SEDIMENTATION POND PERFORMANCE FROM THREE-DIMENSIONAL MODELLING

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ABSTRACT (300 WORDS MAXIMUM)

In two separate studies, three-dimensional numerical modelling has been used to investigate the performance of stormwater and sediment control ponds. A mud transport module was used to model sedimentation and re-entrainment of the sediment the ponds are intended to trap. The wide range of fall velocities found in stormwater sediment results in quite different sedimentation patterns, and therefore required that several fractions of suspended sediment be modelled.

The first study applied either a constant flow of sediment-laden stormwater or a single runoff event, to various pond designs. This was to determine the effect of various parameter on pond efficiency (expressed as the fraction of incoming suspended sediment that is trapped). The variables investigated included pond size and geometry, inlet geometry, and baffles that redirect flow.

The second study investigated the long-term efficiency of a standard stormwater treatment pond design, by modelling the inflow derived from a one-year gauged rainfall record. This approach aimed to determine the pond efficiency in absolute terms, which can be done as long as inflow time series of inflow and sediment concentration are known as well as the range of sediment fall velocities.

The models provided not only the pond efficiency data but also visual and quantitative information on details of the sedimentation. For example:

- Even in symmetric ponds, flows are often asymmetric, reducing trapping efficiency somewhat;

- A circular pond with inlet and outlet at its edge can be inefficient if forced vortex flow results, because the pond's centre remains free of sediment. Directing the inflow more radially inwards than tangentially prevents this.

Three-dimensional modelling including mud transport thus can increase our understanding of what is needed for an effective sedimentation pond.

KEYWORDS

Stormwater treatment; numerical modelling

PRESENTER PROFILE

Graham Macky holds a Master's degree in Civil Engineering from Canterbury University, and researched river mechanics and sediment transport for 11 years at NIWA. Prior to that he worked at the Central Laboratories of the Ministry of Works & Development (MWD) designing and operating physical scale models of river flow problems. Graham also worked for one year within MWD on water resource policy.

Graham moved to Auckland in 1999 to work on stormwater management and stormwater modelling. He was also at the Auckland Regional Council for five years, where he developed stormwater management best practice for minimising stormwater runoff and stream channel erosion and capturing urban contaminants. Graham joined DHI's Auckland office in late 2009, where his role includes specifying, building and operating hydrological catchment models, one- and two-dimensional models of river and overland flow, and sediment transport modelling. .

1 INTRODUCTION

1.1 STORMWATER TREATMENT PONDS

Stormwater Treatment ponds are settling ponds designed to remove sediment from urban runoff. In Auckland, their design is specified in Auckland Regional Council (ARC) (2003) (commonly referred to as TP10), and the intent is to remove 75% of the incoming sediment load on a long-term basis.

The ponds are usually also designed to provide other stormwater management benefits: reduction of flood risk by providing flood storage volume above the treatment pond, and reduction of channel erosion downstream by allowing the slow release of treatment pond water.

The design stormwater treatment capability is provided more or less independently of these other design goals. ARC (2003) requires a design volume of pond (effectively a design runoff depth) with a restriction on pond depth. .

Photos 1 and 2 show examples of operational stormwater treatment ponds in the Auckland region.

Photo 1: Example of a Long Narrow TP10 Pond

Photo 2: Example of an Oval Shaped TP10 Pond

1.2 PROJECT BRIEFS

In 2006 the Auckland Regional Council engaged DHI to model performance of stormwater treatment ponds. This was an unusually small-scale deployment of the software, which is more normally used to model marine areas. It performs 3-dimensional computations of flow and mud transport module within a flexible computational mesh.

The goal was a better understanding of the factors that will determine how these ponds perform. In particular, the study addressed pond shape, the use of baffles to redirect flow, and pond volume relative to storm runoff volume. The capture of different size fractions was investigated.

In 2011, ARC commissioned DHI to model the long-term performance of rectangular stormwater treatment ponds designed according to ARC (2003), to determine their stormwater treatment efficiency over a full year. This long-term pond efficiency, defined as the fraction of suspended sediment that is captured by the pond over 1 year, is a more direct measure of the environmental benefits than the steady-state efficiencies determined earlier.

Simulations with reduced pond volume were to be included, as it is sometimes necessary to build a smaller pond, particularly when retro-fitting a pond in an existing stormwater network. The pond configuration was otherwise to be kept constant.

2 METHODOLOGY FOR STEADY STATE SIMULATIONS

2.1 OVERVIEW

Various pond geometries were modelled using DHI's MIKE 3 Flexible Mesh hydraulic modelling software, including its Mud Transport module. The first set of simulations, in 2009, applied a steady inflow until steady state pond conditions were reached.

The modelled ponds have an area of roughly 650m^2, and are represented by triangular mesh elements about 1-1.5m^2 in area. There are 5 vertical mesh layers, making for a mesh of roughly 2500 elements.

In order to obtain robust data for comparing pond configurations, simple steady-state conditions were sought that would represent well the range and overall effect of conditions that exist during runoff events. Some simplifying assumptions were therefore necessary:

- Inlet and outlet structures modelled by source and sink points that are submerged throughout the simulation.
- A constant inflow rate.
- A constant inflow sediment concentration

The (steady-state) treatment efficiency E is given by:

$$E = (1\text{-}C_o)/C_i$$

where C_o is the outflow sediment concentration and C_i is the inflow sediment concentration).

This efficiency is the final or steady-state fraction of inflowing sediment captured by the pond, and differs from the flow-integrated efficiency for a finite runoff event.

The model was run with an initially clear pond, long enough to ensure that steady-state conditions were obtained. Simulation of five hours of stormwater inflow was found to achieve this. At present (2015), using a 20s time step, these model runs take ten minutes on a standard laptop computer.

The bathymetry for the ponds modelled was set up using a mesh generator. Care was taken to create a mesh that was regular and detailed enough to define the shape of the pond well, while keeping the grid size reasonable. This task is easier with the artificial regular shaped ponds that were modelled than with more complex shapes.

2.2 PRELIMINARY MODELLING TO DETERMINE REPRESENTATIVE CONDITIONS

A range of flow rates, from 50% to 200% of the design peak runoff, were modelled using the five different settling velocities identified by ARC (2003) as being representative of urban stormwater sediment (Table 1). Analysis of these model runs led to a value of 74% for the overall treatment efficiency of the optimum pond (which is identified in Section 3.1 below).

Table 1 Design Settling velocities (after ARC (2003))

Case	Settling Velocity		Note
	(cm/hr)	(m/s)	
A	0.9	2.5E-06	
B	9.1	2.53E-05	
C	46	0.000128	Chosen as RSV (refer below)
D	210	0.000583	
E	2,000	0.005556	

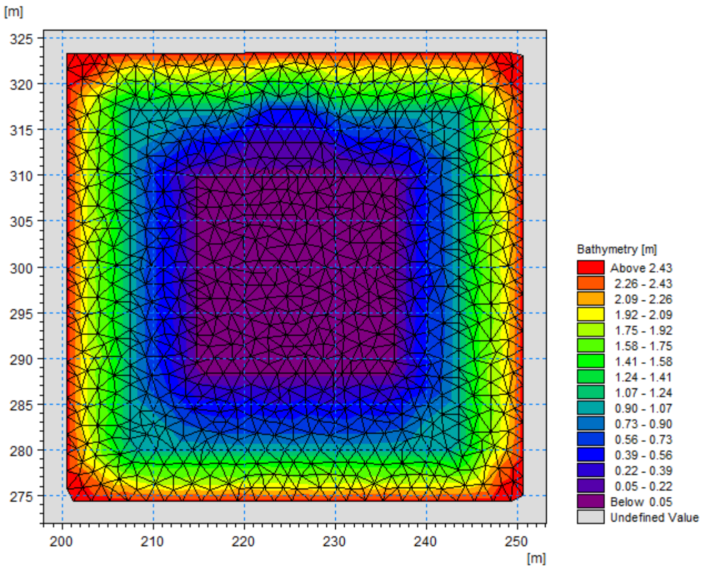
From these model runs, a settling velocity of 46cm/hour (the middle of the five representative values) was chosen as the representative settling velocity (RSV) to model with the design runoff in assessing different pond configurations. For this settling velocity and stormwater flow rate the design pond's treatment efficiency is 49%. This efficiency is considerably lower than the overall efficiency of the pond (calculated to be 74%) but this choice of RSV provides a good comparison between different pond configurations.

2.3 SIMULATION OF DIFFERENT POND CONFIGURATIONS

Modelling was undertaken to quantify the relative performance of different configurations of stormwater treatment pond. The base case for this comparison was the most commonly used rectangular pond geometry.

First, the effect of aspect ratio was investigated for rectangular ponds, and the most efficient aspect ratio (which was found to be 4:1 length:width) was adopted as the base case. Figure 2-1 shows the computational mesh used for a 1:1 (square) pond.

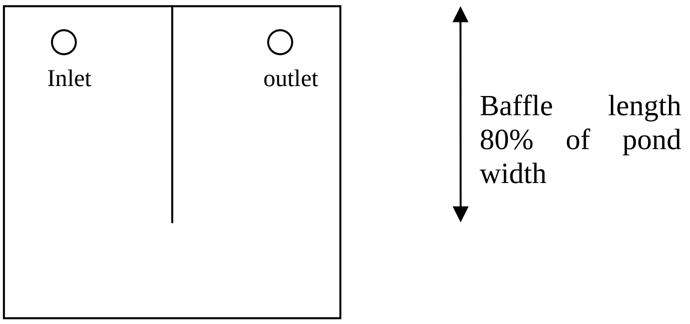
Figure 2-1 Bathymetry and computational mesh for square treatment pond



Second, the efficiency of other pond designs was investigated: rectangular ponds with baffles, and circular, L-shaped and trapezoidal shaped ponds. The efficiency of each of these ponds was compared these with that of the “optimum” rectangular pond.

Figure 2-2 is a plan of the baffle applied to a square treatment pond, including the inlet and outlet locations.

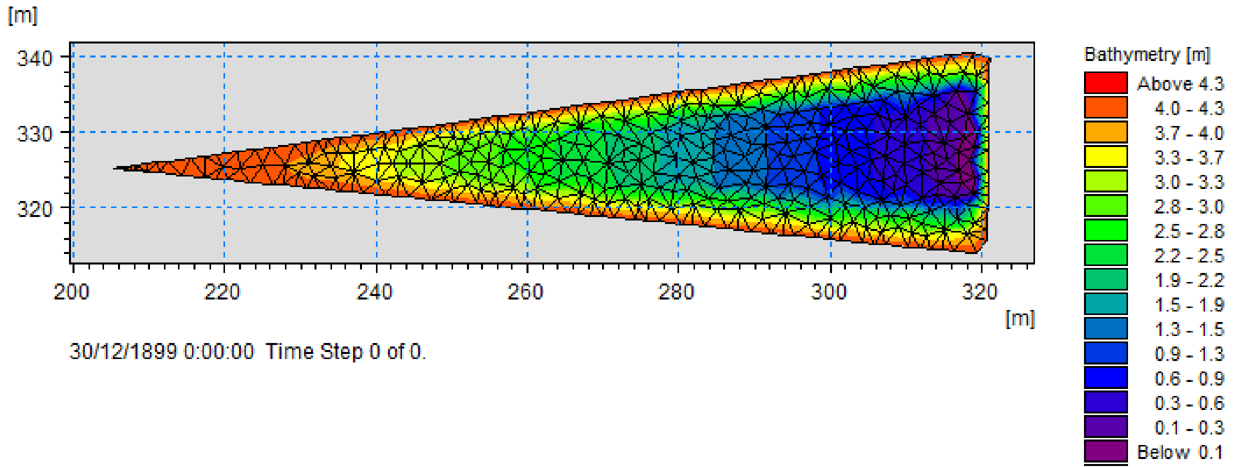
Figure 2-2   : Baffle Arrangement for 1:1 (Square) Pond



The bathymetry for an L-shaped pond is similar to the rectangular equivalent apart from the right-angle bend.

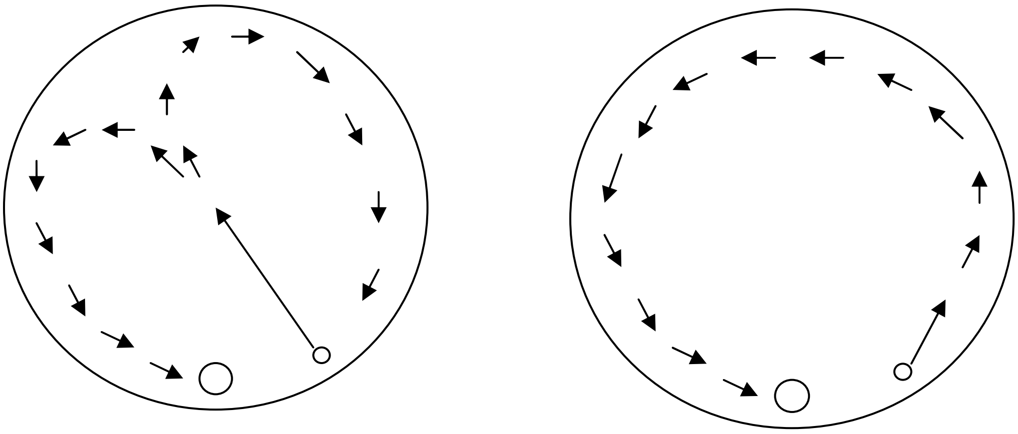
The bathymetry and computational mesh adopted for a trapezoidal pond are shown in Figure 2-3. The trapezoidal form, deeper at its outlet, can easily be constructed in a natural gully.

Figure 2-3   Bathymetry and computational mesh for deep trapezoidal treatment pond



Two different inlet geometries were modelled for the circular pond, and are illustrated in Figure 2-4:

Figure 2-4   Inlet and outlet configurations for modelled circular ponds: inlet directed radially inward (left) and inlet directed close to tangentially (right)

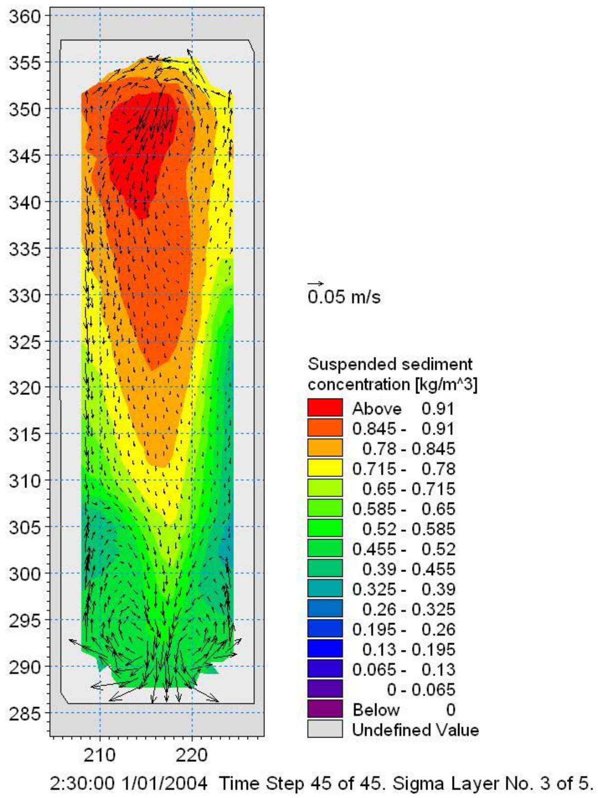


3 RESULTS

3.1 RECTANGULAR PONDS

ASPECT RATIO:
An aspect ratio of 4:1 gave highest treatment efficiencies; the efficiency for the design flow and the RSV was calculated to be 49% The pattern of flow and suspended sediment even for this planform is not ideal, showing some asymmetry, with reverse flows near the inlet and outlet (Figure 3-1) shows velocity vectors in the mid-depth layer).

Figure 3-1 Plan View 4:1 Aspect Ratio: Suspended sediment concentration and flow vectors at mid-depth.



Higher aspect ratios (i.e. longer, narrower ponds) are only slightly less efficient, and the flow pattern is qualitatively the same as in the 4:1 pond (Figure 3-2). In contrast, ponds with lower aspect ratios are significantly less efficient, and the computed velocity vectors indicate two circulation cells with reverse flow along the sides of the pond. The square pond of Figure 3-3 is perhaps an extreme example.

Figure 3-2   Plan View 7:1 Aspect Ratio: Suspended sediment concentration and flow vectors at mid-depth.

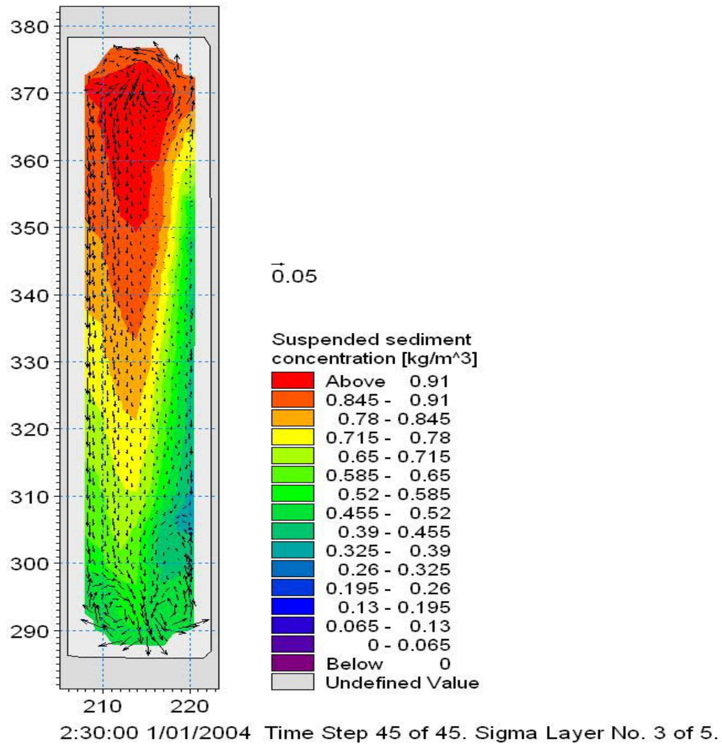
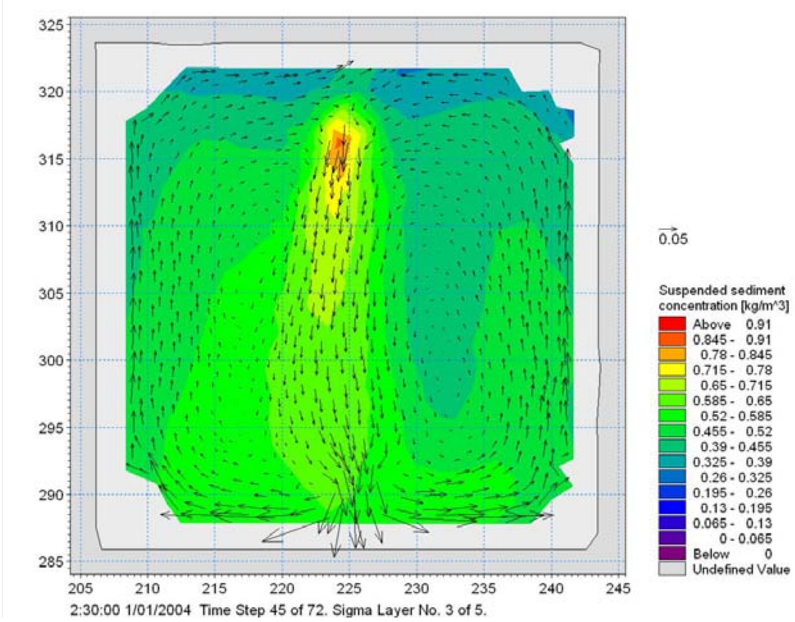


Figure 3-3   Plan View 1:1 Aspect Ratio: Suspended sediment concentration and flow vectors at mid-depth.



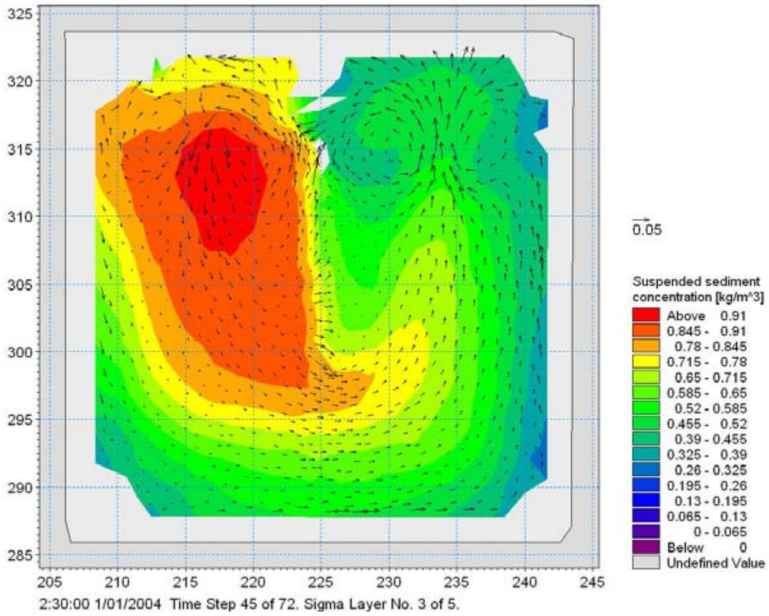
3.1.1 USE OF BAFFLES TO IMPROVE TREATMENT EFFICIENCY

Including one or more baffles in a pond with low aspect ratio, with appropriate repositioning of the inlet and outlet, generally gave treatment efficiencies better than the same pond without baffles.

One example is presented, a square pond with one baffle (Figure 3-4). Its computed treatment efficiency is 45.3%, closer to that of the optimum pond

(48.3%) than the simple square pond (38.1%). The baffle has made the pond more hydraulically like a pond of aspect ratio 2:1, and there are no “dead areas” or circulation cells between the inlet and the outlet.

Figure 3-4 Square pond with 1 Baffle. Suspended sediment concentration and flow vectors at mid-depth.



3.2 OTHER POND SHAPES

CIRCULAR PONDS

The circular ponds modelled had the inlet and outlet 20 degrees apart. Model runs revealed that the efficiency of these circular treatment ponds is dependent on the direction of the inflow. Figure 3-5 shows the mid-depth velocity vectors and sediment concentration for an inlet directed towards the centre of the pond, and Figure 3-6 is the equivalent graph for inflow directed close to tangentially around the pond’s edge. The respective treatment efficiencies for the RSV are 23.9% and 14.6%, both well below the 48.3% modelled for the optimum 4:1 rectangular pond.

The reason for this poorer performance is evident in Figure 3-5 and Figure 3-6: in both cases circulation cells are established, leaving the centres of these cells playing little part in the settling process.

Figure 3-5 Round Pond; Inlet 20 degrees from outlet, pointing radially inwards. Sediment concentration and velocity vectors at mid-depth.

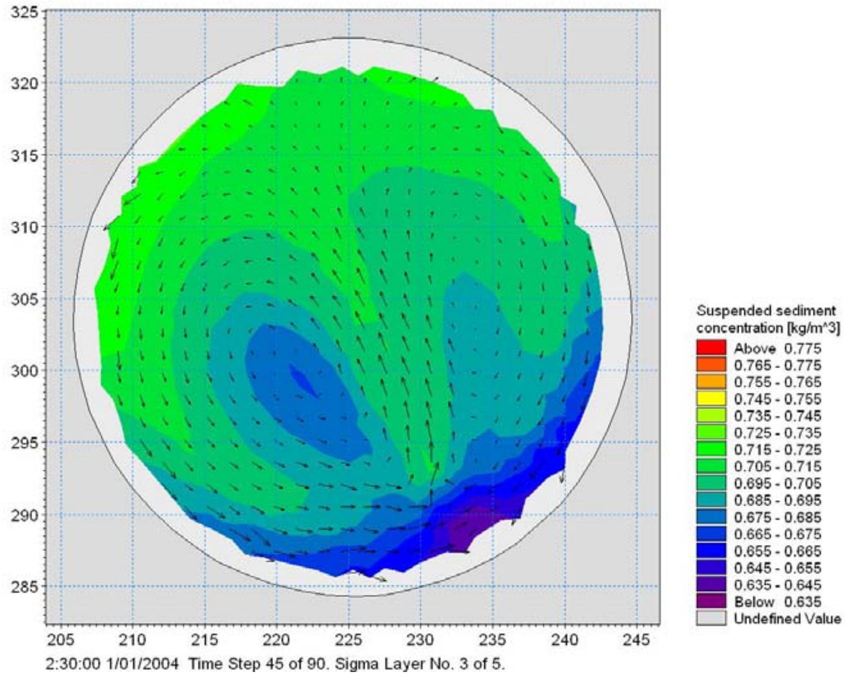
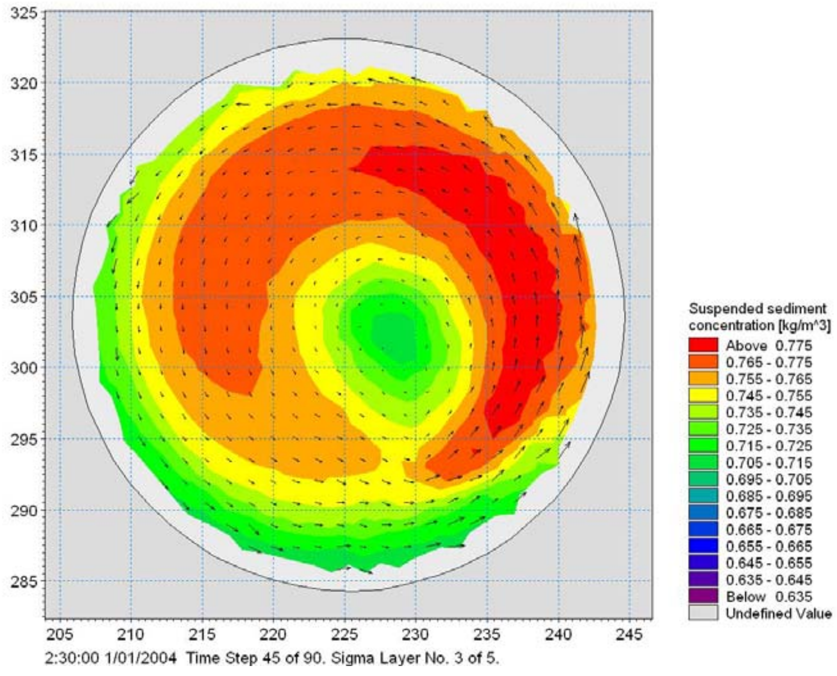


Figure 3-6 Round Pond; Inlet 20 degrees from outlet, pointing 30 degrees from tangent. Sediment concentration and velocity vectors at mid-depth

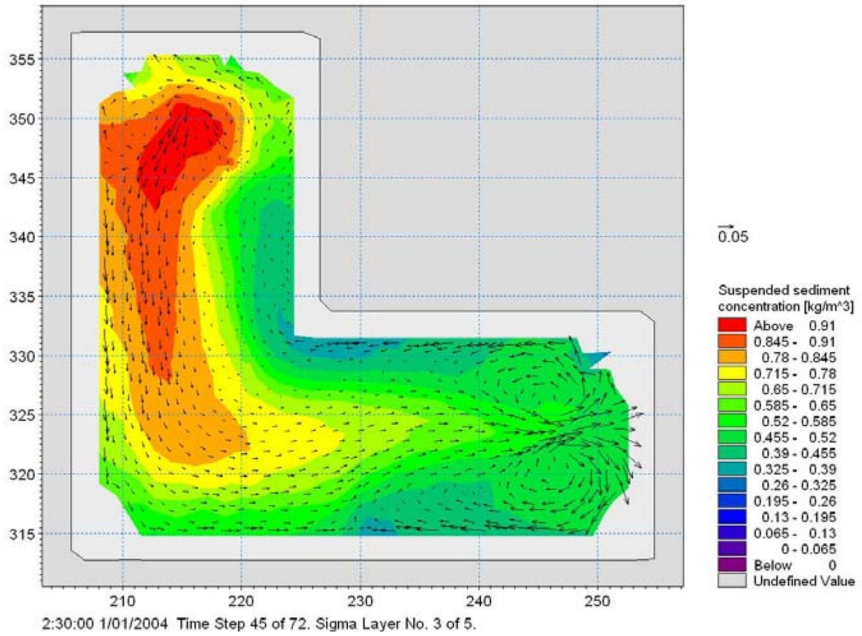


L-SHAPED PONDS

Modelling results show that L-shaped ponds are nearly as efficient in capturing sediment as the equivalent straight rectangular pond.

Figure 3-7 shows the mid-depth velocities and sediment concentration for an L-shaped pond that is otherwise identical with the optimum 4:1 rectangular pond. From visual comparison of Figure 3-7 with Figure 3-1, the asymmetry of flow that might be ascribed to the bend is comparable to the asymmetry evident in the straight channel. Consistent with this comparison, the computed treatment efficiency for the RS is 46.7%, only slightly less than the 48.3% of the optimum pond.

Figure 3-7 L-shaped pond, 4:1 aspect ratio. Sediment concentration and velocity vectors at mid-depth

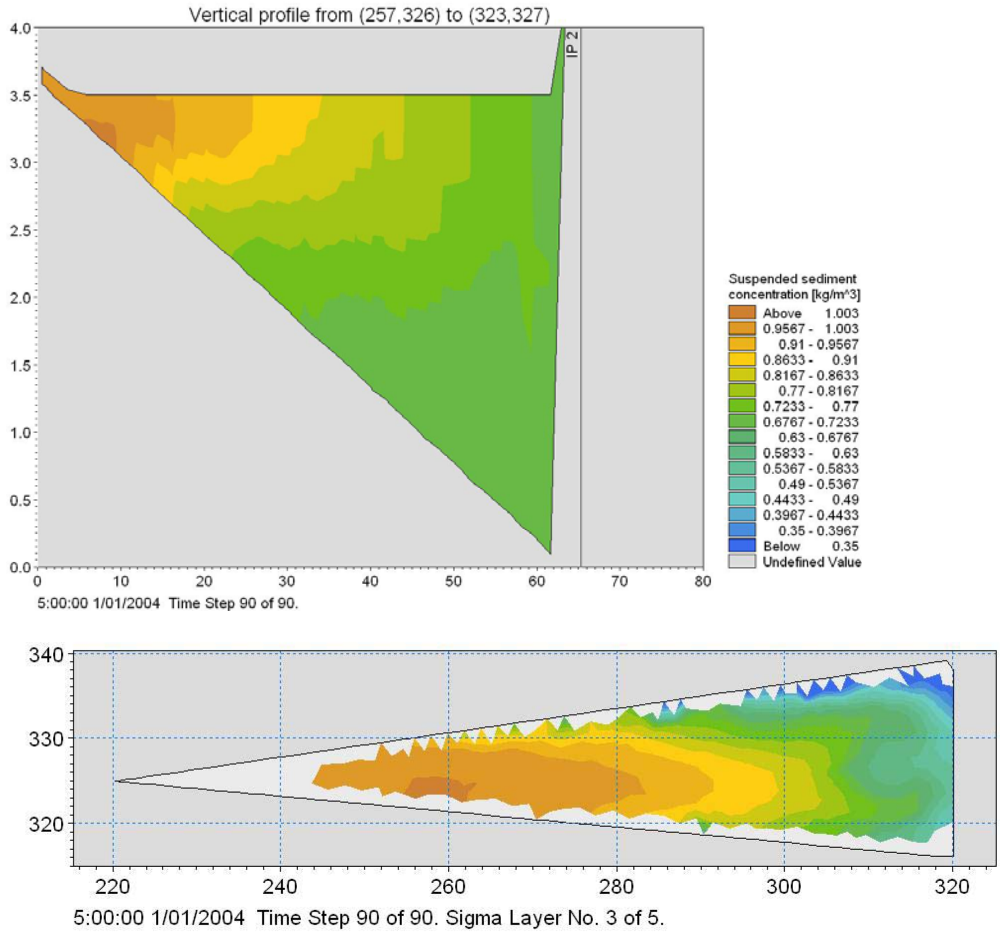


TRAPEZOIDAL PONDS

The model runs showed that the treatment efficiency of a trapezoidal pond depends strongly on the particular geometry. Mid-depth sediment concentration and a vertical profile of sediment concentration are shown in Figure 3-8 for a deep trapezoidal pond (4m depth at the outlet). This pond's computed treatment efficiency is 36.5%, but other shallower designs (not presented) have higher efficiencies close to the 48.3% of the optimum pond.

The reason for the poorer performance is evident in the vertical profile. As sediment is carried towards the outlet, its settlement velocity if not high enough to take it closer to the sloping bed, so that the water nearest the bed has the lowest sediment concentration.

Figure 3-8 Sediment concentration in a deep trapezoid Pond: Plan at mid-depth and vertical profile.



4 SIMULATION METHODOLOGY FOR LONG-TERM MODELLING

The general modelling approach and the software used were the same for the year-long simulations as for the earlier steady-state simulations.

4.1 POND GEOMETRY

The ponds include a forebay, separated from the main pond by a weir just 0.3m below outlet weir level. The “design” pond (Figure 4-1) has an area of roughly 1700m^2, and are represented by triangular mesh elements about 1.5m^2 in area. There are again 5 vertical mesh layers, but for this model the vertical layer boundaries are set at fixed elevations (Figure 4-3) so that lower layers have fewer cells altogether. The mesh thus has very roughly 4000 elements (somewhat more than the meshes used for the steady state simulations).

The original mesh was scaled to get meshes for 2 smaller ponds (20% and 50% volume reduction), retaining the same pond depth. This results in steeper batters in the smaller ponds, a detail which is unlikely to significantly affect pond efficiency.

Figure 4-1   Design stormwater treatment pond for long-term simulations

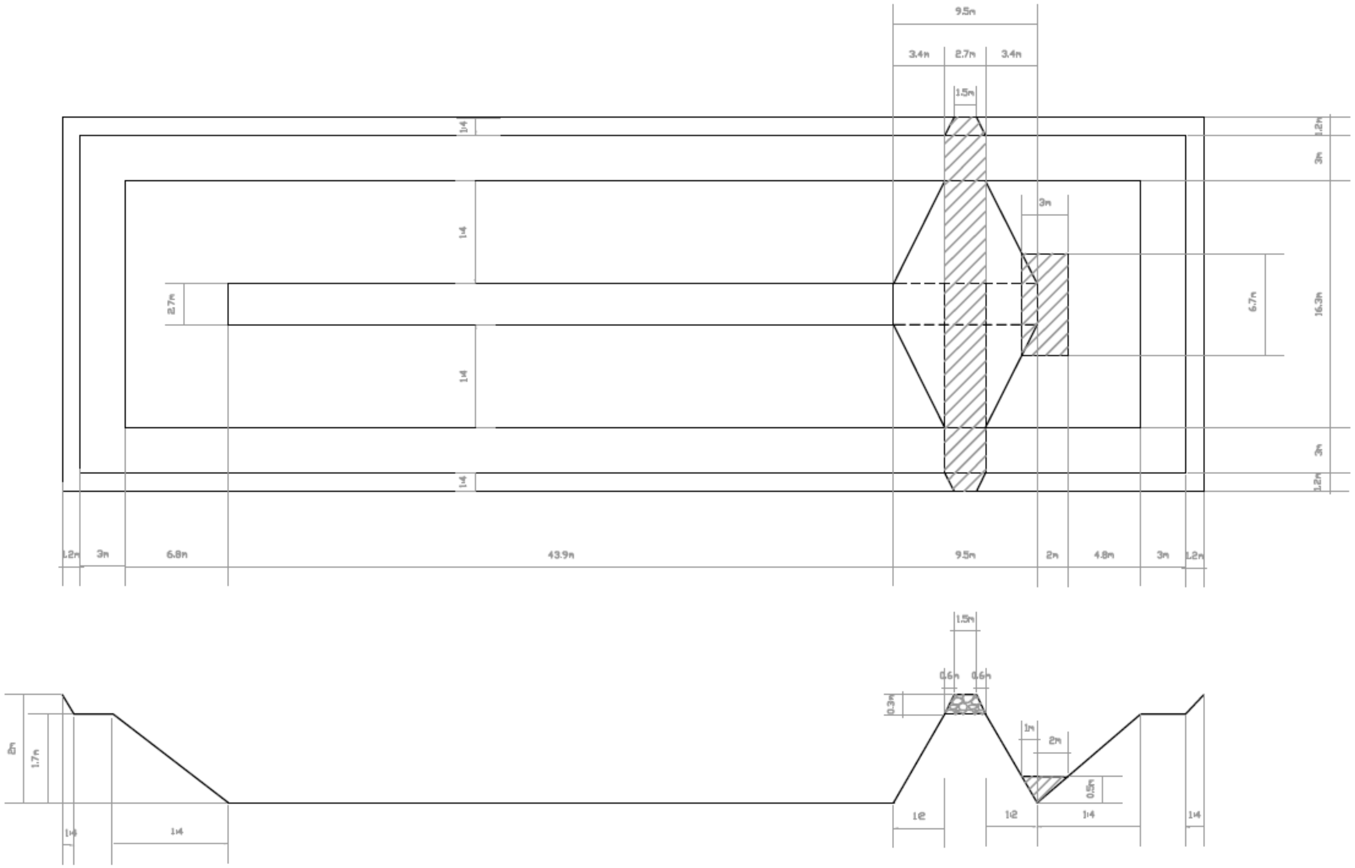


Figure 4-2 Bathymetry and computational mesh for pond detailed in Figure 4-1.

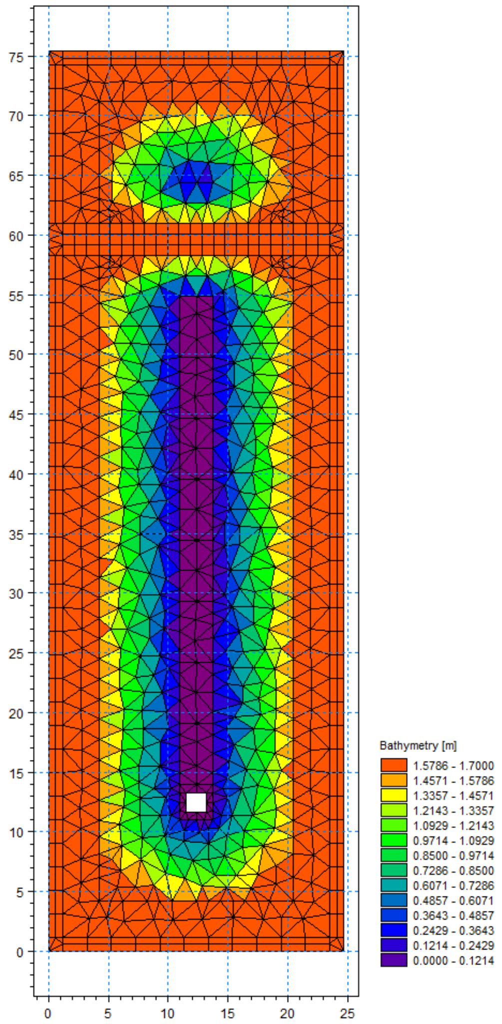
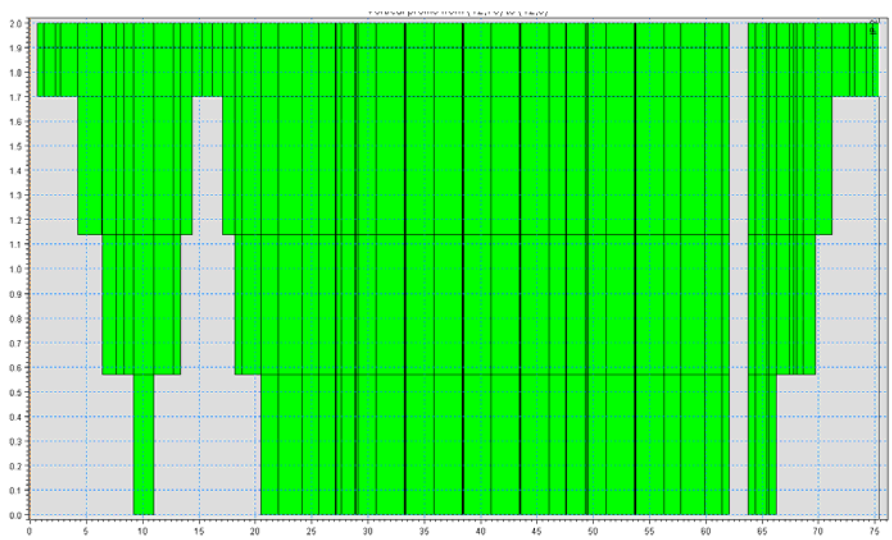


Figure 4-3 Longitudinal profile of the pond model shown in Figure 4-2. The inlet (in the top layer) is at far left, and the outlet structure can be seen on the right at 63m.



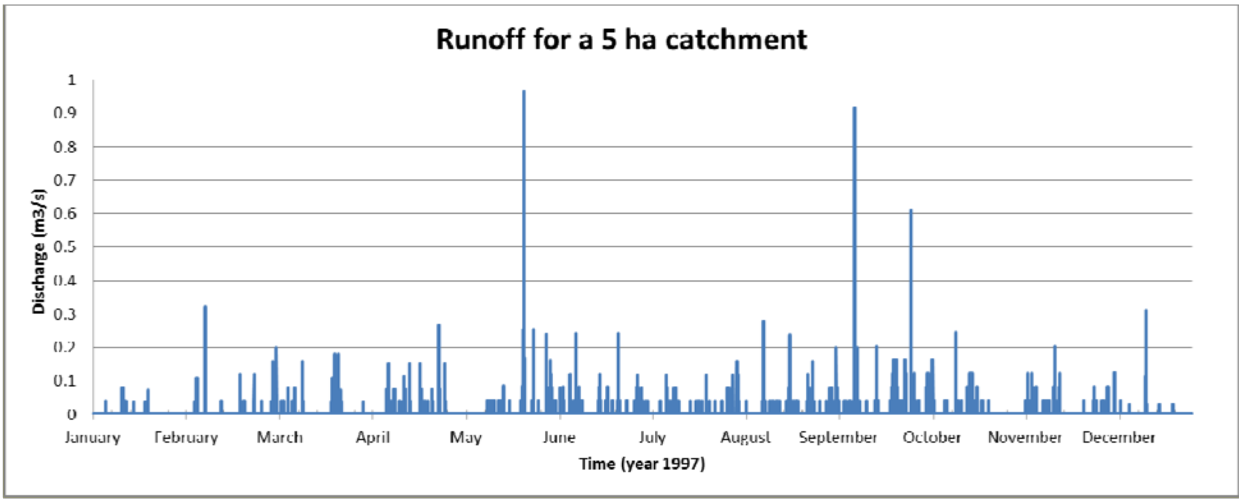
4.2 HYDROLOGY AND HYDRAULICS

The inlet is modelled as a source located in the upper layer at left in Figure 4-3. This source is thus higher than the mid-depth source modelled in the steady-state runs, but still fully submerged during the whole simulation. A (horizontal) velocity straight into the pond is specified, representing the inflow emerging from a 0.8m culvert, so that the velocity is proportional to the inflow rate.

In contrast to the steady-state models, the outlet shape is included in the model. The outlet water level is held constant at Reduced Level 2.0m, and a numerical sink nearby ensures that the outflow is always comparable to the inflow (with only minor changes in the stored water volume). The pond water level will generally be slightly higher than RL 2.0m, which is also the level of the pond's berms, and the water is then contained by vertical "glass walls".

The pond design (Figure 4-1) is for a 5ha urban catchment, for which the computed runoff hydrograph for the year 1997 is shown in Figure 4-4.

Figure 4-4 Runoff hydrograph for 1997 from a 5ha urban catchment



4.3 SEDIMENT TRANSPORT, DEPOSITION AND RE-SUSPENSION

The 2011 modelling included 8 size fractions of sediment (Table 2), many of them quite coarse compared to the RSV of 46 cm/hour applied in the above steady-state modelling.

Table 2 Modelled Sediment Characteristics

Modelling fraction ID	AC particle size (micro m)	Model Settling velocities (m/s)	Percentage of total load	Total mass (kg)	Concentration at inlet (g/m3)
1	<1	8.29E-07	2.6%	68	1.14
	1 - 4				
2	5 - 6	1.14E-05	4.8%	128	2.14
	7 - 8				
	9 - 10				
3	11 - 25	3.47E-04	9.5%	251	4.18
4	26 - 40	1.07E-03	7.0%	186	3.10
5	41 - 45	1.62E-03	7.0%	185	3.08
	46 - 50				
6	51 - 100	8.01E-03	45.4%	1204	20.09
7	101 - 125	1.43E-02	13.2%	351	5.85
8	126 - 150	1.78E-02	10.4%	277	4.62

With significant flows being passed through the modelled pond at times, the conditions for sediment deposition and for re-suspension (i.e. erosion) must be defined. For the threshold below which deposition can occur, the default shear stress of 0.07 Pa is used. A critical shear stress of 0.1 Pa for re-suspension is applied throughout.

4.4 CHALLENGES WITH LONG-TERM SIMULATIONS

Several practical difficulties arose in carrying out the year-long simulations:

NUMERICAL INSTABILITIES

With a wide range of flow conditions to be modelled, it is perhaps not surprising that instabilities caused the simulation to fail on occasions. These instabilities were resolved in two ways. First, the outlet details described in Section 4.2 were decided on following the failure of simulations using more literal representation of the outlet. Second, it was possible to restart the model after the failures, and the results present in Section 5.1 have been aggregated from several simulations of a few months each.

ELAPSED TIME OF SIMULATIONS

The one-year simulations each required a long time even using a dedicated "run machine". Improving computer specifications have brought simulation times down, but indications are that each run would still take several days on a laptop computer,

The choice of mesh was influenced by the long simulation times. A finer mesh would be likely to provide more accurate results and to avoid some of the numerical instabilities that occur with the present mesh.

RESIDUAL VELOCITIES

It was noticed for times when there had been no inflows for several days that the velocity data included eddies that showed no signs of diminishing over time. It is not known whether these eddies are realistic or an artifice of the numerical configuration. Their velocities are very small by most measures, but are sometimes significant when settling of the finer fractions of sediment is considered. Until their presence can be explained, predictions of settling of these finer fractions must regarded as approximate only.

5 RESULTS FROM LONG-TERM MODELLING

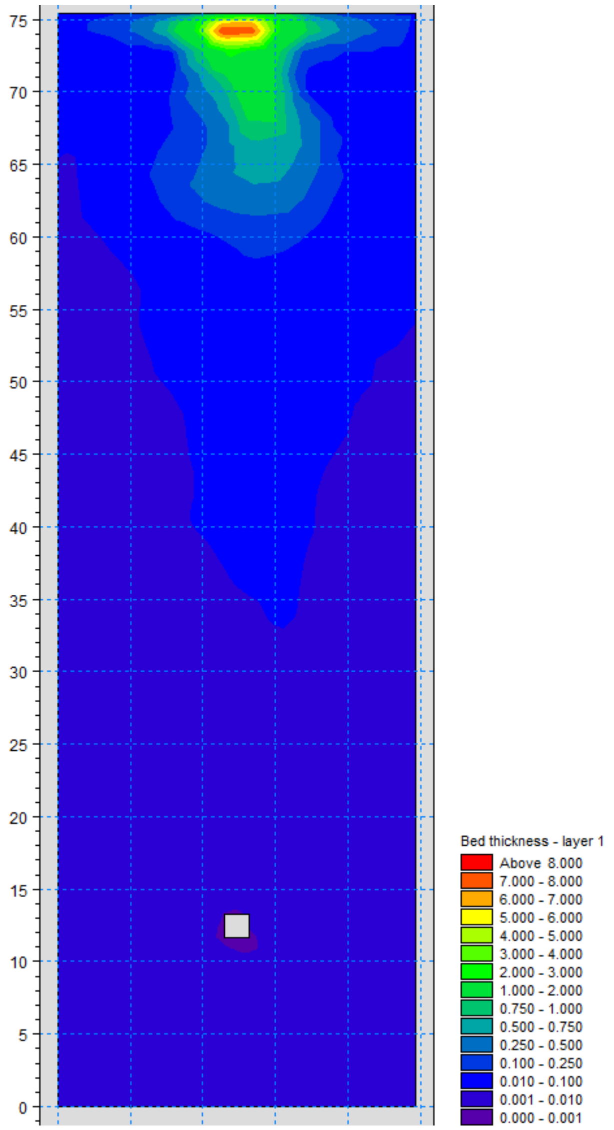
5.1 LONG-TERM TREATMENT EFFICIENCY AND PATTERN OF DEPOSITION

Modelling for the full 1997 year gave the resulting pattern and depth of deposition, for the different settling velocities. The finer fractions, including settling velocities of 8.5 cm/hour and 125 cm/hour, provide a meaningful comparison with the steady state modelling (which adopted the RSV of 46 cm/hour).

Post-processing of these depositional data allows a long-term treatment efficiency to be computed for each settling velocity and for an overall treatment efficiency to then be computed. These calculations are not presented in the present paper, as they need to be carefully interpreted in the context of the particular choice of settling velocities and of the year of inflow data. A separate paper is warranted.

Figure 5-1 shows the pattern of final deposition for the design pond and for a settling velocity of 8.5 cm/hour.

Figure 5-1 Final sedimentation (in cm), design pond, settling velocity 8.5cm/hour



6 CONCLUSIONS AND RECOMMENDATIONS

6.1 STEADY STATE MODELLING

Three-dimensional modelling of hydraulics and mud transport has been able to satisfactorily simulate the settling of stormwater-borne suspended sediment, and quantify the sediment capture efficiency of a range of pond configurations.

The optimum aspect ratio for rectangular ponds was found to be 4:1. However, even in this pond the modelled velocity pattern was not ideal.

Some pond configurations have treatment efficiencies significantly lower than the optimum configuration, this study identifying circular and square shapes as well as a deep trapezoidal pond.

In all cases, it was identified that increasing the pond volume fully mitigates the relatively poor performance. In addition, adding an impermeable baffle to the square pond (with repositioned inlet and outlet) was shown to significantly improve its efficiency.

6.2 LONG-TERM SIMULATIONS

Long-term three-dimensional modelling of treatment pond hydraulics and mud transport has been carried out to determine the overall treatment efficiency over a year. This modelling also determined the pattern of deposition, including how much material is captured in the forebay.

Long-term simulations are still not straightforward, however, if the present example is typical. There were difficulties with numerical instability, and the runs take a long time, difficulties that were overcome with persistence. There were also residual velocities in quiescent periods long after inflows had ceased. These remain unexplained at present, and cast doubt on the model output for the finest sediment fractions.

Nevertheless, long-term simulations are practicable enough to provide valuable validation of steady-state or single-event simulations, and to assist in understanding deposition patterns and planning pond maintenance.

6.3 RECOMMENDATIONS FOR FURTHER MODELLING

Modelling of untested or unusual pond configurations as described in this paper is recommended, to determine the treatment efficiency and (where the efficiency is significantly below optimum) to test design alterations.

Further model simulations could provide valuable information on the "lifetime" performance of various treatment pond designs. These simulations might include:

- Inflow hydrographs from typical or design rainfall events, rather than the steady flow modelled in this study. These simulations should include a post-event period of at least a day as flows recede and settling continues.
- Pond configurations with purposes additional to treatment: extended detention (i.e. slow release) and /or flood detention.
- The effect of wind

- The effect of a temperature difference between pond water and inflowing runoff.

- The effect of captured sediment: the pattern of bed aggradation and its effect on treatment efficiency.

- Different inflow configurations, in particular inflow into different levels (at the water surface and near-bed, compared to the mid-depth inflows assumed in the present study.

A limited number of long-term simulations of representative or standard designs are recommended to assist interpretation of short-term simulations for generally similar pond configurations. These representative designs should include any significant departure from present pond designs.

ACKNOWLEDGEMENTS

Funding for these projects from the Auckland Regional Council is gratefully acknowledged.

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