the flow through the pond did not

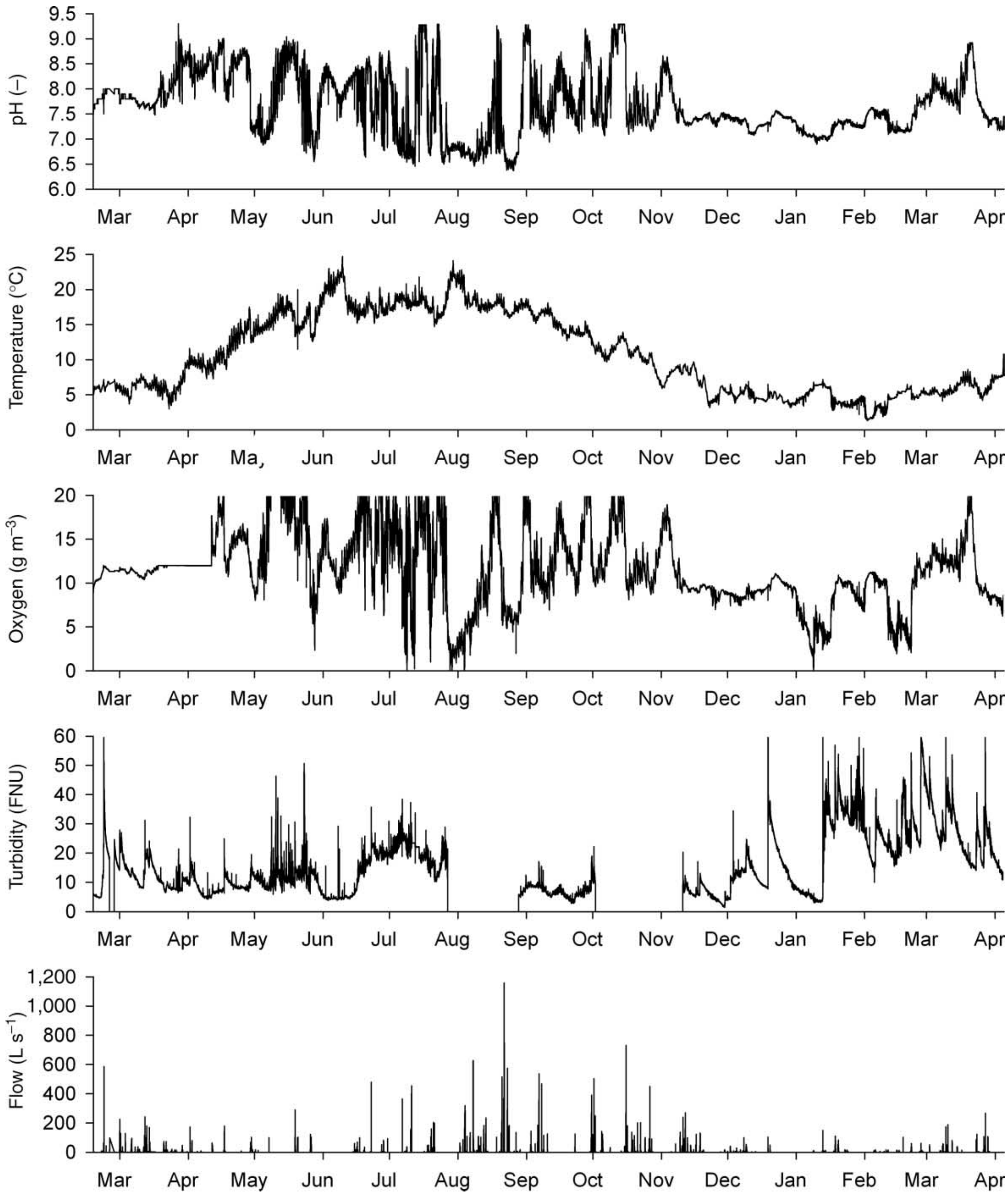

Figure 3 | pH, Temperature DO and turbidity in the middle of the pond as well as pond inflow for the period February 12, 2008 till April 5, 2009.

occur as plug-flow and that the incoming stormwater was rapidly mixed with the water initially in the pond. Vollertsen *et al.* (2007) reports a similar observation analyzing the treatment efficiency of a Norwegian stormwater pond of comparable geometry.

Length to width ratios of retention ponds have typically been recommended to above 3:1 to ensure that the incoming stormwater does not shortcut its way to the outlet (Mays 2001). However, as even the length to width ratio of 4.5:1 applied in the studied pond resulted in a flow pattern closer

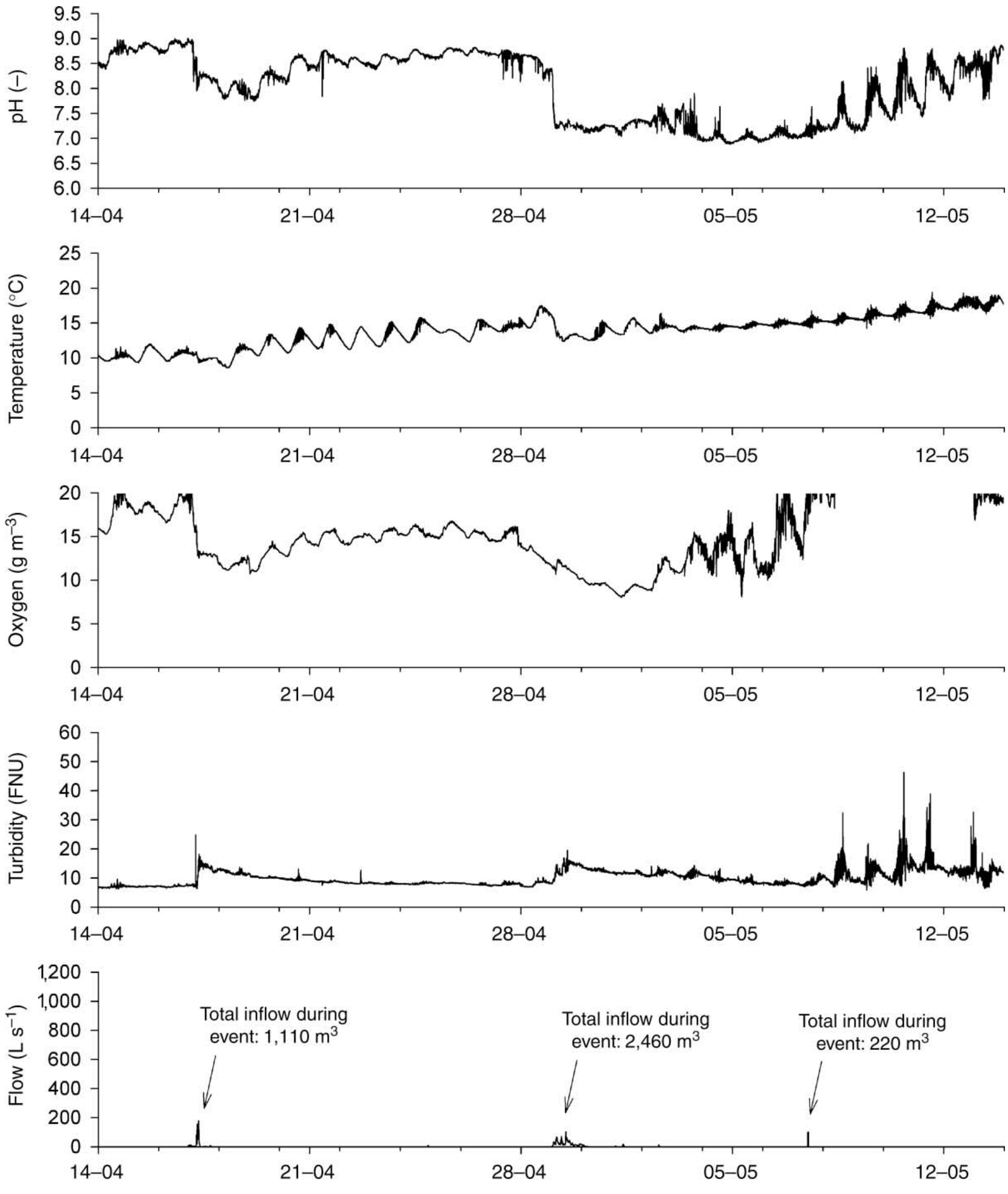

Figure 4 | One month of the continual measurements shown in Figure 3.

to a completely mixed reactor than to a plug flow reactor, the important design parameter is not so much the length to width ratio but the avoidance of shortcuts between inlet and outlet. The later can be achieved with any pond configuration when designing the inlet and outlet appropriately.

With respect to removal of nitrogen and phosphorus the treatment train consisting of wet pond, sand filter and sorption filter was very efficient (Figure 5). It removed orthophosphate to below the detection limit (0.005 g P m^{-3}) for 75% of the time, total phosphorus to an average of

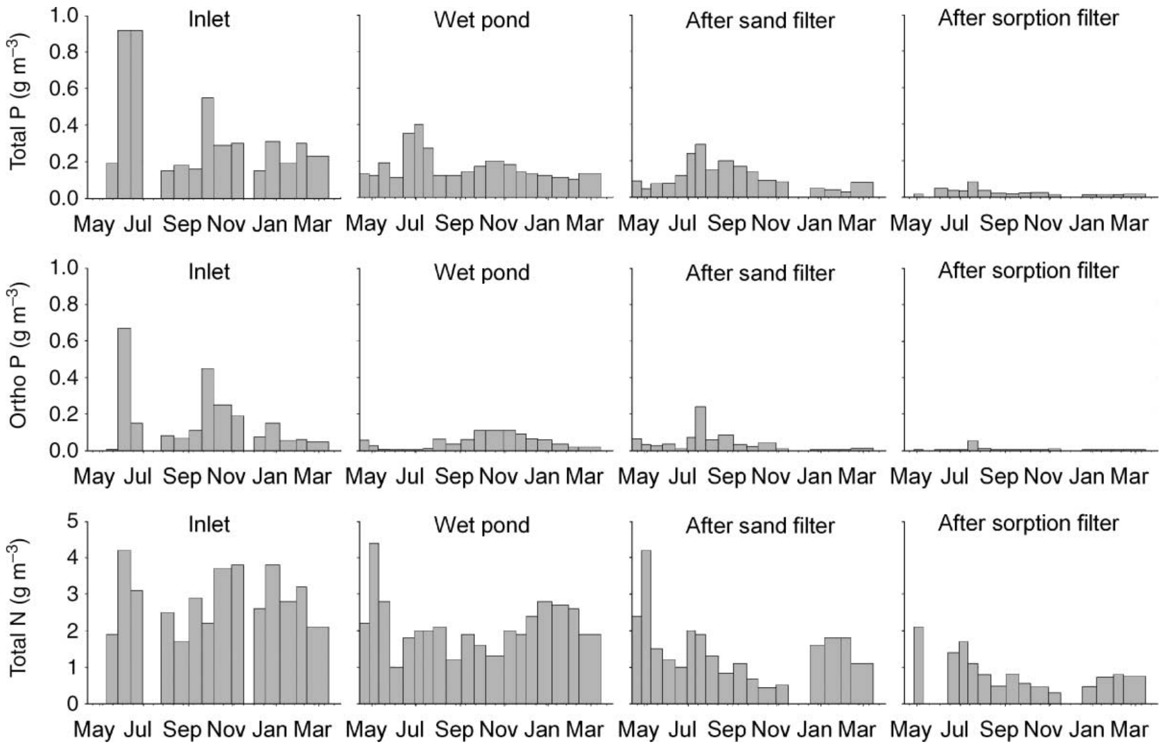

Figure 5 | Total phosphorus, orthophosphate and total nitrogen from April, 2008 till March, 2009.

$0.028\,g\,P\,m^{-3}$ and total nitrogen to an average of $1.3\,g\,N\,m^{-3}$.

The removal processes in such a treatment train is a combination of sedimentation, biological uptake, filtration and sorption. Taking for example phosphorus in the pond, an increase in total phosphorus in June and July was accompanied by low concentrations of orthophosphate because the algae bloom during this period caused a depletion of bioavailable phosphorus. The sand filters removed some total phosphorus but little orthophosphate, while the sorption filters were much more effective in this respect. With respect to nitrogen, the sedimentation in the wet pond and the sand filtration was the most effective unit operations.

CONCLUSION

Continuous measurements of pH, turbidity, temperature and DO have been applied to monitor the startup of a newly established stormwater retention pond. The data showed for example that algal photosynthesis was important from early spring till late autumn. During this part of the year, diurnal variations in DO and pH were quite significant and DO could over night go from supersaturation to nearly zero. Another important observation was that the flow through the pond did not occur as plug flow but that the water rapidly became completely mixed–even though the length to width ratio was as high as 4.5:1. The removal of phosphorus and nitrogen in the facility was very good, and the effect of the different unit operations in the treatment train was documented. For total phosphorus and orthophosphate the sorption filters were crucial to ensure low outlet concentrations, whereas they played a minor role for total nitrogen.

The monitoring of the pond continues till autumn 2009, and includes measurement of heavy metals and PAH. Together with the online measurements, the chemical water quality parameters are expected to yield knowledge on the detailed behavior of the pond which will allow an improved understanding of the pollutant removal mechanisms in wet retention ponds.

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REFERENCES

Brix, H., Arias, C. A. & del Bubba, M. 2001 Media selection for sustainable phosphorus removal in subsurface flow constructed wetlands. *Water Sci. Technol.* **44**(11–12), 47–54.

Calver, A. 2001 Riverbed permeabilities: information from pooled data. *Ground Water* **39**(4), 546–553.

Dechesne, M., Barraud, S. & Bardin, J.-P. 2005 Experimental assessment of stormwater infiltration basin evolution. *J. Environ. Eng.–ASCE* **131**(7), 1090–1098.

Genc-Fuhrman, H., Mikkelsen, P. S. & Ledin, A. 2007 Simultaneous removal of As, Cd, Cr, Cu, Ni and Zn from stormwater: experimental comparison of 11 different sorbents. *Water Res.* **41**(3), 591–602.

Houston, S. L., Duryea, P. D. & Hong, R. 1999 Infiltration considerations for ground-water recharge with waste effluent. *J. Irrigation Drainage Eng.* **125**(5), 264–272.

Hvitved-Jacobsen, T., Johansen, N. B. & Yousef, Y. A. 1994 Treatment systems for urban and highway run-off in Denmark. *Sci. Total Environ.* **146**/**147**, 499–506.

Marsalek, J., Rochfort, Q., Mayer, T., Servos, M., Dutka, B. & Brownlee, B. 1999 Toxicity testing for controlling urban wet-weather pollution: advantages and limitations. *Urban Water* **1**(1), 91–103.

Mays, L. W. (ed.) 2001 *Stormwater Collection System Design Handbook*. McGraw-Hill, (ISBN 0-07-135471-9).

Pettersson, T. J. R., German, J. & Svensson, G. 1999 Pollutant removal efficiency in two stormwater ponds in Sweden. In: Joliffe, I. B. & Ball, J. E., *Proceedings of the 8th International Conference on Urban Storm Drainage, Sydney, Australia, August 30–September 3, 1999, 866–873*. ISBN 0-85825-718-1.

Rauch, W. & Stegner, Th. 1994 The colmation of leaks in sewer systems during dry weather flow. *Water Sci. Technol.* **30**(1), 205–210.

Reed, S. C., Crites, R. W. & Middlebrooks, E. J. 2006 *Natural Wastewater Treatment Systems*. Taylor & Francis Group, LLC; CRC Press, (ISBN 0-8493-3804-2).

Semadeni-Davies, A. 2006 Winter performance of an urban stormwater pond in southern Sweden. *Hydrological Processes* **20**(1), 165–182.

Tuccillo, M. E. 2006 Size fractionation of metals in runoff from residential and highway storm sewers. *Sci. Total Environ.* **355**(1–3), 288–300.

Vohla, C., Põldvere, E., Noorvee, A., Kuusemets, V. & Mander, Ü. 2005 Alternative filter media for phosphorus removal in a horizontal subsurface flow constructed wetland. *J. Environ. Sci. Health A Tox. Hazard. Subst. Environ. Eng.* **40**(6–7), 1251–1264.

Vollertsen, J. & Hvitved-Jacobsen, T. 2003 Exfiltration from gravity sewers: a pilot scale study. *Water Sci. Technol.* **47**(4), 69–76.

Vollertsen, J., Åstebøl, S. O., Coward, J. E., Fageraas, T., Madsen, H. I., Nielsen, A. H. & Hvitved-Jacobsen, T. 2007 Monitoring and modeling the performance of a wet pond for treatment of highway runoff in cold climates. In: Morrision, G. M. & Rauch, S. (eds) *Highway and Urban Environment. Alliance for Global Sustainability Bookseries Science and Technology: Tools for Sustainable Development*. Springer, The Netherlands, pp. 499–509, (ISBN 978-1-4020-6009-0).

Westholm, L. J. 2006 Substrates for phosphorus removal–potential benefits for on-site wastewater treatment? *Water Res.* **40**(1), 23–36.