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Bentzen, Thomas Ruby; Larsen, Torben; Rasmussen, Michael R.

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Wind effects on retention time in highway ponds

T.R Bentzen, T. Larsen and M.R. Rasmussen
Aalborg University, Department of Civil Engineering, Soil & Water
Sohngaardsholmsvej 57, 9000 Aalborg, Denmark
Phone : +45 96358587 E-mail : trb@civil.aau.dk

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.

Keywords: Basins, circulation, CFD-modelling, runoff, shear stress, topography

Introduction
Pollution of the water environment (primarily ditches, streams and rivers) caused by highway runoff focuses especially on heavy metals and PAH's. 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, 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 on high scientific level for decades e.g. Lavel et al. (2003); Herb and Stefan (2005); Rueda et al. (2005). But the literature concerning wind effects on smaller ponds and basins seems almost non-existing. 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 (1996); Matthews et al. (1997); 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 meters 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 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 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.

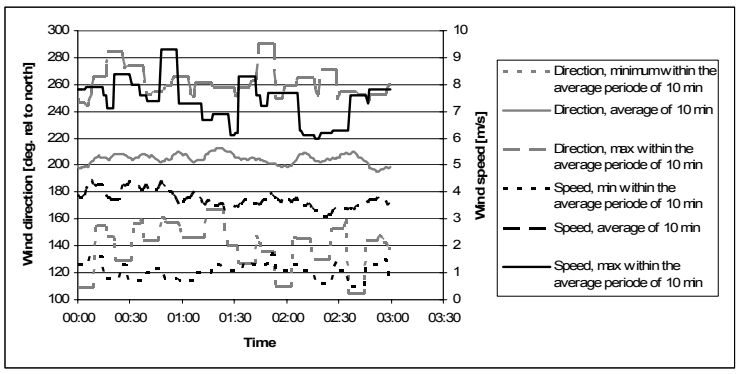

Figure 1. Measured wind speed and direction two meters above the water surface of the pond, treated in this study.

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 a 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 2500 m^2, a water depth of 0.6 m under dry weather condition, 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 2400 m^2, a water depth of 0.7 m under dry weather condition, 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).

Topography and bathymetric

The topography of the surroundings of the pond with a radius of 200 meter (fig. 2) and the bathymetric of the pond (fig. 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 meters.

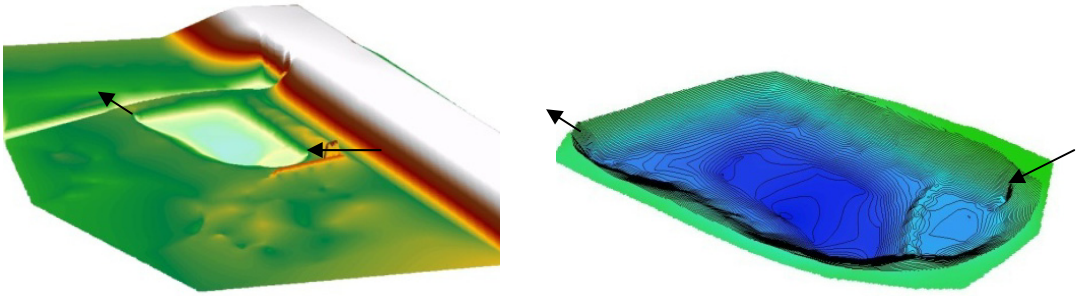

Figure 2. Left: The topography near the highway detention pond. Right: The bathymetric of the highway detention pond. (Arrows indicate the location of inlet and outlet from the pond).

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 x 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.

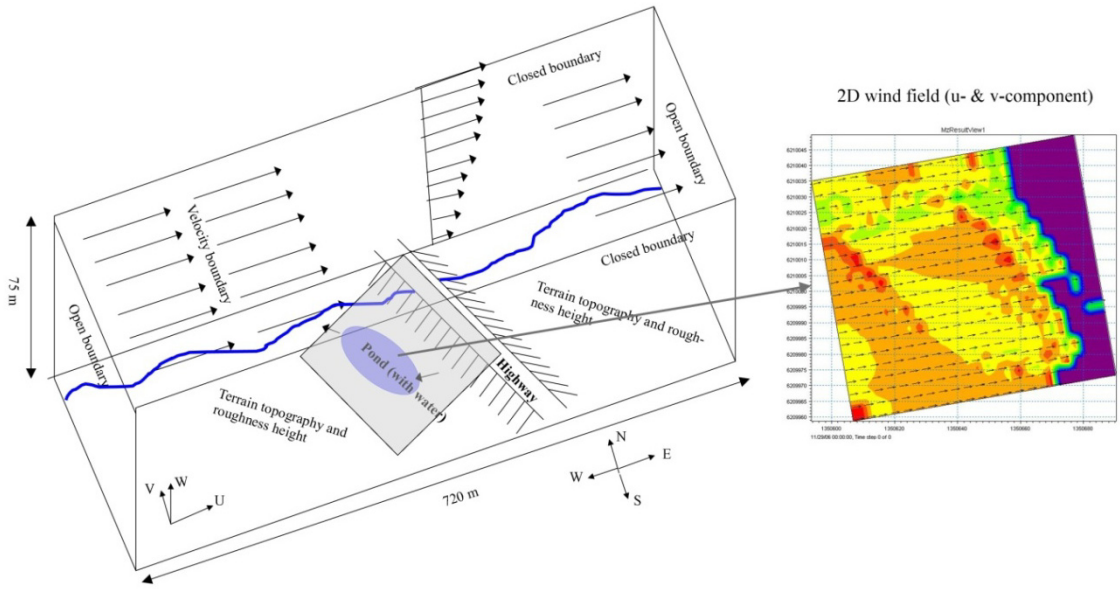

Figure 3. Sketch illustrating the wind model setup for east and west simulations.

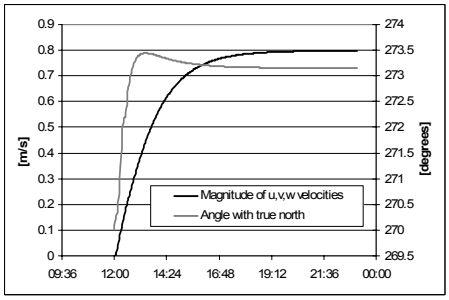

Figure 4. Example of control of velocity and direction steadiness (here in an arbitrary grid cell)

The steady spatial *non-uniform* wind field above the water surface is subsequently extracted and interpolated to a 0.8m x 0.8m 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 m^3/s defined as a source/sink.
- Water depth of 0.12 m over the permanent water pool (total water volume of 1450 m^3) which entails a hydraulic retention time $T_h = \frac{Pond\ volume}{Discharge}$ of approximately 57 hours.
- The bathymetric is discretized in 0.8 m x 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 in- an outflow with “pure” water. The simulated period lasts for a total of three days and ten hours.

The wind effect on the retention time and effluent concentration of the tracer pollutant is investigated on following conditions with regards to the effect of wind to 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 $\nu_T \frac{\partial u}{\partial z}$ is set to equalize the wind shear $\frac{\rho_{air}}{\rho_{water}} C_w \cdot W \cdot W_x$ on the water surface. The friction coefficient C_w is set to vary linearly between 0.0016 at a wind speed (W) at 0 m/s to 0.0026 at a speed of 24 m/s. (Smith and 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 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 eq. 1 based on the resulting time series from the pond model:

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

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 figure 5 -12. The following abbreviations are used in the figures: PA = peak arrival, 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 figure 13-17.

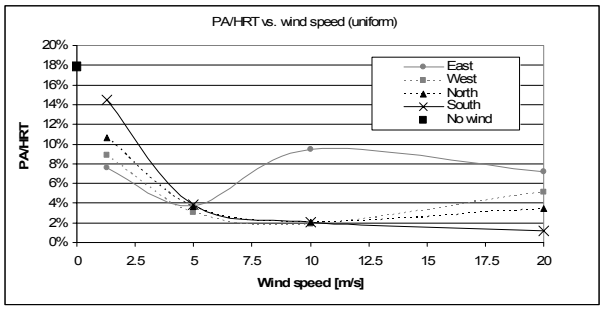

Figure 5. Time for peak arrival related to the hydraulic retention time for uniformly applied wind field.

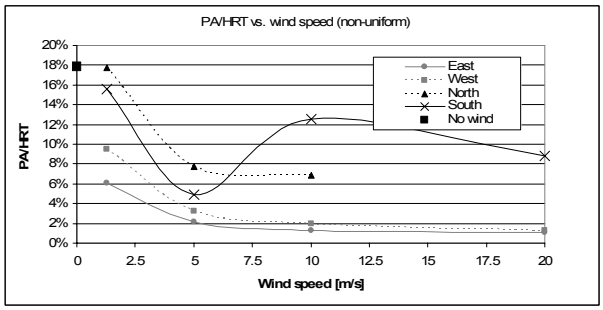

Figure 6. Time for peak arrival related to the hydraulic retention time for non-uniformly applied wind field.

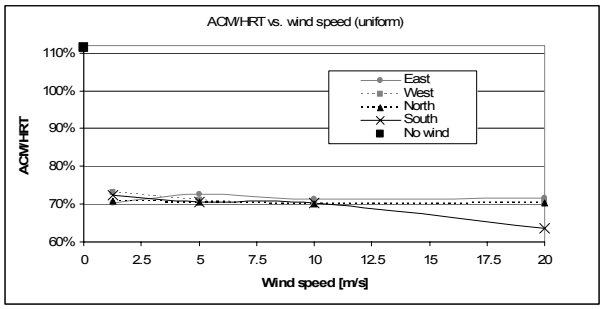

Figure 7. Time for arrival of centre of mass related to the hydraulic retention time for uniformly applied wind field.

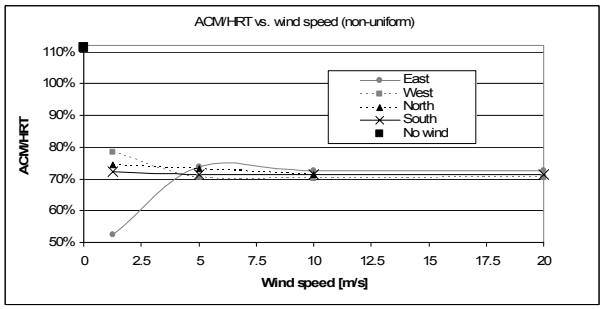

Figure 8. Time for arrival of centre of mass related to the hydraulic retention time for non-uniformly applied wind field.

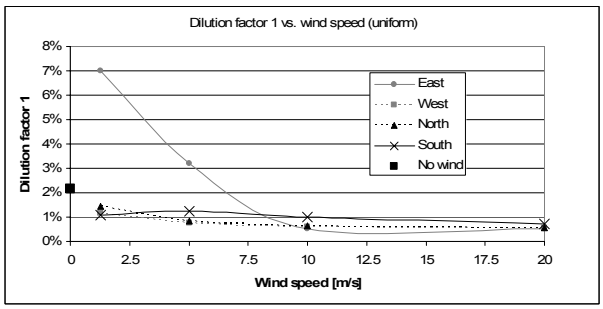

Figure 9. Effluent peak concentration related to the inlet concentration for uniformly applied wind field.

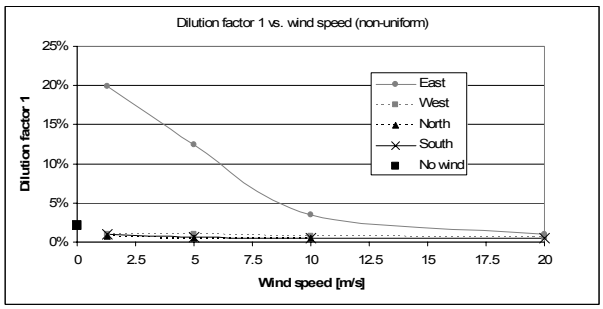

Figure 10. Effluent peak concentration related to the inlet concentration for non-uniformly applied wind field.

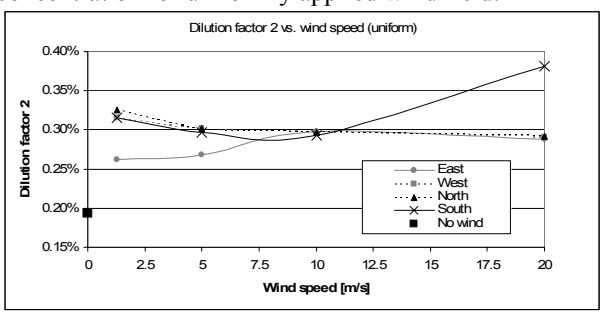

Figure 11. Effluent concentration at arrival of the centre of mass related to the inlet concentration for uniformly applied wind field.

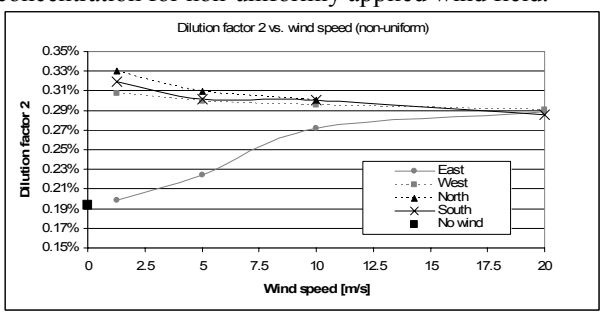

Figure 12. Effluent concentration at arrival of the centre of mass related to the inlet concentration for non-uniformly applied wind field.

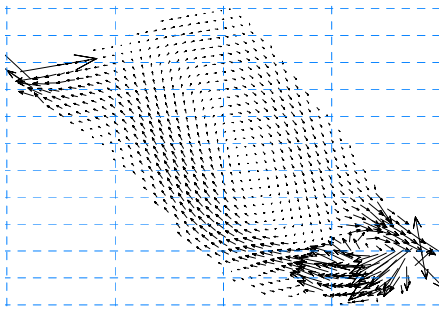

Figure 13. Surface velocities for the "No wind shear stress" situation (The velocity vectors are magnified 8 times compared to the following four figures.)

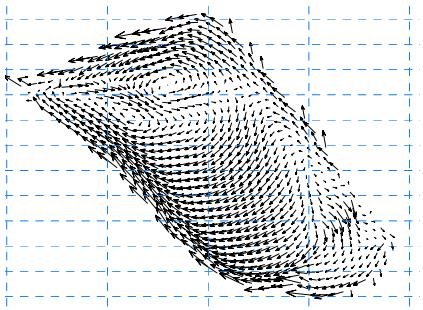

Figure 14. Surface velocities for the "Non-uniform wind shear stress, east 5 m/s" situation

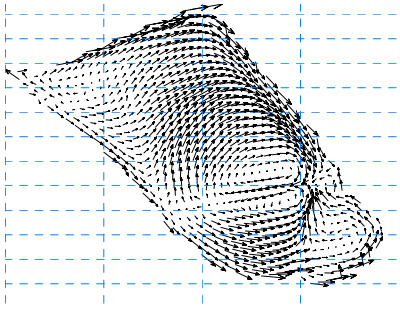

Figure 15. Surface velocities for the "Non-uniform wind shear stress, west 5 m/s" situation

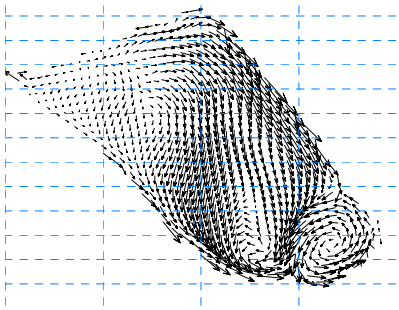

Figure 16. Surface velocities for the "Non-uniform wind shear stress, north 5 m/s" situation

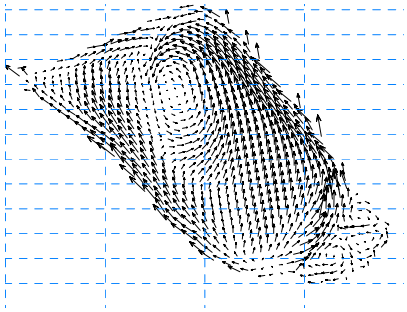

Figure 17. Surface velocities for the "Non-uniform wind shear stress, south 5 m/s" situation

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 on fig. 5-8 and as well as on the flow pattern as seen on fig. 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 (fig. 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 (fig. 9-10), due to contact with a greater water pool (except when the wind 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) (fig. 7-8) 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 (fig. 5-6) 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 (fig. 5-6). 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 (fig. 5-6). The eastern wind is also the one most effected 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 pre-modelling 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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