Performance and Modelling of a Highway Wet Detention Pond Designed for Cold Climate

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A wet detention pond in Norway has been monitored for 12 months. The pond receives runoff from a highway with a traffic load of 42,000 average daily traffic. Hydraulic conditions in terms of inflow, outflow, and pond water level were recorded every minute. Water quality was monitored by volume proportional inlet and outlet samples. During most of the year, excellent pollutant removal was achieved; however, during two snowmelt events the pollutant removal was poor or even negative. The two snowmelt events accounted for one third of the annual water load and for a substantial part of the annual pollutant discharge. The performance of the pond was analyzed using a dynamic model and pollutant removal was simulated by first-order kinetics. Good agreement between measurement and simulation could be achieved only when choosing different first-order rate constants for different parts of the year. However, no relation between the rate constants obtained and the time of year could be identified, and neither did the rate constants for different pollutants correlate. The study indicates that even detailed measurements of pollutant input and output allow only average performance to be simulated and are insufficient for simulating event-based variability in pond performance.

Key words: wet detention pond, snowmelt, first-order process, highway runoff

Introduction

Deterioration of receiving water bodies due to development is a substantial environmental problem, and the wish for improved aquatic environments has driven the implementation of urban wastewater treatment. In many countries, wastewaters are today treated to discharge levels deemed not to harm the environment. Disregarding these efforts, many receiving waters continue to be of poor ecological quality. The reasons are many, but often stormwater discharges from urban areas and roads are an important part of the problem (e.g., Schiff et al. 2003).

The need for treating stormwater runoff is therefore becoming more widespread, and a number of technologies for stormwater runoff treatment have been developed. A technology that in this context has proven itself effective and affordable is the wet detention pond, where a permanent wet pool is combined with a stormwater detention volume. Such a pond is intended for detention of the runoff water long enough to allow physical, chemical, and biological processes to proceed. Well designed wet detention ponds yield very good and stable pollutant reduction (U.S. FHWA 1996).

Under cold climate conditions, freezing and snowmelt constitute major additional challenges for the design and operation of wet detention ponds. During winter, ponds freeze over and during snowmelt, the ponds are often ice covered. The runoff must therefore either pass over the ice or under it, with impaired treatment being the consequence. At the same time, the amount of snow stored on the highway shoulders and adjacent sloping areas can be substantial, and it often melts over just a few days, resulting in long periods of high flow rates through the pond. At the same time, the pollutant content of snow stored on highway shoulders is generally high, containing accumulated contaminants from the road traffic (e.g., Sansalone et al. 2002).

It is the objective of this study to analyze the performance of a wet detention pond designed for cold climate conditions. The pond has been intensively monitored over a 12-month period, including continuous flow measurements and continuous stormwater sampling. The performance of the pond is analyzed and pollutant removal is modelled based on the monitored

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flow and pollutant time series. Pond design methods and approaches to simulate the pond performance are discussed.

**Methods**

The pond investigated is located at the Skullerud junction of the E6 highway in the greater Oslo area, Norway, where the highway has a traffic load of 42,000 average daily traffic. The pond serves a total area of 3.4 ha of which 2.2 ha are paved and 1.2 ha are vegetated. E6 accounts for 1.5 ha of the paved area, while 0.5 ha are junction ramps. The last 0.2 ha are walkways and bikeways (Åstebol and Coward 2004). The annual average temperature in the region is approximately 5°C and the annual average precipitation is between 700 and 1,000 mm.

The pond itself is divided into a rectangular silt trap cast in concrete and an earthen pond with impermeable lining (Table 1 and Fig. 1). The inlet to the silt trap is a 400-mm PVC (polyvinyl chloride) pipe and the outlet from the earthen pond is a 315-mm PVC pipe. Both pipes are submerged to ensure proper hydraulic operation also when the pond is ice covered.

The pond was designed for stormwater treatment according to the U.S. EPA (1986) and Hvitved-Jacobsen et al. (1994), with stormwater residence times exceeding 72 hours for the majority of storm events. Residence times below 72 hours were designed to occur 3 to 4 times a year. The length-to-width ratio of the pond is 4:1 and the pond geometry promotes plug-flow conditions (Fig. 1). Due to physical constraints at the pond site, the storage volume is rather small (Table 1).

The inlet flow and the outlet flow were continuously monitored by two velocity/pressure censors located in the full-flowing and submerged inlet and outlet pipes. The flow and the water pressure were logged every minute and the water pressure was related to the water level of the pond. The flow meters had an accuracy of 2% of the measured value. The inlet flow meter could detect flows between 2.6 and 565 L·s⁻¹ and the outlet flow meter could detect flows between 1.5 and 318 L·s⁻¹. It is estimated that the inlet flow meter allowed 90 to 95% of the flow volume to be recorded. In addition to the flow monitoring, rainfall intensity and air temperature were continuously monitored and recorded.

<table>
<thead>
<tr>
<th>TABLE 1. Pond dimensions</th>
<th>Silt trap</th>
<th>Earthen pond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface area, dry weather (m²)</td>
<td>68</td>
<td>910</td>
</tr>
<tr>
<td>Volume, dry weather (m³)</td>
<td>103</td>
<td>710</td>
</tr>
<tr>
<td>Volume, wet weather (m³)</td>
<td>117</td>
<td>904</td>
</tr>
<tr>
<td>Water depth, dry weather (m)</td>
<td>1.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Max water depth, wet weather (m)</td>
<td>1.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Fig. 1. The Skullerud pond.
Runoff water quality was assessed by flow proportional sampling during the period May 1, 2003 to April 30, 2004. A sample was taken from the inlet and the outlet for every 8 m³ of stormwater runoff. Samples were lumped and 28 combined samples were analyzed from both the inlet and the outlet. The samples covered 87% of the incoming stormwater volume. Samples were analyzed according to Norwegian standards for total PAH, 4-PAH [benzo(b)fluorantene, benzo(k)fluorantene, benzo(ghi)perylene, and indeno(1,2,3-cd)pyrene], oil and grease, suspended solids, total nitrogen, total phosphorus, bioavailable phosphorus [molybdreactive phosphorus according to Blakar and Løvstad (1990)], lead, cadmium, copper, zinc, pH, and conductivity. Basically, these methods correspond to well-known international standards, e.g., APHA et al. (2005).

Average Pollutant Removal Rates

The annual average performance was assessed as the average area-specific removal rate (equation 1) and the average volume-specific removal rate (equation 2); e.g. as applied by Carleton et al. (2001).

\[
\frac{M_{\text{out}}}{M_{\text{in}}} = e^{\frac{-k_{a}}{q_{A}}}
\]

(1)

\[
\frac{M_{\text{out}}}{M_{\text{in}}} = e^{\frac{-k_{v}}{q_{V}}}
\]

(2)

where:
- \(k_{a}\) is an average area-specific rate constant (m·yr⁻¹);
- \(k_{v}\) is an average volume-specific rate constant (yr⁻¹);
- \(M_{\text{out}}\) is the annual pollutant mass discharged from the pond (g·yr⁻¹);
- \(M_{\text{in}}\) is the annual pollutant mass entering the pond (g·yr⁻¹);
- \(q_{A}\) is the area-specific hydraulic loading rate (m²·m⁻²·yr⁻¹);
- \(q_{V}\) is the volume-specific hydraulic loading rate (m³·m⁻³·yr⁻¹).

Dynamic Simulation

The water balance in terms of the pond volume \(V\) was calculated continuously and with a 1-minute time resolution, corresponding to the frequency of the flow and level measurements. The balance consisted of the measured inflow \(Q_{\text{in}}\), the calculated outflow \(Q_{\text{out}}\), the measured precipitation \(I\), the estimated evaporation \(E\), and a residual term \(R_{\text{res}}\) as stated in equation 3. Infiltration and exfiltration were not taken into account as the pond was clad with an impermeable liner. Direct precipitation into the pond was included with 60% of the earthen pond surface \(A_{\text{pond}}\) since approximately 40% of the pond surface was placed beneath a highway bridge and hence protected from most precipitation (Fig. 1). Outlet flows were simulated from the modelled pond water levels since the measured outlet flows could not account for all inlet flow (Fig. 2). The dependency of the flow on the water level was calibrated from flow and water level measurements of large storm events. Evaporation was estimated from decreases in pond water level during dry weather periods, assuming that evaporation occurred from only the earthen pond surface and not from the closed silt trap.

\[
\frac{dV}{dt} = Q_{\text{in}} + I_{p} (0.6 A_{\text{pond}}) - Q_{\text{out}} - E_{a} A_{\text{pond}} + R_{\text{res}}
\]

(3)

The treatment performance of the pond was simulated as a varying-volume reactor and by two different mixing approaches: 1) a number of fully mixed compartments in series where the number of compartments varied from 1 to 200, i.e., from dry weather compartment sizes of 813 m³ to approximately 4 m³, and 2) plug-flow compartments where the compartment sizes equaled the inflows during the 1-minute time steps.

Simultaneous to the water balance, the removal of each pollutant was simulated by first-order kinetics (equation 4) as, for example, proposed by Mitsch et al. (1995). The true removal processes in a wet detention pond are a complex combination of physical, biological, and chemical processes, including particle sedimentation,

Fig. 2. Pond inflow and outflow.
adsorption of pollutants to particles, adsorption of colloids to fixed surfaces, resuspension of sediments, as well as absorption of soluble pollutants by plants and microorganisms. First-order pollutant removal kinetics was chosen even though such simple kinetics has limitations when modelling wet detention pond processes (Kadlec 2000). However, it is believed a reasonable choice for simulation of pollutant removal when the detailed processes are not well understood (Hvitved-Jacobsen et al. 1994).

\[
\frac{dC}{dt} = -k_C C
\]  

(4)

where \(C\) is the concentration of pollutant C [g·m\(^{-3}\)] and \(k_C\) is the specific first-order rate constant of pollutant C [d\(^{-1}\)].

The residence time of the stormwater was found by two approaches. First, the plug flow approach was applied to find the residence time of each plug of stormwater entering the pond. Second the residence time was determined by adding an individual model-tracer to each volume of stormwater entering the pond and following those tracers through the pond. The residence time of a water volume entering the pond was then defined as the time elapsed until half of the model-tracer of that water volume had passed the outlet. A thorough discussion of methods to determine pond residence times is found in Walker (1998).

Result and Discussion

During the measuring campaign, precipitation occurred both as rain and snow, and snowmelt events gave an important contribution to the total runoff to the pond. During periods with strong frost, the pond became ice covered, reducing the true stormwater residence times and treatment volumes. In February 2004, the ice sheet was measured and the free water beneath the ice was found to be just 22 to 32 cm. Furthermore, the effect of the ice sheet became evident in the water level measurements, where small decreases in water level during winter were caused by changes in water pressure due to the snow and the ice sheet (Fig. 3).

In General, more inflow than outflow was recorded, and especially from November to March the discrepancy was significant (Fig. 2). The increase in the residual in the water mass balance during winter is believed due to the ice cover of the pond, causing either pond overflows or errors in flow measurement. However, also during the warmer part of the year, measured outflow was in general less than measured inflow. The later difference was caused by the pond equalizing the outflow so that a higher fraction of the flow was below the detection limit of the outlet flow meter compared with the inlet flow meter.

During summer, significant drops in water level coincided with long dry weather periods (Fig. 3). Assuming that the decreases in water level could be attributed to evaporation only, a maximum evaporation rate of 1.5 mm·d\(^{-1}\) was deduced. Evaporation was assumed to occur from the surface of the earthen pond only since the silt trap was concrete covered. The observed evaporation was in the lower range of evaporation rates reported for the Oslo region, where Engeland et al. (2004) reported typical evaporation rates from land surfaces in the summer months of June, July, and August to be 70 to 80 mm·month\(^{-1}\). Furthermore, evaporation from a free water surface is likely to be greater than or equal to that of a land surface (Linacre 2004). The residual between expected and observed drop in pond water level was most likely caused by groundwater infiltration into the pond, even though the pond was clad with an impervious liner.

Stormwater Residence Times

The ‘plugflow approach’ and the ‘fully mixed compartment approach’ for finding stormwater residence times gave identical results when the number of compartments was chosen to be at least 100. The reduced residence times due to the ice sheet were not accounted for because the thickness of the ice was not continuously measured. This procedure resulted in some overestimation of the residence time during winter periods. As a whole, the observed residence time was below the design residence time of 72 hours for 23.8% of the flow and below 24 hours for 7.3% of the flow (Fig. 4). The residence times below 72 hours all belonged to the two large snowmelt events of February 4 to 8 and March 15 to 24, 2004.
Pollutants Measured

The flow weighted average concentrations of the measured pollutants as well as pH and conductivity are shown in Table 2 and are well within the range of values typical in Norwegian road runoff (Statens vegvesen 2004). The accumulated pollutant mass in the inflow and the outflow are shown in Fig. 5. The removal of cadmium, total PAH, and 4-PAH is somewhat underestimated since the pollutant concentrations in the majority of the outlet samples were below the detection limits. The distribution of data is not known and the conservative approach of setting measurements below the detection limit equal to the detection limit has been applied. High pollutant removal was achieved most of the year. However, during the two large snowmelt events of February 4 to 8 and March 15 to 24 (Fig. 2), pollutant removal for total P, bioavailable P, and total N occasionally became negative and the removal of other pollutants was rather low (Fig. 5). During the snowmelt events, calculated stormwater residence times became as low as 12 hours, and the true residence times must have been even lower—maybe as low as 4 to 6 hours—since the ice cover probably accounted for more than half of the pond volume.

Looking closely at the two large snowmelt events, it becomes evident that a significant part of the annual discharge originated from these events (Fig. 5). For example, for total phosphorus, 70% of the annual discharge originated from the two events, while only 32% of the annual flow and 28% of the incoming total phosphorus had this origin. For other pollutants the tendency was similar, however less pronounced for the heavy metals and total N where 30 to 50% of the annual pollutant discharge originated from the two snowmelt events. This corresponds well with other studies on stormwater ponds in cold climate, where, for example, Semadeni-Davies (2006) reported reduced pollutant removal efficiencies for ice-covered ponds.

Carleton et al. (2001) analyzed reports from 49 stormwater treatment wetlands and found a tendency towards better removal efficiency with increasing residence time. In the wetlands studied, treatment efficiencies improved for residence times above approximately two weeks. In the present study and omitting the two snowmelt events, the correlation between pollutant removal rates and pond residence times was also analyzed. However, no general tendency could be observed and the results indicated that an increased pond volume did not generally yield improved treatment efficiencies. For the management of snowmelt events, however, an increased storage volume would probably have been beneficial.

Average Pollutant Removal Rates

Through analyzing the overall pollutant removal for the measuring campaign by means of equations 1 and 2, the area-specific and volume-specific removal rate constants were found (Table 3). For 39 gravity fed stormwater treatment wetlands, Carleton et al. (2001) reported an average $k_aA$ value for total P of $11.3 \pm 17.6$ m·yr$^{-1}$, which is in very good agreement with the rate found in this study. For a limited number of wetlands, they furthermore reported treatment efficiencies for suspended solids, cadmium, copper, lead, and zinc; here, there is also good agreement with the findings of this study.

**TABLE 2. Flow weighted average pollutant concentrations in the pond inflow and the pond outflow**

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Inlet</th>
<th>Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended solids</td>
<td>276</td>
<td>43</td>
</tr>
<tr>
<td>Total P (g·m$^{-3}$)</td>
<td>0.674</td>
<td>0.262</td>
</tr>
<tr>
<td>Bioavailable P (g·m$^{-3}$)</td>
<td>0.388</td>
<td>0.146</td>
</tr>
<tr>
<td>Total N (g·m$^{-3}$)</td>
<td>1.49</td>
<td>1.05</td>
</tr>
<tr>
<td>Oil &amp; grease (g·m$^{-3}$)</td>
<td>5.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Conductivity (mS·m$^{-1}$)</td>
<td>39</td>
<td>42</td>
</tr>
<tr>
<td>pH</td>
<td>7.39</td>
<td>7.60</td>
</tr>
<tr>
<td>Total PAH (mg·m$^{-3}$)</td>
<td>1.77</td>
<td>0.26</td>
</tr>
<tr>
<td>4-PAH (mg·m$^{-3}$)</td>
<td>0.43</td>
<td>0.05</td>
</tr>
<tr>
<td>Lead (mg·m$^{-3}$)</td>
<td>17.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Cadmium (mg·m$^{-3}$)</td>
<td>0.21</td>
<td>0.08</td>
</tr>
<tr>
<td>Copper (mg·m$^{-3}$)</td>
<td>86</td>
<td>36</td>
</tr>
<tr>
<td>Zinc (mg·m$^{-3}$)</td>
<td>272</td>
<td>78</td>
</tr>
</tbody>
</table>

**TABLE 3. Long-term area-specific ($k_aA$) and volume-specific ($k_vV$) removal rate constants**

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>$k_aA$ (m·yr$^{-1}$)</th>
<th>$k_vV$ (yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended solids</td>
<td>31.0</td>
<td>36.9</td>
</tr>
<tr>
<td>Total P</td>
<td>14.7</td>
<td>17.5</td>
</tr>
<tr>
<td>Bioavailable P</td>
<td>15.4</td>
<td>18.4</td>
</tr>
<tr>
<td>Total N</td>
<td>4.4</td>
<td>5.3</td>
</tr>
<tr>
<td>Oil &amp; grease</td>
<td>28.4</td>
<td>33.7</td>
</tr>
<tr>
<td>Total PAH</td>
<td>30.9</td>
<td>36.7</td>
</tr>
<tr>
<td>4-PAH</td>
<td>37.8</td>
<td>44.9</td>
</tr>
<tr>
<td>Pb</td>
<td>23.4</td>
<td>27.8</td>
</tr>
<tr>
<td>Cd</td>
<td>15.8</td>
<td>18.7</td>
</tr>
<tr>
<td>Cu</td>
<td>13.7</td>
<td>16.2</td>
</tr>
<tr>
<td>Zn</td>
<td>21.6</td>
<td>25.7</td>
</tr>
</tbody>
</table>
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Dynamic Simulation

Simulating the overall pollutant removal with equation 4, the specific first-order rate constants in Fig. 6 were found. The simulations clearly illustrated the common fact that any model parameter depends on the model context in which it is used. For the pollutant removal simulations applying fully mixed compartments, the value of the model parameter $k_{C_{\text{mixed}}}$ decreased with an increasing number of model compartments, asymptotically reaching a constant value at high compartment numbers (Fig. 6). Furthermore, the first-order rate constant for simulation of plug flow pollutant removal ($k_{C_{\text{plug}}}$) correlated strongly with $k_{C_{\text{mixed}}}$. However, the relationship was not linear and $k_{C_{\text{mixed}}}$ followed a power function of $k_{C_{\text{plug}}}$ with a power between 3 and 4.5, decreasing with increasing compartment number.

Hvitved-Jacobsen et al. (1994) simulated the removal of phosphorus and suspended solids by means of a similar model and with one fully mixed compartment. They simulated eight ponds from the U.S.A. as well as one Danish pond, and found specific first-order removal rate constants for dissolved phosphorus, particulate phosphorus, and suspended solids to be 0.1, 0.35, and 0.5 $d^{-1}$, respectively. In the present study, the specific first-order removal rate constants were 2.0 $d^{-1}$ for suspended solids and 0.14 $d^{-1}$ for total phosphorus (Fig. 6); i.e., the removal rate for suspended solids was significantly higher, whereas the removal rate for phosphorus corresponded to what Hvitved-Jacobsen et al. (1994) reported.

Simulating the variability in pollutant discharge over the year and applying the fully mixed compartment approach, there was no general trend towards better simulation for a specific number of compartments. Some pollutants were best simulated by one compartment, while other pollutants were best simulated with a higher compartment number (Fig. 7). The simulation of some pollutants was not significantly affected by changed compartment numbers while others were strongly affected hereby. The quality of the simulation differed a great deal, ranging from the very satisfactory simulation of cadmium to the poor simulation of, for example, total P. The plug-flow approach, on the other hand, yielded in all cases poor agreement with the measurements. During periods of long residence times, this approach severely underestimated the discharged pollutant mass, while it overestimated the discharged mass during the short residence times associated with the snowmelt events.

Only when assuming different specific first-order rate constants (values of $k_{C}$) for different periods of the year, good agreement between measurement and simulation could be obtained. The lengths of the periods (Fig. 8) were chosen to optimize the fit between measurement and simulation. There was a slight tendency towards higher $k_{C}$ values during summer compared with winter (Fig. 8). On the other hand, omitting the two snowmelt periods from the simulations did not cause a systematic change in the rate constants. Specifically, while the $k_{C}$ value for some pollutants increased, it decreased or was unchanged for other pollutants. The reduction in treatment performance during snowmelt runoff must consequently be attributed primarily to reduced stormwater residence times and only to a lesser degree to a phenomenon like resuspension of bottom sediments, as the latter would have affected all pollutants. Similarly, Marsalek et al. (2003) monitored an ice-covered stormwater pond and found that near-bottom water velocities were not sufficient to resuspend bottom sediments.
Fig. 6. Specific first-order rate constants (equation 4).

Fig. 7. Simulation of accumulated amounts of discharged pollutants applying fully mixed compartment approaches as well as a plug flow approach.
No systematic variation in $k_C$ values over the year was found, and in general, seasonal $k_C$ values of any two pollutants did not correlate well (Fig. 8). The only good correlation over the year was between the $k_C$ values of total P and bioavailable P. Furthermore, there was a slight correlation between the values of total PAH and 4-PAH. The poor correlations indicated that no simple assumption could be made on the pollutant removal kinetics. For example, it could not be assumed that pollutant removal followed simple first-order kinetics or that the removal of a pollutant typically associated with particulate matter (e.g., PAH) could be described by the removal of suspended solids.

The high variability in $k_C$ values over the year, together with the poor correlation of the seasonal variations between $k_C$ values of different pollutants showed that measurement of the pond inputs and outputs alone allowed only for simulation of the average treatment performance. In a general perspective, the results obtained indicate that pollutant removal during individual events cannot be predicted with any acceptable accuracy based on such measurements. To simulate the behaviour of a wet detention pond on single event basis, it must be realized that the pollutant removal processes are complex, site specific, and highly variable over time. The processes must therefore be investigated and quantified in great detail in each case. In practice, this is not considered possible.

For the prediction of environmental impacts on receiving water ecology it is important to keep in mind that the main concerns regarding pollutants discharged from urban highways and roads relate to accumulative effects and only to a lesser degree to acute toxicity. It is therefore—seen from the receiving water quality point of view—crucial that annual pollutant loads are reduced, whereas a high variability in pollutant concentrations from event to event is of less importance. As such, the simulation approaches applied in the present study are believed to be applicable for pond design and for the evaluation of pond performance.

A major benefit of a dynamic simulation approach compared with simply estimating an average pollutant removal is that the dynamic simulation approach allows assessment of alternative solutions. Hereby it can for example be evaluated how restrictions in the pond outflow in combination with increased storage volume affect the treatment performance during snowmelt, or how increased depths of the permanent pool affect the operation of an ice-covered pond.

**Design Considerations for Management of Snowmelt Events**

For most of the year, the Skullerud wet detention pond design allowed very good pollutant removal. Even during winter the treatment performance generally was excellent. However, during the two large snowmelt events the function of the pond became significantly impaired. An alternative design with sufficient storage capacity to retain the snowmelt runoff for a number of days would most likely have managed this problem, resulting in an even better overall treatment performance. In case of the Skullerud wet detention pond, winter operation was taken into account by submerging the inlet and the outlet.
pipes, however, physical restrictions at the pond site did not allow much storage to be included in the design.

In the case of the Skullerud wet detention pond and the monitored events, a storage volume of 2 times the actual permanent water volume would have allowed all snowmelt runoff to be detained for at least 3 days. For such a design, simulations with the average pollutant removal rates obtained (Fig. 6) showed significantly improved removal rates for pollutants possessing a high rate constant. However, pollutants possessing a low rate constant were only slightly affected.

Seen over a longer time span, empirical guidelines for wet detention pond design as, for example, formulated by the U.S. FHWA (1996), allow for good treatment performance even under cold climate conditions. In addition hereto, the dynamic modelling of specific processes allows assessment of critical operation conditions. Based hereon, pond design can be adjusted to accommodate these specific conditions, resulting in an overall increase in treatment performance.

**Conclusions and Summary**

The Skullerud wet detention pond located in Oslo, Norway, treats highway runoff. Continuous monitoring of a number of pollutants in the inflow and outflow during one year formed the solid basis for detailed analysis of the treatment performance and modelling of the pollutant removal.

The detention pond exhibited very good overall pollutant removal, although snowmelt events constituted a major challenge for the performance of the pond. These events caused significant pollutant discharges and accounted for the major part of the annual pollutant emission for a number of pollutants. The detailed monitoring illustrated the importance to include management of snowmelt events in the pond design, for example by increasing the storage volume or by diverting snowmelt runoff from less polluted adjacent areas directly to a receiving water body. Also the inlet structure, the outlet structure, and the pond water depth should be optimized to avoid scouring of pond sediments when the pond is ice covered.

Dynamic simulation of the Skullerud wet detention pond with first-order pollutant removal models yielded, on an event basis, poor reproducibility of the variations in discharged pollutants. Only when assuming different rate constants for different parts of the year, good agreement could be obtained. However, there was no systematic variation in the rate constants obtained and the values did not correlate well with each other.

It gives matter for thought that the detailed and comprehensive monitoring of the Skullerud wet detention pond—performed at great expense—did not yield results with a high reproducibility and correlation between pollutants. The simulations indicated that high variability in the pollutant removal processes were the main reasons for that. On this background it is deemed that input/output measurements on wet detention ponds allow only the prediction of average pollutant removal, whereas the pollutant removal on an event basis demands detailed assessment of the individual removal processes at a high temporal resolution. At present, the conceptual background for this approach does not exist.

As a consequence of this detailed analysis of the treatment performance of a wet detention pond, the design procedure for such ponds must remain empirical. However, if such design is based on long-term empirical information on the performance, the purpose of removing pollutants with mainly accumulative effects can be observed. Furthermore, dynamic simulation of pollutant removal applying runoff time series allows assessment of specific design aspects and critical operation conditions.

**References**


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