Changing the Stormwater Pond Design Game
Changer le mode de conception des bassins de rétention

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RÉSUMÉ
Actuellement, la conception des bassins de rétention focalise sur l’atténuation volumétrique des débits d’entrée des eaux d’orage afin de protéger les canalisations aval contre les surcharges. Bien que les bassins d’orage (rétention) soient en mesure d’assurer correctement cette fonction, les mouvements et le mélange des eaux dans les bassins d’orage sont mal compris, tout comme le sont les mécanismes dominants qui déterminent la qualité de l’eau. Nous présentons une étude conceptuelle comparant les caractéristiques de rejet des bassins d’orage traditionnels avec celles d’un nouveau concept de bassin d’orage appelé Bassin Nautilus. Les résultats de simulations numériques de la dynamique des fluides montrent qu’un bassin d’orage traditionnel a tendance à se « court-circuiter » au cours d’un événement pluvieux significatif, ce qui a pour résultat un mauvais rendement de traitement des eaux de pluie et le largage dans l’environnement d’agents contaminants. La comparaison montre qu’un bassin Nautilus est moins sensible au risque de « court-circuit » au cours d’un même événement pluvieux grâce à une meilleure approximation de l’écoulement piston. L’efficacité du bassin Nautilus vient de l’utilisation d’un flux entrant périphérique en spirale vers et au travers de l’orifice central. Les caractéristiques clefs de conception sont discutées pour permettre au flux en spirale souhaité de se développer passivement et sans intervention humaine même lorsque les flux entrants d’eau de pluie sont des événements fortement transitoires. La conception modulaire d’un bassin Nautilus est discutée car elle est liée à leur mise en œuvre sur des sites contraints ou discontinus où les conceptions traditionnelles de bassins d’orage sont particulièrement susceptibles au « court-circuitage » et à la formation de zones mortes.

MOTS CLÉS
Environnemental, modélisation, bassin d’orage, eau

ABSTRACT
Current stormpond designs focus on volumetric attenuation of peak stormwater inflow rates to protect downstream pipes from surcharging. Though stormponds can perform this function effectively, water movement and mixing within stormponds is poorly understood as are the dominant mechanisms determining water quality. A conceptual study is presented comparing discharge characteristics of traditional stormpond designs against a new stormpond design called the Nautilus Pond. Results from computational fluid dynamics simulations show that a traditional stormpond design is prone to short-circuiting during a significant stormwater inflow event thus resulting in stormwater treatment inefficiencies and the potential for early environmental releases of contaminants. A Nautilus Pond is comparatively shown to mitigate against short circuiting during the same inflow event by achieving a better approximation to plug flow. The effectiveness of a Nautilus Pond comes from the use of a perimeter inflow spiraling toward and flowing out through a central outlet. Key design features are discussed that enable the desired spiral flow pattern to develop passively and without human intervention even though stormwater inflows are highly transient events. The modular design of a Nautilus Pond is discussed as it relates to implementation in constrained or discontinuous sites where traditional stormpond designs are particularly susceptible to short-circuiting and dead zone formation.

KEYWORDS
Environmental, modeling, pond, storm, water
1 INTRODUCTION

The art of stormwater pond design has been evolving over the past 30 years with a primary focus on temporarily impounding stormwater runoff to mitigate against surcharging in storm trunk pipes downstream from the pond. Current stormpond designs are able to very effectively provide such volumetric attenuation protection to downstream pipes and can do so with little need to consider the shape of the pond other than to achieve a volumetric storage target.

Current best management practices (BMP) for stormpond design make some attempt to consider water quality issues. However, the effectiveness of stormwater treatment depends not only on having an available receiving stormpond water volume but also on the details of how inflowing stormwater flows and mixes within the pond. Stormponds typically are water bodies subjected to the elements that receive their inflows via highly transient stormwater runoff events. Though all stormponds provide a certain level of treatment for inflowing water, the lack of knowledge regarding internal flow and mixing dynamics has hindered the evolution of performance-based stormpond designs beyond assumptions founded on the simplest of water treatment reactor design concepts.

Like many other jurisdictions, the Canadian Province of Alberta is moving toward a Total Loading Management (TLM) approach to the regulation of stormwater quality. A TLM approach requires that municipalities manage the total load of sediment and other environmental constituents generated within municipal boundaries for eventual discharge to a receiving environment. For municipalities to sustainably allow for population growth within a TLM approach, it is necessary to develop and test promising new stormwater pond designs that may be able to provide enhanced stormwater treatment performance above that possible using current BMP designs. The objective of this paper is to conduct a conceptual computer modeling study on a new set of simple yet focused design elements capable of mitigating against the two major stormwater pond flaws of short circuiting and dead zone formation.

1.1 Traditional Stormpond Designs

1.1.1 Geometry

A typical stormpond design currently implemented in North America is one that includes a forebay cell (left side of Figure 1.1) and a larger settling cell (right side of Figure 1.1) where the two cells may be separated by a submerged berm. The colour shading shown in Figure 1.1 represents depth (in metres) beneath the permanent water surface elevation and the secondary grey contour lines represent 0.5 m elevation contours. A centreline section of the stormpond is shown in Figure 1.2.

The stormpond forebay is intended to receive inflowing water and gently pass it to the settling cell. The settling cell is expected to provide an appropriately quiescent environment suitable for sediment to
settle out of suspension. The stormpond outlet (represented by the triangular shaped object located at the extreme right side of the settling cell in Figure 1.1) is typically located as far away from the inlet as is practical to permit a generally long flow path. The inlet and outlet shown in Figure 1.1 are each represented as an internal triangular shaped boundary that occupies the full water column. The inlet boundary permits water to enter only perpendicular to the right facing boundary segment while the outlet boundary permits water to leave from any point on the boundary.

2 METHODS

2.1 Water Balance

A water balance analysis is simple and reliable when restricted to considering the effect of volumetric attenuation since the pond need only be treated as a storage facility. Spreadsheets and hand calculations are sufficient to generate the analysis results since details regarding the manner in which water flows through a pond need not be considered.

2.2 Flow and Mixing Within A Stormpond

If one seeks to use a stormpond to provide some level of water treatment in addition to volumetric attenuation, the manner in which water flows and mixes throughout a pond is important. In the case of this paper, intrapond flow and mixing were modeled using the two dimensional depth averaged finite element computational fluid dynamics (CFD) modeling package River2D and River2DMix.

The River2DMix software solves the two-dimensional depth averaged advection diffusion equation applied over a flow field solution generated by River2D. River2D solves the St. Venant equations developed from the depth-integrated Navier-Stokes equations (Ghanem 1995). Both River2D and River2DMix utilize a Bossinesq type eddy viscosity formulation for turbulent shear stress ($\tau$) such that

$$\tau_{xy} = \nu_x \left( \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right)$$

where $x$ and $y$ represent spatial coordinates, $U$ and $V$ respectively represent the local depth averaged velocities in the two coordinate directions and $\nu_x$ is the local eddy viscosity given by

$$\nu_x = \nu_2 \frac{h(U^2 + V^2)}{C_s} + \nu_3 h^2 \sqrt{2 \left( \frac{\partial U}{\partial x} \right)^2 + \left( \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right)^2 + 2 \left( \frac{\partial V}{\partial y} \right)^2}$$

where $\nu_2$ and $\nu_3$ represent user definable calibration coefficients, $h$ is the local flow depth and $C_s$ is the dimensionless Chezy coefficient given by

$$C_s = \frac{1}{\kappa} \ln \left( 12 \frac{h}{k_s} \right)$$

where $\kappa$ is Von Karmen's constant and $k_s$ is the equivalent sand grain roughness of the bed. All River2D and River2DMix simulations detailed in this paper were executed with $\nu_2 = 0.13$ and $\nu_3 = 0.1$ and with the local value of $k_s = 0.1$ m wherever the permanent water depth was greater than 0.5 m and $k_s = 5.0$ m wherever the permanent water depth was less than 0.5 m or the surface was dry at the start of the simulation. The intent of varying bed roughness in this manner was to give a first
approximation to the naturally high flow resistance created by long grasses and reeds in the normally
dry or shallow portions of the pond versus the generally much lower flow resistance in the permanently
deep portions of the pond where sediment accumulation is expected. Since this paper is presenting
the results from a conceptual CFD study, no calibration data is available and the authors have made
no attempt to vary the eddy viscosity calibration coefficients or the bed roughness values beyond the
values reported above.

3 RESULTS AND DISCUSSION

3.1 Traditional Stormpond

3.1.1 Water Balance

When a storm event occurs over the catchment area draining to a stormpond, water enters the pond
(commencing from no inflow in Figure 3.1 at a model time of 1.1 hours) and rapidly rises to a very high
inflow rate as shown by the green line in Figure 3.1. After a rapid rise in inflow rate, inflow
hydrographs also typically show a rapid fall in the inflow rate to a moderate level that then gradually
diminishes. The simulated outflow hydrograph for the pond is shown as a red line in Figure 3.1 and
illustrates the volumetric attenuation effect of the stormwater pond where the outflow does not exceed
1 m³/s even though the inflow rate reaches 6 m³/s. This significant benefit with regard to attenuating
the flow delivered to downstream storm trunk pipes is the primary reason that stormponds are
constructed today.

The blue and black lines in Figure 3.1 respectively represent the cumulative total volume of water that
has entered and the cumulative total volume of water that has exited the stormpond. At any given
time, the difference between the blue and black lines represents the storage volume above the
permanent water level that is temporarily impounded in the stormpond.

Typical design criterion applied in Alberta calls for a maximum active variation of 2.0 m in the water
surface elevation in response to a 1:5 year 24-hour storm event. The maximum active volume of
water stored in the pond (approximately 6,780 m³) raises the water surface elevation in the Figure 1.1
pond by approximately 1.5 metres thus the inflow hydrograph shown in Figure 3.1 represents a
significant inflow event. The total volume of water under the inflow hydrograph (approximately
15,500 m³) is more than three times greater than the resident volume of water (approximately
5,050 m³ as shown by the blue dashed line) in the pond prior to the storm event.

![Figure 3.1. Water balance for traditional stormpond during a significant stormwater inflow event](image)

3.1.2 Flow and Mixing Within a Stormpond

Figure 3.2 illustrates the finite element mesh that was used in the traditional stormpond simulation
plotted over a colour map of bed elevation (in metres). A total of 8169 nodes were included with the
highest mesh density deployed in the immediate vicinity of the forebay area where largest gradients of
velocity were anticipated.
Figure 3.2. Finite element mesh used for the traditional pond simulation

Figure 3.3. Simulated distribution of velocity and concentration for a traditional stormpond design

Figure 3.3 shows the distribution of velocity (indicated by vectors) and concentration of inflowing stormwater (shown by colour in units of ppm) at an intermediate time during a stormwater inflow event. All stormwater entering the pond does so with a constant concentration of 10 ppm thus solid yellow colours represent undiluted inflowing storm water whereas solid blue colours represent water that was resident in the pond prior to the start of the storm event. The displayed inflow and outflow rate respectively correspond to that given by the green and red lines in Figure 3.1 at a model time of 1 hour 41 minutes and 10 seconds. The complex flow patterns in Figure 3.3 are only a snapshot of the system where the large eddy structures are rapidly changing and dynamically interacting in a process that causes rapid entrainment and mixing with resident water. Given that the resident water was already treated, the high level of mixing between resident and new stormwater results in treatment inefficiencies since previously treated water should be retreated prior to discharge.
Figure 3.4 shows the simulated temporal outlet concentration as a blue line, the total volume of water discharged from the pond as a black line and the volume of resident water that has been discharged as an orange line. Values for the orange line were computed based on the dilution of inflowing water that entered the pond at a constant concentration of 10 ppm. For example, if the average outlet concentration is 7.0 ppm from a model time of 1.6 hours onward, 30% of the water discharged after a model time of 1.6 hours was resident prior to the storm event. The simulated fluctuations in outlet concentration result from eddies with varying concentration sweeping past the outlet.

For an ideal pond with perfect plug flow, the orange line in Figure 3.4 would follow the black line until the approximate simulation time of 3.0 hours is reached when all of the resident water (approximately 5050 m³) is discharged. The outlet concentration would be zero until all the resident water is discharged at which time the outlet concentration would change to a constant value of 10 ppm. The more prone a pond is to short-circuiting the earlier, and to a greater degree, will the outlet concentration rise from zero. Based on the simulation results, the traditional pond appears to be prone to short-circuiting since it exhibits an early and large increase in simulated outlet concentration that causes the orange line to trace a path significantly below the black line. As a result, less than 50% of the resident water volume has been flushed two hours after the storm event started.

Figure 3.4. Simulated traditional stormpond temporal outlet concentration and resident water volume discharged

3.2 Proposed Pond Design

3.2.1 Geometry

Figure 3.5 shows a conceptual layout for a stormpond called the Nautilus Pond (trademark and patent pending) with nearly identical bulk characteristics (i.e. overall footprint area, stage storage curve, etc.) as the traditional stormpond shown in Figure 1.1. Figure 3.6 shows a centreline bed profile comparison between a Nautilus Pond and the traditional stormpond shown in Figure 1.1. The inlet shown in Figure 3.5 is represented as an internal triangular shaped boundary that occupies the full water column. The inlet boundary permits water to enter only perpendicular to the right facing boundary segment. The outlet shown in Figure 3.5 is represented as an internal octagonal boundary that occupies the full water column. The outlet permits water to leave from any point on the boundary.

Unlike traditional pond designs, a Nautilus Pond typically introduces stormwater near the pond perimeter and, in the case of an approximately circular pond, in a generally tangential manner. The intent of the island berm shown in Figure 3.5 is to confine the inflowing water during the high inflow rate portion of the inflow hydrograph so that a general circulation pattern can be established in a controlled manner by displacing resident water. Once the inflow hydrograph peak has passed, the desired general circulation pattern should be well established thus the berm may be submerged. The authors anticipate that other design elements, such as the intentional placement of flow resisting vegetation communities, can also be applied to beneficially reinforce intended circulation patterns.

Spiral flow clarifiers have been applied in water and wastewater treatment industries, however, clarifiers in those industries operate under relatively steady flow conditions and are constantly monitored and managed by operations staff using an assortment of pumps, mixers, valves and
chemical injection systems among other equipment. In contrast, a stormwater management pond is rarely monitored in any way or actively managed. Furthermore, all inflow to a stormpond typically arrives via an inflow hydrograph characterized by having a very high but brief peak inflow rate and essentially no inflow at all for time scales ranging from hours to weeks between storm events.

Figure 3.5. Nautilus Pond depth (in metres) beneath the permanent water surface elevation

Figure 3.6. Centreline bed elevation section comparison between a traditional pond and a Nautilus Pond

3.2.2 Water Balance

By virtue of the fact that the Nautilus Pond shown in Figure 3.5 has a stage-storage curve that is very similar to the Figure 1.1 pond, using the same inflow hydrograph at the inlet and the same stage-discharge curve at the outlet yields a Nautilus Pond water balance that is essentially the same as that shown in Figure 3.1.

3.2.3 Flow and Mixing Within A Nautilus Pond

Figure 3.7 illustrates the finite element mesh that was used in the Nautilus Pond simulations. A total of 4826 nodes were included with the highest mesh density deployed in the immediate vicinity of the inlet pipe.

Figure 3.8 shows the distribution of velocity and concentration of inflowing stormwater in a Nautilus
Pond at an intermediate time during a stormwater inflow event. The model time, vector scales and colour legend scale in Figure 3.8 are presented in a manner consistent with Figure 3.3 to facilitate a direct visual comparison. As was the case for the traditional pond, all new stormwater entering the Nautilus Pond does so with a constant concentration of 10 ppm thus solid yellow colours represent undiluted stormwater whereas solid blue colours represent water that was resident in the pond prior to the start of the storm event. In contrast to traditional stormpond designs that tend to mix resident with inflowing water, the resident water in a Nautilus Pond tends to be displaced toward the central drain.

Figure 3.9 shows the same four lines as were presented in Figure 3.4 with the red and the green lines added to represent the comparative Nautilus Pond simulation results. When comparing the red and blue lines in Figure 3.9, the Nautilus Pond outlet concentration gradually increases as resident water is discharged in favour of retaining newly inflowing stormwater around the pond perimeter. When comparing the green and orange lines in Figure 3.9, it is not until a model time of almost two hours that the Nautilus Pond simulation results begin to deviate significantly from the perfect plug flow black line. For the first hour that each pond is responding to the storm event (i.e., between the approximate model times of 1.5 and 2.5 hours), the Nautilus Pond discharges from the outlet at significantly lower concentrations than the traditional pond design. After a model time of 2.5 hours the Nautilus Pond discharges at a slightly higher concentration than the traditional design.

Based on the above results, a Nautilus Pond is likely to be much more resistant to short-circuiting than traditional stormpond designs. In fact, from the moment stormwater begins entering each pond, it takes 2.5 hours for the traditional pond to discharge 50% of the resident water volume whereas flushing the same resident water volume takes only 1.5 hours for a Nautilus Pond. As a result, a Nautilus Pond should enable better overall stormwater treatment opportunities by providing generally longer stormwater retention given the same stormpond footprint area. Furthermore, the spiral flow of a Nautilus Pond is resistant to dead zone formation (except in local areas like the wake of islands) since the entire pond volume is generally flushed from the perimeter toward the central outlet.

Figure 3.7. Finite element mesh used for Nautilus Pond simulation
Figure 3.8. Simulated distribution of velocity and concentration for a Nautilus Pond

Figure 3.9. Simulation results summary comparison plot between a traditional and a Nautilus Pond
In most climates, small and frequent stormwater events (i.e., much smaller than the inflow event modeled in this paper) generate the majority fraction of total hydraulic and pollutant loading to receiving waters thus these events are referred to as water quality events. In Southern Alberta, 90% of the total runoff volume is generated by events equal to or smaller than the 1:2 year 3-hour storm event (AMEC, 2007). By preferentially discharging resident water to yield longer residence time for inflowing stormwater, a Nautilus Pond is likely to be particularly well suited to providing enhanced treatment for the multitude of low volume water quality events.

3.3 Further Discussion

3.3.1 Use of Depth Averaged Computer Modeling Tools

The use of depth averaged CFD analysis software may be inappropriate when the resident stormpond water exhibits density stratification or when the stormwater entering a pond does so at a different temperature than the resident water. In this paper, the cumulative volume of the modeled inflow hydrograph was three times the resident water volume in the receiving stormpond. The authors hypothesize that such significant stormwater inflow events enter a receiving stormpond with a sufficiently large total volume and energy that the inflow event generally overwhelms stratification effects. If the author's hypothesis tests true then there is value in applying depth averaged CFD tools for a conceptual study as presented in this paper. Future research efforts should include physical modeling, detailed monitoring programs in prototype stormponds and/or 3D CFD modeling to evaluate the significance of stratification effects on both traditional stormponds and on Nautilus Ponds.

3.3.2 Application in Challenging Sites

Large municipal expenditures are going toward retrofitting stormponds into areas where stormwater drainage infrastructure was constructed before it was common practice to incorporate stormponds into development plans. There typically are a limited number of sites where retrofit stormponds could be constructed and available sites are often constrained or, in extreme cases, may be discontinuous. Existing stormpond designs deployed in such challenging sites are particularly prone to short-circuiting and the formation of dead zones thus reducing the value of constructing a pond for the primary purpose of stormwater treatment. The Nautilus Pond design concepts detailed in this paper can be deployed in parallel and/or in series configurations where the outlet from one Nautilus Pond cell feeds into another cell. This type of design modularity could be effectively deployed in both conventional pond footprint areas or in very challenging locations that are highly constrained and/or discontinuous.

3.3.3 Beneficial Coriolis Effects

If, for whatever reason, an external event (i.e., such as the passing of a strong wind storm) induces unexpected flow patterns in a Nautilus Pond, Coriolis forces will act to eventually reestablish the intended general circulation pattern passively and without human intervention. It follows that the rotational direction of a Nautilus Pond should have the opposite sense if constructed in the southern hemisphere. Having a mechanism for reestablishing an intended circulation pattern in the event that it is upset is in contrast to traditional pond designs where no such mechanism is considered. For traditional stormponds, a passing wind storm event can induce flow patterns that may or may not positively contribute toward stormwater treatment or persist for an extended periods of time.

4 CONCLUSIONS

A CFD conceptual study was undertaken where the outlet concentration generated by a traditional stormpond design in response to a significant storm inflow event was compared to the outlet concentration generated by a newly proposed stormpond layout called the Nautilus Pond. The traditional stormpond was shown to be susceptible to short circuiting and resulted in a high degree of mixing between the inflowing water and water resident in the pond prior to the storm event. A Nautilus Pond was shown to be resistant to short circuiting by introducing stormwater at the pond perimeter and allowing it to spiral in toward a central drain. By inducing a controlled spiral flow path, the Nautilus Pond preferentially discharges resident water before the newly inflowing stormwater thus resulting in longer stormwater retention and better overall stormwater treatment opportunities.

LIST OF REFERENCES

AMEC Earth & Environmental (2007). Calgary Stormwater Quality Retrofits Level 1 Study. Submitted to the City of Calgary, Water Services, 2007