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Accumulation of Pollutants in Highway Detention Ponds

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Accumulation of pollutants in highway detention ponds

PhD Thesis Defended at Aalborg University (30-10-2008)

Thomas Ruby Bentzen



Aalborg University Department of Civil Engineering Water and Soil

DCE Thesis No. 13

Accumulation of pollutants in highway detention ponds

Defended at Aalborg University (22-09-2008)

by

Thomas Ruby Bentzen

September 2008

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Preface

This thesis was written as a part of a PhD study during the past three years at the Department of Civil Engineering, Aalborg University, Denmark. The thesis consists of a collection of following seven technical papers and this extended summary of those. The issues in chapter 8 and 9 are not referring to any of the papers directly.

- Paper I Bentzen T.R. Larsen T., Thorndal S. and Rasmussen M. R. (2005) Removal of Heavy Metals and PAH in Highway Detention Ponds. Proceedings of the 10th International Conference on Urban Drainage, Copenhagen/Denmark 21-26 August 2005.
- Paper II Bentzen, T.R., Larsen, T. and Rasmussen, M.R. (2007). Can we close the longterm mass balance equation for pollutants in highway ponds? *Alliance for global sustainability bookseries*. *Vol 12 Highway and Urban Environment. Springer*. 511-520.
- Paper III Bentzen, T.R., Larsen, T. and Rasmussen, M.R. (2008a) Wind effects on retention time in highway ponds. *Wat. Sci. Tech.* 57(11), 1713-1720.
- Paper IV Bentzen, T.R. and Larsen, T. (2008) Heavy metal and PAH concentrations in highway runoff deposits fractionated on settling velocities. *Submitted for Journal of Environmental Engineering July 2008*.
- Paper V Bentzen, T.R., Larsen, T. and Rasmussen, M.R. (2008b) Critical shear stress for resuspension of deposits in highway detention ponds. *Submitted for Water Research July 2008*.
- Paper VI Bentzen, T.R., Larsen, T. and Rasmussen, M.R. (2008c) Predictions of resuspension of highway detention pond deposits in inter rain event periods due to wind induced currents and waves. *Submitted for Journal of Environmental Engineering September 2008*
- Paper VII Bentzen, T.R., Larsen, T., Bach, C., and Raaberg, I. (2008d) Numerical modelling of suspended transport and deposition of highway deposited sediments. Technical report. Series number 47, *Department of Civil Engineering, Aalborg University*

The study was supervised by Professor Torben Larsen and co-supervised by Associate Professor Michael R. Rasmussen. First of all I would like to thank my two supervisors for fruitful input during my study. Especially Professor Torben Larsen who has a remarkable overview over what is important and what is not.

The study was financed by The Danish Road Directorate (Vejdirektoratet). I would like to thank the staff in Skanderborg for taking great interest in my work and making the whole study possible.

I would also like to express my gratitude to assistant professor Thomas Lykke Andersen, Palle Meinert, former employee Morten Kramer and associate professor Michael Brorsen and other colleagues from the department for their involvement in the study. Furthermore, I am grateful to my colleague and friend Søren Thorndahl with whom I have discussed and shared many professional and private matters. Ole Svenstrup Petersen at DHI is acknowledged very much for his expertise that he has placed at my disposal, and also the laboratory technicians at the department and especially Niels Drustrup and my private neighbour Henrik Fog for proof reading should not be forgotten.

Finally, I would like to thank my beloved wife Lene without whose love and support I could not have completed the project and my little daughter Martha that with her childish joy has given me the best three years of my life.

Thanks!

Aalborg University, 22nd of September, 2008

Thomas Ruby Bentzen

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Resumé (in Danish)

Projektet omhandler en undersøgelse af stof- og vandtransport under regn igennem afvandingssystemet for motorveje. Målet er at identificere metoder og modeller til at give en beskrivelse af de stof- og vandstrømme som sendes videre fra vejenes afløbssystem til omgivelserne samt at anvende disse modeller med henblik på at opnå viden til brug for forbedret dimensioneringspraksis for disse systemer, således at forureningspåvirkningen af omgivelserne evt. kan reduceres. Samarbejdsprojektet med Vejdirektoratet har udgangspunkt i lovene vedrørende anlæg af nye motorveje og motortrafikveje henholdsvis ved Herning, mellem Odense og Svendborg og mellem Holbæk og Vig, hvor der i henhold til bemærkningerne til lovene skal iværksættes de her omtalte undersøgelser for de nye vejstrækninger.

Der knytter sig særlige problemer når det gælder om at forudsige forureningsbelastningen fra regnbetingede afstrømninger fra vejsystemer. Hovedproblemet er, at regnens intensitet er meget varierende hvilket medfører at afstrømningen ligeledes varier stærkt i tiden. Derfor er det er i praksis umuligt ud fra enkelte målinger, at forudsige, hvad de gennemsnitlige årlige forhold er. Den metode, som har vist sig at være den mest effektive, til at overkomme problemet med den tidsmæssige variation er at foretage et såkaldt hindcast, hvor man ud fra en database med mange års regnmålinger (historiske regn) simulerer det præcise afstrømningsforløb af samtlige regnhændelser. Ud fra disse resultater kan så de gennemsnitlige årlige værdier beregnes. Denne metode er efterhånden blevet almindelig praksis ved beregning af kommunale afløbssystemer. Imidlertid er tredimensionelle beregninger meget beregningstunge. Igennem projektet er det forsøgt via hændelses baserede tredimensionelle modeller at danne en forståelse af de styrende parametre for primært stoftilbageholdelse, for herigennem at kunne fastlægge metoder til den almindelige dimensionering af afvandingssystemer for motorveje.

Undersøgelsen omfatter primært forureningskomponenter på partikulær form og omfatter polycycliske aromatiske hydrokarboner (PAH), fraktioner af hydrokarboner (benzen \rightarrow tunge olier) samt tungmetallerne bly, cadmium, kobber, krom, nikkel og zink pga. af deres hyppige forekomst i vejvand og deres negative miljømæssige effekt.

Der udføres detaljerede målinger på vand og stoftransporten i afløbssystemet på en udvalgt lokalitet ved rute 9, Svendborg – Odense samt otte andre våde bassiner i Danmark. Der etableres et specielt forsøgsbassin, som er mindre end de normale bassiner. Forsøgsbassinet udformes som en kanal udført i beton, hvori der foregår en ensformig todimensional strømning i én retning. Kanalens længde er 30 m, bredde 0,8 m og dybde 1,2 m. Herved opnås de mest veldefinerede forhold i relation til måling af hvorledes det partikulære stof sedimenterer ud på bunden. Resultaterne fra forsøgsbassinet overføres til de virkelige bassiner, hvor strømningen er tredimensional, via numeriske modeller. Det partikulære stof analyseres i laboratoriet for fordeling af sedimentationshastighed på kornstørrelsesfraktioner og de enkelte fraktioner analyseres for forureningskomponenter. Desuden foretages erosionsforsøg (resuspension) i laboratoriet med strøm og bølger.

Overordnet set viser dette studie at størstedelen af den tilførte masse af partikel bundet forurening akkumuleres i de danske regnvandsbassiner. Effektiviteten for tilbageholdelse antager en værdi i størrelsesorden af 80 %. En vigtig parameter i forbindelse med tilbageholdelsen af partikulært stof er vinden forstået således at roligt vand tilbageholder mere stof end uroligt vand. Vindens påvirkning af bassinerne kan reducere effektiviteten kraftigt og endda forårsage en negativ effektivitet grundet resuspension af allerede sedimenteret forureningspartikler.

Der er opsat en endimensional transportmodel som kan beskrive:

- 1. Opbygningen af forurening på vejoverflader
- 2. Fjernelsen af forurening pga. regn
- 3. Transporten af vand og forurening gennem afløbssystemer til regnvandsbassiner

Denne model kan anvendes over flere år med f.eks. historiske nedbørsdata og kan således anvendes til forudsigelse af belastningen af regnvandsbassinerne både med hensyn til stof og vand.

Der er opsat en tredimensional transportmodel for bassinerne som kan beskrive:

1. Transporten af vand, opløst stof og partikulært stof i bassinerne under vilkårlige nedbørshændelser og vind generede strømninger og bølger.

Den tredimensionale model er et essentielt stykke værktøj i forbindelse med evaluering af både eksisterende og planlagte bassiners evne til stoftilbageholdelse og der vurderes om der på grundlag af resultaterne herfra kan opstilles en forsimplet endimensional model til brug for langtidsberegningerne.

Abstract

This PhD study deals with issues related to water and pollutant transport from highway surfaces caused by rain. It is essential in the study to apply methods and models in which improvements in relation to removal of pollutants can be identified and to be able to predict the yearly discharges of heavy metals and polycyclic aromatic hydrocarbons from an arbitrary detention pond to the natural environment. The present thesis is a part of a co-operation between the Danish Road Directorate (Vejdirektoratet) and Aalborg University and is founded in the Danish construction act for new highways and expressways by Herning, between Odense and Svendborg and between Holbæk and Vig. Special problems occur, when it comes to prediction of pollutant load from road runoff. One of the main problems is that the temporal varying intensity of the rain causes high variation of the runoff. Hence it is impossible from few measurements to predict annual pollutant loads from the runoff. The method that has been shown to be the most effective for coping with the time variation in the rain is a so-called hindcast where several years of measured rain are used for simulating the exact variation in runoff from every single rain event. From the hindcast results it is possible to calculate mean water and pollutant loads. This method is commonly used in urban drainage systems for capacity analysis or for prediction of CSO's.

The challenge is to develop a simplified and still accurate description of flow and transport of pollutant adequate for the long-term simulation of the pollutant transport from highways caused by rain. 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. Measurements of water and pollutant transport are carried out in different highway systems. A geometrically well-defined test pond is established, wherein the deposition of particulate matter can be measured. The result from the test pond is transferred to real detention ponds in which the three-dimensional flow is described with a numerical CFD model. The particulate matter is analysed for grain size distributions, settling velocity distributions and corresponding heavy metal and PAH concentration. Erosion/resuspension experiments for detention pond sediments are carried out in the laboratory with currents and waves.

In general the study shows that the bulk of hydrocarbons, PAH's and heavy metals accumulate in detention pond sediments and the removal efficiency for particulate matter in the detention ponds is around 80 %. An important parameter for retention of particulate matter in Denmark is the wind - in that way, the calm water expedites the settling process contrary to turbulent water. The impact from the wind can reduce the pollutant removal efficiency significantly and even result in negative efficiencies due to resuspension of already settled particulate matter.

In the study a well calibrated one-dimensional transport model has been set up for describing:

- 1. The build up of particulate pollution on highway surfaces.
- 2. The removal of particulate pollution on highway surfaces due to rain.
- 3. The transport of water and particulate pollution through the drainage system to the connected detention ponds.

This model can be used for prediction of event loads on detention ponds for several years.

Likewise a well calibrated three-dimensional transport model has been set up for describing:

1. The transport of water, dissolved and particulate pollutants in wet detention ponds during arbitrary runoff events including the impact from wind and waves on the transport mechanisms.

The pond model is an essential tool for evaluating the ability of removal of particulate matter in existing and planned pond.

1. Introduction

It is generally accepted that the pollution of the water environment (primarily ditches, streams and rivers) caused by highway runoff is related primarily to heavy metals and polycyclic aromatic hydrocarbons (PAH's) e.g. in Ellis and Revitt (1981), Ellis *et al.* (1987), Grottker (1987), Mushack (1987), Stone and Marsalek (1996), Wu *et al.* (1998), German and Svensson (2002), Crabtree *et al.* (2005) and Marsalek *et al.* (2006). These components are especially connected to fine particles. In dry weather conditions a certain build up of fine particles on the road surface takes place. The build up of the particles is both related to the traffic, the road and the dust in the air from the surroundings. When raining a part of this accumulation of particles will be washed into the drainage system and another part will be resuspended back into the air because of the wind and the traffic generated turbulence, 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 an accurate modelling of the transport of fine particles from the road surface through drainage system and trough a detention pond to the receiving water.

Different types of sedimentation ponds are commonly used as treatment facilities for polluted highway runoff. 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. Most ponds have been designed only for flow control and peak flow reduction but studies have shown particularly high removal efficiencies for suspended solids and thereby also for heavy metals and organic compounds due to their sorption affinity (Pitt *et al*, 1995, Van Buren, 1997; Petterson et al., 1999; Comings et al., 2000). The removal efficiency for settleable particulate-bounded pollutants is thereby highly dependent on the pond geometry and corresponding hydraulic retention time. Optimizing of pond geometry for higher removal rates has been investigated in various studies e.g. Van Buren (1996), Matthews et al. (1997), Walker (1998), German et al. (2004) and Jansons et al. (2005). It is generally agreed that the removal efficiency varies from one facility to another (Van Buren, 1996) and from one event to another, even including negative efficiencies due to short circuiting flow, resuspension, and release of soluble pollutants due to changes e.g. oxygen condition in the sediment (Lawrence et al., 1996).

Since many ponds also handle infiltration water from the road bed, which leads to a more or less constant flow through the shallow ponds, the critical shear for resuspension of the bottom sediment, due to wind generated currents and waves is investigated, in order to be able to predict the size of the resuspension and the possible size of the discharged masses of pollutants transported with the baseflow out from the ponds. The wind-induced flow in the pond is the driving force for water and pollutant transport especially in dry weather periods with infiltration flow only, or during low intensity rain events as shown in Bentzen *et al.* (2008a). Circulation due to wind generated currents in large water bodies like lakes and estuaries has been studied for decades e.g. Lavel et al. (2003); Herb and Stefan (2005); Rueda et al. (2005). But literature concerning wind effects on smaller ponds and basins seems almost non-existing. The wind-induced flows in these shallow ponds may potentially exceed influence of the in- and outflow generated currents.

Owing to the Danish climate road deicing salt is used in winter time. The annual amount used on highways in Denmark has varied from 22000 to 51000 tons over the last five years. Based on the number of salting events and the area of highway it leads to an average an estimate of 13 g/m² per salting event. The effect of deicing salt on the critical shear stress for

resuspension of the highway pond deposits has also been evaluated. In general the winter performance is not evaluated in this thesis, due to very few annual snowfall events with accumulation of snow at the roadside, thus special considerations due to accumulation and release of pollutants from snowpacks is not taken into account. In literature knowledge about special winter performance of highway drainage systems is highly available e.g. Boom and Marsalek (1988), Sansalone and Buchberger (1996), Marsalek *et al.* (2003a), Marsalek *et al.* (2003b), Oberts (2003), Westerlund and Viklander (2006), Semadeni-Davies (2006) and many others.

In respect to resuspension of deposited materials not only the wind-induced currents introduce a bed shear stress, but also the wind-induced waves. The waves depend primarily on the wind speed and the fetch (in Denmark up to a few hundred metres of fetch). But even small waves will generate additional shear stresses at the bottom of the pond and resuspend a bulk of the bed material, which eventually will be transported with the currents to the outlet. The wind-wave-water-bottom interaction has been studied intensively in the past, however, little work has been done to focus on this interaction in small ponds. Most studies have been carried out on a larger scale and have addressed the interaction in oceans, bays, estuaries and larger lakes. Comparable studies of the wind-wave-water-bottom interaction are done by e.g. Adu-Wusu *et al.* (2001), Mian and Yanful (2002) and Yanful and Catalan (2002), where studies of resuspension in shallow mine tailings ponds due to wind generated waves have been carried out. Adu-Wusu *et al.* (2001) e.g. found that wind speeds exceeding 8 m/s above water covers that are shallower than 1 m create bottom shear stresses above 0.2 N/m^2 which is sufficient to set the bed in motion.

The present thesis is a part of a co-operation between the Danish Road Directorate (Vejdirektoratet) and Aalborg University starting in 2003. The objective 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. 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 particulate pollution can be identified and to be able to predict the yearly discharges of heavy metals and polycyclic aromatic hydrocarbons from an arbitrary detention pond to the natural environment.

For a more direct understanding of the spatial and temporal related variety of the ponds and the derived complexity of describing an arbitrary pond as universal a set of photos has been taken of Danish highway ponds.





Photo 1. Ice covered pond (no. 302.9) near Vodskov (Winter, 2004)

Photo 2. Ice melting. Pond no. 302.9 near Vodskov (Early spring, 2004)







Photo 4. Pond (no. 302.9) near Vodskov (Early spring, 2004) Wind effects. Spatial wind distribution.



Photo 5. Pond no. 95.1 near Fredericia covered by reed and reedmace.(July 2005)



Photo 6. Pond no. 95.3 near Fredericia. Surrounded by trees. (July 2005)





Photo 7 Irregular pond geometry. Pond no. 306.7 near Hjallerup. (July 2005)

Photo 8. Pond no. 13.9 near Aarslev (south of Odense) with a baffle separating the pond. (October, 2006)



Photo 9. Inlet structure at the Aarslev pond no. 13.9. Note the colour of the runoff water. (October, 2006)



Photo 10. The Aarslev pond no. 13.9 during rain. Note the effect of the baffle. (October, 2006)



Photo 11 Suspended transport within the Aarslev pond no. 13.9. (October, 2006)



Photo 12. Submerged inlet structure at the Aarslev pond no. 13.9. (July, 2007)

2. Pollution sources

The main part of the pollution related to highway systems is either dissolved substances or particles with a given pollutants adsorbed. A minor fraction is observed as separate phase pollution in terms of oil or gasoline. The pollutants originate primarily from (in arbitrary order):

- o Road surface wear
- o Road maintenance
- o Deicing agents
- Corrosion of crash barriers
- o Exhausts
- o Tyre wear
- o Brake wear
- o Corrosion of chassis, body work and paint
- Oil, gasoline and grease leakage
- Brake fluid, antifreeze, servo fluid, windscreen washing fluid etc.
- o Litter

And from sources not necessarily connected to the highway system

- Dry deposition of particles
- Wet deposition of pollutants and other dissolved substances

The contributions from each of the listed sources are all subject to a variation due to changes in the conditions of the road surface, traffic intensity, surroundings (urban/rural), time of the year, rain duration, rain intensity, wind etc. Table 1 indicates some of the pollutants originating from these sources. The span of substances found in relation to highway systems is very wide. Eriksson *et al.* (2002) have a comprehensive list of pollutants found in this respect.

	Brakes	Tyres	Chassis and body work	Oil, gasoline and exhaust	Road surface	Deicing agents	Crash barriers	Litter
Cadmium, Cd								
Cromium, Cr								
Copper, Cu								
Iron, Fe								
Lead, Pb								
Nickel, Ni								
Vanadium, V								
Zinc, Zn								
Chloride, Cl								
Inorganic matter								
Polycyclic aromatic hydrocarbons (PAH's)								
Phenols								
Phthalates								
Other organic substances								

Table 1. Metals and xenobiotics related to highway systems



Primary sources (Sansalone and Buchberger (1997)) Secondary sources (Sansalone and Buchberger (1997)) Sources (POLMIT (2002))

Sources (Danish Environmental Protection Agency (1997))

The primary copper pollution originates from brakes wear; in terms of fine particles the brake linings also contains chromium, nickel, lead, iron and asbestos. Tyres contain zinc and cadmium, both in the rubber and in the tyre armour. Tyres loose 10 - 20 % mass during their lifetime and hence are the major source to zinc pollution, unless locally galvanized crash barriers are situated. Zinc from tyres appears as fine dust or particles (POLMIT, 2002). Even though lead has been prohibited in gasoline since 1994 (in Denmark), unleaded gasoline contains a small portion lead and some studies (Danish Environmental Protection Agency, 1997) have shown that the emissions of polycyclic aromatic hydrocarbons (PAH's) from vehicles that use unleaded gasoline are twice as high as those from the cars which used leaded gasoline. The various treatment facilities connected to the highway drainage systems still contain a large bulk of lead due to its high sorption affinity. The PAH emission from the exhaust appears as both gas-phase or as particles. Road surface wear is a major source of the PAH emission due to the content of bitumen in the asphalt.

3. Environmental effects of heavy metals and PAH's

Xenobiotics are characterized as substances that in general are not present in the natural environment or only can be found in very low concentrations. These substances are very slowly degraded or not degraded due to their state of elements, thus they will accumulate in different recipients including plants and living organisms. A short description of the environmental effect of the six heavy metals: Cadmium, chromium, copper, lead, nickel and zinc and the PAH's considered in this study is listed below (Danish Environmental Protection Agency, 1995 and IPCS, 2008).

Cadmium can be acutely toxic both to humans and most animals in the environment. Chronical effects have been detected in mammals, fish and birds due to accumulation in the organisms. Hampering effects on microorganisms and plants growth in aquatic environments have been shown at cadmium concentration of 250 µg/l. Chromium can lead to allergic reactions in human beings. In large doses chromium is carcinogenic; despite of that it is also an important nutrient. Some chromium combinations are extremely toxic. Copper is like chromium an essential nutrient, even though it can be very toxic, especially to aquatic organisms. Lead affects the central nervous system of humans and can lead to loss of learning ability and disruptive behaviour by its accumulation in the bones. High lead concentrations can lead to downright poisoning. Lead can have acute and chronic affects on animals, plants and microorganisms, and in high concentrations inhibits the degradation of organic matter. Lead concentrations down to 1 mg/l have been shown toxic to microorganisms. Nickel can lead to allergic reactions in humans. All plants accumulates nickel especially oats and nuts. Zinc is an essential nutrient for the environment and only toxic to human in very high concentrations. Zinc has been shown to affect the reproductivity and the biochemical, physiological and behavioural characteristics of a variety of aquatic organisms. Dependent on the complexity, the PAH's can have different impact on living organisms. Those with few cycles are characterized with acute toxicity and the more heavy PAH's with chronic effects. Some PAH's are deemed to be carcinogenic to humans and animals and induce damage to the immune system and affects the hereditary genes and the reproductivity. Degradation of PAH's in the natural environment is dependent on the presence of microorganisms and prevailing aerobic conditions. In optimal conditions the half-life is from 2 days to a few years for slowest degradable. Field experiments (Danish Environmental Protection Agency, 1996) have shown much longer half-lifes (from 2 years to 17 years). The presence of heavy metals in high concentrations will inhibit the degradation further. For further knowledge about the impact on the environment and humans, The International Program on Chemical Safety (IPCS) provides a very extensive database. As a final comment a ubiquitous "pollutants" are considered. *Chloride* is per senot toxic but high concentrations affect freshwater plants and organisms. Another but not negligible effect of chloride is the increased corrosion of metals during the de-icing season and the formation of hydrophilic metal-salt combinations which due to their water-solubility more mobile then e.g. particle bound metals.

4. Concentration levels and accumulation rates

Concentrations of different pollutants in highway runoff have been measured for decades worldwide. The newest data available in the literature are presented in Table 2. The data is selected from a compressive monitoring program in UK, Crabtree *et al.* (2008). Both traffic load and climate conditions in the area for the survey are comparable to Danish conditions. The fraction of particle bound pollutant is indicated in the table, based on available total and dissolved concentration in the British survey. Few Danish studies have been carried out in order to measure similar concentrations by Danish Environmental Protection Agency, (1997) and POLMIT (2002). Average pollutant concentrations from these studies are shown in the right margin column in the table.

Table 2. Event mean concentrati	OIIS (EMIC) OI	ponutants in	ingnway ru	non and par	ticle bound	ponutant fraction.
Pollutant	Smallest	Average	Median	Largest	Particle	Average of
	EMC	EMC	EMC	EMC	bound	Danish surveys
					fraction	(particle bound
						fraction in
						brackets)
Cadmium [µg/l]	< 0.01	0.6	0.3	5.4	59 %	0.5 (81 %)
Chromium [µg/l]	< 0.3	7	4	61		8 (41 %)
Copper [µg/l]	4	91	43	877	66 %	95 (56 %)
Lead [µg/l]	< 0.1	38	10	379	90 %	28 (97 %)
Nickel [µg/l]	1	10	7	47		21 (74 %)
Zinc [µg/l]	10	353	140	3510	69 %	217 (71 %)
Total Petroleum	810	6058	4820	10000	80.0/	1200 (74.9/)
Hydrocarbons [µg/l]	810	0938	4820	19900	09 70	1300 (74 70)
Flouranthene [µg/l]	< 0.01	1.0	0.3	12.5		0.5 (88 %)
Benzo(b)flouranthene [µg/l]	< 0.01	1.0	0.5	8.8		
Benzo(k)flouranthene [µg/l]	< 0.01	0.4	0.2	3.5		
Benzo(a)pyrene [µg/l]	< 0.01	0.7	0.3	6.6		0.1 (91 %)
Indeno(1.2.3-cd)pyrene [µg/l]	< 0.01	0.6	0.3	5.6		0.1 (94 %)
ΣPAH [μg/l]	< 0.01	7.5	3.3	62.2	96 %	1.2 (85 %)
De-icing salts (Cl ⁻) [mg/l]	5	350	66	9760		
Total suspended solids [mg/l]	1	244	139	2030		97

Table 2. Event mean concentrations (EMC) of pollutants in highway runoff and particle bound pollutant fraction.

Sediment concentrations and accumulations rates

Eight Danish wet detentions ponds cf. Figure 1 were investigated in this study using the following criteria:

1) The pond only receives water from highway runoff. 2) The drainage system is a closed pipe system without open ditches (the highway has curbs and manholes). 3) The eight highway catchments and ponds cover a wide range of surface area. Site descriptions can be seen in Bentzen et al. (2007). Ten sediment cores in each pond were uniformly sampled and mixed to form composite samples, one for each pond. The composite samples were analysed for metals and organic compounds (Table 3) and two measures The total mass of accumulated calculated: pollutants using the mass of dry sediment and the concentration of the pollutant and the annual accumulation rate per hectare catchment area, using the age of the pond and the catchment area. The average annual increase in sediment depth in the ponds with an age of 6 years was calculated as 1.0 cm/year and for ponds with an age of 11 years as 0.6 cm/year, on average.



Figure 1 Location of detention ponds. The pond numbers are subsequently used as references.

Pollutant Pond	l no. 306.7	302.9	205.4	195.9	187.5	95.3	95.1	92.4	Mean
Relative pond area (pon area / impervious highw area) [m ² /hectare]	id /ay 880	860	620	580	560	240	170	370	
$C_6H_6 - C_{10}$	13	9	13	11	26	13	19	12	14
C_{10} - C_{25}	215	140	290	155	460	250	505	390	301
C ₂₅ -C ₃₅	902	655	1220	625	2175	1195	2375	1655	1350
THC	1140	805	1530	790	2640	1460	2895	2075	1667
Flouranthene	0.14	0.07	0.32	0.11	0.36	0.21	0.47	0.89	0.32
Benzo(b+j+k)flouranthe	ene 0.23	0.12	0.43	0.14	0.53	0.23	0.61	1.06	0.42
Benzo(a)pyrene	0.06	0.04	0.12	0.04	0.14	0.07	0.19	0.28	0.12
Dibenzo(a,h)antracene	0.01	0.01	0.04	0.01	0.05	0.02	0.05	0.10	0.04
Indeno(1.2.3-cd)pyrene	0.09	0.05	0.17	0.06	0.14	0.09	0.25	0.36	0.15
ΣΡΑΗ	0.53	0.28	1.07	0.35	1.21	0.62	1.56	2.68	1.04
Lead (Pb)	20	10	37	22	68	22	51	47	35
Cadmium (Cd)	0.5	0.3	0.5	0.6	0.9	0.4	0.7	0.8	0.6
Copper (Cu)	54	27	125	66	220	81	165	160	112
Chromium (Cr)	24	12	37	22	46	20	43	45	31
Nickel (Ni)	21	10	22	18	33	18	31	35	23
Zinc (Zn)	240	115	420	325	1045	710	1150	715	590
Dry matter fraction	27 %	31 %	38 %	31 %	18 %	29 %	19 %	24 %	27 %
Organic content									
(Loss on ignition)	11 %	6 %	9 %	19 %	16 %	9 %	14 %	15 %	12 %

Table 3. Concentrations [mg/kg dry matter] in the sediments in eight Danish ponds. Pond numbers are referring to distance from the origin of the highway.

The mean pollutant concentrations in the ponds are within the range of what can be found in the literature e.g. German and Svensson (2005), Durand et al. (2003), Stone and Marsalek (1996), Marsalek and Marsalek (1997). The variation in concentration between the ponds is to be expected, due to very different locations with a variance in: surroundings, traffic, vegetation, pH, redox potentials, microbiology, etc. The reason for these variations is not considered any further in this thesis. The annual accumulation rate of contaminants in each pond and a catchment area weighted mean accumulation rate for each of the 15 pollutants are presented in Table 4.

Table 4. Annual accumulation rates per hectare of impervious catchment	$\left[\frac{g}{yr \cdot ha}\right]$.	The mean	values are	weighted
by the catchment area.				

Pollutant	Pond no.	306.7	302.9	205.4	195.9	187.5	95.3	95.1	92.4	Mean
C6H6-C10		43	45	22	25	22	11	6	11	24
C10-C25		720	680	510	350	400	220	170	370	430
C25-C35		3000	3200	2100	1400	1900	1000	800	1600	1900
THC		3800	4000	2700	1800	2300	1300	1000	2000	2300
Fluoranthene		0.47	0.35	0.56	0.24	0.31	0.18	0.16	0.84	0.37
Benzo(b+j+k)fluo	ranthene	0.77	0.57	0.74	0.32	0.46	0.20	0.21	1.01	0.51
Benzo(a)pyrene		0.21	0.17	0.21	0.08	0.12	0.06	0.06	0.27	0.14
Dibenzo(a,h)antra	chene	0.03	0.05	0.06	0.02	0.04	0.02	0.02	0.09	0.04
Indeno(1.2.3-cd)p	yrene	0.29	0.25	0.29	0.14	0.12	0.08	0.08	0.34	0.19
ΣΡΑΗ		1.77	1.38	1.86	0.79	1.06	0.54	0.53	2.56	1.24
Lead (Pb)		67	51	65	49	59	19	17	45	51
Cadmium (Cd)		1.8	1.5	0.8	1.3	0.8	0.3	0.2	0.7	1.0
Copper (Cu)		182	129	218	146	192	70	56	153	156
Chromium (Cr)		79	59	64	48	40	17	14	43	48
Nickel (Ni)		69	50	38	40	29	16	10	33	37
Zinc (Zn)		807	561	734	726	913	615	392	682	709

The results also show that the accumulation rate for heavy metals significantly depends on the relative pond area (pond area divided by catchment area) (Figure 2). Similar relationships were found by Petterson et al. (1999). The curves in this study do not have the same 'flattening-out' tendency at a relative pond area of 250 m²/hectare as in Petterson et al. (1999). For copper and zinc the correlations are low, obviously due to the fact that the two metals are those with the lowest sorption affinity. The relationship between annual accumulation rate and relative pond area for the PAH's is not as clear as for the metals, probably due to various degradation conditions.



Table 5 Regression expressions for annual accumulation in [g/year/hectare] as function of the dimensionless relative pond

alea.		
Metal	Eqn.	R^2
Cd	$0.0006 x^{1.17}$	0.93
Cr	$0.09 x^{0.98}$	0.91
Cu	$1.93x^{0.69}$	0.69
Pb	$0.25x^{0.83}$	0.84
Ni	$0.064 x^{1.004}$	0.92
Zn	$112.8x^{0.29}$	0.42

Figure 2. Annual accumulation rate as function of relative pond area. Regression expressions are given in Table 5.

Many studies e.g. Ellis and Revitt (1981), German and Svensson (2002) and Zanders (2004) show relationships between particle size (diameter) and metal concentration on sediment originating from road runoff. Li et al. (2006) summarize the dependency of particle size on the heavy metal concentration. These relationships are within the context of transport modelling in ponds discussed here, since lack of density and shape of the single particle fraction is prevailing. Recently Kayhanian and Rasa (2007) dealt with the issue of density and showed that fractionated solids from highways varied from 1.6 to 1.8 g/cm³ in density. Hereby, in terms of best management practice, use of the traditional quarts density will lead to an overestimation of the efficiency of e.g. a detention pond.

The prospect of Bentzen and Larsen (2008) is to state the relationship between the settling velocity of the runoff particles and the corresponding metal and PAH concentration directly instead of dealing with two unknown factors: the density and the shape of a single particle fraction in settling velocity calculations with e.g. Stoke's Law and other empirical models which also have limitations within the flow regime around the falling particles. Settling velocity distributions for sediment from four ponds are measured with an application of a 1.65 m vertical cylindrical tube. Five water samples for each of the four pond sediments were collected on the bottom and represented by the following five settling velocity intervals: >5.5 mm/s, 5.5-2.5 mm/s, 2.5-1.3 mm/s, 1.3-0.5 mm/s and 0.5-0.1 mm/s. The effect of flocculation was minimized by repeating the experiments three times in order to get the necessary amount of sediment for metal and PAH analysis. In Figure 3 to Figure 6 the settling velocity intervals are given by the centre of the interval including the size of the interval. The interval sizes are only indicated on the concentration curves. In the same plots the relative amount of pollutants are shown. The sum of the relative amounts for a single pollutant is not necessarily 100 %, due to the unmeasured fraction with a settling velocity below 0.1 mm/s. For cadmium (Figure 3) the sum of the relative amounts exceeds 100%, which is of cause unrealistic, but within the uncertainty of the metal analysis and uncertainty of the settling velocity distribution. For the remaining pollutants refer to Bentzen and Larsen (2008).



Figure 3. Fractionated cadmium concentrations and relative amounts. Pond numbers refers to Figure 1.



Figure 4. Fractionated nickel concentrations and relative amounts. Pond numbers refers to Figure 1.



Figure 5. Fractionated copper concentrations and relative amounts. Pond numbers refers to Figure 1.

Figure 6. Fractionated concentrations of Σ PAH's and relative amounts. Pond numbers refers to Figure 1.

For Cadmium, chromium, zinc, and nickel it is evident that the highest metal concentration is associated with the slowest falling particles and the lowest concentration is associated within the faster falling sand fraction. For ponds number 92.4 and 187.5 this is not so significant, and for copper and lead the tendency is also not so clear. For ponds no. 92.4, 187.5, and partly 205.4, it seems that the concentration curves have an optimum around 2 mm/s and not at the slowest falling particles. The reason for this is most likely due to the more or less constant content of organic matter in the fractions cf. Bentzen and Larsen (2008) for the two ponds 92.2 and 187.5. The main adsorbent of e.g. lead is organic matter (Sipos *et al.* 2005) and similarly for copper (Marsalek and Marsalek, 1997). Despite of threefold differences in concentration levels of the metals between the four ponds, the relative amount of the metals are almost similar. The largest amount of metals within each pond can be found in the particle fraction with a settling velocity of 5.5-2.5 mm/s. For the PAH's there is no clear correlation between the adsorbed concentration and settling velocity. As for the metals the largest amount of PAH's can be found in the particle fraction with a settling velocity of 5.5-2.5 mm/s.

4. System analysis and modelling approaches

There are two governing dispersion mechanisms for the highway associated pollutants – transport with the runoff water and air emission. Which one of the two is prevailing depends on several factors - e.g. physical shape of the pollutant, chemical properties, the weather, traffic intensity and velocity and the condition and the type of pavement. The physical shape of the pollutants determines whether the pollutant falls or remains airborne. Larger particles and liquids are not necessarily settled on the road surface due to the high turbulence caused by passing vehicles and wind. These particles will later on deposit on the road, in the vicinity of the road or far from the road.

Deposited pollutants on the road surface will either be transported away with the rain generated runoff or by splashing generated by vehicles. A porous pavement will reduce the splash significantly. High precipitation intensity will lead to a significant transport of pollutant with the runoff, due to the high shear stress on the road surface. Furthermore thunder storms with high intensity will often appear in summer periods with long preceding dry weather periods resulting in a large pollutant build up. Hence long-term precipitation with low intensity will primarily transport easily soluble substances and fine particulate matter. Only the transport caused by rain induced runoff will be considered further in this thesis, which is not completely true because most Danish highway drainage systems are established with top sliced pipes (The KL type on Figure 8) for dewatering the road bed. Hence there is a more or less constant infiltration flow also in dry periods through the drainage system - not carrying pollution in a significant matter but the constant flow of a few litres per second has an unwanted effect. The outflows from the detention ponds are newer zero, thus for a long term evaluation of the discharges of pollutants to the natural environment, the inter rain event periods should be taken into account due to resuspension caused by wind and wave induced currents and bed shear stresses. Moreover, the fact that "pure" water is entering the ponds entails another negative effect. The bio-removal process of heavy metal using plants contains two uptake processes (Keskinhan et al. 2003): An initial fast reversible, biosorption and a slow irreversible bio-accumulation, thus the biosorption might be affected by the "pure" water entering the ponds. These bioprocesses will not be considered any further. The result of a general analysis of the pollutant transport from highways to the natural environment is given in Figure 7.



Figure 7. Time scales in runoff processes..

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 detention pond to the natural environment. The main problem in these tasks is the time variation in every process involved, hence simple average considerations are hard to archive.

- The runoff from the highway is varying in time, due to variation of rain intentsity
- The pollutant load from the road surfaces is varying in time, due to the varying rain intensity and the variation of the available mass on the surface

Hindcast is the method that has been proved to be the most effective for coping with the time variation in urban drainage modelling, where historical rainfalls are used for simulating the runoff. In terms of computational speed, these hindcasts (even for 10 years) are not a problem any longer due to one-dimensional flow considerations without external forces interfering. When it comes to the particle transport and removal in detention ponds the challenge is increased significantly.

- o The inflow is non-steady and is varying on short time scale
- The outflow is non-steady but with less variance
- The geometry varies from pond to pond.

- Natural and stochastic external forces like wind are generating three dimensional flow patterns and waves
- Pollutants are related to particles with various settling velocities
- \circ The retention time in the ponds is long with respect to the rain runoff duration.
- o Resuspension does also occur during inter rain event periods
- Consolidation of the ponds deposits occurs over time.
- o Etc.

A model capable of taking all these parameters into account and simulating the water and pollutant transport in the ponds over the same long term period as for the runoff is in the present moment not available in terms of computational speed. In modelling terms – a low Courant number is necessary to avoid instabilities of the model, hence with several hundred litres per second in inflow and wind speeds above 10 m/s changing directions a demand of very low time steps (< 1 sec) is prevailing when applying pollutant transport to the hydraulic calculations. If only the hydrodynamics should be solved and the ponds are of regular shape the calculation could be done within a reasonable computational time. Hence this study has focused on setting up and validating a runoff model, which can be used for a hindcast, and setting up and validating a pond model that is able to calculate the water and pollutant transport within the ponds by taking the above mentioned parameters into account. This model will be used for evaluation of the individual processes involved in the total transport. The derived results are subsequently attempted to be generalized in a larger perspective in terms of annual pollutant removal efficiencies. The following two chapters deal with the runoff model for the pollutant build up, the surface flow and the water and pollutant transport in the pipe system and the pond model including all the mentioned involved parameters.

5. Numerical modelling of water and pollutant transport on road surfaces and in pipe systems

In order to predict hydrographs and pollutographs as sources for further evaluation of the efficiency of the detention ponds and the derived discharge to the receiving waters, the description of processes 1-3 in Figure 7 is performed in the commonly used 1-dimensional MOUSE (DHI, 2005) (now a part of MIKE URBAN). The force of the transport model is the possibility to calculate the pollutographs for any runoff events during the year or even all events during e.g. 20 years, provided that the model can reproduce the reality adequately. Hence the model has been setup (according to Bentzen *et al.* (2005)) for the system shown in Figure 8. The system consists of 1 km of a 2x2 lane highway in the northern part of Jutland, Denmark (Vodskov N). The total catchment area is 3.4 hectare of which 2.7 hectare is impervious dense asphalt. In 2002 the average daily traffic load was 14,900 vehicles. 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 m³ (1,000 m³ below outlet level). The receiving water is a small creek with a median-average discharge of 30 l/s.



Figure 8 Section of the drainage plan for the Vodskov detention pond.

In the following paragraphs the mathematical foundation for the used model is described along with calibration and verification results.

Pollutant build up (process 1)

The build up rate of sediment on the road surface, due to the previously mentioned sources is assumed linear over time (eqn. 1). The build up rate is thus a constant for calibration

$$\frac{dM}{dt} = A_c \quad \text{for } M < M_{\text{max}} \tag{1}$$

where M = accumulated mass, t = time and A_c = build up rate.

Surface runoff and pollutant wash off (process 2)

The highway surface is divided into 100 sub-catchments with connected manholes. The *Time-Area* model is used for calculation of the road surface flow. The following parameters are thus subject to calibration: The time-area curve for the catchments, the times of concentration, the hydraulic reduction factors and the initial losses. The removal of sediment due to rain is described as eqn. 2

$$V_{sr} = D_r \cdot \left(\frac{i_r}{i_d}\right)^e \cdot A \cdot (1 - \varepsilon) \cdot A_s$$
⁽²⁾

where V_{sr} = volume of sediment removed per hour, D_r = removal coefficient, i_r = rain intensity, i_d = rain constant (25.4 mm/h), e = exponent, A = catchment area, ε = porosity of the sediment and A_s = part of the catchment covered by sediment. Hence the removal coefficient and the exponent are subject to calibration.

Runoff – pipeflow and pollutant transport (process 3)

The water transport in the pipe system is described by the dynamic wave theory by solving the St. Venant equations (3 and 4) for a one-dimensional flow by an implicit finite difference scheme.

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \tag{3}$$

where Q = discharge, A = cross-section area, t = time and q = source/sink.

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\alpha \frac{Q^2}{A} \right) + g \cdot A \cdot \frac{\partial y}{\partial x} = g \cdot A \cdot I_0 - g \cdot A \cdot I \tag{4}$$

where α = velocity distribution coefficient, g = acceleration due to gravity, I_0 = bottom slope and I = the gradient of the energy loss. Hence the roughness of the pipes is subject to calibration. The sediment transport in the pipes is described by the advection/ dispersion equation (eqn. 5) due to very low settling velocities of the sediment (primarily in the silt fraction), as shown later on.

$$\frac{\partial}{\partial t}(A \cdot C) + \frac{\partial}{\partial x}(Q \cdot C) - \frac{\partial y}{\partial x}\left(A \cdot D\frac{\partial C}{\partial x}\right) = -C_c \cdot q \tag{5}$$

where C = concentration, D = dispersion coefficient and $C_c =$ the source/sink concentration.

Modelling – data - results

In order to obtain calibration and validation data for equations 1 - 4, the following measurements where conducted:

- 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 Thompson V-notch weir.
- Water level in the detention pond
- A discharge/water level (Q/h) relation was calculated for the pond outlet. With a mass balance over time the inlet discharge could be calculated. The weir could for that reason be uninstalled to avoid interfering with the particle transport.
- The inlet concentration of total suspended solids was measured during rain events. Initially, the sampling during rain was carried out manually. Subsequently an automatic sampler (ISCO-6700) was controlled by the rain gauge and sampled every 4th tilt (0.8 mm rain).

The water transport from the highway surface to the detention pond modelled in MOUSE showed good agreement with measured inflow to the detention pond. Figure 9 and Figure 10 illustrates modelled and measured inflow to the pond over two periods.





Figure 9. Gray curve: Measured discharge (Thomson V-notch weir). Black curve: Modelled discharge to the detention pond. R2 = 0.82.

Figure 10. 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 10 can be explained by the way the Q/h relation 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. Examples of the measured concentration and discharge series can be seen in Figure 11 and Figure 12.





Figure 11. Concentrations of SS and discharge in the inlet to the pond. The dry weather period before the rain event (6 mm rain) was 13 days.

Figure 12. Concentrations of SS and discharge in the inlet to the pond. The dry weather period before the rain events (15 mm) was 6 days.

All periods shows a casual relationship between the discharge to the pond and the concentration of SS. The correlation coefficient between discharge and suspended solids (SS) for all events is 0.78. It is clear that the preceding dry weather period and first flush effects also affect the concentration level. The hydrological and hydrodynamic model in combination with the sediment transport and water quality module MOUSE TRAP were subsequently used for describing the build up on the road surface, the removal due to rain (Figure 13) and the transport of SS with the measured concentrations levels as foundation (Figure 14 to Figure 16) with a satisfactory result.



Figure 13. Modelled build up and removal of sediment from a single subcatchment. Rain intensities are shown on the secondary ordinate axis.

Note that not all modelled events have been verified with measurements and due to the automatic sampling setup, the modelled peak concentration on e.g. Figure 15 has not been verified either.



Figure 14. Measured (points) and modelled SS concentrations to the pond.



Figure 15. Measured (points) and modelled SS concentrations to the pond.



Figure 16. Measured (points) and modelled SS concentrations to the pond.

Modelling of water and SS discharges from highways to detention ponds is possible with application of the 1D sewer model MOUSE showing satisfactory agreements with measurements. Based on historical measured rain the model can be used for long term evaluation of both the hydraulics and the pollutant transport within highway drainage systems, due to the rather non complex processes. For a total evaluation of the pollutant transport from the highway surface to the recipient (including the treatment facility – the detention pond) it should be emphasised that a full perfect match in time between the modelled and measured pollutographs for the inlet to the pond is in general of minor importance due the large difference in the time scale as shown in Figure 7. Since the governing force for circulation in ponds located in open land is the wind, as shown in the next chapters, even event mean concentrations could be applied instead of the time varying pollutographs. Hence the phenomenon like *first flush* is more or less irrelevant in terms of the long term evaluation of treatment efficiency, unless of cause, the runoff water contains acute toxic concentrations of a given pollutant and short-circuiting flows are prevailing due to an inappropriate pond design.

6. Numerical modelling of water and pollutant transport in wet detention ponds

Modelling of fine sediment transport within ponds 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. Initially the sediment transport requires an adequate description of the hydrodynamics within the ponds with a sufficient small time-discretization in order to describe the sediment transport processes simultaneously. In the following paragraphs the mathematical foundation for the used model is described along with calibration and verification results.

Hydrodynamic calculations

The hydrodynamics in the ponds is described with the MIKE3 program (DHI, 2008) in three dimensions by solving the Reynolds averaged Navier Stokes (RANS) equation with the assumption of hydrostatic pressure distribution and an incompressible fluid cf. the mass conservation eqn. 6 and the momentum eqn. 7 (for the x-direction). Thus the vertical velocities are calculated only from the continuity equation and not from the momentum

equation. Within the in- and outlet regions of ponds and a band around the shoreline the assumption of hydrostatic pressure may be questionable due to the occurring vertical accelerations, but for the pond as a total system – the assumption of hydrostatic pressure can be adopted due to negligible vertical accelerations within the main part of the pond. Cioffi *et al.* (2005) have tested the difference between a non-hydrostatic 3D and a hydrostatic 3D RANS model for wind driven channel flows and found that, only near the boundaries/walls of the channel the velocity field was significant different between the two models.

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

$$\frac{\partial u}{\partial t} + \frac{\partial uu}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z} =$$

$$(6)$$

$$(7)$$

$$-\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\left(2\nu_T\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_T\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right) + \frac{\partial}{\partial z}\left(\nu_T\frac{\partial u}{\partial z}\right) + u_sS$$

where u, v, w = velocities in the x, y, z directions, S = source/sink term, ρ = density, v_T = eddy viscosity and the pressure term is solved by eqn. (8)

$$\frac{1}{\rho}\frac{\partial P}{\partial x} = \frac{g\rho(\zeta)}{\rho}\frac{\partial \zeta}{\partial x} + \frac{g}{\rho}\int_{z}^{\zeta}\frac{\partial \rho}{\partial x}dz$$
(8)

where g = acceleration due to gravity and $\xi = \text{surface elevation}$. The model has been shown in Bentzen *et al.* (2005) capable of calculating the hydrodynamics and transport of dissolved matter appropriately. This model has subsequently been improved, by replacing the used mixed Smagorinsky/k- ε turbulence formulation with the Smagorinsky formulation (equivalent to Prandtl's mixing length formulation) (eqn. 9) in both directions for calculating the eddy viscosity. The Smagorinsky coefficients were adjusted according to the tracer experiments done in the laboratory and combined with LDA-measurements of velocities in the flume in Bentzen *et al.* (2008d). It was clear that the Smagorinsky/k- ε turbulence and the k- ε turbulence formulation had problems coping with low Reynolds numbers in the experiments (a flow condition that also will occur in the detention ponds). With use of the more easily adjustable Smagorinsky formulation (eqn. 9) the results of the detention pond tracer experiment shown in Bentzen *et al.* (2005) results in a better fit between the measured and modelled outlet concentrations as shown in Figure 17.

$$\nu_T = (C \cdot \Delta s)^2 \sqrt{S_{ij} \cdot S_{ji}} \tag{9}$$

where C = Smagorinsky coefficients (one for the horizontal plane and one for the vertical) Δs = grid spacing and S = velocity gradients.



Figure 17. Re-calculation of tracer experiment. See figure 14 in Bentzen et al.(2005) for comparison.

The ponds are mainly discretized in grids of 0.8 m x 0.8 m (corresponding to a standard inlet structure). The vertical discretization has been varying from 0.05 - 0.2 m to compromise long simulation time. The bed resistance is calculated according to the near bed velocity u^* and the drag coefficient C_D cf. eqn. 10

$$\tau_{bottom} = C_D u^* |u^*| \rho \tag{10}$$

The calculation of the drag coefficient is dependent on the roughness height. To all pond models a roughness height of 0.05 m has been applied.

Wind forces

The wind-induced flows in these shallow ponds may potentially exceed the size of the inflow and outflow generated currents. The study focuses on issues related to relatively small ponds with a few thousand square meters of surface area. In meteorological terms this means that the issue is on microscale to the smaller end of the mesoscale. Owing to that, the study does not deal with the generation of wind on large scales. Near the surface, irregular turbulent motions occur due to the roughness of the surface, the presence of vegetation, trees, buildings, hills etc. All obstacles break the mean wind into irregular twisting eddies varying in force and size. A small obstacle produces small eddies as so does light winds whereas. Buildings, hills, or e.g. highway embankments produce larger eddies corresponding to the size of the obstacle itself as well as various smaller eddies such as rotors. The size is dependent on the wind speed. The mean wind and eddies will influence the water surface of the pond and transport kinetic energy to the water body. The force from the wind on the water surface is calculated by eqn. 11 and hence the upper boundary condition for the shear term.

$$\frac{\tau_{xx}}{\rho} = \upsilon_T \frac{\partial u}{\partial z} = \frac{\rho_{air}}{\rho} C_w W W_x \tag{11}$$

where τ = shear stress, W = wind speed in 10m height and C_w = wind drag coefficient set to vary linear from 0.00063 at W=0 m/s to 0.0026 at W=24 m/s, Larsen, (1995). The effect of the nearby topography on the wind field over the water surface may have great influence on the generation of wind induced currents in the ponds as shown in e.g. Rueda et al. (2005). Results from Bentzen et al. (2008a) shows that: The wind induced flows play a dominant role for the time of retention of a pollutant as well as on the flow pattern. This may produce positive as well as negative effects. A) The retention time (based on peak arrival and arrival of the centre of mass) decreases compared to the "no wind shear" situation. This result would change if

inlet and outlet structures are placed so close to each other that prevalent short-circuiting flow occurs under no-wind conditions see e.g. Bentzen et al. (2005). B) Even then, if retention time is decreased due to the wind shear, the dilution of the pollutant is generally increased, due to contact with a greater water pool (except when the wind direction is parallel to the direction between inlet and outlet structure). The differences in retention time between the use of spatial uniform and spatial non-uniform wind fields calculated for the local topography are not significant in this study. The mixing in the pond varies significantly for wind speeds in the area of 0 - 5 m/s but increased wind speeds do not significantly change the mixing of a dissolved matter further. The mixing is more or less the same for all wind directions with wind speeds above 5 m/s (the average wind speed in Denmark). For the particle transport the story is to a certain extent different, due to still increasing bed shear stress with increasing wind speed. This will be considered further in a later chapter.

Wave forces

Several empirical formulas have been stated to calculate wave heights and periods based on wind speed, water depth, fetch etc. Practically all of the models have been designed for larger depths and fetches that are much longer than in the present study with a fetch of a maximum of 100 - 200 metres. Therefore, corresponding wind and wave measurements were carried out in a detention pond near Hjørring (Figure 18) exposed to wind, and the results are compared with different models cf. Bentzen *et al.* 2008b. The characteristics of wind induced waves (wave height (H_s), wave period (T_s) and the direction (γ)) are modelled by the MIKE21 Nearshore Spectral Wave program (DHI, 2008). In the model it is assumed that waves and currents do not interact with each other, thus $H_s(t,x,y)$, $T_s(t,x,y)$ and $\gamma(t,x,y)$ are independently calculated with same wind speeds and directions as used for the wind induced current calculations. Dissipation of energy due to the roughness of the bed is included by an enhanced version of the quadratic friction law, so directional spreading of the wave energy is included. Results can be seen on Figure 19 and in Table 6 with general good agreement between measurements and model results, especially with respect to the wave periods, which as subsequently shown is the central parameter in respect to the bed shear stress calculations.



Figure 18. Wave measuring point X. Fetch = 113 m.



Figure 19. Example of a model result for the pond shown on Figure 18.

Table 6	Evaluation	of NSW	wind-wave	model
	Lvaluation		winu-wave	mouci.

Measured wind speed	Measured $H_s(H_{m0})$ and $T_s(T_m)$	MIKE 21 – NSW (Kahma & Calkoen (1994))
$U_{10} = 9.4 \text{ m/s},$	$H_s = 0.048 \text{ m} (0.047)$	$H_{m0} = 0.035 \text{ m}$
	$T_s = 0.83 \text{ s} (0.82)$	$T_m = 0.81 \text{ s}$
$U_{10} = 12.8 \text{ m/s}$	$H_s = 0.052 \text{ m} (0.052)$	$H_{m0} = 0.050 \text{ m}$
	$T_s = 0.87 \text{ s} (0.86)$	$T_{m} = 0.90 \text{ s}$
$U_{10} = 13.9 \text{ m/s}$	$H_s = 0.071 \text{ m} (0.079)$	$H_{m0} = 0.055 \text{ m}$
	$T_s = 0.93 \text{ s} (0.93)$	$T_{\rm m} = 0.93 {\rm s}$

Hence an additional bed shear stress is introduced by the near bead wave motion. The bed shear stress is calculated by linear wave theory:

$$\tau_b = \frac{1}{2} f_w \rho U_b^2 \tag{12}$$

where τ_b = bed shear stress, f_w = friction factor, ρ = density of water (999.1 kg/m³), U_b = maximum of the wave orbital velocity near the bed. The friction factor f_w is dependent on the flow regime. The transition from laminar to fully developed smooth turbulent flow starts at amplitude wave Reynolds number $Re_{a,w}$ (eqn. 13) $\leq 1.28 \times 10^4 \rightarrow 6 \times 10^5$ (Jonsson, 1980). In case of laminar flow the friction factor can be calculated by eqn. (14) (Jonsson, 1980) and for turbulent flow by eqn. (15) (DHI, 2008). Equations 12 and 13 have been implemented, in cooperation with DHI, in the MIKE3 – MT model which at the moment is not commercially available.

$$\operatorname{Re}_{a,w} = \frac{U_b a}{v}$$
(13)

$$f_{w,la\min ar} = \frac{2}{\sqrt{\operatorname{Re}_{a,w}}}$$
(14)

$$f_{wturbulent} = 0.04 \left(\frac{a}{k_N}\right)^{-0.25}$$
(15)

where a = maximum displacement of a single particle from its mean position and is calculated by eqn. (16), v = kinematic viscosity of the water and k_n the Nikuradse roughness height.

$$a = \frac{U_b T}{2\pi} \tag{16}$$

The maximum of the wave orbital velocity near the bed U_b is calculated by eqn. (17)

$$U_{b} = \frac{\pi H}{T \sinh(kh)} \cosh(k \cdot dz_{b})$$
(17)

where k = wave number and $dz_b =$ thickness of the bottom most grid cell.

$$k = \frac{2\pi}{L} \tag{18}$$

$$L = \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi h}{L}\right) \tag{19}$$

where L = wave length, h = water depth.

The additional bed shear stresses from the waves are summarized with the current generated bed shear stresses by taken the angles between the waves and currents into account with a parameterized version of Fredsøe (1984), DHI (2008)

Sediment transport calculations

The sediment transport within the ponds is described with the MIKE3 - Mud Transport (MT) program (DHI, 2008). Assumptions for the three sediment transport processes involved (suspended transport, erosion and deposition) are subsequently described as well as the underlying experiments. The suspended transport of sediment within the ponds is described with the advection-dispersion eqn. (20) (for the z-direction).

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial z} \left(c \left(w - w_{s,i} \right) \right) = \frac{\partial}{\partial z} \left(D_z \frac{\partial c}{\partial z} \right) + S_c$$
(20)

where c = concentration of the ith fraction of sediment with the corresponding settling velocity w_s and D_z = dispersion coefficient calculated proportional to eddy viscosity with the Prandtl number. Four experiments have been carried out in order to verify the capability of the MT-model to describe the transport of sediment appropriate. To simplify the complexity of a real pond and for easy control and measurement the sediment transport experiments were carried out in two rectangular channels: one 7.5m x 0.3m, x 0.3 m and one 30m x 0.8 m x 0.6 m (Photo 13) respectively with sediment traps at the bottom. The model calculations showed good correlation with the measured longitudinal sediment net accumulation as seen in Figure 20 and in Bentzen *et al.* (2008d). The sediment used in the experiments originated from the *Vodskov* detention pond.



Photo 13. Channel used for the large scale experiments.



Figure 20. Measured and modelled longitudinal net deposition and median grain size distribution. (Large channel)

Since the model has been shown capable, with an acceptable accuracy to model the transport of highway sediments within the channels it might be assumed that this is also the case in e.g. detention ponds where water depths and flow conditions are comparable with the especially the large channel.

Erosion and consolidation

Worldwide the circular flumes (Photo 14) have been used for determination of erosional and depositional behaviour of sediments e.g. Sheng and Lick (1979), Møller-Jensen (1993),
Johansen, C. (1998), 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. Mehta and Partheniades (1973), Krishnappan (1993) and Petersen and Krishnappan (1994). As described in Bentzen *et al.* (2008b) the erosional and consolidation parameters of the detention pond sediment (from the Vodskov pond no. 302.9) are stated on behalf of mixing phase with high bed shear stress, a settling and consolidation phase from 24 hours to 40 days and a erosion phase with stepwise increment of the bed shear stress. Owing to the Danish climate, road de-icing salt is frequently used in winter. The effect of de-icing salt on the critical shear stress for resuspension of the highway pond deposits has also been evaluated.



Photo 14. Circular flume (and a lot of mess).

The critical shear stress for bringing the sediment to suspension is significantly dependent on the consolidation time according to Figure 21. For low consolidation time and shear levels around 0.1 N/m² the sediment is brought to suspension at rates around 0.1 g/m²/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/m². The evolution of sediment strength due to consolidation time seems to stop referring to Figure 22 where the de-icing effect experiments show that there is no practical difference in the critical shear stress between a consolidation time of 12 and 40 days. The general evolution of strength at increasing salinities shown by Gultarte *et al.* (1980) is non-existing within the material tested and there are no significant differences between the tested salinities. At a bed shear stress of 0.26 N/m² there is a trend showing the opposite conclusion of Gultarte *et al.* (1980). At this incremental step it seems that the increase in salt concentration to 0.1 kg/m³ is more strengthening than higher salt concentrations is. The difference is most likely originating in the differences between the compositions of the materials tested, e.g. local ion concentration, valences of the present ions, elementary charges, etc. (Gultarte *et al.* (1980) used pure illite

and silt). For the highway pond deposit investigated, the results show, that the use of de-icing salt does not change the critical shear stress for resuspension.



Figure 21. Time series of water phase concentration during the consolidation effect experiments.



Figure 22. Time series of water phase concentration during the deicing effect experiments.

The erosion and resuspension is also evaluated during wave activity in a 20 m long and 1.2 m wide rectangular wave flume as described in Bentzen et al. (2008b). 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 wood plate was covering the bottom of the flume. In the plate hole was made and filled with sediment from the same pond as used at the circular flume experiments (Photo 15).



Photo 15. Setup for evaluation wave generated resuspension

The visual evaluation of the bed movement and suspension showed good agreement with the current generated resuspension in the circular flume. 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 . The wave testing results are summarized in Table 7, where the corresponding wind speed U₁₀ has been calculated as the converted average of the *wind stress factor* derived from the SPM84 model based on the Sverdrup, Munk & Bretschneider method (U.S. Army Coastal Engineering Research Centre, 1984) and with the modified coefficients as described in Bentzen *et al.* (2008b). The wind

speeds U_{10} for obtaining the present wave parameters are calculated for four different fetches (25, 50, 100 and 200 m) at a water depth of 0.6 m.

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Ī	H _m	T _m	Ub	τ_b	U _{10, 25m}	U _{10, 50m}	U _{10, 100m}	U _{10, 200m}	Sediment motion at
	[m]	[s]	[cm/s]	$[N/m^2]$	[m/s]	[m/s]	[m/s]	[m/s]	water depths = 0.6 m
	0.026	0.58	0.02	0.001	13	8	5	4	No
	0.044	0.64	0.12	0.004	17	11	8	5	No
	0.047	0.69	0.26	0.009	20	13	8	6	No
	0.062	0.73	0.6	0.02	23	15	10	7	No
	0.072	0.77	1	0.03	27	17	12	8	Beginning of bed transport
	0.089	0.81	1.8	0.05	31	20	13	9	Bed transport
	0.08	0.85	2	0.06	32	20	13	9	Bed transport
	0.087	0.9	3	0.08	35	23	15	10	Bed transport
	0.104	0.94	4.5	0.12	40	26	17	11	Bed and slight beginning of suspended transport
	0.129	0.99	6.8	0.18	46	30	20	13	Suspended transport
	0.134	1.03	8.2	0.22	50	32	21	14	Suspended transport
	0.155	1.08	10.8	0.28	56	36	23	16	Suspended transport
	0.178	1.16	14.9	0.37	65	41	27	18	Suspended transport

Table 7. Results from the wave erosion/resuspension experiment. The mean wave parameters H_m and T_m measured are similar to the significant wave height and period due to the regularity of the waves in the experiment.

In the evaluation of long-term efficiency of highway detention ponds, the shear strength of the sediment must be applied to the model used, so that the effect of possible resuspension during intense rain events, wind generated currents and waves, etc., can be predicted. MIKE3 Mud Transport (DHI, 2008) has been used for reproduction of both the circular flume experiments and the wave erosion experiments. The primary task was to calibrate the erosion coefficients *C* and α in eqn. 21 and to implement the effect of consolidation on the shear strength. The erosion rate *E* of sediment is described as given in eqn. (21) (Mehta *et. al.* 1989).

$$E = C \cdot e^{\alpha \sqrt{(\tau_b - \tau_{ce})}} \tag{21}$$

where *C* and α = erosion coefficients which have been calibrated for the pond sediment in Bentzen *et al.* (2008), τ_b = bed shear stress from the currents and waves, and τ_{ce} = critical bed shear stress for erosion. The consolidation process is simply described by a transfer rate between the layers describing the bed, thus sediments with a lower density and lower critical shear stress for resuspension are transferred with a constant rate to the underlying bed layer with higher density and higher critical shear stress and so on. In Figure 23 the result of the modelling is visualized, hence the model describes both erosion and consolidation adequately for detention pond sediment. In respect to the wave forcing in the model - as previously mentioned, the code has been modified in order to also handle the prevailing laminar condition near the bed and hereby the independency of the roughness height, and shows good agreement with the observed bed motions.





Table 8. Results picked out from the numerical modelling of the wave erosion/resuspension.

H _s [m]	T _m [s]	$\tau_b \left[N/m^2 \right]$	Bed mass change over three minutes [g/m ² /min]
0.047	0.69	0.009	0
0.072	0.77	0.03	-0.01
0.08	0.85	0.06	-0.3
0.104	0.94	0.13	-0.8
0.155	1.08	0.31	-2.2

Figure 23. Measured and modelled concentration time series of the concentration in the water phase.

Deposition

The deposition of suspended material is governed by the critical shear stress for deposition τ_{cd} . No measurements were conducted for stating this. The critical shear stress for deposition is set in relation to the critical shear stress for resuspension to vary between 0.04 N/m² for the fastest falling particles and 0.03 N/m² for the slowest. The deposition *D* of the actual fraction is described as given in eqn. 22 (DHI, 2008).

$$D = w_s c_b p_d \tag{22}$$

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

7. Prediction of annual resuspension due to wind generated currents and waves

In Bentzen et al. (2008c) the pond model described in previous sections is used for evaluation of the annual resuspension and sediment transport from the Vodskov pond and to evaluate different methods for reducing the resuspension process. All numerical calculations of the wind impact on the pond sediment are based on 30 years of wind statistics from a nearby wind station. The effect of the wind on the resuspension process is evaluated in inter rain event periods only with a baseflow/infiltration flow of 3 l/s. Based on the duration of 18 years of measured rainfall events (\approx 300 events/year), which leads to a sum of approximately 25 days of rain per year, an approximate concentration time in the drainage system of 20 minutes, 2 days of retention within the ponds for rainfall events with a depth above 4 mm, this leads to a period of approximately 230 days for the Vodskov pond. The result shows clear correlation between the wind speed and the mean outlet concentration of suspended solids from the pond as shown in Figure 24 and Table 9. The correlations are universal in that sense that the wind statistics for the present pond has not yet been adopted in the calculation and is not universal; in that case it is only valid for ponds with the same fetch (100 m x 40 m) and mean depth of 0.43 m and maximum of 0.6 m in the middle region. By using a well correlated expression for all wind directions, the relative placement of in and outlet are negligible.



Figure 24. Modelled mean outlet concentration of suspended solids as function of the wind force from eight directions.

Table 9. Regression expressions. y = estimated mean outlet concentration [mg/l] and x = wind speed [m/s]

Direction	Regression expression
North	$y = 1.15E-03x^{4.00}$
	$R^2 = 1.0$
North-east	$y = 7.44E-04x^{4.37}$
	$R^2 = 1.0$
East	$y = 2.01E - 04x^{4.99}$
	$R^2 = 0.99$
South-east	$y = 1.9E-05x^{5.94}$
	$R^2 = 1.0$
South	$y = 3.95E-04x^{4.82}$
	R2 = 0.97
South-west	$y = 1.82E-04x^{5.11}$
	$R^2 = 0.85$
West	$y = 1.93E - 05x^{5.81}$
	$R^2 = 0.96$
North-west	$y = 3.4E-06x^{0.377}$
	$R^2 = 0.89$
All	$y = 8.71E-05x^{5.30}$
	$R^2 = 0.91$

The modelled outlet concentrations of TSS during dry weather periods show casual agreement with (the few) measured ones cf. Table 10. Measurement should also be conducted under very strong wind to validate the high end of the expressions

Date	Measured wind speed and	Measured outlet TSS	Modeled outlet TSS
	direction	concentration	concentration
May 2008	0-2 m/s	Below 2 mg/l	0 - 0.1 mg/l
10. June 2008	3-10 m/s / SW	2.8 mg/l	0.1 – 7.7 mg/l
18. June 2008	4 -7 m/s / SW	2.8 mg/l	1.3 mg/l
24. June 2008	9-11 m/s / W, SW	5.2 mg/l	4.3 - 7.7 mg/l

Table 10. Measured vs. modeled effluent TSS concentrations.

The total mass of annual resuspended solids, metals, and PAH's discharged to the natural environment from the Vodskov pond can be seen in Table 11. The masses are based on the composition of the outlet pollutographs (the concentration of each of the seven fractions sediment) and multiplied with the corresponding pollutant concentration as given in Bentzen and Larsen (2008). The outlet masses of solids, metals and PAH's are compared with the annual accumulation rate of the given pollutant.

Table 11. Modelled total mass of annual resuspended solids, metals and PAH's discharged to the natural environment due to resuspension during dry weather periods. *) Might be underestimated (see Bentzen *et al.* 2008*a*)

) Wight be underestimated (see Bentzen et al. 2008C)								
Wind	TSS	Cd*	Cr*	Cu*	Pb*	Ni*	Zn*	∑PAH*
direction	[kg/year]	[g/year]						
Ν	11	0.02	0.5	1	0.4	0.5	9	0.001
NE	32	0.04	0.8	2	0.7	0.9	15	0.001
Е	108	0.14	3.2	8	2.8	3.2	59	0.020
SE	131	0.16	3.6	9	3.2	3.6	66	0.022
S	66	0.12	2.6	7	2.3	2.6	48	0.013
SW	432	0.41	9.1	24	7.9	9.0	166	0.061
W	520	0.46	10.1	26	8.9	10.1	187	0.055
NW	23	0.03	0.7	2	0.6	0.7	13	0.002
All	1323	1.38	30.5	79	26.7	30.6	562	0.174
Percentage of yearly accumulated mass	10 %	8 %*	7 %*	7 %*	7 %*	9 %*	8 %*	2 %*

Depth of pond and sheltering vegetation

A computational fluid dynamic (CFD) model is a beneficial tool in terms of e.g. optimizing the pond configuration for larger pollutant removal. In terms of the studied resuspension process, additional calculations were done for the wind directions south and west at wind speeds of 5, 13 and 18 m/s, but with increased water depths of 0.2 m and 0.4 m respectively which correspond to an increase of the mean water level with 46 % and 93% respectively. The impact of the wind on the resuspension process is reduced radically as shown in Table12. It has been shown in Bentzen and Thorndahl (2004) that the hydraulic capacity of the present pond is extremely oversized, hence an upward movement of the outlet structure is a simple solution for reduction the wind impact on the bottom.

Wind direction and speed	Reduction at 0.2 m increase in water level (46 % of present water level)	Reduction at 0.4 m increase in water level (93 % of present water level)		
South 5 m/s	49 %	56 %		
South 13 m/s	55 %	68 %		
South 18 m/s	36 %	71 %		
West 5 m/s	42 %	42 %		
West 13 m/s	52 %	68 %		
West 18 m/s	77 %	83 %		

Table 12. Effect of increased water depth on the total mass of annual resuspended solids discharged to the natural environment

Another possibility for reducing the wind impact on the bottom sediment is reducing the wind speed by living shelterbelt. It is generally known from crop and soil protection in agriculture that well designed shelter belts can reduce the wind speed with 60-80 percent within distances not exceeding the longest fetch of the pond. By reducing the wind speeds, with 20% and 50% and a recalculation of the wind statistics (the possibility for a given speed from a given direction) this also leads to a radical fall in wind generated resuspension as shown in Table 13. The ponds will not only in the dry weather periods benefit from the shelter, the settling of particles during rain events will also increase radically due to the derived decrease in turbulence in the water body as seen in the next chapter. It must as an additional comment be mentioned, that reducing the wind impact on the ponds gives rise to a more strict relative placement of the inlet and outlet (in other words – they should be placed far from each other)

Wind direction	TSS with	TSS with
	20 % reduction of	50 % reduction of
	wind speed	wind speed
	[kg/year]	[kg/year]
Ν	7 (-39 %)	0.6 (-94 %)
NE	18 (-44 %)	1.3 (-96 %)
E	51 (-52 %)	1.8 (-98 %)
SE	45 (-65 %)	1.3 (-99 %)
S	26 (-61 %)	1.3 (-98 %)
SW	111 (-74 %)	1.8 (-100 %)
W	94 (-82 %)	3.2 (-99 %)
NW	13 (-43 %)	1.2 (-95 %)
All	366 (-72 %)	12.5 (-99%)

Table 13. Effect of wind shelterbelts on the total mass of annual resuspended solids discharged to the natural environment

8. Three dimensional modelling of pollutant removal efficiencies in wet detentions ponds - based on hindcast runoff results

With the fully developed MOUSE model for calculation of water and sediment transport from highway surfaces to the connected detention ponds, including the build up of sediments on the surfaces and the wash off due to the rain, it is now possible to do a hindcast for a single detention pond catchment for several years with historical rainfall events. The functioning of the connected detention pond can now be evaluated for an arbitrary event and optimal for a longer time period (> 1 year) including several rainfall events and different wind conditions, with the developed three dimensional MIKE 3 Mud Transport model. The events in Table 14 have been modelled in order to predict the efficiency of pollutant removal in two ponds – the Vodskov pond (Photo 16) and the Aarslev pond (Photo 17). The efficiency for solid removal is defined as:

$$E = \frac{\sum (C_{in} \cdot Q_{in}) - \sum (C_{out} \cdot Q_{out})}{\sum (C_{in} \cdot Q_{in})}$$



Photo 16. The Vodskov pond. Surface area = 2400 m^2 , average depth = 0.43 m (max 0.62 m) under dry weather condition.



(23)

Photo 17. The Aarslev pond. Surface area = 2100 m^2 , average depth = 0.62 m (max 1.1 m) under dry weather condition.



Figure 25. Bathymetry of the Vodskov pond. Arrows indicates inlet and outlet. Outlet direction = 243° rel. to true north. In chapter 9 - the red lines refers to half the pond and one third of the pond.

Figure 26. Bathymetry of the Aarslev pond. Arrows indicates inlet and outlet. Outlet direction = 315° rel. to true north.

Pond/Event Date	Comments
Vodskov - $16/6/2008 - 22/6/2008$	Initial sediment on the bottom
Event 1	Wind included (measured 10 km SW for the pond)
	Waves included
	Outlet concentration has been measured in this period
Vodskov - 14/8/2006 - 17/8/2006	No initial sediment on the bottom
Event 2 Extreme rainfall event	1) No wind include
	2) Constant wind speed 5 m/s from north \pm waves
	3) Constant wind speed 5 m/s from west + waves
	4) Constant wind speed 10 m/s from north + waves
	5) Constant wind speed 10 m/s from west + waves
Vodskov - 8/11/2007 - 11/11/2007	No initial sediment on the bottom
Event 3	1) No wind include
	2) Constant wind speed 5 m/s from north $+$ waves
	3) Constant wind speed 5 m/s from west + waves
	4) Constant wind speed 10 m/s from north + waves
	5) Constant wind speed 10 m/s from west + waves
Vodskov - 6/5/2007 - 10/5/2007	No initial sediment on the bottom
Event 4	1) No wind include
	2) Constant wind speed 5 m/s from north $+$ waves
	3) Constant wind speed 5 m/s from east $+$ waves
	4) Constant wind speed 5 m/s from south $+$ waves
	5) Constant wind speed 5 m/s from west + waves
	6) Constant wind speed 10 m/s from north $+$ waves
	7) Constant wind speed 10 m/s from east $+$ waves
	8) Constant wind speed 10 m/s from south + waves
	9) Constant wind speed 10 m/s from west + waves
Vodskov - 25/2/2007 - 3/3/2007	No initial sediment on the bottom
Event 5	1) No wind include
	2) Constant wind speed 5 m/s from north $+$ waves
	3) Constant wind speed 5 m/s from west + waves
	4) Constant wind speed 10 m/s from north + waves
	5) Constant wind speed 10 m/s from west + waves
Vodskov - 3/1/2005 - 10/1/2005	Initial sediment on the bottom.
Event 6 Full storm	Measured wind included
	Waves NOT included, due to model limitations
Vodskov - 24/6/2007 - 29/6/2007	No initial sediment on the bottom
Event 7	1) No wind include
	2) Constant wind speed 5 m/s from north $+$ waves
	3) Constant wind speed 5 m/s from west + waves
	4) Constant wind speed 10 m/s from north + waves
	5) Constant wind speed 10 m/s from west + waves
Aarslev – 4/10/2006 – 31/12/2006	Initial sediment on the bottom.
58 events	1) No wind included
	2) Measured wind included, waves NOT included due to model
	limitations.
	58 events > 1 mm rain. Total 250 mm rain over the period
	*

Table 14. Modelled events for solid removal efficiency prediction



0.000

00:00:00 17-6-2008 00:00:00 18-6-2008

Event data can be seen on following figures.

Figure 27. Rainfall intensity (red line) over the Vodskov detention pond catchment. Discharge from the Vodskov detention pond catchment (blue line) and discharge from the detention pond (green line). For EVENT 1.

00:00:00 19-6-2008

00:00:00 20-6-2008

00:00:00 21-6-2008

00:00:00 22-6-2008



Figure 29. Rainfall intensity (red line) over the Vodskov detention pond catchment. Discharge from the Vodskov detention pond catchment (blue line) and discharge from the detention pond (green line). For EVENT 2.



Figure 31. Rainfall intensity (red line) over the Vodskov detention pond catchment. Discharge from the Vodskov detention pond catchment (blue line) and discharge from the detention pond (green line). For EVENT 3, 4 and 5.



Figure 28. Concentration of total suspended solids (red line) from the Vodskov detention pond catchment. Build up and removal of sediment (blue line) from a single sub-catchment to the pond. For EVENT 1.



Figure 30. Concentration of total suspended solids (red line) from the Vodskov detention pond catchment. Build up and removal of sediment (blue line) from a single sub-catchment to the pond. For EVENT 2.



Figure 32 Concentration of total suspended solids (red line) from the Vodskov detention pond catchment. Build up and removal of sediment (blue line) from a single sub-catchment to the pond. For EVENT 3, 4 and 5.

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Figure 33. Rainfall intensity (red line) over the Vodskov detention pond catchment. Discharge from the Vodskov detention pond catchment (blue line) and discharge from the detention pond (green line). For EVENT 6.



Figure 35. Wind speed and wind direction at Aalborg Airport (10km SW from the Vodskov pond). For EVENT 6.



Figure 36. Rainfall intensity (red line) over the Aarslev detention pond catchment. Discharge from the Aarslev detention pond catchment (blue line) and discharge from the detention pond (green line). For the Aarslev events.



Figure 34 Concentration of total suspended solids (red line) from the Vodskov detention pond catchment. Build up and removal of sediment (blue line) from a single sub-catchment to the pond. For EVENT 6.



Figure 37 Concentration of total suspended solids (red line) from the Aarslev detention pond catchment. Build up and removal of sediment (blue line) from the catchment to the pond. For the Aaslev events.



Photo 18. Wind speed and direction measurement equipment at Aarslev detention pond. Installed two metres above water surface. Recalculated to 10 metres height.

Figure 38. Measured wind speed and wind direction at the Aarslev detention pond (in 10 meters height).

Results of event modelling

The event outlet pollutographs for the ponds are shown in following figures and the efficiencies and comments are summarized in Table 15.



Figure 39. Measured and modelled outlet TSS concentration. The automatic sampler was time triggered to sample one sample every sixth hour and two samples per bottle, thus the same concentration in two successive samples. Vodskov pond.



Figure 40. Modelled inlet and outlet TSS concentrations for event 2. Vodskov pond.



Figure 41. Modelled inlet and outlet TSS concentrations for event 3. Vodskov pond.



Figure 43. Modelled inlet and outlet TSS concentrations for event 5. Vodskov pond.



Figure 45. Modelled inlet and outlet TSS concentrations for event 7. Vodskov pond.



Figure 42. Modelled inlet and outlet TSS concentrations for event 4. Vodskov pond.



Figure 44. Modelled inlet and outlet TSS concentrations for event 6 and applied wind speed. Vodskov pond.



Figure 46. Modelled inlet and outlet TSS concentrations for 58 events during autumn 2006 in the Aarslev pond.

Event	Efficiency	Comments				
	(TSS – removal)					
Vodskov - 1	83 %	Modelled TSS concentrations show in general good agreement with measurements. (Both in magnitude and time)				
Vodskov - 2	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				
Vodskov - 3	98 % (no wind) 99 % (5 m/s north) 98 % (5 m/s west) 91 % (10 m/s north) 55 % (10 m/s west)	 Events 2 – 5 and 7 shows almost complete removal for the "no wind" and wind of 5 m/s situations. Even though it is only a few percents, slight wind tends to 				
Vodskov - 4	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)	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				
Vodskov - 5	98 % (no wind) 100 % (5 m/s north) 88 % (5 m/s west) 90 % (10 m/s north) 86 % (10 m/s west)	due to the orientation of the outlet structure (243°)				
Vodskov - 6	- 51 %	Initial sediment on the bottom. Negative efficiency, due to wind generated resuspension. Waves are not included, thus the efficiency is underestimated.				
Vodskov - 7	98 % (no wind) 99 % (5 m/s north) 98 % (5 m/s west) 95 % (10 m/s north) 68 % (10 m/s west)					
Aarslev (autumn 2007)	84 % (with real 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.				

Table 15. Result overview.

Information on the composition of the solids leaving the ponds during the event can be achieved from the model result files. An example of this is shown in Figure 47 for events 1 and 2. Based on the compositions the discharged masses of the heavy metals can be predicted by following the procedure described in Bentzen *et al. 2008c*. Discharged masses of heavy metals from the Vodskov pond (for event 1, 2) and from the Aarslev pond (for the autumn 2006) can be seen in Figure 48.



Figure 47. Composition of the TSS leaving the Vodskov pond.



Figure 48. Discharged masses of particle bound heavy metals from different events. For event 1: the pollutant removal efficiency for the metals varies between 79% - 84%. For event 2: 98% for the no wind and 5 m/s simulations. 95% for the 10 m/s north and 76%-79% for the 10 m/s west simulation. For the autumn 2006 in Aarslev the particle bound metal removal efficiency varies between 81% and 83%.



Figure 49. Outlet concentration of TSS. Comparison of linear decay model and the three dimensional model for Event 3 – No wind. $K=0.74 \ hr^{-1}$



Figure 52. Outlet concentration of TSS. Comparison of linear decay model and the three dimensional model for Event 3 – Wind 5 m/s north. $K=3.97 hr^{-1}$



Figure 55. Outlet concentration of TSS. Comparaison of linear decay model and the three dimensional model for Event 5 – Wind 5 m/s west. $K=0.11 hr^{-1}$



Figure 50. Outlet concentration of TSS. Comparison of linear decay model and the three dimensional model for Event 5 – No wind. $K=0.84 \ hr^{-1}$



Figure 53. Outlet concentration of TSS. Comparison of linear decay model and the three dimensional model for Event 3 – Wind 5 m/s west. $K=0.94 hr^{-1}$



Figure 56. Outlet concentration of TSS. Comparaison of linear decay model and the three dimensional model for Event 7 – Wind 5 m/s north. $K=2.18 hr^{-1}$



Figure 51. Outlet concentration of TSS. Comparison of linear decay model and the three dimensional model for Event 7 – No wind. $K=0.84 hr^{-1}$



Figure 54. Outlet concentration of TSS. Comparison of linear decay model and the three dimensional model for Event 5 – Wind 5 m/s north. $K=4.14 hr^{-1}$



Figure 57. Outlet concentration of TSS. Comparaison of linear decay model and the three dimensional model for Event 7 – Wind 5 m/s west. $K=1.03 \ hr^{-1}$



Figure 58. Outlet concentration of TSS. Comparison of linear decay model and the three dimensional model for Event 3 – Wind 10 m/s north. $K=0.67 hr^{-1}$



Figure 59. Outlet concentration of TSS. Comparison of linear decay model and the three dimensional model for Event 3 – Wind 10 m/s west. K=0.02 hr^{-1} . The linear decay model can be enhanced by a reduction of the pond volume with a factor of 3 for taking the fast short circuiting flow, generated by the western wind, into account. K=0.02 hr^{-1}



Figure 60. Outlet concentration of TSS. Comparison of linear decay model and the three dimensional model for Event 5 – Wind 10 m/s north. $K=0.22 hr^{-1}$



Figure 61. Outlet concentration of TSS. Comparison of linear decay model and the three dimensional model for Event 5 – Wind 10 m/s west. $K=0.10 hr^{-1}$. The linear decay model fits better during this event even with 10 m/s of wind; this can be explained by the great volume of water discharged to the pond during the event giving rise to high water level which reduces the effect of the wind.



Figure 62. Outlet concentration of TSS. Comparison of linear decay model and the three dimensional model for Event 7 – Wind 10 m/s north. $K=0.83 hr^{-1}$



Figure 63. Outlet concentration of TSS. Comparison of linear decay model and the three dimensional model for Event 7 – Wind 10 m/s west. $K=0.03 hr^{-1}$. The linear decay model can be enhanced by a reduction of the pond volume with a factor of 5 for taking the fast short circuiting flow, generated by the western wind, into account. $K=0.03 hr^{-1}$.





Figure 64. Outlet concentration of TSS from the Aarslev pond. Comparison of linear decay model and the three dimensional model for 58 events during the autumn 2006. Real wind. $K=0.29 hr^{-1}$.

9. Simplified pollutant removal model for suspended solids – an application for long term evaluation of pond removal efficiencies

Based on the three dimensional simulations of the pollutant transport in detention ponds during different events it has been essential to simplify the mathematical description of the pollutant removal process in order to be able within acceptable computational time to predict long term removal efficiencies of particulate matter. A simple linear decay model based on the fully mixed reactor theory (eqn. 24) has subsequently been set up for events 3, 5 and 7 (from chapter 8); this mathematical removal formulation is ready for adoption in e.g. the MOUSE model for pollutant removal in ponds.

$$\frac{dV \cdot C}{dt} = Q_{in} \cdot C_{in} - Q_{out} \cdot C - K \cdot C \cdot V$$
(24)

where V = total volume of the pond, C = concentration of TSS in the pond, (assuming fully mixed) Q = discharge, $C_{in} =$ inlet concentration and K = linear decay constant. The decay constant has been calculated on behalf of the minimum least square error between the outlet concentrations from the three dimensional model and the outlet concentration from the linear decay model. As shown in figures 49-57 the linear decay model fits the three dimensional model very well for situations without wind or with slight wind for the Vodskov pond. The reason for this is, that only a small volume of the pond is utilised for the particle transport and hence can be assumed fully mixed. Two additional simulations for event 3 were done (without wind) – one with half the pond size and one with one third of the pond size (c.f. Figure 25) and new outlet discharge time series due to the increased change in water level variation. These simulations show that the removal efficiency is similar to the full pond model.

For situations with higher wind speeds (10 m/s) the fully mixed linear decay model is unsuitable both due to the larger eddies and resuspension. For the Aarslev pond the linear decay model is not suitable cf. Figure 64, and also for the "no wind" situation due to the geometry of the pond. If linear decay constant model should be applied for the Aarslev pond, the pond should be divided into x numbers of compartments with different decay constants as done in e.g. Vollertsen *et al.* (2007). For high wind exposed ponds at least two parameters (including the wind speed and direction) shall probably be included in the simplified model in order to achieve a better fit for these situation.

10. Conclusions

Sediments and pollutants

- As expected hydrocarbons, PAH's and heavy metals accumulate in the pond sediment. The comparison of the accumulation in relation to the load shows that the bulk of the incoming heavy metals can be found in the sediments whereas the organic compounds can only partly be found in the ponds. The ponds show high efficiency (> 80 %) for retaining particle bound pollutants.
- For the metals, cadmium, chromium, zinc, and nickel, it is evident that the highest metal concentration is associated with the slowest falling particles and the lowest concentration is associated with the faster falling sand fraction. For some ponds this is not so significant and for copper and lead the tendency is also not so clear, most likely due to the more or less constant content of organic matter in the particle fractions.
- Despite of a threefold differences in concentration levels of the metals between the ponds, the relative amounts of the metals on a single particle fraction are almost similar.
- For the PAH's there is no clear correlation between the adsorbed concentration and settling velocity.
- The characteristics of the sediment tested in this study, with respect to grain size distribution, organic content and pollutant levels, are what can be found world-wide in the literature.
- Sediment from a permanent wet highway detention pond has been tested for its critical shear stress for resuspension. The critical shear stress for resuspension is found to vary between $0.1 0.26 \text{ N/m}^2$ dependent on the consolidation time.
- The critical shear is found to be the same, due to wave generated bottom shear stress as for the current generated shear stress.
- The effect of deicing salt, corresponding to higher salinities in the deeper regions of the ponds does not seem to have significant influence on the critical bed shear stress, most likely due to the prevailing chemical conditions in the ponds due the presence of metal ions in the porewater.

Modelling in general

- Modelling of pollutant build up and wash off of pollutants from highway surfaces due to rain is possible with application of the one dimensional sewer model MOUSE TRAP based on a linear build up function and an exponential removal function. The model shows good agreement with measurements.
- Water and suspended solid discharges from the highway to detention ponds can be described with the one dimensional MOUSE and MOUSE TRAP model based on the St. Vernant equations and the advection/dispersion equation. The model shows good agreements with measurements and can provide hydrographs and pollutographs for evaluation of the particle removal efficiency in detention ponds based on several years of historical rainfall data.
- Modelling of hydrodynamics and transport of dissolved pollutants in wet detention ponds is possible with application of the three dimensional model MIKE 3 based on the three dimensional Navier Stokes equation and the advection/dispersion equation. The model shows good agreement with measurements.

- Modelling of hydrodynamics and transport of particles in wet detention ponds is possible with application of the three dimensional model MIKE 3 – Mud Transport. The model shows good agreements with measured transport and deposition.
- In general the long term removal process in the ponds cannot be coupled directly to the MOUSE model as a linear decay model (as available in MOUSE).
- For specific ponds long term measurements or three dimensional modelling must be carried out prior to stating a linear decay constant. For highly wind exposed ponds or irregular ponds with complex flow pattern a linear decay model makes no sense.

Influence of wind on the pollutant transport in ponds

- The results drawn from this investigation show that modelling retention times of e.g. a dissolved pollutant or flow patterns in shallow detention ponds, wind shear stress ought to be taken into account.
- In modelling used for long term evaluations of retention times, in which the accurate flow pattern is of less importance, there is no need for the use of spatial non-uniform wind fields assuming, of course, that very local wind data are available for a uniform description and the topographical effects are small. However, if the aim is to describe flow patterns within the pond accurately during a single rain event the spatial non-uniform wind field is preferable, including the temporal variation.
- Within the order of magnitude the pond model is capable of predicting the annual resuspension process during dry weather periods caused by wind induced currents and waves.
- In the Vodskov pond the current and wave generated bed shear stresses entail a discharged bulk of pollutants corresponding to approximately 10 % of the annual accumulation of pollutants due to the baseflow in the pond.
- The modelled mean outlet concentration of suspended solids is very well correlated with the wind speed. The general regression expression in table 2 can be used universally for ponds with similar size and depth (≈100m x 50m x 0.5m) to predict the outlet concentration from a pond with a baseflow of a few litres per second independent of relative placement of inlet and outlet.
- To reduce the resuspension of deposited materials, two mechanisms are prevailing. Either increase the water depth of the pond to minimize the effect of the wind in the near bed region or reduction of the wind to some degree.
- An increase in water depth of 46 % will give a reduction of the yearly discharge mass with the baseflow with approximately 50 %. A further increase of water depth does only increase this with minor percentages, which can be explained by the rapidly declining wave impact with increasing water depth and a more slowly declining impact of the near bed return flow.
- The most efficient action for reducing the wind impact on the shallow waters is establishment of shelterbelts as known from the agriculture. Just a 20 % reduction of the yearly wind speeds will reduce the outlet mass with 70 % and a 50 % reduction with almost 100 %. A 50 % reduction of the wind speed is far from impossible to achieve with relatively small investments.
- Reducing the wind impact on the ponds gives also rise to a more efficient settling process during rain events.
- A nearly complete removal of particles is reached by establishment of low cost shelterbelts.

Future work

The bullets on following list should be paid more attention in the future, in order to understand the pond system even further and optimize the total pollutant removal efficiency of highway ponds.

In direct relation to this study:

- Long term 3D simulations of several pond configurations
- A multiple regression analysis of the long term simulations in order to set up a simplified tool for evaluation of the removal efficiency of existing and planned detention ponds, by taking rainfall intensity and duration, pond geometry, placement of inlet and outlet and wind speed and direction into account.
- Reconfiguration of the outlet structures in the ponds for an optimal utilisation of the pond volume for pollutant removal.
- Effect of submerged aquatic plants on the resuspension process
- Effect of the predicted climate changes on the total highway drainage system and pollutant removal efficiencies.

In indirect relation to this study:

- Based on the high removal rates for particulate pollution in detention ponds the focus should be placed on dissolved pollutants in future.
- The 3D pond model can be enhanced even further (and is ready for it) so it not only takes the particle transport into account but also time varying water quality phenomenon like nutrient transport, oxygen transport and consumption, growth, death and degradation of vegetation into account
- Effect of submerged pond plants on the dissolved pollutant transport (biosorption and accumulation)
- Implementation of low tech filters for retaining dissolved pollutants
- Bioaccumulation of pollutants in the food chain a controversial issue about whether high contaminated ponds (placed in nature) leads to increased accumulation compared to spreading the pollution over a larger area (river -> oceans)

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Paper I

Removal of Heavy Metals and PAH in Highway Detention Ponds

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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.



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Figure 2. Location of study area. (copyright, 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 m³ (1,000 m³ below outlet level). The receiving water is a small creek with an approximate median-average discharge of $0.03 \text{ m}^3/\text{s}$.

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 μ m – 700 μ m. 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: $D_{90} = 100 \ \mu m$ $-600 \ \mu m$ (fine to medium fine sand), $D_{50} =$ 50 μ m – 100 μ m (coarse silt to fine sand) and $D_{10} = 10 \ \mu m - 20 \ \mu m$ (medium fine silt).



Figure 7. Measured settling velocities for pond sediment. The experiment indicates a lognormal 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/m³ 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 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 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 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 6^{th} 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.



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 po	ond.
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Cd	Cr	Cu	Pb	Zn	PAH
0.6	4.5	89.3	39.0	383.1	2.9
0.4	6.5	70.2	1.2	156.5	0.5
	Cd 0.6 0.4	Cd Cr 0.6 4.5 0.4 6.5	Cd Cr Cu 0.6 4.5 89.3 0.4 6.5 70.2	Cd Cr Cu Pb 0.6 4.5 89.3 39.0 0.4 6.5 70.2 1.2	Cd Cr Cu Pb Zn 0.6 4.5 89.3 39.0 383.1 0.4 6.5 70.2 1.2 156.5

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.

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Paper II

Can we close the long-term mass balance equation for pollutants in highway ponds?

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Can we close the long term mass balance equation for pollutants in highway ponds?

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Abstract

The paper discusses the prospects of finding the long term mass balance on basis of short term simulations. A step in this process is to see to which degree the mass balance equation can be closed by measurements. Accordingly the total accumulation of heavy metals and PAH's in 8 Danish detention ponds only receiving runoff from highways have been measured. The result shows that the incoming mass of heavy metals from short term runoff events is accumulated. This is not observable in the same magnitude for the toxic organic compounds. The results also show that the accumulation rates significantly depend on the relative pond area (defined as the pond area divided by the catchment area). The conclusion is that the investigation indicates that a combination of short and long term viewpoints can close the mass balance for highway ponds with an acceptable accuracy.

Keywords

Heavy metals, xenobiotics, PAH, sediment, runoff, mass balance

1. Introduction

Variants of sedimentation ponds are commonly used as treatment facilities for polluted highway runoff. Many ponds have been designed only for flow control and peak reduction but studies have shown particularly high removal efficiencies for suspended solids and thereby also for heavy metals and organic compounds due to their sorption affinity [19], [13] and [2]. The removal efficiency for settleable particulate-bounded pollutants is thereby highly dependent on the pond geometry and corresponding hydraulic retention time. Optimizing of pond geometry for higher removal rates has been investigated in various studies e.g. [18], [12], [20], [7] and [8]. It is generally agreed that the removal efficiency varies from one facility to another [18] and from one event to another, even including negative efficiencies due to short circuiting flow, resuspension, release of pollutants due to changes e.g. oxygen condition in the sediment [9].

In many studies the efficiencies of pollutant removal in the detention ponds are calculated from event based mass balances, where flow, inlet and outlet concentrations have been measured. The question is now whether these short term balances hold in respect to balances over many years of function. The mass balance equation runs as:

Accumulation = Influx - Degradation - Outflux

In short term studies only influx and outflux can be measured and in long term studies only accumulation and rough estimates of influx can be determined. This study is based on the total accumulated masses of the pollutants in the bottom sediment in 8 Danish highway wet detention ponds. The sizes of the ponds and the connected catchments areas are varying. The corresponding load (influx) to the ponds has been estimated on basis of generalised measurements from a number of locations. The advantage of dealing with the total accumulated masses in the ponds instead of concentration is that many years are taken into account and therefore event, season and yearly variations of the pollutant loads are averaged out. The pollutants considered in this paper are chosen due to their prevalent presence in highway runoff [15] and toxicological effects onto the environment and humans [10]. The aim of the present study is to quantify the relation between the total accumulation and the total load on a long term basis, in order to make probable that a long term mass balance realistically seen can be calculated from a sum of short term events. The work should also be

understood as a preliminary study of an ongoing detailed description and modelling of the removal of pollutants in highway ponds.

2. Method

In order to state the terms in the mass balances for the pollutants in the 8 wet detention ponds, following measurements and approaches have been taken.

The 8 Danish ponds investigated in this study have been selected under four following criteria: The ponds should only receive water from highway runoff. The drainage systems should be closed so no infiltration or sedimentation in ditches occurs. The highway is established with curbs so that all runoff water is collected in gullies. The catchment area to the pond should differ from site to site. Site details can be seen in table 1.

Table 1. Site description.

Pond/Station number [km]	306.7	302.9	205.4	195.9
Nearby city	Hjallerup	Vodskov	Randers S	Hadsten N
Pond area [m ²]	1500	2299	2300	3480
Catchment area [ha]	1.7	2.7	3.7	6.0
Opening year for traffic	1999	1999	1994	1994
Annual day traffic in 2004	15400	14800	32100	30200
Annual precipitation [mm]	820	820	690	690

Table 1 continued. Site description.

Pond/Station number [km]	187.5	95.3	95.1	92.4
Nearby city	Grundfoer	Fredericia	Fredericia	Fredericia
Pond area [m ²]	2300	200	380	600
Catchment area [ha]	4.1	0.8	2.2	1.6
Opening year for traffic	1994	1994	1994	1994
Annual day traffic in 2004	33800	24100	24100	24100
Annual precipitation [mm]	690	770	770	770

2.2. Accumulation

10 samples (fig. 1) were taken with a 56 mm cylinder in each pond representing 1/10th of the bottom area. Each sample within the ponds was taken out in the entire sediment depth, so that a mix of all 10 samples was representing the entire pond.



Fig. 1. Sampling method.

The total mass of the ten wet sediment samples from each pond was measured and mixed heavily with a whisk on a drill machine, packed in 2x250 ml glass jars and kept cool until shipment to 2 independent accredited laboratories. Furthermore information on sediment depths and general background information was also taken. Based on the dry matter fractions of the sediment the total masses of dry sediment in the ponds were calculated. Based on the total masses of dry sediment and the measured concentrations the total masses of accumulated pollutants were calculated and based on the total accumulations, the age of the ponds and connected catchment area the annual accumulation rate per hectare impervious catchment area were calculated.

2.4. Influx

In absence of inlet pollutant flux measurements under each rain event during the past 6 or 11 years, two opportunities are available to predict the flux of pollutants to the ponds: Either a pollution buildup/wash off model for the catchments or a mean highway runoff concentration model. It is not possible to state which model is the most suitable for this purpose but since the basis for getting concentration data are fairly good, the influx to the ponds are based on literature values for pollutant concentrations in highway rain runoff, local annual rain fall and annual initial rain loss. The use of literature values may be highly questionable for short term event based balances due to the temporal and spatial variability in runoff concentrations. By dealing with long term balances the temporal variability can be ignored. The spatial variability can of cause not be ignored due to the long time frame. But it must be remembered that this paper is not about whether one term in the mass balance equation is completely correct but about the prospects to close the mass balances for highway ponds based on short term flux measurements and long term accumulation measurements. The estimated annual pollutant influxes are based on following data:

5

Concentration and flow data

- An average of concentrations of 24 runoff samples from two highway location in Denmark, where all runoff water was collected each month over one year and analysed for pollutants [14] and 60 EMC from highway runoff in the UK [3]. The concentrations applied are seen in table 2

- Annual rainfall measured within a maximum distance of 20 km to the catchments and averaged over the years of pond function (c.f. table 1) [4] and a mean annual initial loss. The initial loss during one rain event was assumed to be 0.6 mm for all highway catchments. The loss has in preceding studies [1] been studied for the catchment to the Vodskov 302.9 detention pond. Based on the average number on rain events over a 20 years period and a initial loss of 0.6 mm for rain events over 0.6 mm (215 events) and a initial loss of 0.3 mm for rain events under 0.6 mm (50 events) the annual initial loss has been estimated to 140 mm per year.

Table 2. Applied average runoff concentrations in $[\mu g/l]$

Pollutant	Concentration	Pollutant	Concentration
Σ C6-C35	1623	Lead (Pb)	20.0
Flouranthene	0.19	Cadmium (Cd)	0.4
Benzo(b+j+k)flouranthene	0.19	Copper (Cu)	50.2
Benzo(a)pyrene	0.10	Chromium (Cr)	5.4
Dibenzo(a,h)anthracene	0.08	Nickel (Ni)	5.3
Indeno(1,2,3-cd)pyrene	0.07	Zinc (Zn)	156.7
ΣΡΑΗ	0.63		

2.5. Degradation and outflux

The degradation term in the mass balances for the heavy metals are not considered due to their state of elements. The annual outflux from the ponds can be calculated as the difference between the influx and accumulation. It has be stated that the organic compounds incl. the PAH's are biodegradable either as carbon/energy source or in a co-metabolic process. The biological half-life period for the PAH's varies approximately between 6 to 12 years [17]. The organic outflux from the ponds can due to that not be calculated as for the metals. The local degradation rates are a product of many parameters such as, presence of easily biodegradable substances, oxygen-, pH-, temperature conditions etc. A determination of annual degradation rates is subject to further investigations that can not be done within the frames of this paper. The deficit between the annual influx

and accumulation in the mass balances is owing to that a sum of annual degradation and annual outflux.

4. Results

The average annual increase in sediment depth in the ponds with an age of 6 years was calculated to 1.0 cm/year and for ponds with an age of 11 years to an average of 0.6 cm/year. In previous studies [1] the annual load of suspended solids from the catchment area to the detention pond Vodskov st. 302.9 was approximately 200 kg/(year·ha). Based on the measurements in this study the annual SS load is 25 times higher - showing that the contributor to the accumulated solids may not be the road runoff itself but also solids from nearby surroundings. The mean pollutant concentrations in the pond sediments and ranges are presented in figure 2. The concentrations in the ponds are within the range of what can be found in literature e.g. [6], [5] and [11]. The variation between the ponds is to be expected, due to very different locations with a variance in: surroundings, vegetation, pH, redox potentials, microbiology etc. These parameters are not to be considered any further in this paper. The annual accumulation rate in each pond and a catchment area weighted mean accumulation rate for the organics and metals are presented in table 3. It must be remembered that the calculated accumulation rates are based on ponds only receiving runoff from highways and in that case not to compared with other urban detention ponds receiving water from various areas.



Fig. 2. Mean, minimum and maximum pollutant concentration in the pond sediment.

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Table 3. Annual accumulation rates per hectare of impervious catchment in $\begin{bmatrix} g \\ yr \cdot ha \end{bmatrix}$. The values in the mean column are catchment area weighted mean accumulation rates.

Pollutant	Pond no.	306.7	302.9	205.4	195.9	187.5	95.3	95.1	92.4	Mean
C6H6-C10		43	45	22	25	22	11	6	11	24
C10-C25		723	683	507	346	402	216	172	372	430
C25-C35		3033	3195	2131	1396	1900	1035	809	1579	1881
THC		3835	3927	2673	1765	2307	1264	986	1980	2337
Fluoranthene		0.47	0.35	0.56	0.24	0.31	0.18	0.16	0.84	0.37
Benzo(b+j+k)	fluoranthene	0.77	0.57	0.74	0.32	0.46	0.20	0.21	1.01	0.51
Benzo(a)pyrer	ne	0.21	0.17	0.21	0.08	0.12	0.06	0.06	0.27	0.14
Dibenzo(a,h)a	ntrachene	0.03	0.05	0.06	0.02	0.04	0.02	0.02	0.09	0.04
Indeno(1.2.3-0	cd)pyrene	0.29	0.25	0.29	0.14	0.12	0.08	0.08	0.34	0.19
Sum PAH		1.77	1.38	1.86	0.79	1.06	0.54	0.53	2.56	1.24
Lead (Pb)		67	51	65	49	59	19	17	45	51
Cadmium (Cd)	1.8	1.5	0.8	1.3	0.8	0.3	0.2	0.7	1.0
Copper (Cu)		182	129	218	146	192	70	56	153	156
Chromium (Ci	r)	79	59	64	48	40	17	14	43	48
Nickel (Ni)		69	50	38	40	29	16	10	33	37
Zinc (Zn)		807	561	734	726	913	615	392	682	709

The calculated relative accumulations (fig. 3) compared to efficiency studies based on inlet and effluent concentrations shows similarities for the metals, but with a slight tendency to show lower relative accumulation than the inlet and effluent based efficiencies does [2], [3], [13] and [16]. For primarily chromium and nickel in some of the ponds the relative accumulations are calculated to value higher than 1. Apparently this seems unrealistic but it reflects the uncertainty especially on the estimated loads from the runoff. However this may give an indication of a high retention. For the organic compounds the relative accumulation are in general much lower (c. 50%) than the efficiencies, likely explained by degradation within the pond sediment. The high relative accumulation for some of the metals indicates that resuspension of sediments may have an insignificant role for the pollutant transport.



Fig. 3. Relative accumulations (Annual accumulation / Annual influx).

The results also show that the accumulation rates for the heavy metals significantly depend on the relative pond area (defined as the pond area divided by the catchment area) (fig. 4). Similar dependencies are shown in [13] but as removal efficiencies as functions of the relative pond area instead. The accumulation rates in this study do not have the same flattening out tendency at a relative pond area of 250 m²/ha as in [13]. For direct comparison the relative accumulation could have been plotted instead. But since the uncertainty in the calculated relative accumulations is high due to the estimated influxes this is not done. The accumulation dependency for the PAHs is not as clear as for the metals, probably due to different degradation possibilities in the very varying ecosystems.



Fig. 4. Annual accumulation rate as function of relative pond area.

5. Conclusion

As expected hydrocarbons, PAH's and heavy metals accumulates in the pond sediment. The comparison of the accumulation in relation to the load shows that the bulk of the incoming heavy metals can be found in the sediments whereas the organic compounds can only partly be found in the ponds. Although the results have a significant uncertainty the study indicates that a mass balance approach for the long term removal of pollutants can be coupled to the short term mass balances of the individual runoff event. The results can also be taken as indication that the resuspension from the ponds can only be of minor importance and that the relation between the pond area and the connected catchment area plays a significant role for the accumulation rates.

6. Acknowledgement

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Paper III

Wind effects on retention time in highway ponds.

Bentzen, T.R., Larsen, T. and Rasmussen, M.R.

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Wind effects on retention time in highway ponds

T. R. Bentzen, T. Larsen and M. R. Rasmussen

ABSTRACT

The paper presents results from an experimental and numerical study of wind-induced flows and transportation patterns 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 simulations based on historical rain series of the pollutant discharges from roads and highways. The idea of this paper is to evaluate the effects of wind on the retention time and compare the retention time for the situation of a spatial uniform wind shear stress with the situation of a "real" spatial non-uniform shear stress distribution on the surface of the pond. The result of this paper shows that wind plays a dominant role for the retention time and flow pattern. Furthermore, the results shows that the differences in retention time between the use of uniform and non-uniform wind field distributions are not significant to this study.

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INTRODUCTION

Pollution of the water environment (primarily ditches, streams and rivers) caused by highway runoff focuses especially on heavy metals and PAHs. Variants of sedimentation ponds are commonly used as treatment facilities for polluted highway runoff. Many ponds have been designed only for flow control and hydraulic peak reduction but studies have shown that there are particularly high removal efficiencies for suspended solids and as well as for heavy metals and organic compounds due to their sorption affinity (Van Buren *et al.* 1997; Petterson *et al.* 1999; Comings *et al.* 2000). Thus, removal efficiency for settleable particulate-bounded pollutants is highly dependent on retention time.

The circulation in large water bodies like lakes and estuaries has been studied at a high scientific level for decades e.g. Lavel *et al.* (2003), Herb & Stefan (2005), Rueda *et al.* (2005). But the literature concerning wind effects on smaller ponds and basins seems almost non-existent. The intention of this paper is to introduce some methods applied on larger scale to the small scale of basins and ponds. The weather influence on the transport mechanisms in the ponds has not been studied as intensively as e.g. the pond bathymetric and geometry e.g. Van Buren *et al.* (1996), Matthews *et al.* (1997), doi: 10.2166/wst.2008.267

Walker (1998). The wind-induced flows in these shallow ponds may potentially exceed the size of the inflow and outflow generated currents. The study focuses on issues related to relatively small ponds with a few thousand square metres of surface area. In meteorological terms this means that the issue is on microscale to the smaller end of the mesoscale (Ahrens 2007). Owing to that, the study does not deal with the generation of wind on large scales. Near the surface, irregular turbulent motions occur due to the roughness of the surface, the presence of vegetation, trees, buildings, hills etc. All the obstacles break the mean wind into irregular twisting eddies varying in force and size. A small obstacle produces small eddies, as do light winds, whereas buildings, hills, or e.g. highway embankments produce larger eddies corresponding to the size of the obstacle itself as well as various smaller eddies such as rotors. The size is dependent on the wind speed. The mean wind and eddies will influence the water surface of the pond and transport kinetic energy to the water body. The interesting point is to see whether this transport of energy significantly influences the retention time of the ponds, since the retention time is a relevant parameter within further investigation of the efficiency of the ponds for retaining pollutants. The effect of the nearby topography on the wind field over the water surface may have great influence on the generation of wind induced currents in the ponds as shown in e.g. Rueda et al. (2005). Owing to that, this study compares the retention time for the situation of a uniform wind shear stress with the situation of a "real" non-uniform shear stress distribution on the surface of the pond. To simplify its stochastic nature, this study only focuses on differences between spatial uniformly applied wind shear stress and spatial non-uniform wind shear stress. The temporal variation in the wind field due to changes in the mean wind velocities, the temporal irregularities within the eddies, wind gusts, thermal induced turbulence due to variation in surface temperature, etc., are not considered in this study. The presence of temporal variations in both speed and direction are shown in Figure 1.

The analysis on the effect of the topography on the spatial variation of wind shear stress will provide methods useful for evaluation of initial placement of ponds, relative placement of inlet and outlet structures and placement of e.g. shelterbelts in relation to the locally prevailing wind direction as know from crop and soil protection.

METHODS

As a measure for the wind effects, the retention time for dissolved matter is used as basis for comparison. The temporal parameters that will be compared are the relation between the peak arrival and the hydraulic retention time and the relation between the arrival of the centre of mass and the hydraulic retention time. Additionally, the dilution of the tracer pollutant is also compared.

The retention time for a tracer solution has been measured under varying wind conditions and modelled with the 3D CFD software MIKE 3 in a wet highway pond in the northern part of Denmark. The pond has a surface area of approximately 2,500 m², a water depth of 0.6 m under dry weather conditions, and handles run-off from a 2.7 ha impervious highway catchment. The model has been calibrated and validated on that location (Bentzen et al. 2005). Afterwards, the model has been used on another pond located in the middle part of Denmark. This pond has a surface are of approximately 2,400 m², a water depth of 0.7 m under dry weather conditions, and handles runoff from approximately 4 ha impervious highway catchment (plus additionally 5 ha from an internal pond connected to the drainage system). At this location the numerical part of the study is divided into two phases:

- 1. The wind effect on the retention time with "real" spatial *non-uniformly distributed* wind induced shear stress due to the topography and vegetation of the surroundings. This is done by combining a wind model and a pond advection and dispersion model.
- 2. The wind effect on the retention time based on a spatial *uniformly distributed* wind induced shear stress (based on the average wind direction and speed from the *non-uniform* wind field).



Figure 1 | Measured wind speed and direction two metres above the water surface of the pond treated in this study.

Topography and bathymetric

The topography of the surroundings of the pond with a radius of 200 m (Figure 2) and the bathymetric of the pond (Figure 2) are measured intensively with a Leica GPS system 530 with a precision of a few centimetres. The model area for the wind model is larger and the topographic data are extrapolated under visual and picture restrictions. The difference in elevation between the road surface and the water surface in the pond under dry weather conditions is approximately 7 m.

Wind model

The 3D CFD software MIKE3 has been used for the wind model. The model is used to calculate the wind field above the surface of the detention pond with the measured topography taken into account. The fluid in the model is water but can just as well be considered as air, since both fluids obey Newton's law of viscosity and the issue involves fully rough turbulent flow with very high Reynolds numbers (= assumption of infinite Reynolds number). Thus, the difference between the fluids' molecular viscosities may be ignored in the velocity calculations in the model. The model is based on the mass balance equation and the Reynolds averaged Navier-Stokes equation. According to these the difference in density between air and water is of no importance for the pressure term. Due to the small size of the pond no Coriolis forcings have been applied.

Wind model setup

The model has been set up with following conditions with reference to Figure 3:

- Velocity boundary (shear stress boundary) on the top layer 75 m above the water surface.
- Two open boundaries in flow direction and two closed boundaries perpendicular to the flow direction.
- The topography is discretized in 3.6 m × 3.6 m grid cells. The vertical discretization is 0.75 m.
- The roughness height for the surroundings is set to 0.2 m.
- The eddy viscosities for the shear terms in the model are calculated by means of a *k*-ϵ turbulence formulation.
- The model has been run until a steady wind field was achieved as shown in Figure 4.
- The model has been used for calculation of the spatial non-uniform wind field for four different velocities for each of the four corners of the world.

The steady spatial *non-uniform* wind field above the water surface is subsequently extracted and interpolated to a $0.8 \text{ m} \times 0.8 \text{ m}$ grid used for the advection and dispersion pond model. The average wind direction and speed extracted for the pond model are also calculated for the *spatial uniformly distributed* simulations.

Pond model

Like the wind model, the pond model is made in the 3D CFD program MIKE3. The model is used to calculate the advection and dispersion of a non-degradable dissolved pollutant under the following conditions:

- Static in- and outflow of 0.007 m³/s defined as a source/sink.
- Water depth of 0.12 m over the permanent water pool (total water volume of 1,450 m³) which entails a hydraulic retention time $T_{\rm h} = Pond \ volume/Discharge$ of approximately 57 hours.



Figure 2 | Left: The topography near the highway detention pond. Right: The bathymetric of the highway detention pond. Arrows indicate the location of inlet and outlet from the pond. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.



Figure 3 | Sketch illustrating the wind model setup for east and west simulations. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

- The bathymetric is discretized in 0.8 m × 0.8 m grid cells. The vertical discretization is 0.2 m.
- The roughness height for the bottom is set to 0.05 m.
- The eddy viscosities for the shear terms in the model are calculated by means of a k – ε turbulence formulation.
- The tracer pollutant with a concentration of 50 mg/L is dosed for a period of 20 minutes after four hours of inand outflow with "pure" water. The simulated period lasts for a total of three days and ten hours.



Figure 4 | Example of control of velocity and direction steadiness (here in an arbitrary grid cell).

The wind effect on the retention time and effluent concentration of the tracer pollutant is investigated under the following conditions with regards to the effect of wind on the water surface in the pond model.

- No shear stress applied to the water surface.
- Spatial and temporal uniform wind shear stress applied as a constant speed and constant direction (average of the resulting velocity vectors (u & v) from the spatial non-uniform wind field) to the water surface.
- Spatial non-uniform and temporal uniform wind shear stress applied (from the wind model).
- The water shear term ν_T(∂u/∂z) is set to equalize the wind shear (ρ_{air}/ρ_{water}) C_w·W·W_x on the water surface. The friction coefficient C_w is set to vary linearly between 0.0016 at a wind speed (W) of 0 m/s to 0.0026 at a speed of 24 m/s. (Smith & Banke 1975).

RESULTS

Following the method described above, the data from the MIKE 3 result files has been analyzed for unlikely flow patterns and concentration levels. Thus, one of the



Figure 5 \mid Time for peak arrival related to the hydraulic retention time for uniformly applied wind field.

simulations (north 20 m/s) has been rejected due to numerical instabilities. Time series for the concentrations in the outlet grid cell have been extracted from each of the 3D result files and analysed. In order to evaluate the temporal mixing effect of the wind, the following parameters are compared to the hydraulic retention time: the time for the arrival of the effluent peak concentration of the tracer and the time for the arrival of the centre of mass of the pollutant in the outlet from the pond. The time for the arrival of the centre of mass t_{ACM} is calculated by Equation 1 based on the resulting time series from the pond model:

$$\frac{1}{2}\sum_{i=0}^{t}Q_{in}C_{in}\Delta t = \sum_{i=0}^{t_{ACM}}Q_{out}C_{out}\Delta t$$
(1)

The following parameters are compared to the inlet concentration of the tracer pollutant to evaluate the dilution effect of the wind: effluent peak concentration/ inlet concentration and effluent concentration at arrival of the centre of mass/inlet concentration. The results of 32 simulations are shown in Figures 5–12. The following abbreviations are used in the figures: PA = peak arrival,



Figure 6 | Time for peak arrival related to the hydraulic retention time for nonuniformly applied wind field.



Figure 7 | Time for arrival of centre of mass related to the hydraulic retention time for uniformly applied wind field.

HRT = hydraulic retention time, ACM = arrival of centre of mass, dilution factor 1 = effluent peak concentration/ inlet concentration, dilution factor 2 = effluent concentration at ACM/inlet concentration. The surface velocities for the simulation with no wind and the four non-uniform simulations with a wind speed of 5 m/s are shown in Figures 13-17.

The result deduced from the study shows that: the wind induced flows play a dominant role for the time of retention of a pollutant as seen in Figures 5–8 and as well as on the flow pattern as seen in Figures 13–17. This may produce positive as well as negative effects. (A) The retention time (based on peak arrival and arrival of the centre of mass) decreases compared to the "no wind shear" situation (Figures 5–8). This result would change if inlet and outlet structures are placed so closed to each other that prevalent short-circuiting flow occurs under no-wind conditions, see e.g. Bentzen *et al.* (2005). (B) Even then, if retention time is decreased due to the wind shear, the dilution of the pollutant is generally increased (Figures 9 and 10), due to contact with a greater water pool (except when the wind



Figure 8 | Time for arrival of centre of mass related to the hydraulic retention time for non-uniformly applied wind field.



Figure 9 | Effluent peak concentration related to the inlet concentration for uniformly applied wind field.



Figure 10 | Effluent peak concentration related to the inlet concentration for nonuniformly applied wind field.



Figure 11 | Effluent concentration at arrival of the centre of mass related to the inlet concentration for uniformly applied wind field.



Figure 12 | Effluent concentration at arrival of the centre of mass related to the inlet concentration for non-uniformly applied wind field.



Figure 13 | Surface velocities for the "No wind shear stress" situation (The velocity vectors are magnified 8 times compared to the following four figures).



Figure 14 | Surface velocities for the "Non-uniform wind shear stress, east 5 m/s" situation.



Figure 15 | Surface velocities for the "Non-uniform wind shear stress, west $5\,\text{m/s}$ " situation.



Figure 16 | Surface velocities for the "Non-uniform wind shear stress, north 5 m/s" situation.

direction is parallel with the direction between inlet and outlet structure).

The differences in retention time (the time for arrival of the centre of mass) (Figures 7 and 8) between the use of spatial uniform and spatial non-uniform wind fields for the shear stress calculation on the water surface are not significant in this study. For the time of peak arrival, the differences are more significant and there is a tendency for the use of the non-uniform wind field for the north/south directions (Figures 5 and 6) to cause a delay in time of peak arrival. This is not the case for the west simulations (more or less opposite of the direction between inlet and outlet) in which there are no practical differences (Figures 5 and 6).



Figure 17 | Surface velocities for the "Non-uniform wind shear stress, south 5 m/s" situation.

This was predictable since the western terrain is flat with no obstacles. For the east simulations (more or less the direction between inlet and outlet) there is a tendency for the non-uniformly distributed wind field to expedite the time for the arrival of the peak (Figures 5 and 6). The eastern wind is also the one most affected direction because of the location of the highway embankment.

The mixing in the pond varies significantly for wind speeds in the area of 0-5 m/s but increased wind speeds do not significantly change the mixing further. The mixing is more or less the same for all wind directions with wind speeds above 5 m/s (the average wind speed in Denmark).

CONCLUSIONS

An investigation into the effect that wind shear stress has on retention time has been carried out. The results drawn from the investigation show that when modelling retention times or flow patterns in shallow detention ponds, wind shear stress ought to be taken into account. In modelling used for long term evaluations of retention times, in which the accurate flow pattern is of minor importance, there is no need for the use of spatial non-uniform wind fields assuming, of cause, that very local wind data are available for a uniform description. However, if the aim is to describe flow patterns within the pond accurately during a single rain event the spatial non-uniform wind field is preferable when, in addition, including the temporal variation. The conclusion drawn might change significantly if the topographical effects are larger than in this study, in which the effects are quite small. Surrounding hills, valleys, canyons, buildings, trees etc, would make the non-uniform wind field preferable especially if a large pond is under investigation. If the effects of an implantation of e.g. shelterbelts should be evaluated, a premodelling of the wind field must be done. In that respect, the shelterbelts must be well designed in both height and space between e.g. trees, so that eddies formed on the leeward side will be as small as possible and the transfer of turbulent kinetic energy to the water body will be as low as possible.

The study leads to a further investigation of wind effects on the particle transport within ponds, changes in bottom shear stress and possible resuspension of already settled solids.

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Paper IV

Heavy metal and PAH concentrations in highway runoff deposits fractionated on settling velocities.

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Heavy metal and PAH concentrations in highway runoff deposits fractionated on settling velocities

Technical Note

Submitted for Journal of Environmental Engineering, 30th July 2008

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Abstract: The correlation between settling velocity and associated pollutant concentrations is of major importance for best management practice in designing, re-designing or evaluation of the efficiency of existing pond facilities for retaining unwanted pollutants. The prospect of this note is to state the relationship between the settling velocity of the runoff particles and the corresponding metal and PAH concentration directly instead of dealing with two unknowns – the density and the shape of a single particle fraction in a settling velocity calculations. The measurements shows that the highest cadmium, chromium, zinc, nickel concentration is associated with the most slowly falling particles and the lowest concentration associated within the faster falling sand fraction. This tendency is not clear for some of the sediments due to high content of organic matter and clearly not for lead and copper and there is no significant correlation between PAH concentration and settling velocity. The largest amount of metals and PAH within each pond can be found on the particle fraction with a setlling velocity of 5.5-2.5 mm/s.

Keywords: Best management practice; CFD; detention pond; sedimentation; stormwater; xenobiotics

Introduction

The pollution of the water environment (primarily ditches, streams and rivers) caused by highway run-off focuses especially on heavy metals and PAH's e.g. in studies of Ellis and Revitt (1981), Ellis *et al.* (1987), Mushack (1987), Wu *et al.* (1998) and Crabtree *et al.* (2005) due to their frequent occurrence in highway runoff and their toxicological effects on the environment and human beings (Makepeace, 1995). Sedimentation ponds are commonly used as treatment facilities for polluted

highway runoff. Many ponds have been designed only for flow control and peak reduction but studies have shown particularly high removal efficiencies for suspended solids and thereby also for heavy metals and organic compounds due to their sorption affinity (Van Buren, 1997; Petterson et al., 1999; Comings et al., 2000). The paper presents results from an experimental study of the distribution of heavy metal and polyaromatic hydrocarbons (PAH) on different particle settling velocities. 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 determine the pollutant discharges from roads and highways based on long-term numerical modeling of historical rains series. Accordingly a proper description of the transport of this pollution must emphasize on an accurate modeling of the transport of fine particles from the road surface through drainage system and trough the detention pond to the receiving water.

Many studies e.g. Ellis and Revitt (1981), German and Svensson (2002) and Zanders (2004) show relationships between particle size (diameter) and metal concentration originating from road runoff. Li et al. (2006) summarize heavy metal concentration as function of particle size ranges. These diameter relationships are within the context of transport modeling in ponds of discussable importance, since lack of density and shape of the single particle fraction is prevailing. Recently Kayhanian and Rasa (2007) deal with the issue of density and show that fractionated solids from highways varies from 1.6 to 1.8 g/cm³. Hereby, in terms of best management practice, use of the traditional quarts density will lead to an overestimation of the efficiency of e.g. a detention pond.

The prospect of this study is to state the relationship between the settling velocity of the runoff particles and the corresponding metal and PAH concentration directly instead of dealing with two unknowns – the density and the shape of a single particle fraction in settling velocity calculations with e.g. Stoke's Law and other empirical models which also have limitations within the flow regime around the falling particles.

Sampling procedure

Sediments from four Danish wet detention ponds are used for the experiments. The composite sampling procedure can be found in Bentzen *et al.*, 2007. The ponds only receive runoff from highways, with closed drainage systems and no prior sedimentation occurs over time.

Pond no. ¹)	302.9	205.4	187.5	92.4
Highway	E45	E45	E45	E45
Nearby city	Vodskov	Randers S	Grundfoer	Fredericia
Pond area [m ²]	2299	2300	2300	600
Catchment area [m ²]	27000	37000	41000	16000
Age of pond [years]	7	13	13	13
Annual day traffic 2)	14800	32100	33800	24100
Precipitation [mm/yr]	820	690	690	770

Table 1. Site description. ¹) Pond numbers refer to the distance from origin of the highway. ²) Vehicles per day.

The settling velocity distribution for each of the four ponds is measured with application of a 1.65 m high vertical standing cylindrical tube (diameter of 0.145 m). Five water samples for each of the

four pond sediments were taken out in the bottom representing following five settling velocity intervals: >5.5 mm/s, 5.5-2.5 mm/s, 2.5-1.3 mm/s, 1.3-0.5 mm/s and 0.5-0.1 mm/s. The effect of flocculated or hindered settling were minimized by repeating the experiments three times in order to get the necessary amount of sediment for metal and PAH analysis. The samples were analyzed on an accredited laboratory for the metals: Cadmium, chromium, copper, lead, nickel and zinc and the sum of seven PAH's including specific concentration for benzo(a)pyrene and benzo(ah)anthracene. For additional characteristic of the respective sediments - grain size distributions of the composite samples were determined by laser diffraction analyses (Particle size analyzer – Microtrac II model 7997-20) and the organic content on various settling velocities were determined by loss of ignition at 550°C as shown in figure 1 and 2.



Figure 1. Grain size distributions.

Figure 2. Organic content as function of settling velocity

Fractionated heavy metal and PAH concentrations

Figure 3-11 presents the fractionated pollutant concentrations and the relative amount of pollutants. The relative amount of a single pollutant is calculated as given in eqn. (1).

$$P_{p,i} = \frac{C_{p,i}}{C_0} \frac{M_{SS,i}}{M_{SS,T}}$$
(1)

where $P_{p,i}$ is the relative amount of the pollutant within the sediment, $C_{p,i}$ is the pollutant concentration on the ith fraction of the sediment, C_0 is the pollutant concentration in the non-fractionated sediment, $M_{SS,i}$ is the mass of the ith fraction of sediment and $M_{SS,T}$ is the total mass of sediment.

In the figures the settling velocity intervals are given by the center of the interval including the size of the interval. The interval sizes are only indicated on the concentration curves. The concentration for the PAH benzo(ah)anthracene where for some of the samples below detection limits, hence the non continuous curves on figure 11. The sum of the relative amounts for a single pollutant is not necessarily 100%, due to not measured fraction with a settling velocity below 0.1 mm/s. For cadmium and zinc (figure 3 and 8) the sum of the relative amounts exceeds 100%, which is of cause

unrealistic, but within the uncertainty of the metal analysis and uncertainty of the settling velocity distribution.



Figure 3. Fractionated cadmium concentrations and relative amounts. Legend numbers refers to table 1.



Figure 5. Fractionated copper concentrations and relative amounts. Legend numbers refers to table 1.



Figure 7. Fractionated nickel concentrations and relative amounts. Legend numbers refers to table 1.



Figure 4. Fractionated chromium concentrations and relative amounts. Legend numbers refers to table 1.



Figure 6. Fractionated lead concentrations and relative amounts. Legend numbers refers to table 1.



Figure 8. Fractionated zinc concentrations and relative amounts. Legend numbers refers to table 1.



Figure 9. Fractionated concentrations of Σ PAH's and relative amounts. Legend numbers refers to table 1.



Figure 11. Fractionated benzo(ah)anthracene concentrations and relative amounts. Legend numbers refers to table 1.

Conclusions

For the metals: Cadmium, chromium, zinc, nickel it's evidently that the highest metal concentration is associated with the most slowly falling particles and the lowest concentration associated within the faster falling sand fraction. For pond number 92.4 and 187.5 this is not so significant and for copper and lead the tendency is also not so clear. For pond no. 92.4, 187.5, and partly 205.4 it seems that the adsorption curves have an optimum around 2 mm/s and not at the slowest falling particles. The reason for this is most likely due to the more or less constant content of organic matter cf. figure 2 for the two ponds 92.2 and 187.5. The main adsorbent of e.g. lead is organic matter (Sipos *et al.* 2005) and similar for copper (Marsalek and Marsalek, 1997).

Despite of a threefold differences in concentration levels of the metals between the four ponds, the relative amount of the metals are almost similar. The largest amount of metals within each pond can be found on the particle fraction with a setlling velocity of 5.5-2.5 mm/s.

For the PAH's there is no clear correlation between the adsorbed concentration and settling velocity. As for the metals the largest amount of PAH's can be found on the particle fraction with a setlling velocity of 5.5-2.5 mm/s.



Figure 10. Fractionated benzo(a)pyrene concentrations and relative amounts. Legend numbers refers to table 1.

For numerical modeling purposes, e.g. modeling of efficiencies of a specific pond facility for retaining undesirable pollutants, new design or optimizing existing ponds, the settling velocity for incoming particles are of high merit and in combination with different pollutant levels associated even higher.

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Paper V

Critical shear stress for resuspension of deposits in highway detention ponds

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Critical shear stress for resuspension of deposits in highway detention ponds

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Abstract

The paper presents an experimental and numerical study of resuspension of sediment from highway detention ponds. For low consolidation time (24 hours) and a bed shear stress at approximately 0.1 N/m^2 the sediment are brought to suspension at rates around 0.1 g/m²/s. For one week of consolidation the critical shear level are increased with 50-100 % and the major resuspension occurs somewhere between 0.16 – 0.26 N/m². Further consolidation does not seem to affect the critical shear stress. The critical shear is found to be the same, due to wave generated bottom shear as for the currents generated shear stress. Furthermore, the influence of the use of deicing salt, corresponding to higher salinities in the deeper regions of the ponds does not seem to have significant influence on the critical bed shear stress. The resuspension process both due to currents and waves is shown to be replicable in a numerical model and useful in further investigation of long-term pollutant removal efficiencies for the ponds.

Keywords: CFD, circular flume, consolidation, deicing salt, erosion, heavy metals, wind-induced waves, xenobiotics

Introduction

The study presented here is part of a general investigation of road runoff and pollution in respect to wet detention ponds. The objective is to determine the pollutant discharges from roads and highways based on long-term numerical modeling of historical rains series. The pollution of the water environment (primarily ditches, streams and rivers) caused by highway run-off focuses especially on heavy metals and PAH's e.g. in studies of Ellis and Revitt (1981), Ellis *et al.* (1987), Grottker (1987), Mushack (1987), Wu *et al.* (1998), German and Svensson (2002) and Crabtree *et al.* (2005) due to their frequent occurrence in highway runoff and their toxicological effects on the environment and human beings (Makepeace, 1995). Accordingly a proper description of the transport of this pollution must emphasize on an accurate modelling of the transport of fine particles through the detention ponds to the receiving waters due to high sorption affinity of the metals and organic micropollutants (Pitt *et al.*, 1995; Sansalone and Buchberger, 1997). Detention ponds have shown particularly high removal efficiencies for suspended solids and thereby also for heavy metals and organic compounds (Van Buren, 1997; Petterson *et al.*, 1999; Comings *et al.*, 2000), but a long term evaluation of efficiencies for retaining pollutants cannot be based only on rain event based

measurements or modelling due to a possible resuspension of settled particles or release of pollutants due to changes in physical and chemical conditions within the ponds during e.g. one year. Since many ponds also handle infiltration water from the road bed, which leads to a more or less constant flow through the shallow ponds, the critical shear for resuspension of the bottom sediment is investigated, in order to be able to predict the size of resuspension and the possible size of the effluent. Such studies seem to be non-existing within the area of highway runoff treatment facility studies. This work presents results of circular flume experiments carried out with highway pond deposits. The critical shear stress for resuspension and resuspension rates at different bottom shear stresses has been stated for different consolidation periods of the sediment (24 hrs, 3 days and 7 days). Owing to the Danish climate, road deicing salt is frequently used in winter. The effect of deicing salt on the critical shear stress for resuspension of the highway pond deposits has also been evaluated. Due to the placement of highways in the open land, detention ponds are frequently exposed to external forces such as the wind. Not only the wind-induced currents introduce a bed shear stress, but also the wind-induced waves. The waves are very fetch limited in the relatively small ponds (in Denmark up to few hundred metres of fetch). But even small waves will generate additional shear stresses at the bottom of the pond and probably resuspend the bed material, which will eventually be transported with the currents to the outlet. The wind-wave-water-bottom interaction has been studied intensively in the past, however little work has focused on this interaction in small ponds. Most studies have been carried out on a larger scale and have addressed the interaction in oceans, bays, estuaries and larger lakes. Comparable studies of the wind-wavewater-bottom interaction are done by e.g. Adu-Wusu et al. (2001), Mian and Yanful (2002) and Yanful and Catalan (2002), where studies of resuspension in shallow mine tailings ponds due to wind generated waves have been carried out. Adu-Wusu et al. (2001) e.g. found that wind speeds exceeding 8 m/s above water covers that are shallower than 1 m create bottom shear stresses above 0.2 N/m^2 which is sufficient to set the bed in motion.

A thorough understanding of the resuspension process of bottom sediments will have implication for the optimization of pond geometry/bathymetry and the surroundings of the pond and in combination with a mathematical advection/dispersion model it will be capable to predict the fate of unwanted metal and organic micro-pollutants to the natural environment.

Objectives of the study

- 1. To determine the critical shear stress for resuspension due to currents
- 2. To determine the critical shear stress for resuspension due to waves
- 3. To determine the critical shear stress for resuspension as a function of consolidation time
- 4. To determine the critical shear stress for resuspension as a function of the concentration of deicing salts
- 5. To set up a calibrated numerical model for the current and wave resuspension processes.

Experimental method

Sediment characteristics

The sediment used for the experimental part of the study, is collected from the bottom of a 2300 m² highway detention pond in the northern part of Denmark (pond no. 302.9). The pond only receives contaminated water from approximately $30,000 \text{ m}^2$ of impervious highway. The sediment was representatively sampled with a grab. The grain size distribution for the sediment used is determined by laser diffraction analyses (Particle size analyzer – Microtrac II model 7997-20). In figure 1, the distribution is compared to seven other Danish pond sediments.



Figure 1. Cumulative grain size distribution compared to 7 other Danish highway detention pond sediments. (Sediment numbers refer to the Danish highway pond numbering system.)



Figure 2. Sedimentation velocity distribution for the used sediment.

The characteristics are slightly changed at the end of the experiments after excess of bottom shear stress of 3 N/m^2 as shown in figure 1 – flocks have been broken to smaller particles. The flocculation will reoccur in the settling and consolidation phase. More useful characteristic for e.g. efficiency modelling is the sedimentation velocity distribution cf. figure 2. The settling velocities were measured by adding sediment into a 1.7 m high vertical standing cylindrical tube (D=0.145m). 17 water samples were drawn from the bottom of the tube after 1 min – 2 days. The water samples were analysed for concentrations of suspended solids. The organic content was measured (as loss of ignition at 550 °C) to 15 %. The composition of heavy metals and organic compounds in the used sediment is shown in table 1.

	Concentration
Pollutant	[mg/kg dry matter]
$C_{6}H_{6}-C_{10}$	9
C ₁₀ -C ₂₅	140
C ₂₅ -C ₃₅	655
Total hydrocarbons	805
Fluoranthene	0.071
Benzo(b+j+k)fluoranthene	0.116
Benzo(a)pyrene	0.035
Dibenzo(a,h)antrachene	0.010
Indeno(1.2.3-cd)pyrene	0.052
SUM PAH	0.284
Lead (Pb)	10
Cadmium (Cd)	0.3
Copper (Cu)	27
Chromium (Cr)	12
Nickel (Ni)	10
Zinc (Zn)	115

Table 1 Concentration levels of heavy metals and organic compounds (Bentzen et al., 2007)

Owing to the Danish climate road deicing salt is used in winter time. The annual amount used on highways has been varying from 22000 to 51000 tons over the last five years. Based on the number of salting events and the area of highway it leads to an average of 13 g/m² highway per salting event. On the conservative assumption that all of the salty run-off water stays in the lower part of

the detention ponds during winter, that Blomqvist and Johansson (1999) found that 20-63 % of the salt deposited on the road surface is removed to the adjacent roadside by spray from the passing vehicles, and for an average highway catchment and pond size this leads to bottom salt concentrations from zero to around 30 kg/m³. The effect of deicing salt on the critical shear stress for resuspension has been tested for salt concentrations of 0 kg/m³, 0.1 kg/m³, 2 kg/m³, 5 kg/m³ and 10 kg/m³. The composition of the used deicing salt is shown in table 2.

Table 2 Composition of deicing salt (Pioner Strada Road Salt™)

Sodium Chloride	98.5 %
Sulfate	0.7 %
Calcium+magnesium	0.3 %
Additives Na ₄ [Fe(CN) ₆]	70-100 mg/kg

Measurement of critical shear stress for resuspension due to currents

Worldwide the circular flumes have been used for characterization of erosional and depositional behavior 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. Mehta and Partheniades (1973), Krishnappan (1993) and Petersen and Krishnappan (1994). For experimental studies the relationship between the rotation velocity of the lid and the mean bed shear stress is crucial. For the present flume (figure 3), the relation (eqn. 1) is given by Johansen (1998):

$$\tau_{\rm b} = 0.28 \cdot \mathrm{U}_{\rm lid}^2 \tag{1}$$

where $\overline{\tau_{b}}$ = mean bed shear stress in N/m² and U_{lid} = lid velocity in m/s. The relation has been conducted with a correlation coefficient of 0.98 and a standard deviation of 0.03 N/m².



Figure 3. Circular flume (measurement in mm). Water depth during the experiments was 0.23 m.

The procedure for evaluating the erosional parameters of the detention pond sediment is:

Phase 1: Mixing of the sediment in 15 minutes with $\overline{\tau_b} = 2.9 \text{ N/m}^2 (U_{\text{lid}} = 3.2 \text{ m/s}).$

Phase 2: Settling and consolidation of the sediment with with $\overline{\tau_b} = 0 \text{ N/m}^2$. To evaluate the effect of consolidation time, the duration of phase 2 has been 24 hours, 72 hrs and 187 hrs. To evaluate the effect of deicing salt, the duration of phase 2 has been 72 hr, with a salt concentration of 0 kg/m³, 0.1 kg/m³, 2 kg/m³, 5 kg/m³, and 10 kg/m³. Additional experiments have also been carried out to evaluate the effect of consolidation time combined

with high salinity.

Phase 3: Erosion of sediment, with increasing bed shear stress. The size of $\overline{\tau_b}$ was 0.04 N/m², 0.10 N/m², 0.16 N/m², 0.26 N/m², 0.32 N/m² and for some experiments 0.41 N/m². The duration of each step was 2 hours.

The experiment was conducted with water from the detention pond, but refilled with tap water when needed. The temperature during all experiments was approximately 21° C and a pH level of around 7. The same sediment was used in each experiment. The initial concentration of suspended sediment in each experiment was approximately 10 kg/m^3 . The eroded mass during each shear stress step was estimated by in situ measurements of the concentration of suspended solid in the middle of the flume 10 cm above the bed and re-entered just below the lid to avoid a minimum of disturbance of the bed. The concentration was measured by a self-produced optical density meter. The calibration curve (figure 4) for the density meter was conducted with the same sediment as used for the experiments.



Figure 4. Calibration curve for the density meter

Due to the non-linear relation between measured signal and concentration, the uncertainty of the measurements is increasing at high concentration levels.

Evaluation of erosion and resuspension due to waves

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 with rounded edges 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 5).



Figure 5. 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 during the experiment was recorded on video and evaluated afterwards. 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 in MatLab. The wave length *L* is calculated iteratively by linear wave theory (eqn. 2) given by U.S. Army Coastal Engineering Research Centre (1984).

$$L = \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi h}{L}\right) \tag{2}$$

where g = gravity, T = wave period, h = water depth. The corresponding maximum bed shear stress is calculated by:

$$\tau_b = \frac{1}{2} f_w \rho U_b^2 \tag{3}$$

where τ_b = bed shear stress, f_w = friction factor, ρ = density of water (999.1 kg/m³), U_b = maximum of the wave orbital velocity near the bed. The friction factor f_w is dependent on the flow regime. The transition from laminar to fully developed smooth turbulent flow starts at amplitude wave Reynolds number $\leq 1.28 \times 10^4 \rightarrow 6 \times 10^5$ (Jonsson, 1980). The maximum $Re_{a,w}$ during the experiment was 5000. In case of laminar flow the friction factor can be calculated by eqn. (5) (Jonsson, 1980).

$$\operatorname{Re}_{a,w} = \frac{U_{b}a}{v} \tag{4}$$

$$f_{w} = \frac{2}{\sqrt{\operatorname{Re}_{a,w}}} \tag{5}$$

where a = maximum displacement of a single particle from its mean position is calculated by eqn. (6), v = viscosity of the water (1.1e-6 m²/s).
$$a = \frac{U_b T}{2\pi} \tag{6}$$

The maximum of the wave orbital velocity near the bed U_b is calculated by eqn. (7)

$$U_b = \frac{\pi H}{T \sinh(kh)} \tag{7}$$

where H = wave height and k the wave number

$$k = \frac{2\pi}{L} \tag{8}$$

Corresponding wind speeds

For predicting and modelling the bottom shear stresses generated from the wind-induced waves - absence of long-time series of monitored waves in detention ponds is a problem. On the other hand wind data are highly available. The waves measured in the experiments are subsequently converted to corresponding wind speeds at different fetches. Several empirical formulas have been stated to calculate wave heights and periods based on wind speed, water depth, fetch etc. Practically all of the models have been designed for larger depth and fetches that are much longer than in the present study with a fetch of a maximum of 100 - 200 metres. Therefore, corresponding wind and wave measurements were carried out in a detention pond exposed to wind, and the results are compared to the SPM 84 model (U.S. Army Coastal Engineering Research Centre, 1984). For shallow water waves (h/L < 0.5) the SPM84 model based on Sverdrup Munk & Bretschneider method reads:

$$H_{s} = 0.283 \left(\frac{U_{A}^{2}}{g}\right) \tanh\left(0.53 \left(\frac{gh}{U_{A}^{2}}\right)^{0.75}\right) \tanh\left(\frac{0.00565 \left(\frac{gF}{U_{A}^{2}}\right)^{0.5}}{\tanh\left(0.53 \left(\frac{gh}{U_{A}^{2}}\right)^{0.75}\right)}\right)$$
(9)
$$T_{s} = 7.54 \left(\frac{U_{A}}{g}\right) \tanh\left(0.833 \left(\frac{gh}{U_{A}^{2}}\right)^{0.375}\right) \tanh\left(\frac{0.0379 \left(\frac{gF}{U_{A}^{2}}\right)^{0.25}}{\tanh\left(0.833 \left(\frac{gh}{U_{A}^{2}}\right)^{0.375}\right)}\right)$$
(10)

and for deep water waves (h/L>0.5):

$$H_{s} = 0.0016 \sqrt{\frac{F \,\mathrm{U}_{\mathrm{A}}^{2}}{g}} \tag{11}$$

$$T_{s} = 0.2714_{3} \sqrt{\frac{FU_{A}}{g^{2}}}$$
(12)

where F = fetch and $U_A =$ wind stress factor ($U_A = 0.71 \cdot U_{10}^{1.23}$), $U_{I0} =$ wind speed in 10 m height.

The wind speed and direction was sampled over one-minute periods at a height of 2 metres and calculated to U_{10} . The direction was constant through the sampling period (from north). The waves where sampled with a pressure transducer at 20 Hz, 0.15 m below mean water level and calculated to wave heights by including the depth decline. The mean water level was 1.1 m and the fetch constant at 113 m in the sampling period.

The small experiment showed that measured wave heights are almost similar to calculated height by eqn. (11), but the calculated periods by eqn. (12) are in general much lower. This would lead to underestimation of the bottom shear stresses, due to its high dependency of the wave period. A small modification of the constants in eqns. (11) and (12) leads to a much better fit as shown in table 3. The modified constants are 0.0013 for eqn. (11) and 0.34 for eqn. (12). In table 3, wave heights and periods are also calculated by MIKE 21 Nearshore Spectral Waves (NSW) which is a wind-wave model, which describes the growth, decay and transformation of wind-generated waves (DHI, 2008). The wind-wave interaction is also calculated with SBM84 in the NSW-model. This has been done in order to include the variation in geometry and bathymetry and bottom dissipation for the present pond to see whether this was subject to the discrepancy between the measured and calculated wave parameters by eqns. (11) and (12). The result showed that even larger discrepancies between measured and modelled wave parameters. It was predictable that the NSW integral wave parameters were smaller than those obtained from eqn. (11) and (12), due to the implementation of the correct bathymetry and geometry of the pond. Use of the fetch-limited wave growth equations of Kahma and Calkoen (1994) in the NSW model leads to a much better fit to the measured data as seen in table 2, especially on the mean wave period. A further analysis and calibration of the NSW model, in order to implement the wave forcing in the long term modelling process of the sediment transport in highway detention ponds is not within the scope of this paper.

Calculated U_{10m} (from measured U_{2m}) (AIVC, 1996)	$\begin{array}{l} \text{Measured} \\ \text{H}_{s}\left(\text{H}_{m0}\right) \\ \text{T}_{s}\left(\text{T}_{m}\right) \end{array}$	Equations (11) & (12)	MIKE 21- NSW SBM84	MIKE 21 – NSW Kahma & Calkoen (1994)	Modified equations (11) & (12)
$U_{10} = 9.4 \text{ m/s},$	$H_s = 0.048 \text{ m} (0.047)$	$H_s = 0.058 \text{ m}$	$H_{m0} = 0.032 \text{ m}$	$H_{m0} = 0.035 \text{ m}$	$H_s = 0.047 \text{ m}$
	$T_s = 0.83 \text{ s} (0.82)$	$T_s = 0.62 s$	$T_{\rm m} = 0.44 {\rm s}$	$T_m = 0.81 \text{ s}$	$T_s = 0.78 s$
$U_{10} = 12.8 \text{ m/s}$	$H_s = 0.052 \text{ m} (0.052)$	$H_s = 0.085 \text{ m}$	$H_{m0} = 0.047 \text{ m}$	$H_{m0} = 0.050 \text{ m}$	$H_s = 0.069 \text{ m}$
	$T_s = 0.87 \text{ s} (0.86)$	$T_s = 0.70 s$	$T_{\rm m} = 0.50 {\rm s}$	$T_{\rm m} = 0.90 \ {\rm s}$	$T_s = 0.88 s$
$U_{10} = 13.9 \text{ m/s}$	$H_s = 0.071 \text{ m} (0.079)$	$H_s = 0.094 \text{ m}$	$H_{m0} = 0.052 \text{ m}$	$H_{m0} = 0.055 \text{ m}$	$H_s = 0.076 \text{ m}$
	$T_s = 0.93 \text{ s} (0.93)$	$T_s = 0.73 s$	$T_{\rm m} = 0.52$	$T_m = 0.93 \text{ s}$	$T_s = 0.91 s$

Table 3. Evaluation of wind-wave model.

Experimental results

Effects of consolidation time on critical shear stress for resuspension and resuspension rates The concentration time series measured have passed a moving average filter to reduce noise from the signal. For comparison all experimental results are normalized to an initial zero concentration condition in the water body ($C_{0,24 \text{ hr}} \approx 0.25 \text{ kg/m}^3$, $C_{0,72 \text{ hr}} \approx 0.23 \text{ kg/m}^3$ and $C_{0,187 \text{ hr}} \approx 0 \text{ kg/m}^3$).



Figure 6. Concentration time series during the consolidation effect experiments.



The resuspension rate can be deduced from the measured change in concentration over time.

$$E = h \frac{dc}{dt} \tag{13}$$

where E = resuspension rate, h = water depth and $\frac{dc}{dt}$ the concentration gradient.

The critical shear stress for bringing the sediment to suspension is significantly dependent on the consolidation time according to figure 6 and 7. 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 $0.16 - 0.26 \text{ N/m}^2$. The evolution of sediment strength due to consolidation time seems to stop referring to e.g. figure 8 where the de-icing effect experiments show that there is no practical difference in the critical shear stress between a consolidation time of 12 and 40 days.

The critical shear stress initiating the bed transport cannot be concluded from these experiments, due to placement of the outtake for concentration measurements 10 cm above the bottom of the flume.

Effects of deiceing salt on critical shear stress for resuspension and resuspension rates

Gultarte *et al.*,(1980) have shown that the critical erosional shear stress is increasing significantly for an equal mixture of pure illite and silt at increasing salinities and explain it by double-layer theory, in which the increasing salinity suppresses the double layer which tends to strengthen the inter-particle forces. Offhand, the addition of salt to the highway detention pond deposits tends to increase the critical shear stress from 0.10 N/m^2 to 0.16 N/m^2 , as seen in figure 8 and 9.



Figure 8. Concentration time series during the deicing effect experiments.



The general evolution of strength at increasing salinities shown by Gultarte *et al.* (1980) is nonexisting within the material tested and there are no significant differences between the tested salinities. At a bed shear stress of 0.26 N/m^2 there is a trend showing the opposite conclusion of Gultarte *et al.* (1980). At this incremental step it seems that the increase in salt concentration to 0.1 kg/m³ is more strengthening than higher salt concentrations is. The difference is most likely originating in the differences between the compositions of the materials tested, e.g. local ion concentration, valences of the present ion, elementary charges etc.

For the highway pond deposit investigated, the results show, that the use of deicing salt does not change the critical shear stress for resuspension.

The displacement from 0.10 N/m^2 to 0.16 N/m^2 in figure 8, which could potentially be a slight increase in the critical shear stress, could be explained by the fact that the salt encourages the flocculation and hence a larger particle settling velocity. Hereby the vertical mixing of the sediment is less and the measured concentrations 10 cm above the bottom of the flume are less. So whether the salt introduces a slight increase in critical shear stress for resuspension or that the vertical concentration profile is changed due to higher settling velocities is not to be concluded from the data available. With the present data it can be concluded that the consolidation time is the governing process for increasing the critical shear stress for resuspension and the resuspension rates. It is substantiated with e.g. the average resuspension rate for salt concentration of 10 kg/m³ where the rate drops from 0.37 g/m²/s at a consolidation time of 72 hours to less than 0.02 g/m²/s at a consolidation time of 12 and 40 days.

Evaluation of wave erosion and resuspension

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/m² with rolling of the particles. At 0.12 N/m² saltation and bouncing occur, and suspension of the bed starts somewhere between 0.12 and 0.18 N/m². The wave testing results are summarized in table 4, where the corresponding wind speed U₁₀ has been calculated as the converted average of U_A derived from eqn. (11) and (12) and with the modified coefficients as described previously. The wind speed U₁₀ for obtaining the present wave parameters are calculated for four different fetches (25, 50, 100 and 200 m).

H _m [m]	T _m [s]	U _b [cm/s]	$ au_b$ [N/m ²]	U _{10, 25m} [m/s]	U _{10, 50m} [m/s]	U _{10, 100m} [m/s]	U _{10, 200m} [m/s]	Sediment motion at water depths = 0.6 m
0.026	0.58	0.02	0.001	13	8	5	4	No
0.044	0.64	0.12	0.004	17	11	8	5	No
0.047	0.69	0.26	0.009	20	13	8	6	No
0.062	0.73	0.6	0.02	23	15	10	7	No
0.072	0.77	1	0.03	27	17	12	8	Beginning of bed transport
0.089	0.81	1.8	0.05	31	20	13	9	Bed transport
0.08	0.85	2	0.06	32	20	13	9	Bed transport
0.087	0.9	3	0.08	35	23	15	10	Bed transport
0.104	0.94	4.5	0.12	40	26	17	11	Bed and slight beginning of suspended transport
0.129	0.99	6.8	0.18	46	30	20	13	Suspended transport
0.134	1.03	8.2	0.22	50	32	21	14	Suspended transport
0.155	1.08	10.8	0.28	56	36	23	16	Suspended transport
0.178	1.16	14.9	0.37	65	41	27	18	Suspended transport

Table 4. Results from the wave erosion/resuspension experiment. The mean wave parameters H_m and T_m measured are similar to the significant wave height and period due to the regularity of the waves in the experiment.

Numerical modelling of physical experiments

Circular flume experiment

In order to fulfil the overall objective of the study, the evaluation of long-term efficiency of highway detention ponds, it has been essential to implement the shear strength of the sediment to the CFD model used, so that the effect of possible resuspension during intense rain events, wind generated currents and waves etc. can be evaluated on real ponds on a long-term basis. Thus the capability of the CFD model to reproduce the results from the physical experiments carried out is vital. The commercial CFD code MIKE3 Mud Transport (DHI, 2008) has been used for reproduction of the experiments. The primary task has been the calibration of erosion coefficients and the implementation of the effect of consolidation on the shear strength. Hence, the complex hydrodynamics of the circular flume is not modelled. In the model, the circular flume is described as a 40 m long rectangular channel 1 m wide and 0.23 m deep, with connected source and sink to recycle the water and suspended solid. The discharge through the channel has been modified, so that the modelled bed shear stress equals the bed shear stress in each of the incremental steps of the physical experiments.

The following assumption has been made in the modelling process:

The sediment is divided into 7 fractions representing the velocity distribution in figure 2. The sediment can be described as soft mud.

The sediment bed is divided into 6 six sub-layers.

The critical bed shear stress for erosion τ_{ce} of each layer has been set to 0.03, 0.09, 0.15, 0.25, 0.31 and 0.4 N/m².

The density of the bed layers varies from 200 to 250 kg/m^3 .

The initial individual bed layer thickness is based on the physical experimental results and the predicted density.

The erosion rate E for soft mud is described as

$$E = C \cdot e^{\alpha (\tau_b - \tau_{ce})^{\frac{1}{2}}}$$
(14)

Based on the eroded mass during each of the incremental steps in the circular flume experiment, the bottom area of the circular flume and the time of each step, the average erosion rates are calculated. The erosion coefficient α is set to 1 for each layer, hence an initial guess of the erosion coefficient *C* for each bed layer is calculated and used in the MIKE3 MT model. A fine calibration of the coefficient *C* has taken place afterwards, resulting in *C* values for the six layers from $3.5e-5 \rightarrow 9.9e-3 \text{ kg/m}^2$ /s. The consolidation of the bed 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 experimental and the consolidation time difference). A fine calibration of the transition rates has been made afterwards, resulting in values for the five rates from $8.5e-6 \rightarrow 1.1e-6 \text{ kg/m}^2/s$.





Figure 10. Measured and modeled concentration time series.

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 10. 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.

Wave flume experiment

The commercial CFD code MIKE3 Mud Transport (DHI, 2008) has been used for reproduction of the experiments. The code in the program has been modified in order to also handle the prevailing laminar condition near the bed and hereby the independency of the roughness height. For amplitude Reynolds numbers less than 30,000 the calculation of the wave generated bed shear stresses follows eqn. 2-8 (with some smaller differences due to the solution technique) in the modified version of the program code. The results from the numerical model should hereby be similar to those applied in table 4 – which they are cf. table 5.

H _s	T_m	$ au_{b}$	Bed mass change	Bed thickness change
[m]	[s]	$[N/m^2]$	$[kg/m^2]$	[m]
0.047	0.69	0.009	0	0
0.072	0.77	0.03	-0.00004	-3.00E-07
0.08 0.104	0.85 0.94	0.06 0.13	-0.0008 -0.0024	-0.000004 -0.000012
0.155	1.08	0.31	-0.0066	-0.000033

 Table 5. Results picked out from the numerical modelling of the wave erosion/resuspension.

For evaluating the resuspension process within detention ponds current and wave generated bed shear stresses are summarized with a parameterised version of Fredsøe (1984), derived by Soulsby *et. al.* (1993).

Conclusion

- Sediment from a permanent wet highway detention pond has been tested for its critical shear stress for resuspension. The critical shear stress for resuspension is found to vary between $0.1 0.26 \text{ N/m}^2$ dependent on the consolidation time.
- The critical shear is found to be the same, due to wave generated bottom shear stress as for the current generated shear stress.
- The characteristics of the sediment, with respect to grain size distribution, organic content and pollutant levels are universally.
- The effect of deicing salt, corresponding to higher salinities in the deeper regions of the ponds does not seem to have significant influence on the critical bed shear stress, most likely due to the prevailing chemical conditions in the ponds due the presence of metal ions in the porewater.
- As part of a general investigation on road runoff and pollution as regards wet detention ponds, this study provides two applicable numerical models as sub-models for a larger pollutant transport model for the ponds.

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Paper VI

Predictions of resuspension of highway detention pond deposits in inter rain event periods due to wind induced currents and waves

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Predictions of resuspension of highway detention pond deposits in inter rain event periods due to wind induced currents and waves.

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Abstract

The paper presents a numerical study of resuspension of deposits from highway detention ponds based on a previously experimental study, Bentzen at al. (2008b). The resuspension process is evaluated in dry weather periods with baseflow/infiltration flow through the ponds only. The resuspension is caused by the bed shear stress induced by the return flow near the bed and waves both generated by the wind. Wind statistics for 30 years have been applied for prediction of the annual discharged bulk of suspended solids and associated pollutants; PAH's and the heavy metals cadmium, chromium, cupper, lead, nickel and zinc. The current and wave generated bed shear stresses entails a discharged bulk of pollutants corresponding to approximately 10 % of the annual accumulation of pollutants in the present pond, due to the baseflow in the pond. The mean outlet concentration of suspended solids is very good correlated with the wind speed. To reduce the resuspension of deposited materials, two mechanisms are prevailing. Either increase the water depth of the pond to minimize the effect of the wind in the near bed region or reduction of the wind in some degree. The most efficient action for reducing the wind impact on the shallow waters is establishment of shelterbelts as know from the agriculture. Just a 20% reduction of the yearly wind speeds will reduce the outlet mass with 70% and a 50% reduction with almost 100%. A 50 % reduction of the wind speed is far from impossible to achieve with relative small investments.

Keywords: BMP; CFD; erosion; heavy metals; PAH; shelterbelt

Introduction

The pollution of the water environment (primarily ditches, streams and rivers) caused by highway run-off focuses especially on heavy metals and PAH's e.g. in studies of Ellis and Revitt (1981), Ellis *et al.* (1987), Mushack (1987), Wu *et al.* (1998) and German and Svensson (2002) due to their frequent occurrence in highway runoff and their toxicological effects. The study presented here is part of a general investigation of road runoff and pollution in respect to wet detention ponds. The description of the transport of the highway runoff and associated pollution must emphasize on an accurate modeling of the transport of fine particles through the detention ponds to the receiving waters due to high sorption affinity of the metals and organic micropollutants (Pitt *et al.* 1995; Sansalone and Buchberger, 1997). Detention ponds have shown particularly high removal efficiencies for suspended solids and thereby for heavy metals and organic compounds (Van Buren,

1997 and Petterson et al., 1999), but a long term evaluation of efficiencies for retaining pollutants cannot be based only on rain event based measurements or modelling due to a possible resuspension of settled particles or release of pollutants due to changes in physical and chemical conditions within the ponds during e.g. one year. Infiltration water or groundwater water (baseflow) from the road bed leads to a more or less constant flow through many of the shallow ponds. Bed shear stresses created by the currents from the baseflow (within a magnitude of 1-5 liters/sec) are in general far to low to resuspend the deposited materials in the ponds, but due to the placement of highways in the open land, detention ponds are exposed to external forces such as the wind. The circulation in large water bodies like lakes and estuaries has been studied on high scientific level for decades e.g. Lavel et al. (2003) and Rueda et al. (2005). But the literature concerning wind effects on smaller ponds and basins seems almost non-existing. The wind-induced flows in the shallow ponds are the governing transport mechanism especially in dry weather periods or during low intensity rain events as shown in Bentzen et al. (2008a). In respect to resuspension of deposited material not only the wind-induced currents introduce a bed shear stress, but also the wind-induced waves. The waves are very fetch limited in the relatively small ponds (in Denmark up to few hundred metres of fetch). But even small waves will generate additional shear stresses at the bottom of the pond and probably resuspend the bed material, which will eventually be transported with the currents to the outlet. Previous studies regarding the wind-wave-bottom interaction have been carried out on a larger scale and have concerned oceans, bays, estuaries and larger lakes. Comparable studies of the wind-wave-water-bottom interaction on minor scale are done by e.g. Adu-Wusu *et al.* (2001) and Yanful and Catalan (2002), where studies of resuspension in shallow mine tailings ponds due to wind generated waves and currents have been carried out. Adu-Wusu et al. (2001) e.g. found that wind speeds exceeding 8 m/s above water covers that are shallower than 1 m create bottom shear stresses above 0.2 N/m^2 which is sufficient to set the bed in motion. A thorough understanding of the resuspension process of bottom sediments will have implication for the optimization of pond geometry/bathymetry and the surroundings of the pond and in combination with a mathematical advection/dispersion model it will be capable to predict the fate of unwanted metal and organic micro-pollutants to the natural environment.

Objectives of the study

- 1. To setup a useful model capable of predicting resuspension and sediment transport in an arbitrary detention pond.
- 2. To predict the annual mass of resuspended deposits (suspended solids, cadmium, copper, chromium, lead, nickel, zinc and the sum of 7 PAH's), discharged to the natural environment from a specific pond.
- 3. To evaluate different methods for reducing the resuspension process.

Methods

Study facility

The Vodskov wet detention pond (pond no. 302.9) is located in the northern part of Denmark. The pond has a surface area of approximately 2500 m^2 , an average water depth of 0.43 m (max. = 0.62 m) under dry weather condition, and handles run-off from a 2.7 hectare impervious highway catchment.

The bottom is fairly flat and the sediment (\approx 80 tons dry weight) is more or less uniform distributed all over the bottom area with an annual accumulation rate of approximately 13 tons a year (Bentzen

et al. 2007). The mean sediment depth is approximately 0.07 cm. The baseflow through the pond in dry weather periods is 2.7 l/s.



Figure 1. Vodskov wet detention pond.

Wind statistics

All numerical calculations of the wind impact on the pond sediment are based on the statistics of 30 years of wind measurement at a nearby (within 10 km) wind station. The wind statistic is not corrected for the local topography or vegetation. The effect of topography and vegetation in terms of surround trees (shelter belts) will be evaluated. The frequency ($n_{D,F}$) of wind from direction D with the force F is calculated according to eqn. 1

$$n_{D,F} = \frac{N_{D,F} \cdot 100}{N} (\%) \tag{1}$$

where *N* is the total number of observations in for the whole period of 1931-1960, $N_{D,F}$ is the number of observations of wind from direction D (D= N, NE,, NW) with the force F (F = 0, 1, 2,, 12 on the Beaufort scale) for the whole period 1931-1960. The frequency ($n_{D,F}$) can be seen in table 1.

Table 1. The frequency $(n_{D,F})$ of wind from direction D with the force F at the Vodskov detention pond facility. The asterisks in the table indicated values between 0.0 - 0.05 %. Frydendahl (1970)

usterisks in	the tuble h	iulculcu vu	ides between	10.0 0.05	70. TTydene	uiii (1770)			
Force	2	3	4	5	6	7	8	9	10
Beaufort	Light	Gentle	Moderate	Fresh	Strong	Near	Fresh	Strong	Whole
number	breeze	breeze	breeze	breeze	breeze	gale	Gale	gale	gale/Storm
Speed	1622	3.4-	5570	8 0 10 7	10.8-	12 0 17 1	17 2 20 7	20 8 24 4	24 5 28 4
[m/s]	1.0-3.3	5.4	5.5-7.9	8.0-10.7	13.8	13.9-17.1	17.2-20.7	20.8-24.4	24.3-28.4
Ν	1.6	1.2	0.8	0.5	0.3	0.1	*	*	*
NE	2.1	2.2	1.3	0.9	0.5	0.2	*	*	*
Е	2.1	2.5	1.8	1.2	0.7	0.4	0.1	*	*
SE	2.3	2.7	2.0	1.4	0.8	0.4	0.1	*	*
S	2.2	2.1	1.5	0.9	0.5	0.2	*	*	*
SW	3.5	3.6	2.5	1.8	1.0	0.4	0.1	*	*
W	3.0	3.3	3.1	2.4	2.0	1.2	0.4	0.1	*
NW	1.6	1.3	0.8	0.5	0.3	0.2	0.1	*	*
All	18.4	18.7	13.7	9.6	6.1	3.1	1.0	0.2	0.1

The effect of the wind on the resuspension process is evaluated in inter rain event periods only. Based on the duration of 18 years of measured rainfall events (\approx 300 events/year), which leads to a sum of approximately 25 days of rain per year, an approximate concentration time in the drainage system of 20 minutes, 2 days of retention within the pond for rainfall events with a depth above 4 mm, this leads to a period of approximately 230 days for the *Vodskov* pond.

Hydrodynamics calculations

The hydrodynamics within the pond is described with the CFD program MIKE3 (DHI, 2008) in three dimensions by solving the Navier Stokes equation with assumption of hydrostatic pressure distribution cf. the mass conservation eqn. 2 and the momentum eqn. 3 (for the x-direction).

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = S \tag{2}$$

$$\frac{\partial u}{\partial t} + \frac{\partial uu}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + \frac{\partial}{\partial x} \left(2v_T \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(v_T \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) + \frac{\partial}{\partial z} \left(v_T \frac{\partial u}{\partial z} \right) + u_s S$$
(3)

where u, v, w = velocities in the x, y, z directions, S = source/sink term, ρ = density, v_T = eddy viscosity and the pressure term is solved by eqn. (4)

$$\frac{1}{\rho}\frac{\partial P}{\partial x} = \frac{g\rho(\zeta)}{\rho}\frac{\partial \zeta}{\partial x} + \frac{g}{\rho}\int_{z}^{\zeta}\frac{\partial \rho}{\partial x}dz$$
(4)

where g = acceleration due to gravity and $\xi =$ surface elevation.

The model has previously been shown in Bentzen *et al.* (2005) capable to calculate the hydrodynamics and transport of dissolved matter appropriate.

The pond is discretized in grids of 0.8 m x 0.8 m x 0.05 m (x,y,z), has a surface elevation corresponding to the baseflow situation and an equivalent sand roughness of 5 cm. The eddy viscosity is calculated by means of the Smagorinsky formulation (eqn 5).

$$\boldsymbol{v}_T = \left(\boldsymbol{C} \cdot \Delta \boldsymbol{s}\right) \sqrt{\boldsymbol{S}_{ij} \cdot \boldsymbol{S}_{ji}} \tag{5}$$

where C = Smagorinsky factor (one for the horizontal plane and one for the vertical) $\Delta s = \text{grid}$ spacing and S = velocity gradients. The two Smagorinsky factors have been calibrated against measurements in Bentzen *et al.* (2008c).

Wind forces

The force from the wind on the water surface is calculated by eqn. 6 and hence the upper boundary condition for the shear term.

$$\frac{\tau_{xx}}{\rho} = \upsilon_T \frac{\partial u}{\partial z} = \frac{\rho_{air}}{\rho} C_w W W_x \tag{6}$$

where τ = shear stress, W = wind speed in 10m height and C_w = wind drag coefficient set to vary linear from 0.0016 at W=0 m/s to 0.0026 at W=24 m/s

Time series of the wind has been generated for each of the direction sectors and each of the wind forces cf. table 1. Within a single time series e.g. "East (90°) – wind force 5" the direction is set to vary randomly and uniform distributed between $67.5^\circ - 112.5^\circ$ and the wind speed from (8.0 m/s - 10.7 m/s).

Wave forces

The characteristics of wind induced waves (wave height (*H*), wave period (*T*) and the direction (γ)) are modeled by the CFD program MIKE21 Nearshore Spectral Wind-Wave module (DHI, 2008). It 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 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 has been shown in Bentzen *et al.* (2008b) to calculate the wave parameters reasonable in these small and shallow ponds. Dissipation of energy due to the roughness of the bed is included by an enhanced version of the quadratic friction law, so directional spreading of the wave energy is included. An example of the wind induced wave calculation for a single time step is shown in figure 2 (north, wind force 7).



Figure 2. Example of the wind induced wave calculation. Wind direction = north and wind force 7 (13.9 -17.1 m/s)

Hence an additional bed shear stress is introduced by the near bead wave motion. The bed shear stress is calculated by linear wave theory:

$$L = \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi h}{L}\right) \tag{7}$$

where L = wave length, h = water depth. The corresponding maximum bed shear stress is calculated by:

$$\tau_b = \frac{1}{2} f_w \rho U_b^2 \tag{8}$$

where τ_b = bed shear stress, f_w = friction factor, ρ = density of water (999.1 kg/m³), U_b = maximum of the wave orbital velocity near the bed. The friction factor f_w is dependent on the flow

regime. The transition from laminar to fully developed smooth turbulent flow starts at amplitude wave Reynolds number $\leq 1.28 \times 10^4 \rightarrow 6 \times 10^5$ (Jonsson, 1980). In case of laminar flow the friction factor can be calculated by eqn. (10) (Jonsson, 1980) and for turbulent flow by eqn. (11) (DHI, 2008)

$$\operatorname{Re}_{a,w} = \frac{U_b a}{v} \tag{9}$$

$$f_{w,la\min ar} = \frac{2}{\sqrt{\operatorname{Re}_{a,w}}} \tag{10}$$

$$f_{wturbulent} = 0.04 \left(\frac{a}{k_N}\right)^{-0.25}$$
(11)

where a = maximum displacement of a single particle from its mean position is calculated by eqn. (6), v = kinematic viscosity of the water and k_n the Nikuradse roughness height.

$$a = \frac{U_b T}{2\pi} \tag{12}$$

The maximum of the wave orbital velocity near the bed U_b is calculated by eqn. (13)

$$U_{b} = \frac{\pi H}{T \sinh(kh)} \cosh(k \cdot dz_{b})$$
(13)

where k = wave number and $dz_b =$ thickness of the bottom most grid cell.

$$k = \frac{2\pi}{L} \tag{14}$$

The additional bed shear stresses from the waves are summarized with the current generated bed shear stresses by taken the angles between the waves and currents into account with a parameterized version of Fredsøe (1984), DHI (2008)

Sediment transport calculations

The sediment transport within the pond is described with the CFD program MIKE3 - Mud Transport (MT) (DHI, 2008). Assumptions for the three sediment transport processes involved (suspended transport, erosion and deposition) are subsequently described.

Suspended transport

The deposited sediment in the pond is divided into 7 fractions with different settling velocities, corresponding to measured settling velocity distributions of the real deposited sediment from the *Vodskov* pond. The suspended transport of sediment within the pond is described with the advection-dispersion eqn. (15) (for the z-direction).

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial z} \left(c \left(w - w_{s,i} \right) \right) = \frac{\partial}{\partial z} \left(D_c \frac{\partial c}{\partial z} \right) + S_c$$
(15)

where c = concentration of the ith fraction of sediment with the corresponding settling velocity w_s and D = dispersion coefficient calculated proportional to eddy viscosity with the Prantl number.

Four experiments have previously been carried out in order to verify the capability of the MTmodel to describe the transport of sediment appropriate (Bentzen *et al.* (2008c). To simplify the complexity of a real pond and for easy control and measurement the sediment transport experiments where carried out in two rectangular channels: one $7.5m \ge 0.3m$, $\ge 0.3m$, $\ge 0.3m$ and one $30m \ge 0.8m \ge 0.7$ m (length x width x depth) respectively with sediment traps at the bottom. The model calculations showed good correlation with the measured longitudinal sediment net accumulation. The sediment used in the experiments origins from the *Vodskov* detentions pond.

Erosion

The bed material varies with the depth. The bed is assumed to consist of 6 sub-layers with different densities (varying from 200 kg/m³ - 250 kg/m³) and different critical shear stresses for erosion (varying from 0.03 N/m² – 0.4 N/m²). The vertical extend of the first five layers is about 1 cm thus layer 6 is assumed to describe the rest of the sediment (≈ 5 cm). The density, the critical shear stress for each layer and the vertical extend of each layer have been measured in circular flume experiments in a previous study Bentzen *et al.* (2008b). The composition of sediment within each layer is assumed to equalize the composite sample as described in the section above.

The erosion rate E of sediment is described as given in eqn. (16) (DHI, 2008).

$$E = C \cdot e^{\alpha \sqrt{(\tau_b - \tau_{ce})}} \tag{16}$$

where *C* and α = erosion coefficients which have been calibrated for the pond sediment in Bentzen *et al.* (2008b), τ_b = bed shear stress from the currents and waves and τ_{ce} = critical bed shear stress for erosion.

Deposition

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/m² for the fastest falling particles and 0.03 N/m² for the slowest. The deposition *D* of the ith fraction is described as given in eqn. 17 (DHI, 2008).

$$D_i = w_s^i c_b^i p_d^i \tag{17}$$

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

Effluent mass calculations

Total suspended solids

Time series for the suspended solid concentration C of the ith fraction of sediment in the outlet grid cell have been extracted from each of the 62 model simulations corresponding to table 1. By following eqn. 18 this gives the annual effluent mass $M_{TSS,D,F}$ from each of combinations between wind force and direction in table 1.

$$M_{TSS,D,F} = \left(\sum_{i=1}^{7} \overline{C}_{SS,i}\right) \cdot Q \cdot n_{D,F} \cdot DWP$$
(18)

where Q = baseflow and DWP = the defined annual dry weather period.

Heavy metal and PAH's

Based on the results of Bentzen and Larsen (2008), where metal and PAH concentrations where fractionated on different sediment settling velocities as shown in figure 3, the associated concentration of metals and PAH's to the simulated seven sediment fractions in this study are deduced by eqn. 19. For the fraction 6 and 7 the metal curves are extrapolated in order to obtain an associated metal concentration. For the PAH's only a concentration for the fraction 1-6 is applied due to the non tedious curve.



Figure 3. Measured heavy metal and PAH concentration associated with different particle settling velocities. The sediment origins from the Vodskov pond. The vertical dashed lines indicates the seven fractions used in the model as representative for composition of the pond sediment.

$$M_{pol,D,F} = \left(\sum_{i=1}^{7} \overline{C}_{ss,i} \cdot C_{pol,i}\right) \cdot Q \cdot n_{D,F} \cdot ADWP$$
⁽¹⁹⁾

where M_{pol} = annual mass of specific metal or PAH discharge to the natural environment, $C_{pol,i}$ = associated metal or PAH concentration to the ith fraction of sediment.

Results

The data from the numerical model has been analyzed for unlikely flow patterns and concentration levels. Thus, five of the simulations (*northeast* wind force 7, *east, southeast* and *southwest* all wind force 8 and *west* wind force 9) have been rejected due to numerical instabilities. As a consequence of this, mean effluent concentrations of suspended solids for those five have been calculated by extrapolation of curvefit expressions as seen in figure 4 and in table 2. For all directions the regression lines have a correlations coefficient above 0.85. The correlations are universal in that sense that the wind statistics for the present pond not yet has been adopted in the calculation and not universal in that case it only valid for ponds with same fetch (100m x 40 m) and mean depth of 0.43 m and maximum of 0.6 m in the middle region. By use of the good correlated expression for all wind direction, the relative placement of in and outlet are negligible.



Figure 4. Mean effluent concentration as function of the wind force from eight directions.

Table 2. Regression expressions. y = mean outlet concentration [mg/l] and x = wind speed [m/s]

concentration	[mg/I] and x = wind speed $[m/s]$
Direction	Regression expression
North	$y = 1.15E-03x^{4.00}$
	$R^2 = 1.0$
North-east	$y = 7.44E-04x^{4.37}$
	$R^2 = 1.0$
East	$y = 2.01E-04x^{4.99}$
	$R^2 = 0.99$
South-east	$y = 1.9E-05x^{5.94}$
	$R^2 = 1.0$
South	$y = 3.95E-04x^{4.82}$
	R2 = 0.97
South-west	$y = 1.82E-04x^{5.11}$
	$R^2 = 0.85$
West	$y = 1.93E-05x^{5.81}$
	$R^2 = 0.96$
North-west	$y = 3.4E-06x^{6.377}$
	$R^2 = 0.89$
All	$y = 8.71E-05x^{5.30}$
	$R^2 = 0.91$

Measurements of the outlet concentrations of TSS during dry weather periods show good agreement with the modeled ones cf. table 3.

Table 3. Measured vs. modeled effluent TSS concentrations.

Date	Measured wind speed and	Measured outlet TSS	Modeled outlet TSS
	direction	concentration	concentration
May 2008	0-2 m/s	Below 2 mg/l	0 - 0.1 mg/l
10. June 2008	3- 10 m/s / SW	2.8 mg/l	0.1 - 7.7 mg/l
18. June 2008	4 -7 m/s / SW	2.8 mg/l	1.3 mg/l
24. June 2008	9-11 m/s / W, SW	5.2 mg/l	4.3 - 7.7 mg/l

The total mass of annual resuspended solids, metals and PAH's discharged to the natural environment can be seen in table 4. The effluent masses of the metals and PAH's are compared with the annual accumulation rate of the given pollutant. The annual accumulation rates A_{pol} for comparison are calculated by eqn. 20. The total amount of 1.3 tons corresponds to 10 % of the annual accumulation $A_{Sed,year}$ of sediment with in the pond. The yearly discharged masses of the metals and PAH's are underestimated due to the missing composition of SS-fractions of the five missing simulations and the lack of PAH concentration associated with fraction 7 as described previously.

$$A_{pol,year} = \sum_{i=1}^{7} C_{pol,i} \cdot X_{Sed,i} \cdot A_{Sed,year}$$
(20)

where X = fraction of the sediment with a given settling velocity.

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Wind	TSS	Cd*	Cr*	Cu*	Pb*	Ni*	Zn*	∑PAH*
direction	[kg/year]	[g/year]	[g/year]	[g/year]	[g/year]	[g/year]	[g/year]	[g/year]
Ν	11	0.02	0.5	1	0.4	0.5	9	0.001
NE	32	0.04	0.8	2	0.7	0.9	15	0.001
E	108	0.14	3.2	8	2.8	3.2	59	0.020
SE	131	0.16	3.6	9	3.2	3.6	66	0.022
S	66	0.12	2.6	7	2.3	2.6	48	0.013
SW	432	0.41	9.1	24	7.9	9.0	166	0.061
W	520	0.46	10.1	26	8.9	10.1	187	0.055
NW	23	0.03	0.7	2	0.6	0.7	13	0.002
All	1323	1.38	30.5	79	26.7	30.6	562	0.174
Percentage of yearly accumulated mass	10 %	8 %*	7 %*	7 %*	7 %*	9 %*	8 %*	2 %*

Table 4. Total mass of annual resuspended solids, metals and PAH's discharged to the natural environment due to resuspension during dry weather periods * = Underestimated

Depth of pond and sheltering vegetation

A computational fluid dynamic (CFD) model is a beneficial tool in terms of e.g. optimizing the pond configuration for larger pollutant removal. In terms of the studied resuspension process, additional calculations were done for the wind directions south and west at wind speeds of 5, 13 and 18 m/s, but with an increased water depth of 0.2 m and 0.4 m respectively which correspond to an increase of the mean water level with 46 % and 93% respectively. The impact of the wind on the resuspension process is minimized radical as shown in table 5. It has been shown in Bentzen and Thorndahl (2004) that the hydraulic capacity of the present pond is extremely oversized, hence an upward movement of the outlet structure is a simple solution for reduction the wind impact on the bottom.

Peduction at 0.2 m increase	Peduction at 0.4 r
resuspended solids discharged to the natural envir	onment
Table 5. Effect of increased water depth on the tot	tal mass of annual

Wind direction and speed	Reduction at 0.2 m increase in water level (46 % of present water level)	Reduction at 0.4 m increase in water level (93 % of present water level)
South 5 m/s	49 %	56 %
South 13 m/s	55 %	68 %
South 18 m/s	36 %	71 %
West 5 m/s	42 %	42 %
West 13 m/s	52 %	68 %
West 18 m/s	77 %	83 %

Another possibility for reducing the wind impact on the bottom sediment is reducing the wind speed by living shelterbelt. It is generally known from crop and soil protection in agriculture that well designed shelter belts can reduce the wind speed with 60-80 percent within distances not exceeding the longest fetch of the pond. By reducing the wind speeds in table 1, with 20 % and 50 % and a recalculation of the possibilities for a given speed from a given direction this also leads to a radical fall in wind generated resuspension as shown in table 6. The ponds will not only in the dry weather periods benefit from the shelter, the settling of particles during rain events will also increase radical due to the derived decrease in turbulence in the water body.

Wind direction	TSS with	TSS with
	20 % reduction of	50 % reduction of
	wind speed	wind speed
	[kg/year]	[kg/year]
Ν	7 (-39%)	0.6 (-94 %)
NE	18 (-44 %)	1.3 (-96 %)
E	51 (-52 %)	1.8 (-98 %)
SE	45 (-65 %)	1.3 (-99 %)
S	26 (-61 %)	1.3 (-98 %)
SW	111 (-74 %)	1.8 (-100 %)
W	94 (-82 %)	3.2 (-99 %)
NW	13 (-43 %)	1.2 (-95 %)
All	366 (-72 %)	12.5 (-99%)

 Table 6. Effect of wind shelterbelts on the total mass of annual resuspended solids discharged to the natural environment

Conclusion

- Within the order of magnitude the pond model is capable of predicting the annual resuspension process during dry weather periods caused by wind induced currents and waves.
- The current and wave generated bed shear stresses entails a discharged bulk of pollutants corresponding to approximately 10 % of the annual accumulation of pollutants in the present pond, due to the baseflow in the pond.
- The mean outlet concentration of suspended solids is very good correlated with the wind speed. The general regression expression in table 2 can be used universal for ponds with similar size and depth (100m x 50m x 0.5m) to predict the outlet concentration from a pond with a baseflow of a few liters per second independent of relative placement of inlet and outlet.
- To reduce the resuspension of deposited materials, two mechanisms are prevailing. Either increase the water depth of the pond to minimize the effect of the wind in the near bed region or reduction of the wind in some degree.
- An increase in water depth of 46 % will give a reduction of the yearly discharge mass with the baseflow with approximately 50 %. A further increase of water depth does only increase this with minor percentages, which can be explained by the rapidly declining wave impact with increasing water depth and a more slowly declining impact of the near bed return flow.
- The most efficient action for reducing the wind impact on the shallow waters is establishment of shelterbelts as know from the agriculture. Just a 20% reduction of the yearly wind speeds will reduce the outlet mass with 70% and a 50% reduction with almost 100%. A 50 % reduction of the wind speed is far from impossible to achieve with relative small investments.
- It must as an additional comment be mentioned, that reducing the wind impact on the ponds gives rise to a more strict relative placement of the inlet and outlet (in other words – they should be placed far from each other)

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Paper VII

Numerical modelling of suspended transport and deposition of highway deposited sediments

Bentzen, T.R., Larsen, T., Bach, C., and Raaberg, I.

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Numerical modelling of suspended transport and deposition of highway deposited sediments

Technical report,

Series number 47

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Good data for calibration and validation of numerical models are of high importance. In the natural environment 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 in two rectangular channels: one 7.5m x 0.3m, x 0.3 m and one 30m x 0.8 m x 0.7 m (length x width x depth) respectively with sediment traps at the bottom. The model calculations showed good correlation with the measured longitudinal sediment net accumulation as shown subsequently. The sediment used in the experiments origins from the *Vodskov* detentions pond and settling velocity distributions was initially measured in a vertical tube for characterizing the sediment. The hydrodynamics within the channels are described with the CFD program MIKE3 (DHI, 2008) in three dimensions by solving the Navier Stokes equation with assumption of hydrostatic pressure distribution cf. the mass conservation eqn. 1 and the momentum eqn. 2 (for the x-direction).

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

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

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

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

where g = acceleration due to gravity and $\xi =$ surface elevation. The eddy viscosity is calculated by means of the Smagorinsky formulation (eqn 4).

$$\nu_T = (C \cdot \Delta s) \sqrt{S_{ij} \cdot S_{ji}} \tag{4}$$

where C = Smagorinsky coefficients (one for the horizontal plane and one for the vertical) $\Delta s =$ grid spacing and S = velocity gradients. The sediment transport within the channels is described with the CFD program MIKE3 - Mud Transport (MT) (DHI, 2008). The sediment pumped to the channel is in the model divided into 7 fractions with different settling velocities, corresponding to measured settling velocity distributions of Vodskov pond sediment. The suspended transport of sediment within the channels is described with the advection-dispersion eqn. (5) (for the z-direction).

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial z} \left(c \left(w - w_{s,i} \right) \right) = \frac{\partial}{\partial z} \left(D_c \frac{\partial c}{\partial z} \right) + S_c$$
(5)

where c = concentration of the ith fraction of sediment with the corresponding settling velocity w_s and D = dispersion coefficient calculated proportional to eddy viscosity with the Prantl 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/m² for the fastest falling particles and 0.03 N/m² for the slowest. The deposition D of the ith fraction is described as given in eqn. 6 (DHI, 2008).

$$D_i = w_s^i c_b^i p_d^i \tag{6}$$

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

Experiment 1

Experiment 1 was carried out in a channel 7.5 m long and 0.3 m wide with a constant water level of 0.3 m The channel is discretized in grids of $0.075 \text{m} \times 0.04 \text{m} \times 0.028 \text{m} (x,y,z)$ and applied an equivalent sand roughness of 0.001 m. Only water and dissolved Rodamin was used and the Rodamin concentration was measured in the outlet of the channel. Laser Doppler Anamometry was used for velocity measurements. The aim of the experiment was to calibrate the hydrodynamic description (the Smagorinsky coefficients, eqn. 4)) for low flow velocities, which are common in detention ponds, and dispersion coefficients for the dispersion term in eqn. 5. Figure 1 to Figure 6 shows the experiment and results of the calibrated model, with Smagorinsky coefficients of 0.11 for the horizontal plane and 0.14 for the vertical plane and dispersion factors of 0.3 and 1 proportional to the eddy viscosity. By adjusting the Smagorinsky coefficients the turbulence formulation is not longer an actual Smagorinsky turbulence formulation but a mixing length formulation.



Figure 1. Initial phase of the tracer experiment.



Figure 2. The spread of tracer after 25 minutes.



Figure 3. Model results for the centre of the channel. The colour are visualizing the U velocity component and vectors the resultant of U and W.



Figure 4 Model and measured U velocities in the centre of the channel 0.4 m from the inlet.



x = 2.9 m 0 -0.05 -0.1 📥 measured Depth [m] - mike3 -0.15 -0.2 -0.25 -0.3 -0.004 -0.002 0 0.002 0.004 0.006 0.008 U [m/s]

Figure 5 Model and measured U velocities in the centre of the channel 2.9 m from the inlet.

Figure 6. Model and measured Rodamin concentration in the outlet from the channel.

Experiment 2

The experiment 2 was conducted in a 30 m long and 0.8 m wide concrete channel placed beside the Aarslev detention pond (Figure 9). An overview of the experiment is given in Figure 7. The inlet structure in this experiment (2) is different than the one showed on Figure 7 which is a pipe inlet used in experiment 3. In experiment 2, the water and sediment are pumped to the channel in a device spreading the water and sediment uniform over the width and placed at the very beginning of the channel.



Figure 7 Longitudinal cut of the channel used in experiment 2/3.

As initial condition, the channel was filled with water from the detention pond to a water level corresponding to Figure 8. Subsequently water was pumped to the barrel as shown on Figure 7 where water and sediment from the Vodskov detention pond was mixed and pumped to the channel. The outlet was a siphon pipe with a discharge corresponding to Figure 8. At the bottom of the channel sediment traps were placed (Figure 10 and Figure 11).



Figure 8. Discharges and water level in experiment 2.



Figure 9. Channel used for the large scale experiments.



Figure 10. Sediment plates at the bottom of the channel.



Figure 11. Sediment plates at the inlet and outlet zone respectively.

Initially the settling velocity distribution measured in a vertical tube in still water was used as input parameter for the MIKE 3 – Mud Transport model. Several attempt on calibrating the model were done, but without luck. The sediment did only settle in the first $2/3^{rd}$ of the channel in the model and almost 80 percent within the first few metres. In conjunction with the measured longitudinal net accumulation, sediment grain size distributions for the accumulated sediment within each sediment trap was measured by laser diffraction analysis. The longitudinal grain size distribution showed a very good correlation with the mass accumulation distribution as shown in Figure 12 and Figure 13.



Figure 12. Longitudinal net deposition and median grain size distribution.

Figure 13. Longitudinal net deposition as function of median grain size.

Thus with knowledge about the longitudinal mass distribution of the sediment, the mass that have left the channel through the outlet and with appliance of Stokes law for settling with a fractionated density as described in e.g. Kayhanian and Rasa (2007). A new settling velocity distribution was calculated and used as input parameter for the sediment description with a satisfactory result as shown in Figure 14. A possible reason for a changed settling velocity distribution could be explained by the presence of the pump. The initial settling velocity distribution was measured by adding a bulk of sediment to a vertical tube with still water. Thus flocculation of particles might have increased the settling velocity whereas in the channel experiment the bulk of sediment added

has passed several facilities with very high turbulence and mechanic stresses in contact with the pump blades. As shown in Figure 15 the grain size distribution is not significant disturbed through the inlet facilities, which can be explained by the way the laser diffraction analysis where done. Here sediment/water is re-circulated by a pump through small pipes with high velocity. The undisturbed sample and the samples taken in the inlet facility have thus passed the same stress conditions.



Figure 14. Measured and modelled longitudinal net deposition and median grain size distribution.



Figure 15. Grain size distributions for initial added sediment and sediment passing the inlet facilities.

Experiment 3 and 4

For validation of the sediment transport model, two experiments were subsequently done, one in the small channel and one in the large channel. The small channel experiment is similar to experiment one described previously but with sediment continuously added over 40 minutes. The inlet concentrations were measured at 1 Hz sampling frequency with a density meter as described in Bentzen *et al.* (2008a). Flow data and concentration data can be seen in Figure 16 and photo from the experiment in Figure 17. The model showed good correlation with the measured deposition as shown in Figure 18 except for the area just below the inlet pipe. The mass balance for the experiment holds: 148 grams of sediment was added, 148 grams was recovered at the bottom (in the model 149 grams was recovered on the bottom). Additional information about the composition of the deposited sediment was achieved cf. Figure 19 where, as expected, with increasing organic content in the longitudinal direction.



Figure 16. Flow through the channel and inlet concentration.



Figure 17. Sediment transport trough the channel. Outlet to the right.



Figure 18. Measured and modelled longitudinal net deposition and median grain size distribution.



Figure 19. Longitudinal variation of the organic content within the sediment.

The validation experiment in the large channel is sketched in Figure 7, with a pipe inlet as shown on Figure 20 and Figure 21. Results can be seen in Figure 22 and Figure 23. The model showed fairly good correlation with the measured deposition as shown in Figure 18. The deposition is underestimated in the model within the area of three to six metres from the inlet pipe and slight overestimated in end of the channel. Whether this is due to a change in settling velocity distribution compared to experiment 2 or uncertainties in the model can not be concluded from the present data. The measured and modelled outlet concentration are timely good correlated, but the modelled outlet mass is underestimated as shown in Figure 23. This corresponds with the higher deposition in end of the channel in the model. So whether it is to less turbulence in the end of the channel or still the settling velocity distribution that might not be completely correct is not to be said. But never the less the model has be shown capable with an acceptable accuracy to model the transport of highway sediments within the channels.



Figure 20. Adjusting the pipe inlet prior experiment 4.



Figure 21. Initial phase of experiment 4 with sediment inflow.



Figure 22. Measured and modelled longitudinal net deposition and median grain size distribution.



Figure 23. Measured and modelled outlet concentration from the channel.

Conclusion

Since the model has been shown capable with an acceptable accuracy to model the transport of highway sediments within the channels it might be assumed that this is also the case in e.g. detention ponds where water depths and flow conditions are comparable with the especially the large channel. Previously the model has been shown capable to model the hydrodynamics and transport of dissolved tracer pollutants with highly acceptable accuracy e.g. in Bentzen et al. (2005), Bentzen et al. (2008b) and in Bentzen, T. R., 2008c.

References

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Appendix – MIKE 3 Mud Transport setup for experiment 4

: 2008-08-28 15:27:48 // Created // DLL id : c:\programmer\fælles filer\dhi\mikezero\pfs2004.dll // PFS version : Nov 27 2007 20:39:43 [MIKE3_FLOW_MODEL] [BASIC_PARAMETERS] [OPTION_PARAMETERS] EndSect // OPTION_PARAMETERS [MODULE_SELECTION] Touched = 1IncludeSalinity = true IncludeTemperature = false IncludeAD = false IncludeMT = true IncludeECOLab = false ADScheme = 1ADUpdateFrequency = 1 HydroStaticEngine = true InternalComponentLoop = false EndSect // MODULE_SELECTION [BATHYMETRY_SELECTION] Touched = 1MzSEPfsListItemCount = 1 NoOfAreas = 1 HotStart = false Projection = 'PROJCS["UTM-30",GEOGCS["Unused",DATUM["UTM Projections", SPHEROID["WGS 1984",6378137,298.257223563]],PRIMEM["Gr eenwich",0],UNIT["Degree",0.0174532925199 433]],PROJECTION["Transverse_Mercator"],P ARAMETER["False_Easting",500000],PARA METER["False_Northing",0],PARAMETER[" Central_Meridian",-3],PARAMETER["Scale Factor",0.9996],PAR AMETER["Latitude_Of_Origin",0],UNIT["Met er",1]] Layers = 14 GridSpacing = 0.04Use3DBathymetry = false CoriolisForce = false strUTMModified = 1 LayerNumModified = 1 [AREA_1] Touched = 1ValidBathymetry = 1 NoOfCalculationPoints = 9842 [DATA_FILE] Touched = 1FILE_NAME = |.\Grid1.dfs2| ITEM_COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA FILE EndSect // AREA_1 EndSect // BATHYMETRY SELECTION [SIMULATION PERIOD]

Touched = 1 StartTime = 2007, 6, 18, 13, 55, 0 NumberOfTimesteps = 400000TimeStepInterval = 0.05 WarmUpPeriod = 0

EndSect // SIMULATION_PERIOD [BOUNDARY] Touched = 1MzSEPfsListItemCount = 0ZeroGradient = false NumberOfBoundaries = 0ProgramDetected = true EndSect // BOUNDARY [SOURCE_AND_SINK] Touched = 1MzSEPfsListItemCount = 2 NumberOfSources = 2 [SOURCE_SINK_1] Touched = 1Type = 0SourceSinkPoint = 4, 10, 13 Area = 1SourcePoint = 0, 0, 13 SourceArea = 1SinkPoint = 0, 0, 13 SinkArea = 1 EndSect // SOURCE SINK 1 [SOURCE_SINK_2] Touched = 1Type = 0 SourceSinkPoint = 37, 10, 12 Area = 1SourcePoint = 0, 0, 13SourceArea = 1 SinkPoint = 0, 0, 13SinkArea = 1 EndSect // SOURCE SINK 2 EndSect // SOURCE_AND_SINK [FLOOD_AND_DRY] Touched = 1EnableFloodAndDryChecking = false DryingDepth = 0.001FloodingDepth = 0.003EndSect // FLOOD AND DRY [TURBULENCE_MODEL] Touched = 1TurbulenceModel = 3 EndSect // TURBULENCE MODEL [MASS_BUDGET] Touched = 1MzSEPfsListItemCount = 0NoOfPolygons = 0 EndSect // MASS_BUDGET EndSect // BASIC_PARAMETERS [HYDRODYNAMIC PARAMETERS] [OPTION PARAMETERS] EndSect // OPTION PARAMETERS [INITIAL SURFACE ELEVATION] Touched = 1MzSEPfsListItemCount = 1 [AREA_1] Touched = 1

Touched = 1FILE NAME = \parallel ITEM COUNT = 1ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA 1 EndSect // INITIAL SURFACE ELEVATION [BOUNDARY_CONDITIONS] Touched = 1MzSEPfsListItemCount = 0EndSect // BOUNDARY CONDITIONS [RESISTANCE] Touched = 1MzSEPfsListItemCount = 1 IncludePiers = false NoOfPiers = 1IncludeBedFriction = true [SLIP_FACTORS] Top = 1Bottom = 1Walls = 1EndSect // SLIP_FACTORS [DATA_FILE] Touched = 1 $FILE_NAME = \parallel$ ITEM COUNT = 1 ITEM NUMBERS = 1 EndSect // DATA FILE [AREA_1] Touched = 1 Format = 0ConstantValue = 0.001 [DATA FILE] Touched = 1 FILE_NAME = || ITEM_COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA FILE EndSect // AREA 1 EndSect // RESISTANCE [TURBULENCE_PARAMETERS] Touched = 1MzSEPfsListItemCount = 1 [AREA_1] Touched = 1Format = 0VCoefficient = 0.14 HCoefficient = 0.11EddyXLimits = 1.799999933485565e-027.128 EddyYLimits = 1.79999933485565e-027, 0.3528000116348267 EddyZLimits = 1.799999933485565e-027, 0.3199999928474426

Format = 0

ConstantValue = 0

[DATA FILE]

[DATA FILE] Touched = 1FILE_NAME = || ITEM COUNT = 1ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA_1 EndSect // TURBULENCE PARAMETERS [DENSITY] Touched = 1 IncludeDamping = true HorizontalCoefficient = 0VerticalCoefficient = 10 PrescribedOutFlowBC = false RangeChecking = false SalinityRange = 0, 32 TemperatureRange = -1.20000047683716, 30 M21ADSalt = false M21ADTemp = false EndSect // DENSITY [SALINITY] Touched = 1Formulation = 0 BackgroundValue = 0 ImplVertDisp = true [INITIAL_VALUE] Touched = 1 MzSEPfsListItemCount = 1 [AREA 1] Touched = 1Format = 0 ConstantValue = 0 [DATA_FILE] Touched = 1 FILE NAME = \parallel ITEM COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA 1 EndSect // INITIAL VALUE [DISPERSION_FACTORS] Touched = 1MzSEPfsListItemCount = 1 [AREA 1] Touched = 1DispersionFactors = 0.1000000014901161, 0.1000000014901161 EndSect // AREA_1 EndSect // DISPERSION FACTORS [DISPERSION_LIMITS] Touched = 1MzSEPfsListItemCount = 1 [AREA_1] Touched = 1XLimits = 0, 0.005000000353902578 YLimits = 0, 0.005000000353902578 ZLimits = 1.799999933485565e-027, 0.007199999876320362 EndSect // AREA 1 EndSect // DISPERSION LIMITS

EndSect // SALINITY [TEMPERATURE] Touched = 1Formulation = 0 BackgroundValue = 17 ImplVertDisp = true [INITIAL_VALUE] Touched = 1MzSEPfsListItemCount = 1 [AREA_1] Touched = 1Format = 0ConstantValue = 17 [DATA_FILE] Touched = 1FILE_NAME = || ITEM_COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA_1 EndSect // INITIAL_VALUE [DISPERSION_FACTORS] Touched = 1MzSEPfsListItemCount = 1 [AREA 1] Touched = 1DispersionFactors = 0.100000014901161, 0.1000000014901161 EndSect // AREA_1 EndSect // DISPERSION FACTORS [DISPERSION_LIMITS] Touched = 1MzSEPfsListItemCount = 1 [AREA_1] Touched = 1XLimits = 0, 0.03999999910593033 YLimits = 0, 0.008999999612569809 ZLimits = 1.80000006824121e-007, 0.02999999932944775 EndSect // AREA 1 EndSect // DISPERSION LIMITS EndSect // TEMPERATURE [PRECIPITATION] IncludePrecipitation = false ConstantValue = 0Format = -1NetPrecipitation = true [PrecipTemp] Touched = 1 Format = -1ConstantValue = 0[DATA FILE] Touched = 1FILE NAME = \parallel ITEM_COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA FILE EndSect // PrecipTemp [EvapTemp] Touched = 1Format = -3ConstantValue = 0

[DATA_FILE] Touched = 1FILE_NAME = || ITEM COUNT = 1ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // EvapTemp [DATA_FILE] Touched = 1 FILE_NAME = || ITEM COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // PRECIPITATION [PARTICLE_TRACKING] Touched = 0MzSEPfsListItemCount = 0NumberOfParticleSources = 0 Releases = 0, 0, 1TimeSteps = 0, 100, 30 FILE_NAME = || Title = " EndSect // PARTICLE TRACKING [WIND CONDITIONS] Touched = 1Format = 0ConstantWindDirection = 270 ConstantWindSpeed = 10 NeutralPressure = 1013TypeOfWindFriction = 0 ConstantFriction = 0.0026 LinearFriction = 0.0015999999595806, 0.00260000007078052 LinearSpeed = 0, 24 IncludeAirPressureVariation = false IncludeAirPressureCorrections = false [DATA FILE] Touched = 1FILE_NAME = || ITEM COUNT = 1ITEM_NUMBERS = 1 EndSect // DATA FILE EndSect // WIND_CONDITIONS [DISCHARGE_CALCULATIONS] Touched = 1MzSEPfsListItemCount = 0NumberOfLines = 0 EndSect // DISCHARGE_CALCULATIONS [HD_SOURCE_SINK] Touched = 1MzSEPfsListItemCount = 2[SOURCE_1] Touched = 1Format = 1 IncludedInFile = false Salinity = 0Temperature = 10 [DATA FILE] Touched = 1FILE_NAME = |.\Indloeb.dfs0| ITEM COUNT = 3ITEM NUMBERS = 1, 2, 3EndSect // DATA FILE

EndSect // SOURCE_1 [SOURCE_2] Touched = 1Format = 1IncludedInFile = false Salinity = 0Temperature = 10 [DATA FILE] Touched = 1FILE NAME = |.\Udloeb.dfs0| $ITEM_COUNT = 3$ ITEM NUMBERS = 1, 2, 3EndSect // DATA_FILE EndSect // SOURCE 2 EndSect // HD_SOURCE_SINK [MASS BUDGET] Touched = 1 MzSEPfsListItemCount = 0 NoOfMassFiles = 0 EndSect // MASS BUDGET [OUTPUT_SPECIFICATIONS] Touched = 1MzSEPfsListItemCount = 2 NumberOfOutputAreas = 2 [AREA_1] Touched = 1AssociatedArea = 1 XRange = 0, 38, 1 YRange = 0, 20, 1ZRange = 0, 14, 1TRange = 0, 400000, 4000UVelocity = true VVelocity = true WVelocity = true Pressure = false SurfaceElevation = false Density = true Temperature = false XEddy = trueYEddy = falseZEddy = false TKE = false TKD = false Salinity = false TimeAveraged = true FILE_NAME = 'aarslev3.dfs3' Title = ' EndSect // AREA 1 [AREA 2] Touched = 1AssociatedArea = 1 XRange = 0, 38, 1 YRange = 0, 20, 1 ZRange = 14, 14, 1 TRange = 0, 400000, 4000 UVelocity = false VVelocity = false WVelocity = false Pressure = false SurfaceElevation = true Density = false Temperature = false XEddy = false YEddy = falseZEddy = false TKE = falseTKD = false

Salinity = false TimeAveraged = true FILE_NAME = 'aarslev3.dfs2' Title = " EndSect // AREA_2 EndSect // OUTPUT_SPECIFICATIONS [HOT_FILES] Touched = 1 MzSEPfsListItemCount = 1 GenerateHotData = true TRange = 325000, 325000, 1 [AREA_1] Touched = 1 FILE NAME = 'Aarslev hotstart.dfs3' Title = EndSect // AREA_1 EndSect // HOT_FILES EndSect // HYDRODYNAMIC PARAMETERS [ADVECTION_DISPERSION_PARAMETER S] [OPTION_PARAMETERS] EndSect // OPTION PARAMETERS EndSect // ADVECTION DISPERSION PARAMETERS [MUD TRANSPORT PARAMETERS] [OPTION_PARAMETERS] EndSect // OPTION PARAMETERS [TASK_SELECTION] Touched = 1Number_of_layers = 1 Number of fractions = 7IncludeHeavyMetals = false MTincludesalinity = false EndSect // TASK_SELECTION [INITIAL_CONDITIONS] Touched = 1[INITIAL CONCENTRATIONS] Touched = 1MzSEPfsListItemCount = 7 [FRACTION_1] Touched = 1MzSEPfsListItemCount = 1 Gamma = 1[AREA 1] Touched = 1Format = 0ConstantValue = 0[DATA FILE] Touched = 1 $FILE_NAME = ||$ ITEM COUNT = 1ITEM NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA 1 EndSect // FRACTION_1 [FRACTION 2] Touched $=\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1

[AREA_1] Touched = 1Format = 0ConstantValue = 0 [DATA_FILE] Touched = 1 $FILE_NAME = \parallel$ ITEM_COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA_1 EndSect // FRACTION 2 [FRACTION 3] Touched $=\overline{1}$ MzSEPfsListItemCount = 1Gamma = 1 [AREA 1] Touched = 1Format = 0ConstantValue = 0 [DATA FILE] Touched = 1 $FILE_NAME = \parallel$ ITEM COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA FILE EndSect // AREA_1 EndSect // FRACTION_3 [FRACTION 4] Touched = $\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1 [AREA_1] Touched = 1Format = 0ConstantValue = 0 [DATA_FILE] Touched = 1FILE NAME = \parallel ITEM COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA FILE EndSect // AREA_1 EndSect // FRACTION 4 [FRACTION 5] Touched $=\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1[AREA 1] Touched = 1Format = 0ConstantValue = 0 [DATA_FILE] Touched = 1 $FILE_NAME = \parallel$ ITEM_COUNT = 1 ITEM NUMBERS = 1 EndSect // DATA FILE EndSect // AREA_1 EndSect // FRACTION 5 [FRACTION 6]
Touched = 1MzSEPfsListItemCount = 1 Gamma = 1 [AREA 1] Touched = 1Format = 0ConstantValue = 0[DATA_FILE] Touched = 1FILE NAME = || ITEM COUNT = 1ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA_1 EndSect // FRACTION 6 [FRACTION_7] Touched = 1 MzSEPfsListItemCount = 1Gamma = 1 [AREA 1] Touched = 1Format = 0ConstantValue = 0 [DATA FILE] Touched = 1FILE NAME = \parallel ITEM_COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA 1 EndSect // FRACTION 7 EndSect // INITIAL_CONCENTRATIONS [INITIAL BED THICKNESS] Touched = 1MzSEPfsListItemCount = 1 [LAYER_1] Touched = 1MzSEPfsListItemCount = 1 [AREA_1] Touched = 1Format = 0ConstantValue = 0 [DATA FILE] Touched = 1FILE_NAME = || ITEM_COUNT = 1 ITEM NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA 1 EndSect // LAYER 1 EndSect // INITIAL_BED_THICKNESS [INITIAL BED SEDIMENT DISTRIBUTIO N] Touched = 1MzSEPfsListItemCount = 1 [BED_LAYER_1] Fraction Distribution = 14, 14, 14, 14, 14, 14, 16 EndSect // BED_LAYER 1

EndSect // INITIAL BED SEDIMENT DISTRIBUTION EndSect // INITIAL CONDITIONS [DISPERSION_SPECIFICATIONS] Touched = 1[DISPERSION FACTORS] Touched = 1MzSEPfsListItemCount = 7 [COMPONENT 1] Touched = 1 MzSEPfsListItemCount = 1 Formulation = 0[AREA_1] Touched = 1DispersionFactors = 0.300000011920929, 1, 0 EndSect // AREA_1 EndSect // COMPONENT 1 [COMPONENT 2] Touched = 1MzSEPfsListItemCount = 1 Formulation = 0[AREA 1] Touched = 1DispersionFactors = 0.300000011920929, 1, 0 EndSect // AREA 1 EndSect // COMPONENT_2 [COMPONENT_3] Touched = 1MzSEPfsListItemCount = 1 Formulation = 0 [AREA_1] Touched = 1 DispersionFactors = 0.300000011920929, 1, 0 EndSect // AREA_1 EndSect // COMPONENT 3 [COMPONENT 4] Touched = 1MzSEPfsListItemCount = 1 Formulation = 0[AREA_1] Touched = 1DispersionFactors = 0.300000011920929, 1, 0 EndSect // AREA 1 EndSect // COMPONENT_4 [COMPONENT 5] Touched = 1MzSEPfsListItemCount = 1 Formulation = 0 [AREA 1] Touched = 1 DispersionFactors = 0.300000011920929, 1, 0 EndSect // AREA 1 EndSect // COMPONENT_5 [COMPONENT 6] Touched = 1MzSEPfsListItemCount = 1

Formulation = 0 [AREA 1] Touched = 1DispersionFactors = 0.300000011920929, 1, 0 EndSect // AREA 1 EndSect // COMPONENT_6 [COMPONENT 7] Touched = 1MzSEPfsListItemCount = 1 Formulation = 0[AREA_1] Touched = 1DispersionFactors = 0.30000011920929, 1, 0 EndSect // AREA_1 EndSect // COMPONENT 7 EndSect // DISPERSION FACTORS [DISPERSION_LIMITS] Touched = 1MzSEPfsListItemCount = 7[COMPONENT_1] Touched = 1MzSEPfsListItemCount = 1 [AREA_1] Touched = 1XLimits = 0, 0.200000029802322 YLimits = 0, 0.003528000088408589 ZLimits = 0, 1.9999999994950485e-006 EndSect // AREA_1 EndSect // COMPONENT_1 [COMPONENT 2] Touched = 1MzSEPfsListItemCount = 1 [AREA_1] Touched = 1XLimits = 0, 0.200000029802322 YLimits = 0, 0.003527999855577946 ZLimits = 0, 1.9999999994950485e-006 EndSect // AREA 1 EndSect // COMPONENT 2 [COMPONENT 3] Touched = 1MzSEPfsListItemCount = 1[AREA_1] Touched = 1XLimits = 0, 0.200000029802322 YLimits = 0, 0.003527999855577946 ZLimits = 0, 1.9999999994950485e-006 EndSect // AREA 1 EndSect // COMPONENT 3 [COMPONENT_4] Touched = 1MzSEPfsListItemCount = 1

> [AREA_1] Touched = 1

YLimits = 0, 0.003527999855577946 ZLimits = 0, 1.9999999994950485e-006 EndSect // AREA 1 EndSect // COMPONENT_4 [COMPONENT_5] Touched = 1MzSEPfsListItemCount = 1 [AREA_1] Touched = 1XLimits = 0, 0.200000029802322 YLimits = 0, 0.003527999855577946 ZLimits = 0, 1.999999994950485e-006 EndSect // AREA 1 EndSect // COMPONENT_5 [COMPONENT_6] Touched = 1MzSEPfsListItemCount = 1 [AREA 1] Touched = 1 XLimits = 0, 0.200000029802322 YLimits = 0,0.003527999855577946 ZLimits = 0, 1.999999994950485e-006 EndSect // AREA 1 EndSect // COMPONENT 6 [COMPONENT_7] Touched = 1MzSEPfsListItemCount = 1 [AREA 1] Touched = 1XLimits = 0, 0.200000029802322 YLimits = 0, 0.003527999855577946 ZLimits = 0, 1.9999999994950485e-006 EndSect // AREA 1 EndSect // COMPONENT_7 EndSect // DISPERSION LIMITS EndSect // DISPERSION SPECIFICATIONS [MT_BOUNDARIES] Touched = 1MzSEPfsListItemCount = 7 [COMPONENT_1] Touched = 1MzSEPfsListItemCount = 0EndSect // COMPONENT 1 [COMPONENT_2] Touched = 1 MzSEPfsListItemCount = 0EndSect // COMPONENT_2 [COMPONENT_3] Touched = 1MzSEPfsListItemCount = 0 EndSect // COMPONENT 3

XLimits = 0, 0.200000029802322

[COMPONENT 4] Touched = 1MzSEPfsListItemCount = 0EndSect // COMPONENT_4 [COMPONENT_5] Touched = 1MzSEPfsListItemCount = 0EndSect // COMPONENT 5 [COMPONENT_6] Touched = 1MzSEPfsListItemCount = 0EndSect // COMPONENT 6 [COMPONENT_7] Touched = 1MzSEPfsListItemCount = 0EndSect // COMPONENT 7 EndSect // MT_BOUNDARIES [MT SOURCES] Touched = 1MzSEPfsListItemCount = 2[SOURCE 1] Touched = 1Format = 0 ConstantValues = 0.01, 0.01, 0.01, 0.01, 0.01, 0.01, 0.01 [DATA_FILE] Touched = 1 FILE NAME = |.\7 fraktioner new dist.dfs0| ITEM $\overline{COUNT} = 7$ ITEM_NUMBERS = 1, 2, 3, 4, 5, 6, 7 EndSect // DATA FILE EndSect // SOURCE 1 [SOURCE 2] Touched = 1Format = -1ConstantValues = 0, 0, 0, 0, 0, 0, 0[DATA FILE] Touched = 1FILE NAME = \parallel ITEM COUNT = 7ITEM_NUMBERS = 1, 2, 3, 4, 5, 6, 7 EndSect // DATA_FILE EndSect // SOURCE 2 EndSect // MT SOURCES [FORCINGS] Touched = 1[WAVES] Touched = 0WaveFormat = 0UseInterpolationInTime = false MinWaterDepthForIncludingWaves = 0 Include_Liquefaction = false Liquefaction factor = 1[CONSTANT WAVES] Touched = 0SignificantWaveHeight = 0.3 ZeroCrossingWavePeriod = 3 MeanWaveDirection = 0EndSect // CONSTANT WAVES

[TIME AND SPACE_VARYING_WAVES] Touched = 0 [DATA_FILE] Touched = 1FILE_NAME = || ITEM_COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA FILE EndSect // TIME_AND_SPACE_VARYING_WAVES [DATABASE] Touched = 0MzSEPfsListItemCount = 1 Data_Base_File_Name_1_1_1 = " [WIND_SPEED] Touched = 1 StartingValueOfWindSpeed = 5 IncrementValueOfWindSpeed = 5 NumberOfWindSpeeds = 1 EndSect // WIND SPEED [WIND_DIRECTION] Touched = 1StartingValueOfWindDirection = 90 IncrementValueOfWindDirection = 90 NumberOfWindDirections = 1 EndSect // WIND DIRECTION [WATER_LEVEL] Touched = 1StartingValueOfWaterLevel = 0 IncrementValueOfWaterLevel = 1 NumberOfWaterLevels = 1 EndSect // WATER LEVEL EndSect // DATABASE EndSect // WAVES EndSect // FORCINGS [WATER_COLUMN] SandFractionDescription = 0 IncludeDensityFeedbackOnHD = true [SAND FRACTIONS] Mean_Fall_Velocity_Fraction_1 = 0.001 Sand fraction 1 =false Mean_Fall_Velocity_Fraction_2 = 0.001 Sand fraction 2 =false Mean_Fall_Velocity_Fraction_3 = 0.001 Sand_fraction_3 = false Mean Fall Velocity Fraction 4 = 0.001 $Sand_fraction_4 = false$ Mean_Fall_Velocity_Fraction_5 = 0.001 $Sand_fraction_5 = false$ Mean Fall Velocity Fraction 6 = 0.001 Sand fraction 6 =false Mean_Fall_Velocity_Fraction_7 = 0.001 Sand fraction 7 =false EndSect // SAND FRACTIONS

[VISCOSITY_PARAMETERS]

Touched = 1DensityOfSediment = 1600 BaseInViscosityFormula = 100 ConcInViscosityFormula = 600 EndSect // VISCOSITY_PARAMETERS [SETTLING] Touched = 1 Flocculation Description = 0 Hindered_Settling_Description = 0 RhoSed = 2650GelPoint = 50 CHinder = 10 C floc = 0.01W sn = 1[SEDIMENT FRACTION 1] Touched = $\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1 [AREA 1] Touched = 1Format = 0 ConstantValue = 0.00310000089034438 [DATA_FILE] Touched = 1 FILE NAME = \parallel $ITEM_COUNT = 1$ ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA_1 EndSect // SEDIMENT FRACTION 1 [SEDIMENT FRACTION 2] Touched = $\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1[AREA 1] Touched = 1Format = 0ConstantValue = 0.001099999994039536 [DATA FILE] Touched = 1FILE NAME = \parallel ITEM COUNT = 1 ITEM NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA 1 EndSect // SEDIMENT FRACTION 2 [SEDIMENT_FRACTION_3] Touched $=\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1 [AREA 1] Touched = 1 Format = 0 ConstantValue = 0.0004499999922700226 [DATA FILE] Touched = 1FILE NAME = || ITEM COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA FILE EndSect // AREA_1

[SEDIMENT FRACTION 4] Touched = 1 MzSEPfsListItemCount = 1 Gamma = 1[AREA_1] Touched = 1 Format = 0ConstantValue = 0.00023999999393709 [DATA_FILE] Touched = 1FILE_NAME = || ITEM COUNT = 1 ITEM NUMBERS = 1 EndSect // DATA FILE EndSect // AREA_1 EndSect // SEDIMENT FRACTION 4 [SEDIMENT FRACTION 5] Touched = $\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1 [AREA 1] Touched = 1 Format = 0ConstantValue = 0.00015999999595806 [DATA_FILE] Touched = 1FILE_NAME = || ITEM COUNT = 1 ITEM NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA_1 EndSect // SEDIMENT FRACTION 5 [SEDIMENT_FRACTION_6] Touched = $\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1[AREA 1] Touched = 1Format = 0ConstantValue = 6.7000008540228e-005 [DATA FILE] Touched = 1FILE NAME = \parallel ITEM_COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA 1 EndSect // SEDIMENT FRACTION 6 [SEDIMENT FRACTION 7] Touched = 1MzSEPfsListItemCount = 1 Gamma = 1 [AREA 1] Touched = 1Format = 0ConstantValue = 4.800000169780105e-005 [DATA_FILE] Touched = 1

EndSect // SEDIMENT_FRACTION_3

 $FILE_NAME = \parallel$ ITEM COUNT = 1ITEM_NUMBERS = 1 EndSect // DATA FILE EndSect // AREA_1 EndSect // SEDIMENT_FRACTION_7 EndSect // SETTLING [CRITICAL SHEAR STRESS DEPOSITION Touched = 1[SEDIMENT FRACTION 1] Touched = $\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1 [AREA 1] Touched = 1Format = 0ConstantValue = 0.02999999932944775 [DATA_FILE] Touched = 1 FILE NAME = \parallel ITEM_COUNT = 1 ITEM NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA_1 EndSect // SEDIMENT FRACTION 1 [SEDIMENT FRACTION 2] Touched $=\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1[AREA_1] Touched = 1Format = 0ConstantValue = 0.02999999932944775 [DATA FILE] Touched = 1FILE_NAME = || ITEM COUNT = 1 ITEM NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA 1 EndSect // SEDIMENT FRACTION 2 [SEDIMENT_FRACTION_3] Touched = $\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1 [AREA 1] Touched = 1Format = 0 ConstantValue = 0.02999999932944775 [DATA FILE] Touched = 1FILE NAME = \parallel ITEM COUNT = 1ITEM_NUMBERS = 1 EndSect // DATA FILE

EndSect // AREA_1

EndSect // SEDIMENT_FRACTION_3 [SEDIMENT FRACTION 4] Touched = 1MzSEPfsListItemCount = 1 Gamma = 1 [AREA_1] Touched = 1 Format = 0ConstantValue = 0.02999999932944775 [DATA_FILE] Touched = 1FILE_NAME = || ITEM COUNT = 1 ITEM NUMBERS = 1 EndSect // DATA FILE EndSect // AREA_1 EndSect // SEDIMENT FRACTION 4 [SEDIMENT FRACTION 5] Touched $=\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1 [AREA 1] Touched = 1 Format = 0 ConstantValue = 0.01999999955296516 [DATA_FILE] Touched = 1 FILE_NAME = || ITEM_COUNT = 1 ITEM NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA_1 EndSect // SEDIMENT FRACTION 5 [SEDIMENT_FRACTION_6] Touched = $\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1 [AREA 1] Touched = 1Format = 0ConstantValue = 0.009999999776482582 [DATA_FILE] Touched = 1FILE NAME = || ITEM_COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA 1 EndSect // SEDIMENT FRACTION 6 [SEDIMENT_FRACTION_7] Touched $=\overline{1}$ MzSEPfsListItemCount = 1 Gamma = 1 [AREA 1] Touched = 1Format = 0 ConstantValue = 0.009999999776482582 [DATA_FILE] Touched = 1

EndSect // AREA 1 EndSect // SEDIMENT_FRACTION_7 EndSect // CRITICAL SHEAR STRESS DEPOSITION EndSect // WATER COLUMN [BED_PARAMETERS] [EROSION COEFFICIENTS] CMax = 50[BED_LAYER_1] Touched = 1MzSEPfsListItemCount = 1 Em = 1 $Erosion_Description = 0$ [AREA 1] Touched = 1Format = 0 ConstantValue = 5e-005 [DATA FILE] Touched = 1FILE_NAME = || ITEM_COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA_FILE EndSect // AREA 1 EndSect // BED LAYER 1 [CRITICAL_SHEAR_STRESS_EROSION] [BED_LAYER_1] Touched = 1MzSEPfsListItemCount = 1 [AREA_1] Touched = 1Format = 0ConstantValue = 0.1 [DATA FILE] Touched = 1FILE NAME = || ITEM_COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA FILE EndSect // AREA 1 EndSect // BED_LAYER_1 EndSect // CRITICAL SHEAR STRESS EROSION EndSect // EROSION COEFFICIENTS [DRY DENSITY] [BED_LAYER_1] Touched = 1 MzSEPfsListItemCount = 1 [AREA_1] Touched = 1Format = 0ConstantValue = 300 [DATA FILE] Touched = 1FILE NAME = \parallel

 $FILE_NAME = \parallel$

ITEM COUNT = 1

ITEM_NUMBERS = 1

EndSect // DATA FILE

EndSect // DATA_FILE EndSect // AREA_1 EndSect // BED LAYER 1 EndSect // DRY DENSITY [BED ROUGHNESS] Touched = 1MzSEPfsListItemCount = 1 [AREA_1] Touched = 1Format = 0ConstantValue = 0.01 [DATA_FILE] Touched = 1 FILE_NAME = || ITEM_COUNT = 1 ITEM_NUMBERS = 1 EndSect // DATA FILE EndSect // AREA_1 EndSect // BED ROUGHNESS [TRANSITION] Touched = 1MzSEPfsListItemCount = 0IncludeTransitionBetweenLayers = 0 EndSect // TRANSITION EndSect // BED PARAMETERS [MASS_BUDGET] Touched = 0MzSEPfsListItemCount = 0 NoOfMassFiles = 0 EndSect // MASS BUDGET [MT_OUTPUT] Touched = 1MzSEPfsListItemCount = 3 NumberOfOutputAreas = 3 [AREA 1] Touched = 1AssociatedArea = 1 XRange = 0, 38, 1 YRange = 0, 20, 1 ZRange = 0, 14, 1TRange = 0, 400000, 4000Title = FILE NAME = 'aarslev3 MT.dfs3' [MAIN OUTPUT ITEMS] SSC $\overline{\text{Fraction}}_1 = \text{true}$ SSC_Fraction_2 = true $SSC_Fraction_3 = true$ $SSC_Fraction_4 = true$ $SSC_Fraction_5 = true$ SSCFraction 6 = trueSSC Fraction 7 = true Bed_Mass_Layer_1_Fraction_1 = false Bed Mass Layer 1 Fraction 2 = false Bed_Mass_Layer_1_Fraction_3 = false Bed_Mass_Layer_1_Fraction_4 = false Bed_Mass_Layer_1_Fraction_5 = false

ITEM COUNT = 1

ITEM NUMBERS = 1

Bed_Mass_Layer_1_Fraction_6 =
false Bed Mass Layer 1 Fraction 7 =
false
Eldseet // MAIN_001101_11EMS
[DERIVED_OUTPUT_ITEMS] Bed_Thickness_Layer_1 = false Net_Deposition_Fraction_1 = false Net_Deposition_Fraction_2 = false Net_Deposition_Fraction_3 = false Net_Deposition_Fraction_4 = false Net_Deposition_Fraction_5 = false Net_Deposition_Fraction_6 = false Net_Deposition_Fraction_7 = false
Net_Deposition_Accumulated_Fraction_1 = false
Net_Deposition_Accumulated_Fraction_2 = false
Net_Deposition_Accumulated_Fraction_3 = false
Net_Deposition_Accumulated_Fraction_4 = false
Net_Deposition_Accumulated_Fraction_5 = false
Net_Deposition_Accumulated_Fraction_6 = false
Net_Deposition_Accumulated_Fraction_7 = false
Net_Deposition_Accumulated_Total = false
Total_Bed_Thickness_Change = false Total_Bed_Mass_Change = false Total_Ssc = false EndSect // DERIVED_OUTPUT_ITEMS
bekiveb_oon or_nekis
[PROCESS_OUTPUT_ITEMS] Bad_Shaar_Stracs_folse
Settling Velocity Fraction $1 = $ false
Settling_Velocity_Fraction_2 = false
Settling_Velocity_Fraction_3 = false
Settling_Velocity_Fraction_4 = false
Settling Velocity Fraction 6 = false
Settling_Velocity_Fraction_7 = false
Deposition_Fraction_1 = false
Deposition_Fraction_2 = false Deposition_Fraction_3 = false
Deposition_Fraction_4 = false
Deposition_ $Fraction_5 = false$
Deposition_Fraction_6 = false
Erosion Fraction $1 = false$
$\frac{1}{1} = \frac{1}{1} = \frac{1}$
$Erosion_Fraction_3 = false$
$Erosion_Fraction_4 = talse$ Erosion_Fraction_5 = talse
Erosion_Fraction_ $6 = $ false
ErosionFraction $7 = false$
U_V elocity = true V_Velocity = true
W Velocity = true
Wave_Height = false
Wave Period - false
Wave Direction = false

EndSect // PROCESS OUTPUT ITEMS NoOfComponents = 61 EndSect // AREA_1 [AREA_2] Touched = 1 AssociatedArea = 1 XRange = 0, 38, 1YRange = 0, 20, 1 ZRange = 14, 14, 1 TRange = 0, 400000, 4000 Title = FILE_NAME = 'aarslev_MT.dfs2' [MAIN OUTPUT ITEMS] SSC_Fraction_1 = false SSC_Fraction_2 = false $SSC_Fraction_3 = false$ SSC_Fraction_4 = false SSC_Fraction_5 = false $SSC_Fraction_6 = false$ SSC Fraction 7 = false Bed_Mass_Layer_1_Fraction_1 = true $Bed_Mass_Layer_1_Fraction_2 = true$ Bed_Mass_Layer_1_Fraction_3 = true Bed Mass Layer 1 Fraction 4 = true Bed_Mass_Layer_1_Fraction_5 = true Bed_Mass_Layer_1_Fraction_6 = true Bed_Mass_Layer_1_Fraction_7 = true EndSect // MAIN_OUTPUT_ITEMS [DERIVED_OUTPUT_ITEMS] Bed Thickness Layer 1 = falseNet_Deposition_Fraction_1 = false Net_Deposition_Fraction_2 = false Net_Deposition_Fraction_3 = false Net Deposition Fraction 4 = false Net_Deposition_Fraction_5 = false Net_Deposition_Fraction_6 = false Net Deposition Fraction 7 =false Net_Deposition_Accumulated_Fraction_1 = true Net_Deposition_Accumulated_Fraction_2 = true Net_Deposition_Accumulated_Fraction_3 = true Net Deposition Accumulated Fraction 4 = true Net Deposition Accumulated Fraction 5 = true Net_Deposition_Accumulated_Fraction_6 = true Net Deposition Accumulated Fraction 7 = true Net_Deposition_Accumulated_Total = true Total_Bed_Thickness_Change = true Total Bed Mass Change = true Total Ssc = falseEndSect // DERIVED_OUTPUT_ITEMS [PROCESS OUTPUT ITEMS] $Bed_Shear_Stress = true$ Settling Velocity Fraction 1 = false

Settling_Velocity_Fraction_2 = false Settling_Velocity_Fraction_3 = false Settling_Velocity_Fraction_4 = false Settling_Velocity_Fraction_5 = false Settling_Velocity_Fraction_6 = false Settling_Velocity_Fraction_7 = false Deposition_Fraction_1 = false $Deposition_Fraction_2 = false$ Deposition Fraction 3 =false DepositionFraction 4 = false $Deposition_Fraction_5 = false$ Deposition_Fraction_6 = false Deposition Fraction 7 =false $Erosion_Fraction_1 = false$ $Erosion_Fraction_2 = false$ Erosion Fraction 3 = falseErosion Fraction 4 = falseErosion_Fraction_5 = false $Erosion_Fraction_6 = false$ Erosion Fraction 7 =false U Velocity = false V_Velocity = false \overline{W} Velocity = false Wave_Height = false Wave_Period = false Wave_Direction = false EndSect // PROCESS_OUTPUT_ITEMS NoOfComponents = 61 EndSect // AREA 2 [AREA_3] Touched = 1AssociatedArea = 1 XRange = 37, 37, 1 YRange = 10, 10, 1 ZRange = 12, 12, 1 TRange = 0, 400000, 4000 Title = FILE NAME = 'aarslev3 MT.dfs0' [MAIN OUTPUT ITEMS] $SSC_Fraction_1 = true$ $SSC_Fraction_2 = true$ SSC_Fraction_3 = true SSC_Fraction_4 = true $SSC_Fraction_5 = true$ SSC_Fraction_6 = true SSC_Fraction_7 = true Bed_Mass_Layer_1_Fraction_1 = false Bed_Mass_Layer_1_Fraction_2 = false Bed Mass Layer 1 Fraction 3 = false Bed_Mass_Layer_1_Fraction_4 = false Bed_Mass_Layer_1_Fraction_5 = false Bed_Mass_Layer_1_Fraction_6 = false Bed_Mass_Layer_1_Fraction_7 = false EndSect // MAIN_OUTPUT_ITEMS [DERIVED OUTPUT ITEMS] Bed Thickness Laver 1 = falseNet_Deposition_Fraction_1 = false Net_Deposition_Fraction_2 = false Net Deposition Fraction 3 =false Net Deposition Fraction 4 =false Net_Deposition_Fraction_5 = false Net Deposition Fraction 6 =false

Net_Deposition_Fraction_7 = false

Net_Deposition_Accumulated_Fraction_1 = false

Net_Deposition_Accumulated_Fraction_2 = false

Net_Deposition_Accumulated_Fraction_3 = false

Net_Deposition_Accumulated_Fraction_4 = false

Net_Deposition_Accumulated_Fraction_5 = false

Net_Deposition_Accumulated_Fraction_6 = false

Net_Deposition_Accumulated_Fraction_7 = false Net_Deposition_Accumulated_Total = false Total_Bed_Thickness_Change = false Total_Bed_Mass_Change = false

Total_Ssc = true EndSect // DERIVED_OUTPUT_ITEMS

[PROCESS_OUTPUT_ITEMS] Bed_Shear_Stress = false Settling_Velocity_Fraction_1 = false Settling_Velocity_Fraction_2 = false Settling_Velocity_Fraction_3 = false Settling_Velocity_Fraction_4 = false Settling_Velocity_Fraction_5 = false Settling Velocity Fraction 6 = false Settling_Velocity_Fraction_7 = false Deposition_Fraction_1 = false Deposition Fraction 2 =false Deposition Fraction 3 =false $Deposition_Fraction_4 = false$ Deposition_Fraction_5 = false Deposition Fraction 6 =false Deposition_Fraction 7 =false Erosion_Fraction_1 = false Erosion Fraction 2 = false Erosion Fraction 3 =false ErosionFraction 4 = false Erosion_Fraction_5 = false Erosion Fraction 6 = falseErosionFraction 7 = falseU_Velocity = false V_Velocity = false \overline{W} Velocity = false Wave_Height = false Wave_Period = false Wave Direction = false EndSect // PROCESS OUTPUT ITEMS NoOfComponents = 61 EndSect // AREA_3 EndSect // MT OUTPUT EndSect // MUD_TRANSPORT_PARAMETERS

[ECO_LAB_PARAMETERS] [OPTION_PARAMETERS] EndSect // OPTION_PARAMETERS [MODEL_DEFINITION] Touched = 0 ModelDefinitionFile = || IntegrationMethod = 1 UpdateFrequency = 1 DisableProcesses = false EndSect // MODEL_DEFINITION

[STATE_VARIABLES] Touched = 0 MzSEPfsListItemCount = 0 NoOfComponents = 0 EndSect // STATE_VARIABLES

[INITIAL_CONDITIONS] Touched = 0 MzSEPfsListItemCount = 0 EndSect // INITIAL_CONDITIONS

[AD_TRANSPORT_PARAMETERS] [AD_BOUNDARY] Touched = 0 MzSEPfsListItemCount = 0 EndSect // AD_BOUNDARY

[AD_DISPERSION] ImplicitVerticalDispersionScheme = false

[AD_DISPERSION_FACTOR] Touched = 0 MzSEPfsListItemCount = 0 EndSect //

AD_DISPERSION_FACTOR

[AD_DISPERSION_LIMIT] Touched = 0 MzSEPfsListItemCount = 0 EndSect // AD_DISPERSION_LIMIT

EndSect // AD_DISPERSION

[AD_SOURCE_AND_SINK] Touched = 0MzSEPfsListItemCount = 2 [SOURCE_SINK_1] Touched = 0Format = 0ConstantValues = 0 [DATA_FILE] Touched = 0FILE NAME = \parallel $ITEM_COUNT = 0$ ITEM NUMBERS = EndSect // DATA FILE EndSect // SOURCE_SINK_1 [SOURCE_SINK_2] Touched = 0Format = 0ConstantValues = 0 [DATA FILE] Touched = 0^{-1} FILE NAME = \parallel ITEM COUNT = 0

ITEM_COUNT = 0 ITEM_NUMBERS = EndSect // DATA_FILE

EndSect // SOURCE_SINK_2

EndSect // AD_SOURCE_AND_SINK

[AD_PRECIPITATION] Touched = 0 MzSEPfsListItemCount = 0 EndSect // AD PRECIPITATION

[AD_DEPOSITION] IncludeSurfaceDeposition = false IncludeSoilDeposition = false [AD_DEPOSITION_SOIL] Touched = 0 MzSEPfsListItemCount = 0 EndSect // AD_DEPOSITION_SOIL

[AD_DEPOSITION_SURFACE] Touched = 0 MzSEPfsListItemCount = 0 EndSect // AD_DEPOSITION_SURFACE

EndSect // AD DEPOSITION

EndSect // AD_TRANSPORT_PARAMETERS

> [CONSTANTS] Touched = 0 MzSEPfsListItemCount = 0 NoOfConstants = 0 EndSect // CONSTANTS

> [FORCINGS] Touched = 0 MzSEPfsListItemCount = 0 NoOfForcings = 0 EndSect // FORCINGS

> [MASS_BUDGET] Touched = 0 MzSEPfsListItemCount = 0 NoOfMassFiles = 0 EndSect // MASS BUDGET

[RESULTS] Touched = 0 MzSEPfsListItemCount = 0 [ADDITIONAL_OPTIONAL_OUTPUT] NoItems = 0 EndSect // ADDITIONAL_OPTIONAL_OUTPUT

NumberOfOutputAreas = 0 EndSect // RESULTS

EndSect // ECO_LAB_PARAMETERS

EndSect // MIKE3_FLOW_MODEL

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