Chapter 21

Circulation and Water Quality Model for Stormwater Ponds

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A two-dimensional vertically averaged hydrodynamic model has been adapted to compute the circulation and sedimentation patterns in a proposed stormwater detention pond. The model had previously only been used in applications with grid lengths greater than about 50 m and time steps of a minute or more. This application has shown that the model can be used with grid sizes of 5 m or less and a time step of 1 second. The model is an improvement over existing plug flow models based on a series of constantly stirred tank reactors that cannot compute circulation patterns. The model can identify areas in the pond where short-circuiting and dead zones occur. Sedimentation, based on first order decay, was computed and the rates were highest in areas of the pond where water transport speeds were the smallest.

21.1 Introduction

Stormwater detention ponds have gained increasing popularity as management tools for control of the quality of runoff. Current predictive models for estimating removal of settleable pollutants and for developing sizing guidelines represent a settling pond as a sequence of completely-mixed compartments (sometimes referred to as constantly stirred tank reactors, or CSTRs). These

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models rely on assumptions about hydraulic mixing and dispersion conditions within the pond that may not always be valid. Therefore, CH2M Gore and Storrie Limited (CG&S) developed a hydrodynamic circulation model that can compute the water movement in stormwater ponds due to hydraulic forcing, bathymetry, shoreline geometry and wind stress. The transport of conventional pollutants, decay of bacteria and settling of suspended material can also be simulated with the model which is based on the two-dimensional vertically averaged equations of momentum and continuity for estuaries and shallow waters. The model thereby provides explicit representation of internal pond hydraulics and does not rely on any assumptions that the flow regime is “plug flow” or completely mixed.

The model can be applied to a proposed stormwater pond design. The computed circulation patterns provide visual evidence of how effective the pond design is in minimizing dead zones, eliminating short circuiting and providing sufficient time for the settling of solids or decay of bacteria. This model would also be effective in designing sedimentation forebays for ponds. Different settling rates of suspended particles can be accounted for by providing the gradation of the suspended solids in the flow. Therefore, the rates of accumulation of the different sized particles can be simulated in the model. This provides a method to determine the maintenance requirements for pond operation.

The advantage of a dynamic model over the more conventional plug flow or CSTR type models is a more accurate representation of the flow pattern which governs where and how fast settling will occur. A multi-CSTR model cannot adequately represent the variable bathymetry and shoreline geometry that controls the circulation patterns. The effect of flow obstructions (islands for habitat development), deep zones for velocity equalization and channelization cannot be properly represented with a plug flow or CSTR model.

21.2 Hydrodynamic Model Formulation

The model is based on the work by Dr. Jan Leenderste and the Rand Corporation which developed the original model for the Jamaica Bay Estuary in New York City, New York. The model was further developed for the Delta Works in the Netherlands. CH2M Hill's staff have been involved in the application and upgrading of this particular model for over fifteen years. Several contracts for the Ontario Ministry of Environment & Energy (MOEE) in the 1980s were responsible for porting the program from a mainframe environment to the present form running on PCs. Graphics and some menu features were also developed at that time.

For two-dimensional flow in well-mixed conditions such as estuaries and shallow lakes, vertical integration of the momentum and continuity equations yields the following basic equations for the hydrodynamic model (as found in Leendertse, 1970 and 1971):

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV + g \frac{\partial \xi}{\partial x} + \frac{\tau_x^b}{\rho H} - \frac{\tau_x^w}{\rho H} - k \left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) = 0 \quad (21.1)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU + g \frac{\partial \xi}{\partial y} + \frac{\tau_y^b}{\rho H} - \frac{\tau_y^w}{\rho H} - k \left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) = 0 \quad (21.2)$$

$$\frac{\partial \xi}{\partial t} + \frac{\partial (HU)}{\partial x} + \frac{\partial (HV)}{\partial y} = 0 \quad (21.3)$$

where:

- f = Coriolis parameter (1/s)
- g = acceleration of gravity (m/s²)
- H = $h + \xi$ (m)
- k = momentum dispersion coefficient
- h = water depth at datum (m)
- ξ = water elevation above datum (m)
- τ_x^w, τ_y^w = wind stress component in the x, y direction (g/m/s²)
- τ_x^b, τ_y^b = bottom stress component in the x, y direction (g/m/s²)
- ρ = water density (g/m³).

The momentum dispersion term in Equations 21.1 and 21.2 were added during the upgrading by Leendertse.

The wind stress components are:

$$\tau_x^w = \Phi \rho_a w^2 \sin \psi, \quad \tau_y^w = \Phi \rho_a w^2 \cos \psi$$

where:

- Φ = wind stress coefficient, usually = 0.0026
- ρ_a = density of air (g/m³)
- w = wind velocity (m/s)
- ψ = angle between the wind direction and the x axis

The bottom stress components are:

$$\tau_x^b = \rho g U \frac{\sqrt{U^2 + V^2}}{C^2} \quad \tau_y^b = \rho g V \frac{\sqrt{U^2 + V^2}}{C^2}$$

where:

$$C = \text{Chezy Coefficient (m}^{0.5}/\text{s)}.$$

The Chezy coefficient C is determined at each grid point from:

$$C = \frac{1.49}{N} H^{\frac{1}{6}}$$

where:

$$N = \text{Manning's } N$$

Land points are specified with a zero (0) Chezy value. Values for Manning's N are specified at each grid point. N is either constant throughout the grid or varied depending on the specific conditions of each grid point. Smooth sand or flat bottoms will have a different bottom roughness than heavy aquatic growth or boulder strewn bottoms. Most bottom conditions can be represented with this method. In addition, the Chezy coefficient can be recalculated at specified time periods to account for variable water depths due to flooding or drying of the grid points.

In the finite difference approximation of Equations 21.1, 21.2, 21.3 the discrete values of the variables are described on a staggered grid as shown below.

k+2	+	-	+	-	+	-	+	-	+	+	water level ξ and
		o		o		o		o			mass density ρ_A
k+1	+	-	+	-	+	-	+	-	+	o	water depth h
		o		o		o		o		-	U velocity
k	+	-	+	-	+	-	+	-	+		V velocity
		o		o		o		o			
k-1	+	-	+	-	+	-	+	-	+		
	j-2	j-1		j		j+1	j+2				

where the x direction is represented by the j index and the y direction is represented by the k index. The water level ξ and mass density ρ_A are computed at integer values of j and k , while the values of h , obtained from hydrographic charts and field surveys, are given at half-integer values of j and k . The velocities U are computed at half integer values of j and integer values of k , while the velocities V are computed at half-integer values of k and integer values of j . The solution of these equations in time is based on the split time formulation.

The sequential use of the finite difference approximation to the momentum and continuity equations results in the use of the spatial derivatives alternatingly forward and backward. Thus, over a whole time step the use of this procedure results in terms that are either central in time or averaged over that time interval.

The numerical solution of the finite difference equations presented above using the structure described has been shown to lead to stable solutions in both time and space (Leenderste, 1970, 1971).

The basic mass balance equation for two dimensional transport of a water quality parameter can be expressed as:

$$\frac{\partial(HP)}{\partial t} + \frac{\partial(HUP)}{\partial x} + \frac{\partial(HVP)}{\partial y} - \frac{\partial(HD_x \frac{\partial P}{\partial x})}{\partial x} - \frac{\partial(HD_y \frac{\partial P}{\partial y})}{\partial y} + [K]HP + HS = 0 \quad (21.4)$$

where:

$$P = \frac{1}{H} \int_{-h}^{\xi} \rho_A dz \quad (21.5)$$

- ρ_A = mass density of substance A (g/m³)
 D_x, D_y = dispersion coefficients in x and y direction (m²/s)
 S = source or sink discharge (g/m³/s)
 $[K]$ = kinetic reaction array (1/s)

The basic model, which is available from the MOEE, was developed to provide simulations of areas on the Great Lakes at scales much larger than typical stormwater ponds. Most applications of the model have a grid size of at least 100 m and a time step of about a minute or more. It was not known if the model could be used with smaller scales on the order of a meter. However, after developing this application, the model's robustness is proof that the original formulation is sound and can be applied over a wider range of length and time scales than previously thought.

21.3 Hydraulic Connectivity of Stormwater Ponds

Stormwater ponds are hydraulically connected by some type of control structure. These may consist of a weir, a submerged orifice, a pump or some other type of mechanism. The aim of the present model development was to develop a method of simulating the hydraulic connection.

CG&S had simulated the dynamics of a two cell water supply reservoir by a simple system of sources and sinks. The two reservoirs were mechanically linked by three large diameter pipes equally spaced along adjacent walls. In the model the three inlets of the supply reservoir were simulated as sinks with a negative discharge and the three outlets coming into the second reservoir were simulated as sources with a positive discharge. The water level in each cell was identical due to the hydraulic connection and was maintained throughout the simulation. The model was able to simulate the flow pattern in the reservoir with this configuration and continuity was preserved.

The stormwater pond model was set up with four source/sink connections (more connections can be implemented). The model simulates a discharge by calculating the resulting water elevation increase in the grid point due to the increase in the volume of the cell. A grid point has an initial water depth of h with a fluctuating water elevation of ξ resulting in a final depth of $H = h + \xi$. If a grid point has a source of flow of strength $S = 1 \text{ m}^3/\text{s}$ then the change in volume over a time step Δt of say 1 second is 1 m^3 . The change in ξ is 1 m^3 divided by the area of the grid point which is the square of the grid size Δx . So for a 5 m grid size ξ changes by $1/5^2$ or 0.04 m in one time step.

During each time step the water elevation in the four connecting grid points was monitored and when the elevation exceeded a set level of H which represented the top of the weir then flow between the ponds commenced. A broad crested weir equation was used to determine the volume of water to remove from the upper pond-sink cell and to add the same volume to the lower pond source cell. Other types of structures could be substituted for the control of the flow between the ponds. These could be water level dependent such as submerged orifices or pumps with variable rates depending on the water level.

21.4 Sediment Removal

The primary purpose of stormwater ponds is removal of pollutants accomplished by sedimentation. Other processes such as bacteria die-off and algal and aquatic plant uptake of soluble nitrogen and phosphorous reduce the level of pollutants in the pond effluent.

Bacteria die-off is modeled as a first order decay process. The MOEE model has been used extensively in the past to simulate the bacteria levels in receiving waters. These studies have resulted in the construction of two large detention tanks at the City of Toronto Eastern Beaches and Toronto's Western Beaches has a detention tunnel in design.

Sedimentation of suspended solids (SS) is also modeled as a first order decay process as:

$$C = C_0 e^{\left[\frac{-v_s}{Q/A} \right]} \text{ or } C = C_0 e^{(-kt)} \quad (21.6)$$

where :

- v_s = settling velocity of particles (m/s)
- Q/A = rate of applied flow divided by surface area of pond (m/s)
- k = v_s/h (1/s) and h = average depth of pond (m)
- t = residence time or in dynamic conditions time in pond (s)
- C_0 = initial concentration of stormwater influent (g/m^3).

The settling rate of the SS, k , was set to 0.00005 which is equivalent to 98.6% removal over a period of 24 hr. The model has the ability to simulate several different species of pollutants with independent settling rates. However, only one pollutant is simulated in this trial.

The new model was tested on a proposed two-cell pond. The bathymetry of the pond which varied from 0.3 m to 1.6 m was digitized on a 5 m square grid. The bottom of the pond is mainly flat with the shallow areas predominating. Deep zones are aligned across the pond perpendicular to the flow and are designed to

equalize the flow and promote settling because of the slower advective velocities. Two islands were created in the larger lower pond for habitat. The model area is shown in Figure 21.1.

Figure 21.1 Geometry and layout of proposed two-cell model.

A hydrograph was generated from land use characteristics and rainfall records and was used as the inflow to the two pond system. The hourly flow rates are provided in Table 21.1.

The SS levels for the runoff event are included in Table 21.1. The pond is wet with a base flow of about $0.06 \text{ m}^3/\text{s}$. The model was allowed to stabilize for two hours before introducing the runoff event. The water level of the upper pond was set to the weir height and consequently there was continuous flow over the weir.

Table 21.1 Hydrograph and pollutograph for test case.

Hour	Flow (m^3/s)	Suspended Solids (mg/L)
0	0.06	20
1	0.085	60
2	0.118	110
3	0.140	310
4	0.145	1410
5	0.139	1110
6	0.107	1310
7	0.095	510
8	0.087	310
9	0.081	210
10	0.074	110
after 10 hours	0.06	20

The time step of the model was 5 seconds. The Courant condition, the standard method to verify the time step, is:

$$\Delta t < 2.5 \Delta x / (gh)^{1/2} \quad (21.7)$$

where:

$$\begin{aligned} \Delta x &= \text{grid size (5 m)} \\ g &= \text{acceleration of gravity (9.81 m/s}^2\text{)} \\ h &= \text{maximum depth of water (1.5 m).} \end{aligned}$$

The Courant condition determines the time step to be 3.25 s or less. However, the model has a second order advection scheme that allows the Courant condition to be exceeded. Some models have exceeded the Courant condition by a factor of more than five.

The flow pattern at the base flow is shown in Figure 21.2. A period during the peak inflow from the storm event is shown in Figure 21.3. The velocity vector is the standard method for expressing the concept of speed and direction. In hydrodynamic models the velocity vector is essential for observing the currents simulated by the model. Usually the length of arrows are relative to some upper speed to provide sufficient resolution of the vectors. Our standard is to break the range of speeds into three categories and display the arrows in different colours so as to identify areas of high speed, average speed and slow speed water movement. Arrows with a fourth or fifth colour can identify speeds either above some threshold or below it. For the black and white presentation the arrow thickness has been varied and a gray scale used.

The two ponds have been split in the figure in order to provide better resolution. The upper pond is shown above the lower pond. In the figure the inlet to the weir in the upper pond is at the left side and the outlet from the weir is on the right side of the bottom pond.

The figure shows where there are deep spots by the darker bands of thin arrows which are the slowest speed category. The slow speed zones will also have the most settling of SS. The shallow areas have higher speeds and are shown with lighter arrows, particularly in the bottom pond between the two islands. Pond designers can use information on water speeds to modify the pond shape and bathymetry to optimize the operation of the pond. Resuspension of previously settled solids may occur in certain areas of a pond that have water speeds that are too high. Other areas in a pond may have speeds that are too slow and SS may build up and alter the shape of the pond or affect the circulation. Dead zones and short circuiting can be easily identified with this type of graphic information.

The concentration of SS is shown in Figures 21.4 and 21.5 about 6 hours after the start of the storm event. The plume has moved through the upper cell and is about half-away across the lower pond. The concentration levels have been

Figure 21.2 Velocity vector plot of circulation pattern during base flow conditions. Peak velocity is only 0.35 cm/s.

Figure 21.3 Velocity vector plot of circulation pattern during storm flow conditions. Peak velocity is over 13 cm/s.

set low to observe the plume in the lower pond in Figure 21.5. The units of concentration are mg/L. The upper pond has concentrations ranging from 10 mg/L to 100 mg/L at this period in the simulation. The lower pond has SS concentrations ranging from 5 to 50 mg/L. The concentration gradient in the lower pond is due to both advection and sedimentation. As the plume moves through the lower pond SS are being removed from the water column. In addition the SS laden water flowing over the weir is further diluted with the existing water in the pond that is much cleaner due to a long residence time. The upper pond has the high SS levels because the residence time in the pond is relatively short (6 hr or less) and sedimentation has not reduced the levels of SS.

The highest inlet concentration of SS was 1,400 mg/L as shown in Table 21.1. The model computed the concentration of SS at the outlet of the lower pond to be less than 1.0 mg/L. This is a reduction of over 1400 and illustrates the potential effectiveness of stormwater ponds in reducing the level of pollutants in stormwater runoff.

Sediment accumulation was calculated by summing the amount of SS that was computed to settle during each time step in every active grid point. Sedimentation will remove a percentage of the mass in a grid point equal to k which has units of s^{-1} , therefore in one time step the mass removed from the water column is:

$$M = (\Delta x)^2 (h + \xi) C k \Delta t \quad (21.8)$$

where:

- M = mass removed (g)
- Δx = grid size (m)
- h = water depth at datum (m)
- ξ = water depth above datum (m)
- C = concentration of SS in grid point (g/m^3)
- k = sedimentation rate (s^{-1})
- Δt = time step (s)

For example if the concentration of SS in a grid point is 100 gm/m^3 , the time step is 5 s, total water depth 1 m, k is $0.00015/s$ and the grid size is 5 m then the amount of SS that settles in a time step is $M = 1.875 \text{ g}$.

Figures 21.6 and 21.7 show the accumulation of SS in the ponds after 20 hours from the start of the storm event. The units are grams of SS in each 5 m grid. The upper pond has SS accumulation amounts ranging from 1500 g/grid or 300 g/m near the inlet to 100 g/m at the outlet weir. In the bottom pond, the banding shows the effectiveness of the deep sections. The SS amounts in the lower cell range from 0.2 g/m to over 10 g/m.

At this point in the development of the model sediment build up does not affect the water depth. This aspect of pond dynamics can be implemented if the particles are sufficiently coarse to form a solid bottom layer and bind with the

Figure 21.4 Suspended sediment levels 6 hours after start of storm event. Concentrations range from 100 mg/L to 10 mg/L in upper cell.

Figure 21.5 Suspended sediment levels 6 hours after start of storm event. Concentrations in the lower cell range from less than 1.0 mg/l to 50 mg/L.

Figure 21.6 Accumulated Sediment patterns about 20 hours after the storm event. Concentrations in upper pond range from 1500 gm/5m to 500 gm/5m.

Figure 21.7 Accumulated sediment patterns about 20 hours after the storm event. Concentrations in lower pond range from 50 gm/5m to 1 gm/5m.

existing surface material. The finer particles will require longer periods to consolidate and consequently the impact of this component of the SS can be ignored in short simulations.

The pond used in the model has not been built so there are no data to calibrate or verify the model predictions. Detailed SS build up rates or measurements of currents in ponds would be required to validate the model predictions.

21.5 Conclusions

A stormwater pond model has been developed that can simulate dynamic water circulation, pollutant concentration and sedimentation patterns. The model can be used to determine the effectiveness of the pond in reducing the concentration of pollutants. Modifications to the pond in terms of bathymetry, shoreline geometry and inlet-outlet configurations can be made before construction.

The model computed the suspended solids outlet concentration to be less than 1.0 mg/L which was over 1,400 times smaller than the maximum inlet concentration of 1,400 mg/L.

Sedimentation was computed to occur in areas of slowly moving water.

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