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Removal of soluble and colloidal pollutants from stormwater in full-scale detention ponds

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ABSTRACT

The startup of a wet retention pond designed for extended stormwater treatement was monitored by continued measurement of hydraulic parameters (inflow, outflow and water levels) as well as quality parameters in the pond itself (pH, temperature, dissolved oxygen, turbidity). The data revealed that algae became active as early as the beginning of March, affecting the dissolved oxygen content. 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 large as 4.5:1.

KEYWORDS

Stormwater, retention pond, continuous monitoring

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. phosphorous, 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 land use, such as traffic intensities, industries, building materials, and etceteras.

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 technology successfully addresses the issue of removing pollutants associated with particulate matter and the issue of avoiding scouring of stream beds. However, the impacts of the colloidal and soluble pollutants are not addressed. Among the commonly applied technologies, wet basins and constructed wetlands are the more efficient 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 have an excellent pollutant removal performance with respect to particulate matter. However, the removal rate of dissolved and colloidal pollutants is comparatively low (Vollertsen et al., 2007). Unfortunately, especially pollutants on dissolved form or associated with colloids are mobile in the aquatic ecosystem, are more available for biological uptake and do consequently have a higher potential for causing ecotoxic impacts on the receiving water bodies.

It is therefore an environmental issue to remove the dissolved and colloidal fraction of the 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 micropollutants. 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, a sand filter and a technology for sorption of dissolved and colloidal pollutants. In contrast to traditional wet retention ponds, these ponds do not only apply the treatment process of sedimentation, but also actively apply the treatment by plant uptake, filtration and sorption.

The 3 facilities are planted with different plant species and apply different technologies for pollutant sorption, namely:

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

The facilities are constructed with continuous monitoring in mind, and contain equipment for measuring of inlet flow, outlet flow, dissolved oxygen (DO), pH and turbidity as well as flow proportional water sampling of all incoming and outgoing water. Water samples are analyzed for water quality parameters and used to establish the efficiency of the different treatment processes implemented in the designs. The monitoring began primo 2008 and the project is completed by September 2009.

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 initial monitoring results.

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 runoff from the catchment is estimated to 55.500 m^{3}. A permanent rain gauge from the Danish SVK system (SVK 28186) is located a few kilometers from facility.

The layout of the facility

The stormwater is piped to the facility by two 800 mm concrete pipes. The facility is constructed as a wet retention pond followed by sand filtration and fixed media sorption (Figure 1). The sand filtration 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, within the pond, after the sand filters and after the sorption filters. A number of water quality parameters are measured continuously in the pond water. The pond went into operation November 2007.

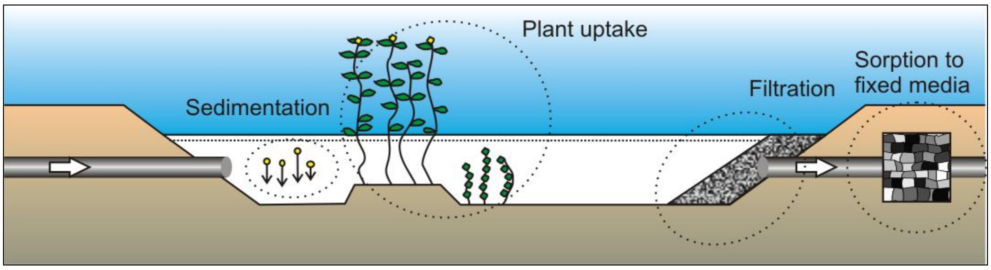

Figure 1. Schematics of the facility with sorption in fixed media filters

Wet pond

The pond is located east-west with a public footpath paralleling the northern embankment and industries located to the south (Figure 2). On the northern side, the embankment has a slope of 1:5 and on the southern side the slope is 1:3. The pond bottom is made impermeable by a clay membrane of no less than 30 cm magnitude.

The southern embankment is planted with large littoral helophytes (ranunculus lingua, phragmites australis, typha angustifolia, rumex hydrolapathum, typha latifolia), whereas the northern embankment is planted with smaller littoral helophytes (typha minima, iris pseaudacorus, sagittaria sagittifolia, calla palustris, iris pseaudacorus, alisma lanceolata). In the center of the pond, at a water depth of 1.5 m, nymphaea nuphar is planted.

Figure 2. The pond seen from the inlet (left photo) and from the outlet (right photo)

Key design data for the wet pond is shown in Table 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).

Table 1. Key design data for the wet pond

Retention volume	1,992 m^3	Length to width ratio	4.5 m m^{-1}
Surface area of retention volume	2,064 m^2	Max depth of retention volume	1.45 m
Detention volume	1,310 m^3	Max outflow from the facility	0.025 m^3 s^{-1}
Surface area at max detention water level	2,689 m^2	Number of annual overflows	5

Sand filters

Sand filtration of the effluent from a wet retention pond is an efficient method for retaining particles. During the filtration process, particles are deposited on the surface of the filter, creating a colmation layer. This layer will typically have a much lower hydraulic conductivity than the filter medium, controlling the overall hydraulic capacity of the filter. 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 project, three different sand filter layouts are tested (Figure 3):

- A horizontal filter placed at the same level as the permanent water level of the pond. When the water level rises, all the filter surface becomes submerged simultaneously and becomes subject to an evenly distributed water pressure while the pond water level rises and falls. This filter is expected to build up a colmation layer of homogenous depth as all the surface is subject to stormwater.
- A sloping filter placed at the embankments. The active filter area starts on level with the permanent water level of the pond and goes up to the allowable maximum water depth of the storage volume. When the water level rises, the active filter area increases correspondingly. This filter is expected to build up the deepest colmation layer close to the water surface, with a decreasing colmation layer depth towards the maximum water level of the pond.
- A vertical filter placed in the pond. The active filter area starts on level with the permanent water level of the pond and goes up to the allowable maximum water depth of the storage volume. When the water level rises, the active filter area increases correspondingly. The filter material is kept in place by a rigid structure and a geo textile. This filter is expected to build up only a thin colmation layer as the colmation layer is expected to crack off the geo-textile during dry weather periods and fall back into the permanent water pool. The lowest leakage factor is expected close to the water surface.

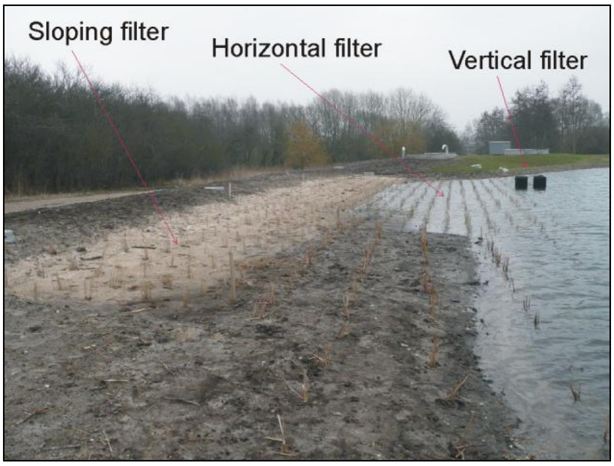

Figure 3. Sand filters

The sand filter has been designed based on a leakage factor approach as e.g. applied by Vollertsen and 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 and Stegner, 1994). I.e. the flow through the colmation layer can be described by Equation 1.

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

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 the conclusion that the hydraulic conductivity of a colmation layer formed under a permanent water level is likely to be no less than 10^{-7} m s^{-1}, and that a likely value is 1-2 decades higher (Vollertsen and Hvitved-Jacobsen, 2003; Houston et al., 1999; Calver 2001; 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 10^{-4} m^3 m^{-2} s^{-1} at 0.5 m of water depth, i.e. a leakage factor of 2.2 10^{-4} s^{-1}. For stormwater infiltration through a filter with intermittent loading, a design leakage factor of around 10^{-4} s^{-1} therefore seems to be a conservative choice. The horizontal sand filter is believed to develop the deepest colmation layer, followed by the sloping filter and the vertical filter. Based here on the filter dimensions in Table 2 have been applied.

Table 2. Sand filter dimensions. The water runs through the filters by gravitation.

	Design leakage factor	Dimensions	Area
Horizontal sand filter	10^{-4} s^{-1}	1 filter of 20 m length and 5 m width	100 m^2
Sloping sand filter	10^{-3} s^{-1}	1 filter of 30 m length, 3 m width and slope 1:5	90 m^2
Vertical sand filter	10^{-2} s^{-1}	4 filters of 0.5 m diameter and 0.55 m height	3.5 m^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 (Westholm, 2006; Brix et al., 2001; Vohla et al., 2005). When it comes to the control of heavy metals, materials containing alumina and iron have shown to be effective (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 in 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 surface area of 24 m^2 and holds 55 m^3 of Oyta Shells (Oytaco Ltd, Denmark), a natural product obtained from large deposits of fossil oyster shells in the shallow waters of the North Sea. The material 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.

Inlet flow monitoring

The first step of the flow monitoring is a silt trap of 26 m^3 under dry weather conditions. The main purpose of the silt trap is to protect the flow meters from permanent deposits. Flow measurement itself 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 (Figure 4). 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 (Figure 4). 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. After the pond has been in operation for some time, the weir equation will be calibrated based on the full flowing magnetic flow meters together with information from the rain gauge and hydrodynamic model simulations.

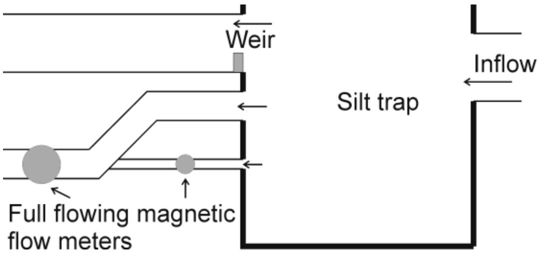

Figure 4. Flow metering at the pond inlet

Outlet flow monitoring

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 measurement accuracy better than 1% for flow rates above 1.5 L s^{-1}.

Water quality sampling

Flow proportional water samples are collected by automated water samplers of type Maxx TP IV, holding 24 1-liter 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.

Continued measurement in the wet pond

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 (Figure 5). 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 in place on the bottom of the pond by means of a concrete slab.

Figure 5. Placement of the continuous measurement probes in the pond.

Results

Figure 7 through Figure 9 show the result of continued water quality measurements in the pond (Figure 5) for the period March 6-18, 2008. The graphs on the left hand side show the water quality parameters related to the measured inflow rate; the graphs on the right hand side show the same parameters related to the water level in the pond. As the outlet from the pond is restricted to a maximum of 0.025 $m^3\ s^{-1}$ (Table 1), the water level in the pond gives an indication of the total runoff volume during events of higher intensity.

During the measuring period, several smaller storms and one larger storm occurred. The total inflow to the pond during that period was 5,920 m^3, corresponding to 3.0 times the retention volume of the basin (Table 1). The large runoff event around March 11-13 caused runoff for about 42 hours and a runoff volume of 3,220 m^3, corresponding to 1.6 times the retention volume of the pond.

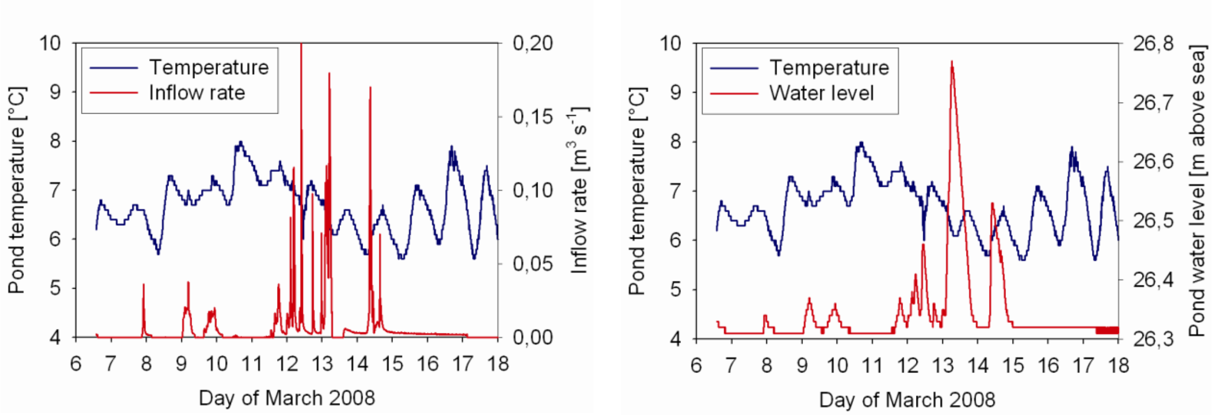

Figure 6. Continued measurement of temperature versus the inflow rate to the pond and the water level in the pond

The temperature of the pond water showed a clear diurnal variation with amplitude up to 1°C (Figure 6). The lowest temperature occurred in the morning and the highest temperature in late afternoon – i.e. corresponding to the daylight period. 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.

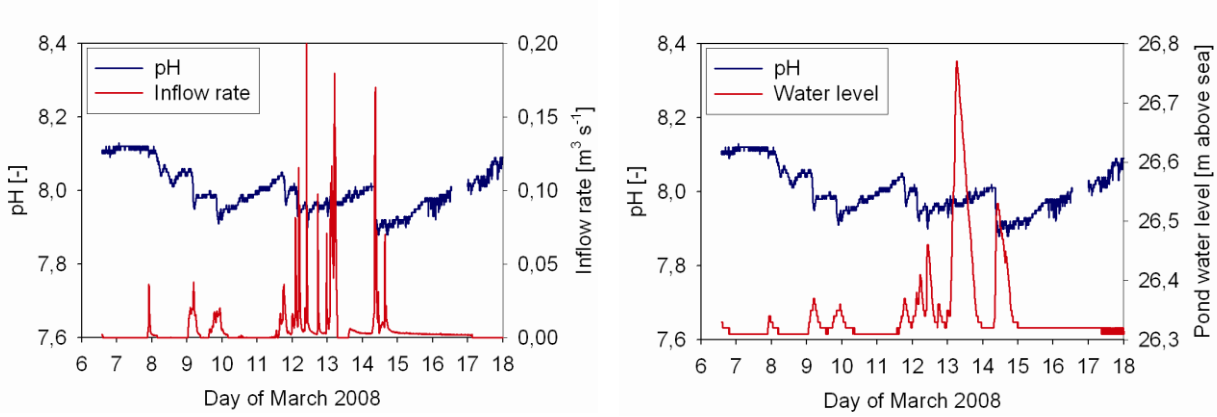

Figure 7. Continued measurement of pH versus the inflow rate to the pond and the water level in the pond

The pH of the pond water was, on the other hand, affected by the incoming stormwater (Figure 7). In case of the smaller runoff events, the stormwater caused pH-drops of around 0.05 to 0.1 pH-units. For example the event occurring during the night between March 7 and March 8, caused pH to drop from 8.10 to 8.01, a drop of 0.09 even though the total runoff volume was only 180 m^3 – i.e. only 9% of the pond retention volume. During the large runoff event around March 11-13, only the first part of the event caused a pH-drop, the later part of the event did only affect the pH slightly, even though the runoff volume was much larger during that part of the event. This seems to indicate that the small runoff events and the first part of the larger events were of lowest pH.

During dry weather periods, the pH slowly increased to around 8.1. Such pH change can be caused either by chemical equilibrium kinetics (the carbonate system) or by biological activity (algae growth). The increase had a tendency to occur somewhat in steps – with most (but not all) of the increases occurring during the daytime hours. This indicates that biological activity played a major role in the pH increases.

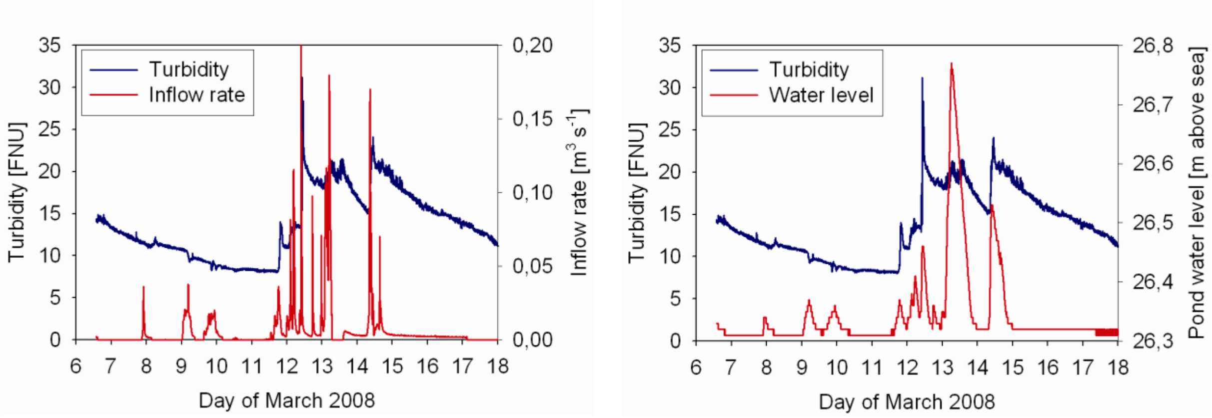

Figure 8. Continued measurement of turbidity versus the inflow rate to the pond and the water level in the pond

The turbidity of the pond water was strongly affected by the larger runoff events but nearly unaffected by the smaller events (Figure 8). Comparing the effect of the inflow rate on the turbidity (left hand graph) with the effect of the water level (right hand graph), it becomes clear that the later is the more important parameter with respect to turbidity increase. A large runoff volume of high intensity would cause more turbulence in the pond compared to a smaller runoff volume of a similar intensity or a similar runoff volume of smaller intensity. It therefore seems appropriate to conclude that the increase in turbulence is caused by resuspension of pond bottom material – i.e. by resuspension of material from the clay membrane.

During dry weather periods, the turbidity of the pond water decreased with a rate that was approximately exponential. During a prolonged dry weather period occurring the first half of February, the turbidity decreased down to 5 FNU (data not shown).

Scrutinizing the turbidity of the pond water in comparison with the inflow to the pond it is seen that the change in turbidity occurred 1 to 6 hours after the onset of the inflow. The response time of the turbidity on the incoming stormwater tended to decrease with increasing inflow rates. The average retention time of the water from the individual events was significantly larger than the time until the turbidity in the middle of the pond was affected, meaning that the flow through the pond did not 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 (ed.), 2001). However, as even the length to width ratio of 4.5:1 applied in the studied pond resulted in a flow pattern closer to a completely mixed reactor than it did to a plug flow reactor, it can be argued that 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.

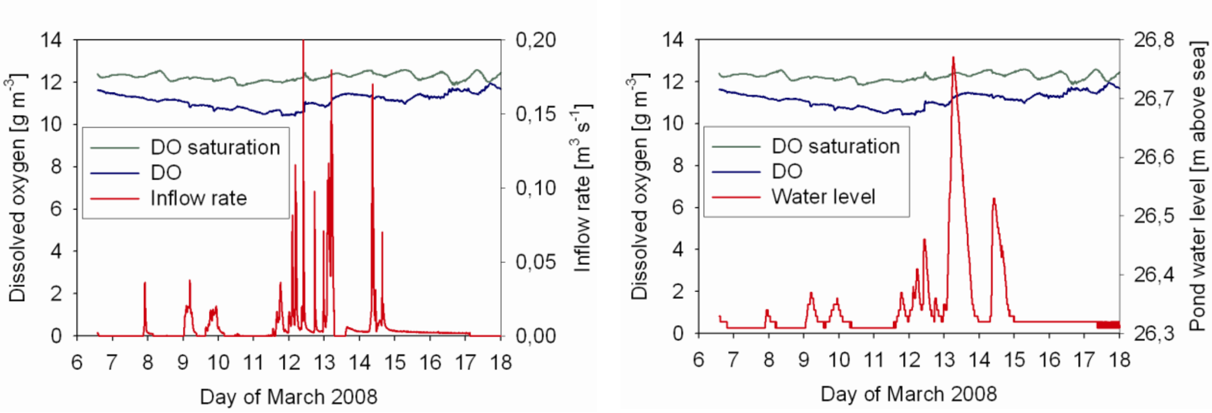

Figure 9. Continued measurement of dissolved oxygen (DO) and the theoretical DO saturation concentration versus the inflow rate to the pond and the water level in the pond

DO in the pond water was always below the theoretical saturation concentration (Figure 9), meaning that oxygen removing processes must have occurred in the pond. Such processes would be of biological nature, a hypothesis which is strengthened by observing the DO variation over the day. During dry weather, the DO concentration increased during the daylight hours and decreases during the night – a pattern typical for the oxygen production and uptake due to photosynthesis. As the planted macrophytes were not yet active during the measuring period, the photosynthesis must be caused by algae. Later the same month (data not shown), DO increased to values around 1.5 times saturation, clearly proofing that photosynthesis was the cause of the variations seen during the reported measuring period.

CONCLUSION

Continuous measurements of pH, turbidity, temperature and dissolved oxygen have been applied to monitor the startup of a newly established stormwater retention pond. The data showed for example that algae in the pond became active already during the month of March as the length of the day – and hereby the incoming sun-radiation – increased. 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 monitoring of the pond will continue for 1½ year, and samples from the inlet and outlet of the pond will be collected for chemical water quality analysis during this period. Together with the online measurements, the chemical water quality parameters will be applied to study the detailed behavior of the pond. It is the believe of the authors that this intensive monitoring, together with the similar monitoring of the two other ponds constructed in the context of the EU LIFE Treasure project, will allow an improved understanding of the pollutant removal mechanisms in wet retention ponds.

ACKNOWLEDGEMENTS

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