3D Numerical Modelling of Transport, Deposition and Resuspension of Highway Deposited Sediments in Wet Detention Ponds

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Published in:
8UDM & 2RWHM : International Conference

Publication date:
2009

Document Version
Publisher's PDF, also known as Version of record

3D numerical modelling of transport, deposition and resuspension of highway deposited sediments in wet detention ponds

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ABSTRACT
The paper presents results from an experimental and numerical study of flows and transport of primarily particle bound pollutants in highway wet detention ponds. The study presented here is part of a general investigation on road runoff and pollution in respect to wet detention ponds. The objective is to evaluate the quality of long term simulation based on historical rains series of the pollutant discharges from roads and highways. A three-dimensional hydrodynamic and mud transport model is used for the investigation. The transport model has been calibrated and validated on e.g. experiments in a 30 m long concrete channel with width of 0.8 m and a water depth of approximately 0.8 m and in circular flume experiments in order to reproduce near-bed specific processes such as resuspension and consolidation. With good agreement with measurements, modelling of hydrodynamics, transport of dissolved pollutants and particles in wet detention ponds is possible with application of a three dimensional RANS model and the advection/dispersion equation taken physical phenomena like wind, waves, deposition, erosion and consolidation of the bottom sediment into account.

KEYWORDS
BMP, runoff, pollution, RANS, wind, particles

INTRODUCTION

The pollution of the water environment caused by highway run-off focuses especially on heavy metals and PAH's e.g. in studies of Muschack (1990) and Wu *et al.* (1998) and many others due to their frequent occurrence in highway runoff and their toxicological effects. The description of the transport of highway runoff and associated pollution must emphasize an accurate description of the transport of fine particles through the wet detention ponds (WDP) to the receiving waters due to high sorption affinity of the metals and organic micropollutants (Pitt *et al*, 1995). The overall idea of the study is to set up numerical models in which improvements in relation to removal of pollutants can be identified and to be able to predict the yearly discharges of pollutant from an arbitrary WDP to the natural environment. Modelling of fine sediment transport within WDP is complex, due to the fact that the phenomena involved are non-linear and three dimensional, time-varying due to the non-steady in- and outflow and non-steady wind shear for ponds located in the open land, wave generated bed shear stresses, dispersion, settling, deposition, consolidation and erosion.

METHODS AND PARTIAL RESULTS

In the following section, the numerical interpretation of the processes involved in the total particle transport in WDP and the underlying physical experiments carried out in the study are described.

Hydrodynamic description

The hydrodynamics in the WDPs are described in three dimensions by solving the Reynolds averaged Navier Stokes equations (RANS) (eqn.1 & 2) with the assumption of hydrostatic pressure distribution and an incompressible fluid. The commercial software MIKE 3, (DHI, 2008) has been used for solving the equations.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S \tag{1}$$

$$\frac{\partial u}{\partial t}+\frac{\partial uu}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial uw}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(2\nu_T\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_T\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)+\frac{\partial}{\partial z}\left(\nu_T\frac{\partial u}{\partial z}\right)+u_s S \tag{2}$$

where u,v,w = velocities in the x,y,z directions, u_s= x-velocity of the source/sink, S = source/sink term, ρ = density, ν_T = eddy viscosity, and the pressure P term is solved by eqn. (3)

$$\frac{1}{\rho}\frac{\partial P}{\partial x}=\frac{g\rho(\zeta)}{\rho}\frac{\partial \zeta}{\partial x}+\frac{g}{\rho}\int_z^{\zeta}\frac{\partial \rho}{\partial x}dz \tag{3}$$

where g = acceleration due to gravity, and ξ = surface elevation.

The ponds are discretized in grids of 0.8 m x 0.8 m x 0.05 m (x,y,z) with an equivalent sand roughness of 5 cm. In the model the roughness is not completely a physical interpretation of the resistance but also a result of the choice of the vertical grid space in the numerical solution, hence the roughness height is a calibration parameter in conjunction with the constants for the Smagorinsky turbulence model from which the eddy viscosity is calculated. The model has been shown in Bentzen *et al.* (2005) capable of calculating the hydrodynamics and transport of dissolved matter appropriately and has been improved further since then.

The wind will influence the water surface of the pond and transport kinetic energy to the water body and is the governing driving force during inter rain event periods and during low intensity rain runoff events as shown in Bentzen *et al.* (2008a). The force from the wind on the water surface is implemented in the RANS model as the upper boundary condition for the shear term as well as the wind generated waves, even though they are generally small but compared to the water depth in the ponds large enough to introduce a significant contribution to the bed shear stress.

Suspended transport

In the natural environment good calibration and verification data can be hard to archive and the stochastic nature have governing influence on the data archived. Hence for modelling of suspended transport and deposition of particles, originating from the highway surfaces, in highway detention ponds, four transport experiments are carried out. To simplify the complexity of a real pond and for easy control and measurement the sediment transport experiments where carried out by simulating the functioning of a real WDP in two rectangular ponds respectively with sediment traps at the bottom (figure 1 & 2). The sediment used in the experiments origins from a detentions pond in Denmark. The sediment from this pond has characteristics, with respect to grain size distribution, organic content and pollutant levels, as can be found world-wide in the literature.

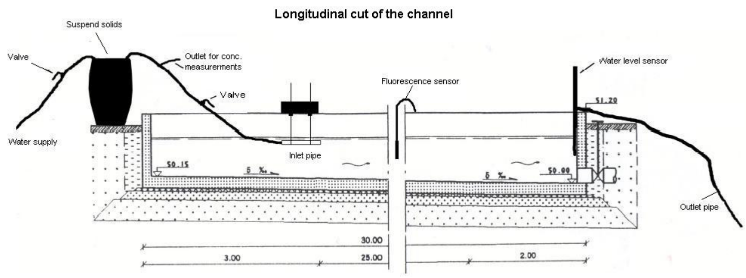

Figure 1. Longitudinal cut of the large geometrical simplified WDP

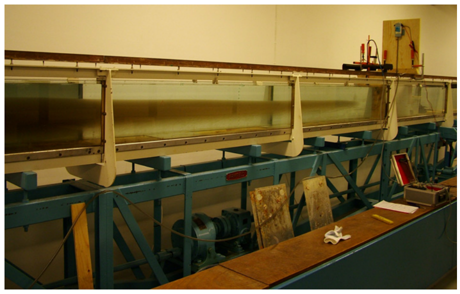

Figure 2. Photo of the small experimental pond.

The sediment pumped to the experimental ponds is in the model divided into 7 fractions with different settling velocities (table 1), corresponding to measured settling velocity distributions of pond sediment. The suspended transport of sediment in the ponds is described with the advection-dispersion eqn. (4) (given for the z-direction).

$$\frac{\partial c}{\partial t}+\frac{\partial}{\partial z}\left(c\left(w-w_{s,i}\right)\right)=\frac{\partial}{\partial z}\left(D_c\frac{\partial c}{\partial z}\right)+S_c \qquad (4)$$

where c = concentration of the i$^{\text{th}}$ fraction of sediment with the corresponding settling velocity w_s and D = dispersion coefficient calculated proportional to eddy viscosity with the Prandtl number. The deposition of suspended material is governed by whether the bed shear stress is below the critical shear stress for deposition τ_{cd}. The critical shear stress for deposition is set to vary between 0.04 N/m^2 for the fastest falling particles and 0.03 N/m^2 for the slowest. The deposition D of the i$^{\text{th}}$ fraction is described as given in eqn. 5 (Krone, 1962).

$$D_i = w_s^i c_b^i p_d^i \qquad (5)$$

where c_b is the near bed concentration and p_d is the probability of deposition $1-\frac{\tau_b}{\tau_{cd}}, \tau_b \le \tau_{cd}$

The reproduction of the experimental pond experiments in the model showed fairly good agreement with the measured longitudinal deposition of solids as shown in figure 3 and 4 and modelled outlet concentration (not shown).

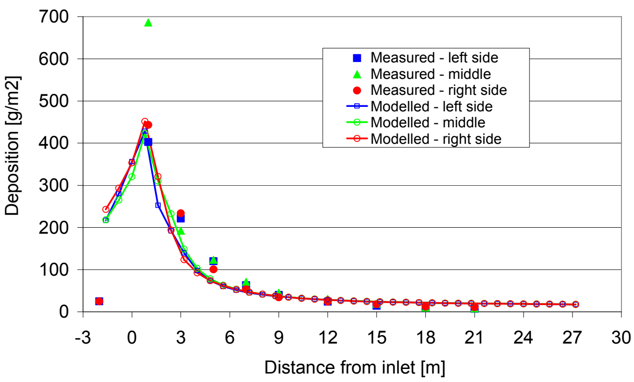

Figure 3. Measured and modelled longitudinal deposition. (Large experimental pond)

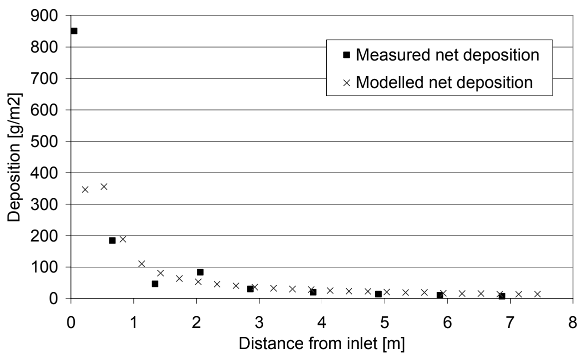

Figure 4. Measured and modelled longitudinal net deposition. (Small experimental pond)

Resuspension

For a long term evaluation of the fate of pollutants in WDP the resuspension process of settled particles is a not insignificant process. Especially in shallow ponds placed in open land where wind exposure is the primary parameter for increased bed shear stresses. Worldwide the circular flumes have been used for characterization of erosional and depositional behaviour of sediments e.g. Sheng and Lick (1979), Møller-Jensen (1993), Krishnappan and Marsalek (2002) and many others. The advantages using the circular flume are the establishment of an infinitely long channel with a uniform flow. The disadvantages of using the flume occurs due to the centrifugal force created by the rotation of the lid, consequently a secondary flow is generated leading to a non-uniform bed shear stress distribution. General investigations of the secondary currents due to the curvature of the flow in the circular flume have been done by e.g. Krishnappan (1993) and Petersen and Krishnappan (1994). The critical shear stress for resuspension of WDP deposits has been measured and adapted into the model as well as additional erosional coefficients for the numerical description according to equation 6 (Mehta *et al.*, 1989).

$$E = C \cdot e^{\alpha\sqrt{(\tau_b - \tau_{ce})}} \qquad (6)$$

where E = erosion rate, C and α = erosion coefficients, τ_b = bed shear stress from the currents and waves, and τ_{ce} = critical bed shear stress for erosion, according to table 1.

The critical shear stress for bringing the sediment to suspension is significantly dependent on the consolidation time according to figure 5. For low consolidation time and shear levels around 0.1 N/m^2 the sediment is brought to suspension at rates around 0.1 $g/m^2/s$. For one week of consolidation the critical shear level is increased by approximately 50-100 % and the major resuspension occurs somewhere between 0.16 – 0.26 N/m^2. The bottom of the ponds is in the model described by six layers and the consolidation process is described as a mass transfer rate between adjacent bed layers. In other words sediment is transported from a layer with lower density and lower critical shear stress for erosion to a layer with higher density and critical shear stress. The initial guess on the transition coefficients between the layers is calculated, on the basis of the physical experimental results (the difference in the eroded mass between the 24 hr and 72 hr/187 hr consolidation experiments and the time difference).

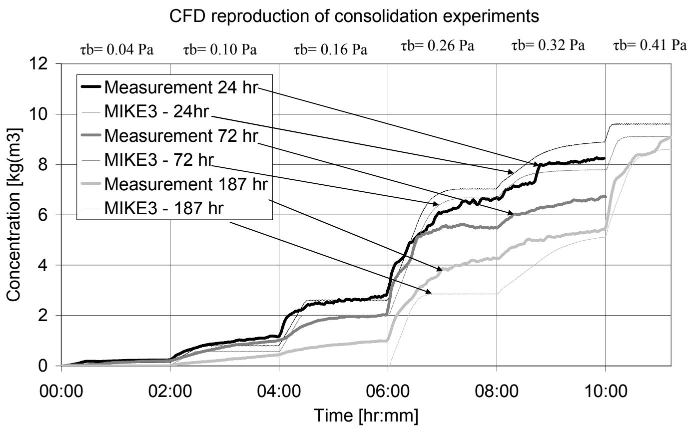

Figure 5. Measured and modelled concentration time series 10 cm above the circular flume bottom.

A fully perfect match between measured and modelled concentration time series was not achieved, but the model is handling the physics reasonably well as shown in figure 5. The model will be applicable for evaluating the resuspension process within the detention ponds and further in conjunction with the hydrodynamics and sedimentation process the total transport of sediment within the ponds.

Not only the currents induced by the inflow, outflow and the wind introduce bed shear stresses but also the wind-induced waves. The waves are very fetch limited in the relatively small ponds. But even small waves will generate additional shear stresses at the bottom of the pond and probably resuspend the bed material or hinder deposition. The erosion and resuspension during waves is evaluated in a 20 m long and 1.2 m wide rectangular wave flume. The water depth was decreasing from 0.7m to 0.5m at the shoreline end, corresponding to a more or less full-scale situation in the detention ponds. At the shore a breakwater was established to reduce the reflection of the waves. In the middle part of the flume a 2.4 m long and 1.6 cm thick wood plate was covering the bottom of the flume. In the plate a 0.5 m x 0.6 m hole was made and filled with sediment from the same pond as used at the circular flume experiments (figure 6).

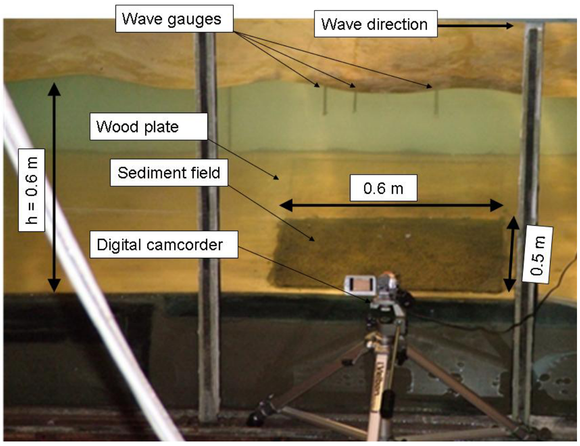

Figure 6. Setup for evaluation wave generated resuspension

The consolidation time was one week, with 0.6 m water above. Additional, but unknown shear strength was applied to the sediment during the placement of the sediment and levelling off. The wave heights were measured at 20 Hz sampling frequency with three wave gauges placed just above the sediment. The bed was exposed to 13 different regular waves. The mean wave height and period for each of the incremental steps was calculated by zero down-crossing analyses. Wave parameters and corresponding bed shear stresses are calculated iteratively by linear wave theory. After a visual evaluation of the digitally recorded video of the bed and overlaying water, the results show good agreement between the critical bed shear stress for erosion/resuspension due to currents and due to waves. Slight bed movement starts around 0.05 N/m^2 with rolling of the particles. At 0.12 N/m^2 saltation and bouncing occur, and suspension of the bed starts somewhere between 0.12 and 0.18 N/m^2. For the adaption of the wave impact on WDP, wave heights (H), wave periods (T) and the directions (γ) are calculated by MIKE21 Nearshore Spectral Wind-Wave (DHI, 2008). It is assumed that waves and currents do not interact with each other, thus $H(t,x,y)$, $T(t,x,y)$ and $\gamma(t,x,y)$ are independently calculated with the same wind time series as used for the wind induced current calculations by means of the fetch-limited wave growth equations of Kahma and Calkoen (1994) which have been shown to calculate the wave parameters reasonably in the relative small and shallow constructed ponds.

Table 1. Model constants: Settling velocity distribution and bed parameters.

Fraction	Settling velocity [mm/s] and (Relative mass)	Bed layer	Critical shear stress for erosion [N/m^2]	Erosion coefficients C [kg/m^2/s], ($\alpha = 1$)	Consolidation transition coefficients [kg/m^2/s]	Initial bed layer thickness [mm]
1	10.30 (5 %)	1	0.03	3.5e-5	8.5e-6 (1→2)	0.3
2	4.70 (35 %)	2	0.09	7.6e-4	7.7e-6 (2→3)	1.1
3	2.60 (44 %)	3	0.15	4.6e-3	6.3e-6 (3→4)	1.9
4	1.50 (4 %)	4	0.25	1.3e-2	2.0e-6 (4→5)	4.2
5	0.70 (3 %)	5	0.31	5.4e-3	1.1e-6 (5→6)	1.8
6	0.19 (5 %)	6	0.4	9.9e-2		Rest
7	0.15 (4 %)					

RESULTS

Due to fact that the model has been shown capable with an acceptable accuracy to model the transport of highway sediments in the experimental ponds it might be assumed that this is also the case in WDP where water depths and flow conditions are comparable with conditions in the experiments. The hydrodynamic and particle transport model has subsequently been used on two real ponds during runoff events; including both the wind and wave impact on the hydrodynamics and corresponding particle transport. In figure 7 the result of one of those can be seen, where the modelled outlet concentration of total suspended solid concentrations in general agrees well with measurements (both in magnitude and time). In figure 8 the model has been used on a 3 month period with real runoff events with and without wind impact and in table 2, the results from the study are summarized.

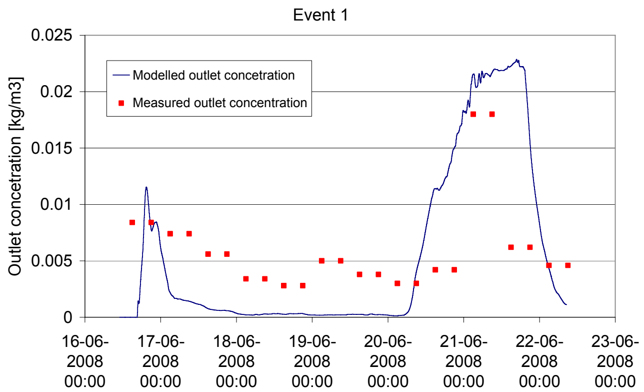

Figure 7. Measured and modelled outflow TSS concentration from the Vodskov pond.

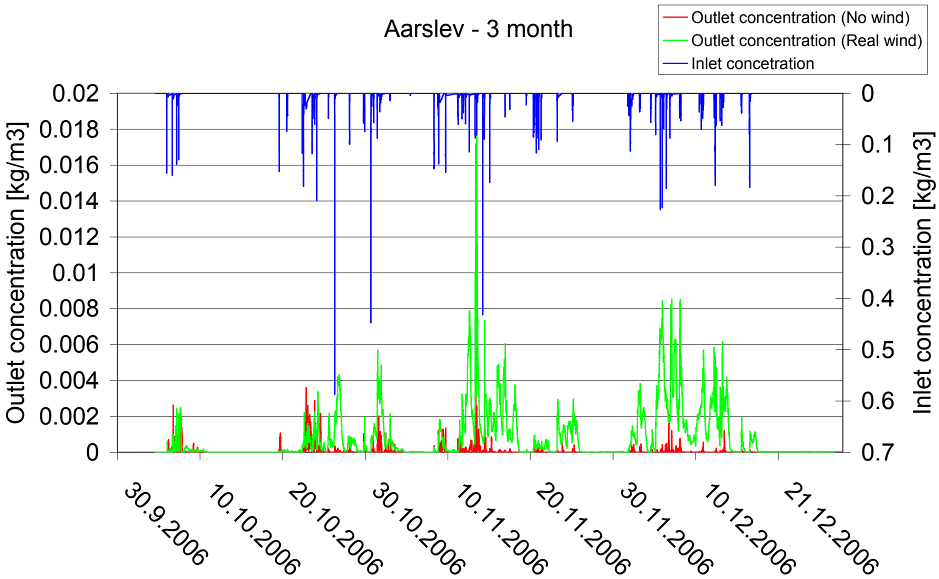

Figure 8. Modelled inlet and outlet TSS concentrations for 58 events during autumn 2006 in the Aarslev pond.

Table 2. Result overview.

Event	Efficiency (TSS – removal)	Comments
Vodskov Pond (16/6/2008 – 22/6/2008)	83 %	Modelled TSS concentrations show in general good agreement with measurements. (Both in magnitude and time)
Vodskov Pond (14/8/2006 – 17/8/2006 Extreme rainfall event)	98 % (no wind) 98 % (5 m/s north) 98 % (5 m/s west) 96 % (10 m/s north) 79 % (10 m/s west)	No initial sediment on the bottom, hence only an evaluation of the removal of incoming particles. Events 2 – 5 and 7 shows almost complete removal for the "no wind" and wind of 5 m/s situations. Even

Vodskov Pond (8/11/2007 – 11/11/2007)	98 % (no wind) 99 % (5 m/s north) 98 % (5 m/s west) 91 % (10 m/s north) 55 % (10 m/s west)	though it is only a few percents, slight wind tends to increase the efficiency in the Vodskov pond, which can be explained by the relative placement of the inlet and outlet structure in the Vodskov pond. The wind induces a flow pattern that enables an optimal utilisation of the pond volume, but with so less energy transferred to the water body that settling is not hindered. For 10 m/s of wind the kinetic energy transferred to the water body hinders the settling and the efficiency drops and especially for the west direction, which was predictable due to the orientation of the outlet structure (243°)
Vodskov Pond (6/5/2007 – 10/5/2007)	99 % (no wind) 100 % (5 m/s north) 99 % (5 m/s east) 100 % (south) 99 % (5 m/s west) 91 % (10 m/s north) 78 % (10 m/s east) 85 % (10 m/s south) 57 % (10 m/s west)	
Vodskov Pond (25/2/2007 – 3/3/2007)	98 % (no wind) 100 % (5 m/s north) 88 % (5 m/s west) 90 % (10 m/s north) 86 % (10 m/s west)	
Vodskov Pond (3/1/2005 – 10/1/2005 Full storm)	- 51 %	Initial sediment on the bottom. Negative efficiency, due to wind generated resuspension. Waves are not included, thus the efficiency is underestimated.
Vodskov Pond (24/6/2007 – 29/6/2007)	98 % (no wind) 99 % (5 m/s north) 98 % (5 m/s west) 95 % (10 m/s north) 68 % (10 m/s west)	
Aarslev Pond (autumn 2007 58 runoff events and inter periods)	84 % (with measured wind) 99 % (no wind)	Initial sediment on the bottom. The 58 events cover widespread rainfall intensity/duration together with wind measured at location. Waves have not been included, thus the efficiency in the simulation including the wind is underestimated in some degree.

CONCLUSIONS

With good agreement with measurements, modelling of hydrodynamics, transport of dissolved pollutants and particles in WDP is possible with application of the three dimensional model based on the Navier Stokes equations and the advection/dispersion equation taken physical phenomena like wind, waves, deposition, erosion and consolidation of the bottom sediment into account. In respect to pollutant removal, the model is a beneficial tool for evaluating new or existing WDP designs and evaluation of e.g. unwanted wind effects on the sedimentation process. The model can be used for single runoff event evaluation as well as for long term evaluation. For evaluation of heavy metal and PAH removal efficiency, concentrations levels for each of the modelled seven fractions of solids can be added to the results. These fractionated metal and PAH concentration levels can be found in (Bentzen and Larsen, in press).

ACKNOWLEDGEMENT

Financial support is provided by the Danish Road Directorate.

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