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Removal of Heavy Metals and PAH in Highway Detention Ponds

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ABSTRACT
The paper presents some of the first results from a study of the removal of pollutants in highway detention ponds in Denmark. The objective of the study is to set up a procedure for long-term modelling of discharges of pollutants to the environment from the many Danish highway detention ponds, which has been designed according to standard design criteria for several decades. The study will focus on heavy metals (Cd, Cr, Cu, Pb and Zn) and polyaromatic hydrocarbons (PAH).
The long-term simulation of input of flow and pollution to the ponds will be a hind cast based on time series of historical rainfalls. The modelling will take place in a special version of the MIKE URBAN. The modelling is calibrated and validated on measurements from selected highway catchments. The removal of pollutants in the ponds is studied by local measurements in combination with CFD modelling using the MIKE 21 and MIKE 3 numerical models.

KEYWORDS
CFD, MIKE 3, MOUSE, runoff, settling, suspended solids

INTRODUCTION
It is general accepted that the pollution of the water environment (primarily ditches, streams and rivers) caused by highway run-off is related primarily to heavy metals and PAH's. These components are especially connected to fine particles. During dry weather a certain build up of fine particles on the road surface take place. The origin of the particles is both the traffic and dust in the air from the surroundings. During rain a part of this accumulation of particles will be washed into the drainage system and another part will be resuspended back to in the air because of the traffic and will to some degree be spread by the wind to the nearby areas.
Accordingly a proper description of the transport of this pollution must emphasize on an accurate modelling of the transport of fine particles from the road surface through drainage system and trough the detention pond to the receiving water.
Highway detention ponds are larger and shallower than normal ponds in storm water systems. The flow and transportation pattern in such ponds is extremely complex and variable because of the influence from wind and unsteady inflow.
Because of the strong non linearity in the processes involved it is obvious that methods based on simple average concentrations cannot be applied when it comes to removal of particles in ponds. It is essential in the study to apply methods and models in which improvements in relation to removal of pollutants can be identified. For example the importance of the geometry of the ponds should be included.

The study will run for 5 years as a co-operation between the Danish State Road Directorate (Vejdirektoratet) and Aalborg University starting in 2005. The challenge is to develop a simplified and still accurate description of flow and transport of pollutant adequate for the long-term simulation based on historical time series of rain. The objective of the study is to be able to predict the yearly discharges of heavy metals (Cd, Cr, Cu, Pb and Zn) and polyaromatic hydrocarbons (PAH) from the outlet from the detention ponds.
In the following some of the methods and ideas in the study will be presented. On the other hand the results shown here should only be taken as preliminary.

Since most of the heavy metals and PAH's mainly are particulate-bound and for that reason enabled for potential removal by settling in e.g. a detention pond. This paper present, on that occasion, results from measurements and modelling of the transport of suspended solids from a highway surface through drainage system and detention pond. A schematically overview of the procedure is presented on Figure 1.

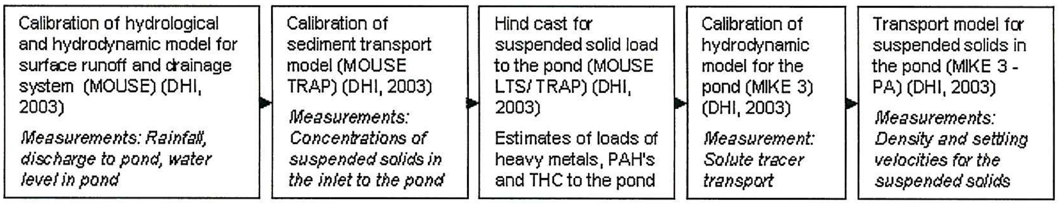

Figure 1. Schematically overview of the methods in this preliminary study.

STUDY AREA

The area of interest in this paper is approximate 1 km of a 2x2 lane highway in northern part of Jutland, Denmark (Figure 2 and Figure 3). The total catchment area is 3.4 ha of which 2.7 ha is impervious dense asphalt. In 2002 the average daily traffic load was 14,900 vehicles.

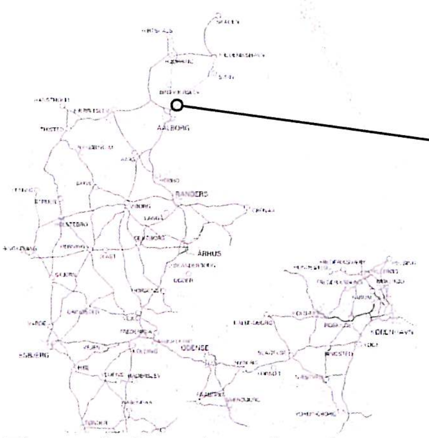

Figure 2. Location of study area. (copyright, Kort & Matrikelstyrelsen G 24-98)

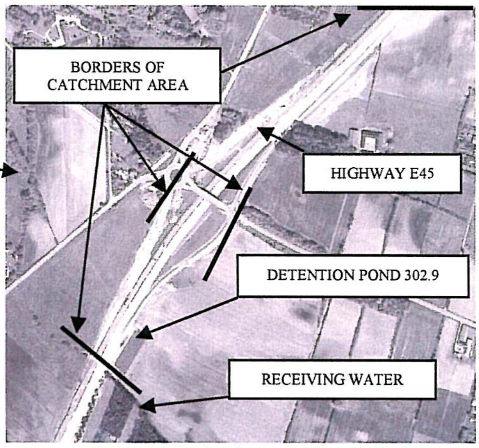

Figure 3. Aerial photo of study area, with main explanation. (IPR: Cowi)

The highway runoff, caused by rain and melted snow is collected in gullies placed within a distance of 30 m and transported in pipes to the wet detention pond no. 302.9 with a total volume of 5,000 m^3 (1,000 m^3 below outlet level). The receiving water is a small creek with an approximate median-average discharge of 0.03 m^3/s.

MODELLING AND MEASUREMENTS OF DRAINAGE SYSTEM

The modelling of water transport in the drainage system is performed in MOUSE (DHI, 2003). The following measurements have been carried out in order to achieve input-data and calibration/validation datasets to the MOUSE-model:

- Locally measured rainfall with 0.2 mm accuracy by a RIMCO rain gauge installed right beside the detention pond.
- Online discharge measurements for calibration of the inflow to the detention pond by a, for this purpose, installed Thompson V-notch weir. The water level beyond the weir was registered every 2 minute with an ultrasonic gauge.
- Water level in the detention pond was measured likewise with a time step of 5 minutes.
- The topography of the pond was levelled out in grid sizes between 5x1 m to 10x2 m.
- A discharge/water level (Q/h) relation was specified for the pond outlet. With a mass balance over time the inlet discharge could be calculated. The weir could for that reason be uninstalled and not interfering with the particle transport.

The water transport from the highway surface to the receiving creek modelled in MOUSE. Good agreement between modelled and measured inflow to the detention pond was achieved with locally measured rainfall as input. The Time-Area model (model A) was used, with the same S-shaped time-area curve for the surface runoff, for every subcatchment, 3 different times of concentrations, a hydraulic reduction factor of 1 and an initial loss of 0.6 mm. For calculation of pipe-flow the dynamic wave model was used and the outlet from the pond was modelled as a pump with a characteristic similar to the measured Q/h – relation. Figure 4 and Figure 5 illustrates modelled and measured inflow to the pond over two periods.

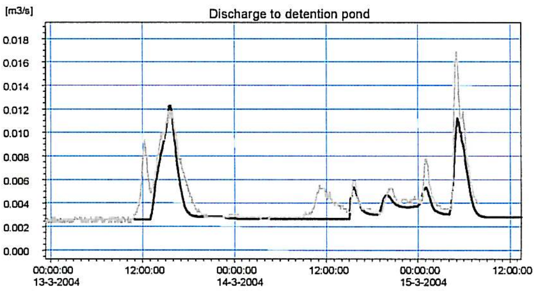

Figure 4. Gray curve: Measured discharge (Thomson V-notch weir). Black curve: Modelled discharge to the detention pond. $R^2 = 0.82$

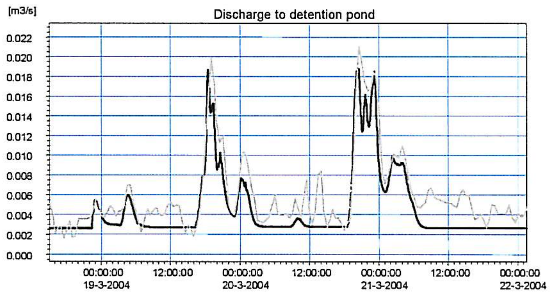

Figure 5. Gray curve: Measured/calculated discharge (Q/h - relation). Black curve: Modelled discharge to the detention pond. $R^2 = 0.88$

The small-scale variation in the measured discharge on Figure 5 can be explained by the way the Q/h realation is calculated. Very small changes in the water level in the pond created by e.g. wind made waves will reflect on the calculation of the inflow to and outflow from the pond. The modelling of the water level in the pond was accurate within 1 cm of the measured. The calibrated hydrological and hydrodynamic model was subsequently used for every particle transport modelling from the highway surface through pipes to the detention pond. For the particle transport modelling the submodule to MOUSE - MOUSE TRAP (DHI, 2003) was used. Water samples were collected flow proportional in the inlet to the pond for determination of concentration levels of suspended solids.

Characterization of suspend solids (SS)

The SS from the water samples were analysed for concentration, organic content and particle size distribution. Top layer sediment from the detention pond with nearly the same particle size distribution as registered in the inlet samples was used for characterizing the suspend solid by its settling velocity. The particle sizes for the SS were determined by laser diffraction analyses (Particle size analyzer – Microtrac II model 7997-20) with a size range form 0.9 μm – 700 μm. For the analyses approximate 200 ml water samples containing SS were used over a sampling period of 20 sec. The settling velocities were measured by adding 475 ml wet sediment (3660 mg SS) into a 1.85 m high vertical standing cylindrical tube. 15 water samples were taken out in the bottom of the tube after 1 min – 180 min. The water samples were analysed for concentrations of SS by filtration, drying and weighing (DS, 1985). The results of those two characterizations methods are shown on Figure 6 and Figure 7.

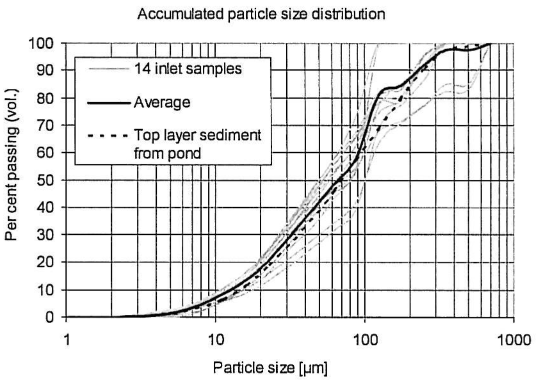

Figure 6. Measured particle size distributions for 14 inlet samples (gray curves). Average of the 14 samples is shown as a full black line. The particle size distribution of the sediment from the pond used for settling velocity determination is plotted for comparison (dashed line). The particle size distribution shows graduated sediment samples with following characteristic fractile values: D_{90} = 100 μm – 600 μm (fine to medium fine sand), D_{50} = 50 μm – 100 μm (coarse silt to fine sand) and D_{10} = 10 μm – 20 μm (medium fine silt).

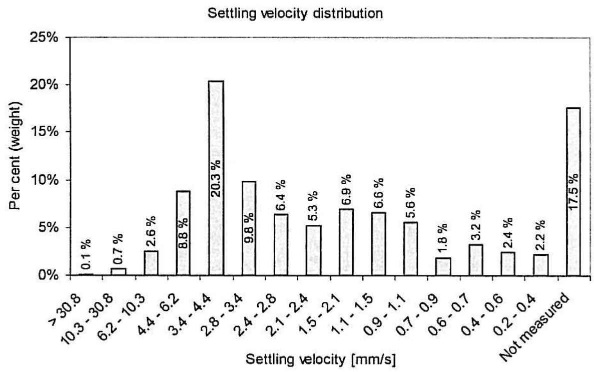

Figure 7. Measured settling velocities for pond sediment. The experiment indicates a log-normal distribution of the settling velocity with a primary fraction of sediment (3.4 – 4.4 mm/s). Due to the equipment a considerable amount of the sediment were collected on the sides of the funnel in the bottom of the tube and were for that reason not measured. Very fine particles with settling velocities below 0.2 mm/s were not measured either. This gives a residue of 17.5 % (weight) that can not be allocated to a specific velocity.

The water samples used for the settling velocity experiment were also used for particle size analyses. With information of both settling velocity and particle size and under assumption that Stokes' Law for settling is valid for this sediment the average density of the sediment was determined to be 1900 kg/m^3 indicating a certain amount of organic matter. This can be explained by the fact that the sediment was taken from the bottom of the vegetation rich pond. This is not the case for the SS taken sampled in the inlet to the pond. 25 samples of SS taken in the inlet were used for loss of ignition determination. The organic fraction varies from 20 – 80 % (weight) with a mean fraction of 40 %. There was not registered any correlation between inflow (rainfall intensity) and the fraction of organic matter. The average 60 % inorganic – 40 % organic distribution was also registered in all 24 outlet samples. The distribution in the outlet sample must be taken with caution because most of the samples were below the threshold limit (5 mg SS/litre).

Concentrations of SS – measurements and modelling

The concentrations of SS in and out from the detention pond were measured over five periods when rain events were present. Initially, the sampling during rain was carried out manually by taking 1 litre of water in the inlet structure and in the outlet pipe. Subsequently an automatic sampler connected to the rain gauge (ISCO-6700) was used for taking 1 litre of water every 4th tilt (0.8 mm rain). Figure 8 to Figure 11 illustrates the concentration levels of SS for the first four periods and the discharges modeled in MOUSE.

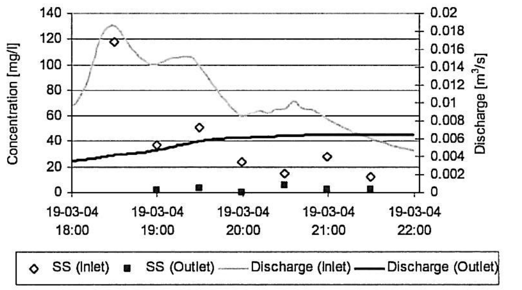

Figure 8. Concentrations of SS and discharges (in- and outlet). Five of the outlet concentration is below threshold limit for SS analysis (DS, 1985). However, they are included as an indication of concentration levels.

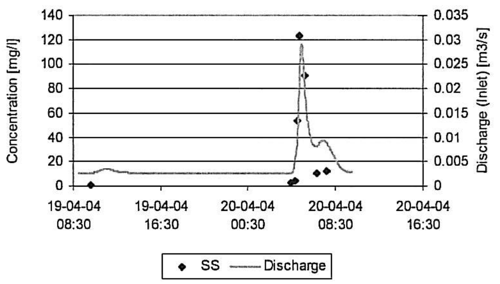

Figure 9. Concentrations of SS and discharge in the inlet to the pond. The dry weather period before rain event (6 mm rain) was 13 days.

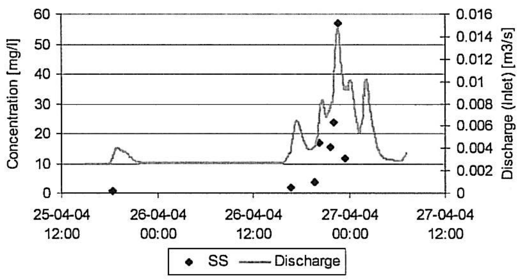

Figure 10. Concentrations of SS and discharge in the inlet to the pond. The antecedent rain event is shown on Figure 9 (6 days before) The total rainfall in this period was 8 mm.

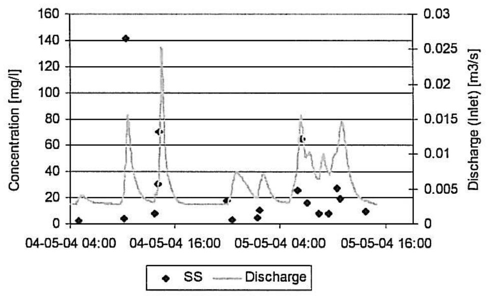

Figure 11. Concentrations of SS and discharge in the inlet to the pond. The antecedent rain event is shown on Figure 10 (6 days before). The total rainfall in this period was 15 mm.

All four periods shows a casual relationship between the discharge to the pond and the concentration of SS. The correlation coefficient between discharge and SS for all events is 0.78. It is clear that the preceding dry weather period and first flush effects also affects the concentration level. 24 water samples were taken in the outlet from the pond every 6th hour. A SS-concentration of 13 mg/l was registered in the first sample where the outflow was higher than the baseflow caused by a small rain event, subsequently a comparatively constant concentration of 3 mg/l was registered. The hydrological and hydrodynamic model in combination with the sediment transport and water quality module MOUSE TRAP were subsequently used for modelling the transport of SS with the measured concentrations levels as foundation. It was found that a linear function could describe the sediment build-up on the road surface with a constant of 0.5 kg/ha/day and an exponential function (function of rainfall intensity among other factors) could describe the removal of sediment from the road surface well. The transport in pipes was modelled with the advection/dispersion module in TRAP. An advantage of using the advective/dispersive transport description in MOUSE TRAP is that the LTS (Long Term Statistics) (DHI, 2003) module can be used. This gives a good tool for quantifying the input amount of sediment to the detention pond on e.g. yearly basis. The results of two modelled periods (same periods as shown on Figure 8 - Figure 11) are illustrated on Figure 12 and Figure 13. Note that not all modelled events have been verified with measurements and due to the automatic sampling setup has the modelled peak concentration on e.g. Figure 13 not been verified either.

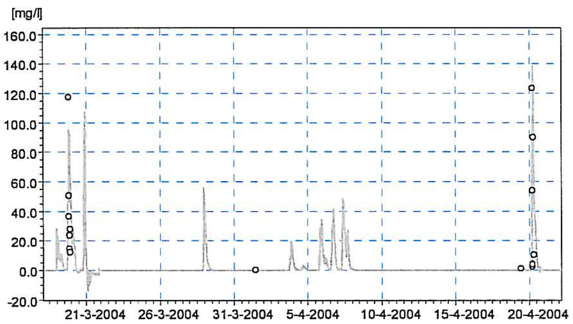

Figure 12. Measured (points) and modelled SS concentrations to the pond.

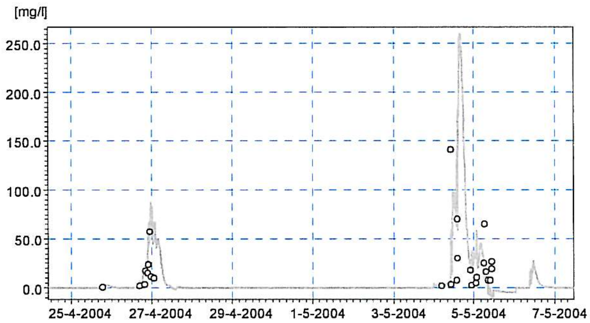

Figure 13. Measured (points) and modelled SS concentrations to the pond.

The use of MOUSE TRAP combined with LTS over ten years simulation period gives an average of sediment input to the pond of 500 kg/year (190 kg/year/red. ha).

Given 12 connected measurements of cadmium, chrome, cobber, lead, zinc, 7 PAH's and SS in highway runoff from the Danish highway E45 at the location Rud, POLMIT (2002) and the distribution between dissolved and particulate-bound pollutants measured in samples from another Danish highway near Copenhagen, Miljøstyrelsen (1997) gives the opportunity to give an input estimate of pollutants to the detention pond based on the measured and modelled loads of SS.

Table 1. Estimated amounts of pollutants transported to the detention pond.

POLLUTANT	Cd	Cr	Cu	Pb	Zn	PAH
Particulate-bound load [g/year/ha]	0.6	4.5	89.3	39.0	383.1	2.9
Dissolved load [g/year/ha]	0.4	6.5	70.2	1.2	156.5	0.5

MODELLING AND MEASUREMENTS OF DETENTION POND

To quantify the loads to the receiving water (or the efficiency of detention), the fate of pollutants in the detention pond must be determined. The determination demands a good description of the hydrodynamics conditions in the pond. With a stated efficiency it will become possible to describe the detention of pollutants in the pond with e.g. MOUSE TRAP. The hydrodynamics of the pond is modelled in both 2 and 3 dimensional in MIKE 21 and MIKE 3 (DHI, 2003). Only results from the MIKE 3 model will be presented. It was found that the velocities within the pond, except for the inlet and outlet zones, were so low, that accurate measurements were impossible to achieve. In order to gauge the transport dynamics, tracer experiments with a solute tracer (rodamin) were carried out during two different inflow conditions. The solute tracer was dosed in the inlet structure and the concentrations were measured in the outlet structure with a fluorometer. Both tracer experiments showed that the transport of tracer more or less took place directly from the inlet to the outlet (placed in the same end of the detention pond see e.g. Figure 15) with no considerable mixture as result. The theoretical hydraulic residence time for e.g. the second experiment was approx. 150 hours, but the peak of concentration reached the outlet after approx. 90 minutes. The modelling of this tracer experiment was carried out both with the assumption that no wind was applied and with time varying wind speed and direction obtained from the nearest observation point 10 km south of the pond. The model was set up in a 0.8m x 0.8m horizontal grid and a vertical discretization of 0.05 m. The turbulence was modelled with a mixed Smagorinsky-k/ε formulation. The results of the modelling are illustrated on Figure 14 . Note that only the first 24 hours of modelling are included on the figure (compared to the hydraulic residence time of 150 hours).

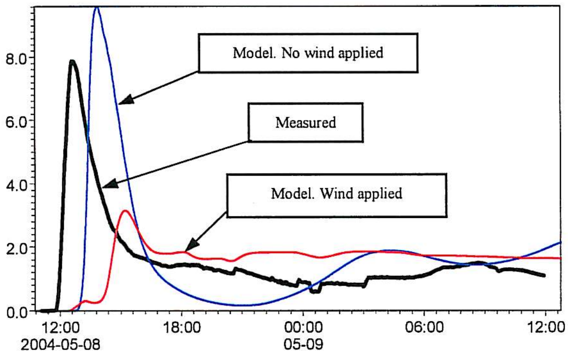

Figure 14. Measured and modelled concentrations in the outlet from the pond. With no wind applied, the modelled passage of peak concentration occurs 160 minutes after dosing. Compared to the theoretical hydraulic residence time this is 2% of the time (1% for the measured). With time varying wind applied, the modelled passage of peak concentration occurs 240 minutes after dosing. Compared to the theoretical hydraulic residence time this is 3% of the time. The wind has great affect on mixture of the tracer, so that the vertical mixing damps the variation in outlet concentration. The concentration levels in the outlet seem a little overestimated with no wind applied and underestimated with wind applied.

With a good agreement between measured and modelled transport of the solute tracer the model was subsequently used for transport modelling of settleable solids. Two models were used for the transport modelling. A finite difference particle transport model was created based on random walk dispersion and time varying flow patterns from the MIKE 21 model and a predefined submodule (PA) to MIKE 3. Only the results of the 3D PA (Particle Analysis) model will be presented. Based on the settling velocities measured and described in the last chapter, four settling velocities were used in the PA-model to characterize the composition of sediment taken from the bottom of the pond. By applying a logarithmic velocity profile the vertical eddy viscosity profile is parabolic and is converted to dispersion with a factor of 1 and resuspension from the bottom is available. 15 steady and non-steady situations with varied in- and outflow and with and without wind applied were modelled. Only one of the simulations results in solids in the outlet, this simulation had strong varying wind from different directions. The simulation of the last solid flux event shown on Figure 13 is shown on Figure 15. The figure shows were the four fractions of solids sediments.

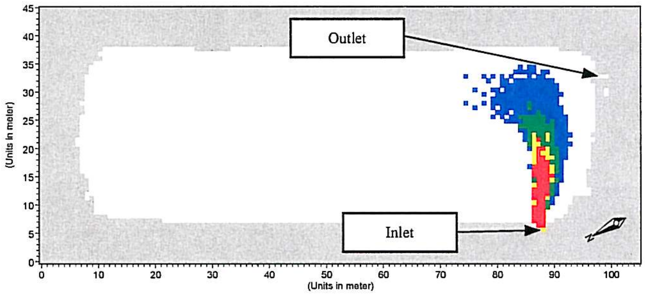

Figure 15. Sedimentation zones under rainfall event 03.05. – 06.05. 2004

CONCLUSION

This preliminary study has shown as follows:

1. Modelling of water and suspended solid discharges to detention ponds are possible with application of the 1D CFD model MOUSE showing agreements with measurements.
2. Modelling of hydrodynamics and transport of pollutants in the detention pond are possible with application of the 3D CFD model MIKE 3 showing agreements with measurements. The impact of wind on the flow pattern in the pond including the interaction with sedimentation and resuspension must be investigated further.
3. The correlations between concentrations of suspended solids and concentrations of pollutants (heavy metals and PAH's) and distribution of pollutants based on settling characteristics must be investigated further in order to quantify the loads of these pollutants more accurate.

ACKNOWLEDGEMENT

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