

Two Studies on Controlling the Outflow from Sediment Basins:

- 1) Developing Discharge Coefficients for
Circular Orifices in Round Riser Pipes, and**
- 2) Optimizing the Solid State Skimmer**

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Alex James McLemore

August 2012

Copyright © 2011 by Alex J. McLemore.

All rights reserved.

ACKNOWLEDGEMENTS

I would like to thank my major professor, Dr. John Tyner, for the time, patients, and guidance he has provided during my graduate work and especially during the completion of this thesis. I also thank my committee members, Dr. Daniel Yoder and Dr. John Buchanan, for their endless support and technical advising throughout my graduate work. Additionally, I thank Mr. Brent Pilon for providing details and knowhow of the SSS. A special thanks to my office mates Sean Nester, Lori Gibson, and Adam Duncan (25% of the time) for keeping me sane. Lastly, I thank my family and friends for their abounding support.

ABSTRACT

Sediment pollution is a major contributor to stream and river impairment. Often, the source of sediment pollution is from a construction site's runoff. A sediment retention basin, especially one with skimming outlet, can help minimize the sediment pollution from construction sites. A sediment retention basin and outlet are specifically designed for each site to retain as much sediment as possible while satisfying other requirements such as peak flow rates and retention times. Because modern design needs have increased requirements, there is a greater need to be as accurate as possible when modeling the hydraulics and the sediment trapping efficiency. This research focuses on two components related to the performance of sediment retention basins; 1) flow through a circular orifice cut into the side of a round riser pipes and 2) an optimization process to increase the efficiency of a sediment retention basin when using a Solid State Skimmer. It was determined that the true area of a circular orifice cut into a round riser pipe is greater than the normally assumed area--which is the area of the bit that cut the orifice--and that flow rate varied because of the unique shape formed by the cut. Three area equations are presented to model the orifice area, and an empirical equation for the coefficient of discharge was developed to increase orifice equation accuracy. The coefficient of discharge decreased as the orifice diameter approached the size of the riser diameter, and slightly increased as the water level neared the orifice. In order to quantify the efficiency of a sediment basin with a skimming outlet, the commonly applied overflow method was modified to account for the elevation and quantity of discharging

polluted stormwater from the basin. The modified overflow method was implemented as the objective function in a MATLAB program that automatically determines the parameters of the Solid State Skimmer for increased sediment trapping efficiency.

TABLE OF CONTENTS

INTRODUCTION	1
CHAPTER I Discussion of “Investigation of Flow through Orifices in Riser Pipes”	4
A version of this chapter was originally published as:	5
Abstract	5
Introduction.....	5
Discussion	6
Conclusion	8
References.....	10
CHAPTER II A study of discharge coefficients for orifices cut into round pipes	11
Abstract	12
Introduction.....	12
Theory	15
Methods.....	20
Results and Discussion	23
Conclusion	37
Notation.....	39
References.....	40
CHAPTER III Optimization of the Solid State Skimmer	42
Abstract	43

Introduction.....	43
Methods.....	47
Results and Discussion	59
MATLAB program	59
Sensitivity analysis.....	62
Conclusion	71
References.....	73
CONCLUSION.....	75
BIBLIOGRAPHY	78
Appendix.....	83
Appendix 1.1.....	84
Appendix 1.2.....	86
Appendix 1.3.....	87
VITA.....	94

LIST OF TABLES

Table 1. Studied bit diameters, riser pipe diameters, and resulting d/D values.....	21
Table 2. R^2 and RMSE values of selected fit equations for measured data with all area definitions.	30
Table 3. Average absolute difference of two replications for the C_d data	32
Table 4. Averaged visual measurements of C_d for each orifice size on a 10.2 cm riser when $h/d \geq 5$	36
Table 5. Single storm simulation sediment trapping efficiencies (%)	65
Table 6. Peak flow rates (cfs) for 2, 5, 10, 25, 50, and 100-yr storm events	66
Table 7. Multiple storm retention efficiencies for the Traditional and SSS riser	68

LIST OF FIGURES

Figure 1. Riser pipe, inner area (A_i), outer area, (A_o), and bit area (A_b).....	7
Figure 2. Ratio of d/D versus ratio of areas	9
Figure 3. A_b , A_o , and A_i 3-D abstraction from pipe and A_e as an approximation, McLemore et al., 2011.....	17
Figure 4. Circular orifice integration setup	19
Figure 5. Setup for photographic examination of the <i>vena contracta</i>	24
Figure 6. 2D plane comparison of A_b , A_o , A_i , and A_e for d/D of 0.5, 0.75, and 1.....	25
Figure 7. A_b , A_o , A_i , and A_e dimensionless comparison.....	26
Figure 8. Collected h (m) versus t (hr) data for $d=2.54$ cm and $D=5.08$ cm	28
Figure 9. C_d data versus h/d for $d/D = 0.125, 0.25, 0.5$, and 0.75 where $A = A_b$, with A_b best fit line.....	29
Figure 10. C_d data versus h/d for $d/D = 0.125, 0.25, 0.5$, and 0.75 where $A = A_e$, with A_e best fit line (Eq. (22)).....	30
Figure 11. Replicate C_d plots	32
Figure 12. Approximation of $C_{d, \text{int}}$ (Eq. (21)) for all areas when d/D is 0.125, 0.25, 0.5, 0.75, and 1.....	33
Figure 13. <i>Vena contracta</i> visual assessment, $D = 10.2$ cm and $d = 7.62$ cm. The width of the jet was 3.07cm and the height was 10.6cm at a distance 5.1cm from the orifice	35
Figure 14. Theorized flow lines for $d/D = 0.75$ (left) and 0.125 (right)	36

Figure 15. Sediment distribution from the inlet, $t = 0$, and to the outlet, $t = i$. Green particles are retained while red particles are subject to discharged.	49
Figure 16. Efficiency and storm routing flowchart.....	53
Figure 17. SSS weir configuration.....	58
Figure 18. Optimization flowchart.....	61
Figure 19. Single storm simulation stage discharge and dh curve.....	64
Figure 20. Single storm simulation inflow and outflow hydrographs	65
Figure 21. Multiple storm simulation stage discharge and dh curves	66
Figure 22. Discharge per elevation at max stage for the multiple storm simulation	70

INTRODUCTION

Many aspects of the water cycle are monitored and managed to ensure quality water is available for drinking, transportation, recreation, and industry related uses. The movement of water via storms can result in fluctuations of quality and quantity if stormwater becomes polluted or concentrated. Ultimately, the runoff created by stormwater enters our streams, rivers, lakes, and oceans. The addition of contaminated stormwater or too much stormwater can negatively affect the habitat, reduce hydraulic capacity and result in flooding, decrease the life-span of manmade structures, and increase drinking water cost (EPA, 2007).

The Clean Water Act (CWA) of 1972 is the pivotal document that enables the government to mandate regulations related to stormwater quality and quantity (EPA, 2007). The Environmental Protection Agency (EPA) requires that each state inventory the quality of their streams and report the source of issues related to the impairment for the National Water Quality Inventory Report to Congress. According to the report from 2009, there were 514,795 miles of impaired creek and streams reported on the impaired waters list out of 970,781 miles of assessed. Of the 514,795 miles of impaired creeks and streams, 106,057 miles are the result of sediment, which was the second highest contributor to impairment (EPA, 2009). The source of this sediment is usually rain-driven erosion on disturbed lands, including agricultural lands, disturbed forests, mined areas, and construction sites (EPA, 2009).

Each year an estimated 35-45 tons of sediment per acre moves off of construction sites due to rain-driven erosion (EPA, 2007). Additionally, construction sites can lead to increased flow rates during storm events because the physical characteristics of the land are altered in a way that reduces both infiltration and the time of concentration (Viessman and Lewis, 2003). The EPA has developed programs and set regulations that mitigate construction site sediment pollution in stormwater. The National Pollutant Discharge Elimination System (NPDES) permitting system, developed by the EPA, mandates that land disturbing construction sites of 10 or more acres are required to have a sediment retention basin (NPDES, 2011). A sediment retention basin not only reduces the amount of discharged sediment, but can also be designed to attenuate peak flow rates so as to minimize downstream flooding impacts.

The design of stormwater basins has progressed over the years to include complex structures and outlet devices that increase the basin's sediment trapping efficiency and reduce peak discharge rates. A recent addition to these is the surface skimmer outlet, which increases basin trapping efficiency by draining water from near the surface of the water column, which is typically cleaner because the sediment has settled out of this water. With the progression of regulations and increased importance given to controlling and treating sediment-polluted stormwater, the accuracy of the models and approaches used to design a sediment retention basin--and specifically the outlet device--are important in order to ensure optimal basin performance.

The following three chapters are three stand-alone publications that address issues related to the performance of sediment retention basins. Chapter 1 is a published discussion of the true area of a circular orifice cut into the side of a round riser pipe for use as a perforated outlet riser. This is important in order to accurately estimate flow through these openings. In chapter 2, the information presented in chapter 1 is applied to a detailed investigation of flow through circular orifices on round riser pipes, and from this an equation to calculate the coefficient of discharge and the representative area is presented, which can be used to increase the accuracy of the orifice equation for the orifice and riser configuration. Chapter 3 presents a modified approach to a sediment basin trapping efficiency design method. The modified method is implemented to optimize the design of an innovative skimming outlet, the Solid State Skimmer (Pillon, 2010). The optimal design of the Solid State Skimmer for a sediment retention basin is automated by a program written in MATLAB. An example sediment basin design is presented to illustrate the optimization process and sensitivity of the model.

Taken together, these publications will hopefully allow practitioners to design and construct outlets that will make sediment basins more effective.

CHAPTER I

**DISCUSSION OF “INVESTIGATION OF FLOW THROUGH
ORIFICES IN RISER PIPES”**

A version of this chapter was originally published as:

Alex J. McLemore, John S. Tyner, Daniel C. Yoder. "A discussion of "Investigation of flow through orifices in riser pipes" by P. D. Prohaska, A. A. Khan, and N. B. Daye." *Journal of Irrigation and Drainage Eng.* 137(9) (2011): 632-633.

Abstract

The use of perforated risers to regulate flow rate is common in stormwater basins. Multiple orifices cut into the side of a perforated riser regulate flow. Normally the orifice is cut with circular bit and the area is assumed equal to that of the bit that cut the hole. In a discussion of a study conducted by Prohaska et al. (2010) related to this assumption, areas formed by the curvature of the riser pipe and the cut created by the bit are examined. Two distinct areas were defined, the outer and inner area. Compared to the area of the bit, each increases as the bit diameter increases for a given riser size. When the bit diameter is $\frac{3}{4}$ the riser diameter, the outer and inner area are 1.09 times larger than the bit area. When the bit and riser diameters are equal, the outer area is 1.27 times larger and the inner area is 1.41 times larger than the bit area.

Introduction

It is common to meter water flow with orifices cut into the side of riser pipes for stormwater systems. A study conducted by Prohaska et al. (2010) examined the use of such orifices and presented a model to improve the accuracy of the flow rate through the circular orifice. The manuscript states that the holes are cut with a bit, so we assume that

A is the area of the bit (we will use the term A_b to distinguish the bit area), but this is not the area of the hole, as the hole perimeter formed by a circular bit drilling into a curved surface appears as a 3-D ellipsoid instead of a circle. If the actual orifice area seen by the flowing water could be described, we hypothesize that it might be better definition to use in the orifice equation than A_b .

Discussion

We can define two distinct areas that describe a hole cut perpendicularly by a circular bit into the center of a round pipe. The first describes an outer surface (A_o) and is equivalent to the area of pipe removed by the bit (Figure 1). The second describes an inner surface (A_i) which curves into the riser (Figure 1). A_o and A_i are always larger than A_b , but they approach the value of A_b as d/D approaches 0, where d is the bit diameter and D is the riser diameter. Both A_o and A_i share a common perimeter described by Stockie (1998) as:

$$\begin{aligned} x &= \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{d}{2}\right)^2 + \left(\frac{d}{2}\right)^2 \cos^2(\theta)} \\ y &= \frac{d}{2} \sin(\theta) \\ z &= \frac{d}{2} \cos(\theta) \end{aligned} \tag{1}$$

where x , y , and z , describe the Cartesian coordinates, and θ describes rotation around the positive x -axis. An equation for A_o can be found from the integral of the product of z and the length of the ellipsoid in the x - y plane through $\pi/2$ radians of rotation. Noting the symmetry of the area about θ , multiplying by 4 yields the total area. The equation for A_i

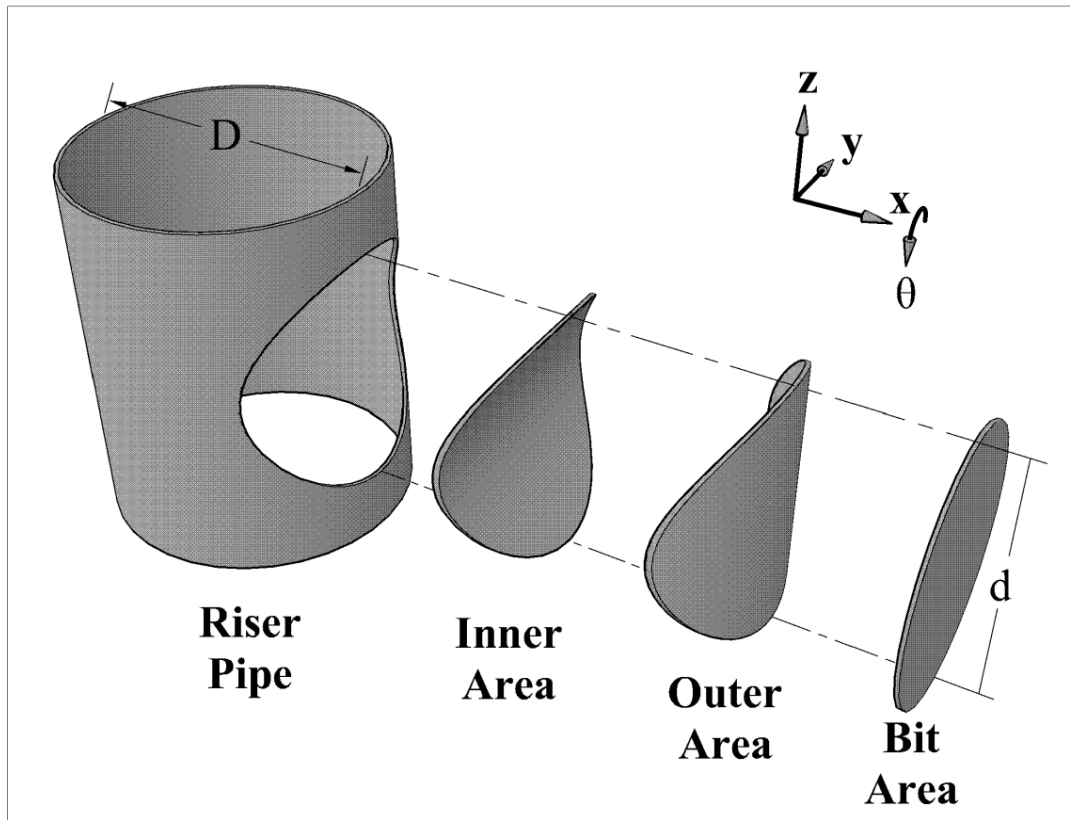


Figure 1. Riser pipe, inner area (A_i), outer area, (A_o), and bit area (A_b)

is similar, but with the product of y and the length of the ellipsoid in the x - y plane.

$$A_o = 4 \int_0^{\frac{\pi}{2}} z \sqrt{\left(\frac{dx}{d\theta}\right)^2 + \left(\frac{dy}{d\theta}\right)^2} d\theta \quad (2)$$

$$A_i = 4 \int_0^{\frac{\pi}{2}} y \sqrt{\left(\frac{dx}{d\theta}\right)^2 + \left(\frac{dz}{d\theta}\right)^2} d\theta \quad (3)$$

The solutions for Eqs. (2) and (3) are complex, including incomplete and complete elliptic integrals of the first, second, and third kind.

Using Maple[®] computational software, we computed A_o and A_i across a range of d/D ratios. Figure 2 presents A_o/A_b and A_i/A_b versus d/D , with A_b/A_b lying atop the x -axis plotted at a value of unity for comparison. When d/D is small A_o , A_i , and A_b are similar. For instance, at $d/D = 0.25$, $A_i/A_b \approx A_o/A_b = 1.01$. As d/D increases, so does the divergence between A_o and A_i to A_b . At $d/D = 0.75$, $A_o/A_b \approx A_i/A_b = 1.09$. As d/D increases further, A_o and A_i begin to diverge from one another. At the extreme case, where d/D approaches one, $A_o/A_b = 1.27$ and $A_i/A_b = 1.41$.

Conclusion

Two distinct areas, A_o and A_i , can be defined for the area created by a circular bit cutting a hole into the side of a round riser pipe. When comparing them to the area of the bit that cut the hole, A_o and A_i increase as d/D increase. Since the orifice area encountered by water entering a riser is described more accurately by A_o or A_i than by A_b , it is interesting to ponder whether the fits to C_d in the referenced manuscript might be further improved with an alternative definition of A .

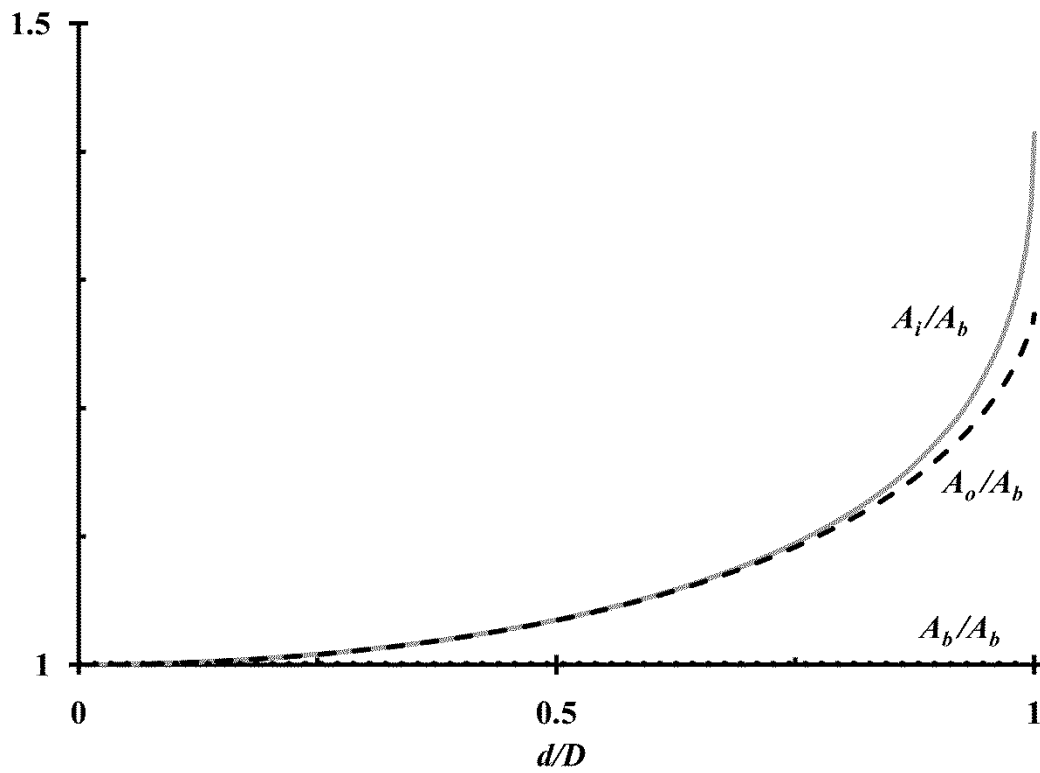


Figure 2. Ratio of d/D versus ratio of areas

References

- Prohaska, P. D., A. A. Khan, and N.B. Kaye. 2010. Investigation of flow through orifices in riser pipes. *J. of Irrigation and Drainage Eng.*, 136(5), 340-347.
- Stockie, John M. 1998. The geometry of intersecting tubes applied to controlling a robotic welding torch. *MappleTech* (Special Issue on Maple in Industry), 5(2-3), 58–66.

CHAPTER II

A STUDY OF DISCHARGE COEFFICIENTS FOR ORIFICES CUT

INTO ROUND PIPES

Abstract

This research focuses on the discharge coefficient (C_d) of orifices cut with a circular bit perpendicular to and along the centerline of a round pipe, a common configuration on perforated risers installed as the principal outlets for stormwater detention or sediment basins. The orifice area is generally defined as the area of the bit used to cut the hole, but the true area of the orifice is larger than the bit due to the curvature of the riser pipe. Four different descriptions for orifice area were tested while attempting to fit C_d to measured discharge experiments. The tests showed that C_d decreases as the orifice diameter increases. Photographic imagery shows this is due to the lateral flow from the riser's curved sides decreasing the *vena contracta* area more than what normally occurs during flow through an orifice on a flat plate. In contrast—but to a lesser extent— C_d increases as the water level in the tank decreases and approaches the top of the orifice. Best fit equations to model C_d were developed to better estimate flow, with the most applicable having a R^2 of 89.1% and a RMSE of 0.028. Orifice elevation above the tank floor was measured and initially modeled but not ultimately not included in the best fit equation because the R^2 improved by only 0.4%.

Introduction

Perforated risers are often made of a vertical pipe with multiple circular orifices cut perpendicular to and along the centerline, and these are commonly used as outlet structures for stormwater detention or sediment basins to regulate stormwater discharge

(Jarret 1993). It is within this context that the authors became interested in flow metering with orifices cut into round pipes, as the stormwater discharge needs be as accurate as feasible. Flow through an orifice is commonly calculated from the orifice equation:

$$Q=C_d A\sqrt{2gh} , \quad (4)$$

derived from the Torricelli's Law and the continuity equation, where A is the cross sectional area of the orifice, g is the acceleration due to gravity, h is the hydraulic head above the center of an orifice, and the discharge coefficient C_d is an empirical term added to account for energy lost due to friction and contraction of the water jet area relative to the hole area (Encyclopædia Britannica, 2012; Finnemore and Franzini, 2002).

C_d is typically 0.61 for circular, thin-walled, square-edged orifices (Finnemore and Franzini, 2002). In cases where orifices are cut perpendicularly to the centerline along the length of a pipe (e.g., as in a basin riser), A is generally calculated as area of a circle in a 2-D plane, where the circular radius is defined by the bit radius used to cut the orifice (Jarret, 1993). Because of the pipe curvature, however, the actual area of the orifice is larger than the bit area.

Visser et al. (1988) experimentally studied perforated risers with water flowing into a pipe through an orifice with A defined by the bit area, and determined that for a 2.5 cm bit diameter on a 15.0 cm diameter vertical riser the C_d is 0.71. The high C_d value was considered to be the result of the curved shape of the riser and was believed to be constant for all stages. Prohaska et al. (2010) also studied flow into a riser, also assuming A equal to the bit area, but considered various orifice sizes on two riser diameters. They

found that C_d varied with the location of the orifice center above the bottom of the reservoir (z_o), the ratio of d/D (where d is the orifice diameter and D is the riser diameter), and h . Specifically, they claimed that C_d increased with decreases in z_o/d , d/D , and h/d . Where z_o/d accounts for restricted flow paths to the orifice because the orifice is near the reservoir bottom, d/D describes variation caused by the curvature of the riser pipe, and h/d explains variation associated with a small head relative to the orifice size. They reported C_d values as low as 0.4 for $d/D = 0.417$ and as high as 0.8 for $d/D = 0.083$.

Gregg et al. (2004) examined the C_d when modeling flow out of a circular orifice (as opposed to into the orifice) on a round pipe, with the intent to describe sparging operations. They compared cutting orifices two different ways: 1) using a circular bit as previously described, and 2) laying a template of a circular bit over a pipe and cutting around the perimeter. For both methods, A in the orifice equation was considered to be equal to the bit area. They ultimately recommended cutting an orifice by laying the circular bit template over the riser because the true area of the removed material is known. Their findings conclude that regardless how the orifice was cut, C_d increased with increasing d/D , which is opposite of the findings from inward flow studies.

The objective of this research is to measure and describe the C_d of the orifice equation for flow into an orifice cut into a round pipe as a function of h , z_o , d , D , while applying various descriptions for A . In doing so, empirically-derived equations relating these variables to C_d will be analyzed. Lastly, we will attempt to explain the results obtained using a photographic examination of flow through the orifices.

Theory

The C_d is defined by

$$C_d = C_v \cdot C_c \quad (5)$$

where C_v is the coefficient of velocity and C_c the coefficient of contraction, defined by

$$C_v = \frac{v}{v_i} \quad (6)$$

$$C_c = \frac{A_{vc}}{A} \quad (7)$$

where v is the actual velocity and v_i is the ideal velocity $(\sqrt{2gh})$. For the case of the orifice cut into the side of a riser pipe, the orifice is considered thin-walled and sharp-edged, with a typical C_v value of 0.98. C_c is the coefficient of contraction and accounts for reduction of the flow jet area at the *vena contracta*, where A_{vc} is the area of the *vena contracta* and A is the orifice area. Common causes of variability in C_c are the result of the orifice entrance and exit shape and the smoothness of the cut. For a thin-walled sharp-edged orifice, C_c is assumed to be 0.62 (Finnemore and Franzini, 2002).

Numerous descriptions of A for an orifice cut into a round pipe with a bit are possible. McLemore et al. (2011) provided three descriptions of A : 1) the area of the bit used to cut the hole (A_b); 2) the outer area (A_o), which is the area of the pipe material removed; and 3) the inner area (A_i), which is area defined by a plurality of lines running across the perimeter of the orifice in a direction perpendicular to the length of the pipe (Figure 3). A_b is defined as

$$A_b = \frac{\pi}{4} d^2 \quad (8)$$

where d is the diameter of the bit that cut the hole. Stockie (1998) defined the perimeter of a circular orifice cut into a round pipe as:

$$x = \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{d}{2}\right)^2 + \left(\frac{d}{2}\right)^2 (\cos(\theta))^2} \quad (9)$$

$$y = \frac{d}{2} \sin(\theta) \quad (10)$$

$$z = \frac{d}{2} \cos(\theta) \quad (11)$$

where x , y , and z are the coordinates of a point located on the perimeter of the cut relative to θ , which is the angle of rotation measured counterclockwise from the positive z direction. A_i is defined as:

$$A_i = 4 \int_0^{\frac{\pi}{2}} y \sqrt{\left(\frac{dx}{d\theta}\right)^2 + \left(\frac{dz}{d\theta}\right)^2} d\theta \quad (12)$$

and an equivalent and simpler version of McLemore et al.,'s (2011) A_o is defined as:

$$A_o = 2 \int_0^{\pi} \frac{dz}{d\theta} \frac{D}{2} \sin^{-1}\left(\frac{d \sin(\theta)}{D}\right) d\theta \quad (13)$$

Due to the complexity of the solutions for A_o and A_i , (i.e., multiple elliptic integrals of the first and second kind), it is desirable to have a simpler definition of A while maintaining the oval shape that is more representative of the actual area (Figure 3). Therefore, we defined an ellipse area (A_e) as:

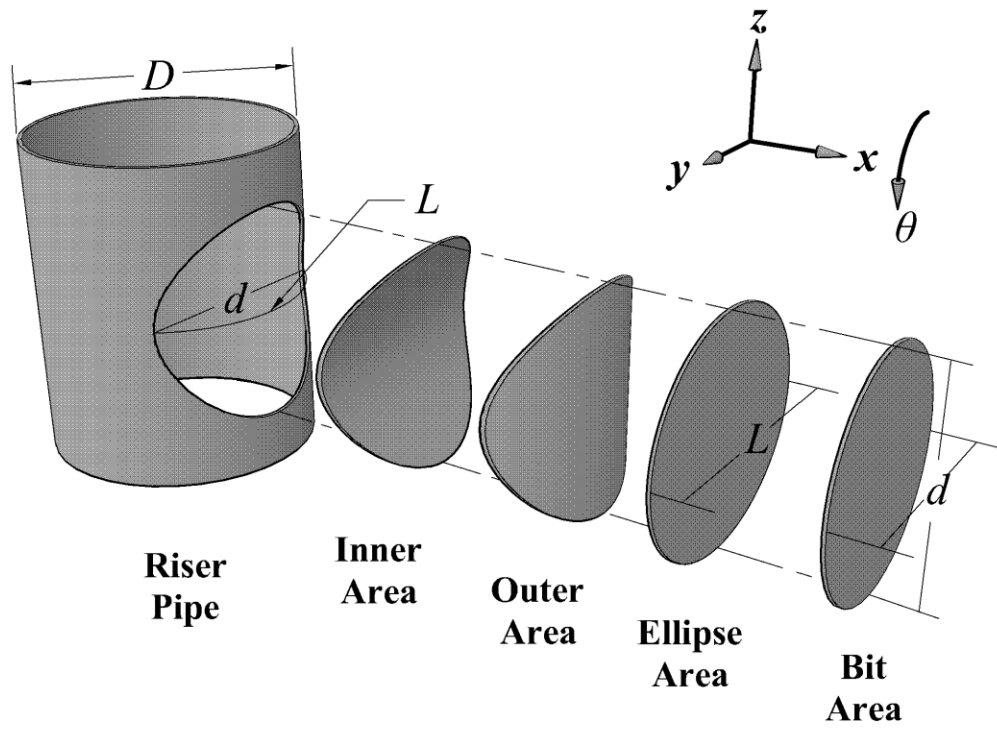


Figure 3. A_b , A_o , and A_i 3-D abstraction from pipe and A_e as an approximation

$$A_e = \frac{\pi}{4} d \cdot L \quad (14)$$

where L is described by the arc length from one side of the cut to the other along the curvature of the pipe, and the minor axis is defined by the bit diameter (Figure 3), or

$$L = D \sin^{-1} \left(\frac{d}{D} \right) \quad (15)$$

Although the A_e is less physically related to the orifice and is simply a relationship defined by two terms (D and d), it simplifies calculations for A as compared to solving Eqs. (12) and (13) for A_o and A_i , respectively.

An erroneous assumption common to all the descriptions of A , as they relate to Eq. (4), is that a single h defined at the center of A accurately describes the head across the entire area of A . When an orifice is small compared to head (high head conditions), errors introduced by applying a single h to the entire A are minimal. But, as orifice depth decreases, the error due to this assumption about h increases. This error can be removed by integrating the head across the area (Davis and Sorensen 1969). The basic form of the integrated orifice equation is given as

$$Q_{int} = 2 C_d \sqrt{2g} \int_0^\pi \sqrt{h - \frac{d}{2} \cos \theta} (w \cdot dh) d\theta \quad (16)$$

where $w \cdot dh$ is an infinitesimally small horizontal slice of A as a function of θ and has a varied definition for each of the four different descriptions of A (Eqs. (8), and (12-14)).

Applying the four definitions of A into Eq. (16) yields:

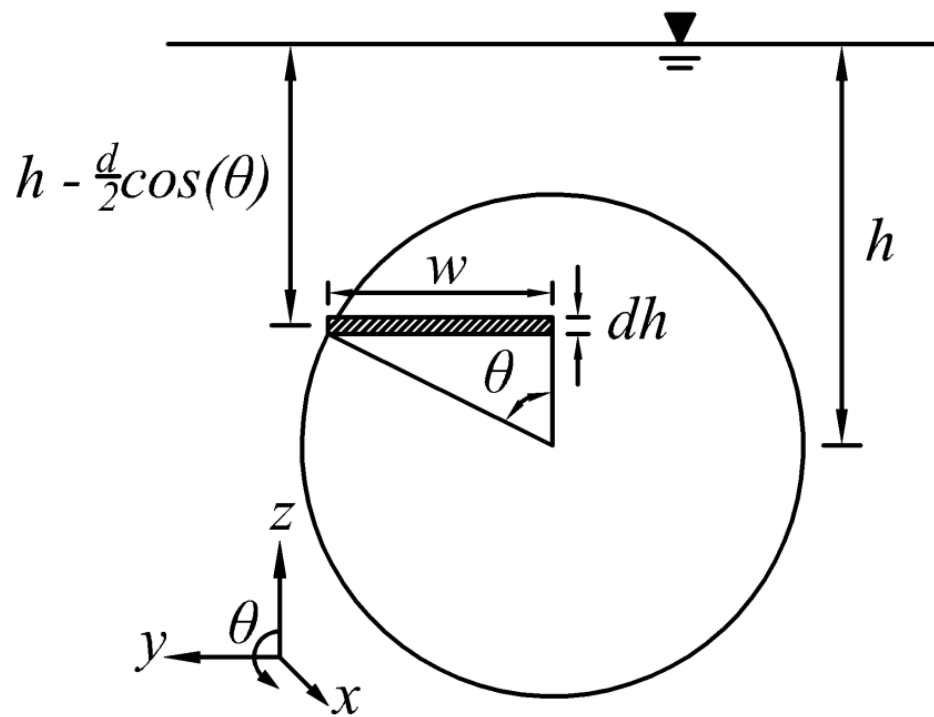


Figure 4. Circular orifice integration setup

$$Q_b = 2 C_d \sqrt{2g} \int_0^\pi \sqrt{h - \frac{d}{2} \cos \theta} y \frac{dz}{d\theta} d\theta \quad (17)$$

$$Q_o = 2 C_d \sqrt{2g} \int_0^\pi \sqrt{h - \frac{d}{2} \cos \theta} \frac{D}{2} \sin^{-1} \left(\frac{2y}{D} \right) \frac{dz}{d\theta} d\theta \quad (18)$$

$$Q_i = 2 C_d \sqrt{2g} \int_0^\pi \sqrt{h - \frac{d}{2} \cos \theta} y \sqrt{\left(\frac{dz}{d\theta} \right)^2 + \left(\frac{dx}{d\theta} \right)^2} d\theta \quad (19)$$

$$Q_e = 2 C_d \sqrt{2g} \int_0^\pi \sqrt{h - \frac{d}{2} \cos \theta} \frac{D}{2} \sin^{-1} \left(\frac{d}{D} \right) \sin(\theta) \frac{dz}{d\theta} d\theta \quad (20)$$

Methods

Orifice discharge experiments were conducted in two separate tanks at the University of Tennessee Hydraulics Laboratory. The first tank was a 1.02 m³ stock tank with a depth of 0.56 m and surface area of 1.82 m². A PVC flange was installed in the bottom of the tank in a manner that allowed various vertical risers to be inserted into the flange. We also employed a 14.5 m³ vertically walled concrete tank with 2.44 m depth and 5.95 m² surface area for testing a 15.24 cm diameter riser. A description of all tested pipe and orifice diameter combinations is given in Table 1. Each riser was made from schedule 40 PVC. The orifices were cut using drill bits or hole-saws placed into a drill press to ensure the orifices were perpendicular to and aligned with the center line of the pipes. Then, each orifice was cleaned of burs and other imperfections so that the edges were uniform and sharp with smooth sidewalls on the inside of the orifice. The orifices and risers were

Table 1. Studied bit diameters, riser pipe diameters, and resulting d/D values.

d/D ratio	Riser pipe diameters (cm)			
	5.08	7.62	10.2	15.2
	Bit diameters (cm)			
0.125	0.635	0.953	1.27	1.91
0.250	1.27	1.91	2.54	3.81
0.500	2.54	3.81	5.08	7.62
0.750	3.81	5.72	7.62	11.4

designed such that at the interior of the orifices the pressure was always atmospheric.

The testing procedure consisted of filling a tank with water and discharging the water through the orifice while simultaneously recording the tank water level and elapsed time such that Q versus Δh could be calculated as

$$Q_{meas} = A_t \frac{\Delta h}{\Delta t} \quad (21)$$

where Δh is the difference in head between time steps, Δt is the time step, and A_t is the horizontal cross-sectional area of the tank. Measurements of h were visually collected using a meter stick in the stock tank, yielding a resolution of one millimeter. In the larger tank, a HOBO UH-20 depth sensor measured absolute pressure from the bottom of the tank at a sampling rate of 1Hz with a resolution of 1.4 mm (HOBO 2011). A second UH-20 collected atmospheric pressure measurements so the data collected by the submerged pressure sensor could be converted from absolute to gauge. Following the flow experiments, C_d values were estimated by inserting the measured discharge data (Eq. (21)) and each of the four defined areas, A_b , A_o , A_i , and A_e (Eqs. (8) and (12-14)) into Eq. (4), as

$$C_{d(b,o,i,e)} = \frac{Q_{meas}}{A_{(b,o,i,e)} \sqrt{2gh}} \quad (22)$$

We calculated discharge coefficients that produce equivalent flow between the traditional method (using Eq. (4)) and the integrated forms (Eq. (17-20)) to describe is the difference in flow rate when a single head is assumed for the entire orifice.

$$C_{d, \text{int}(b,o,i,e)} = \frac{Q_{\text{int}(b,o,i,e)}}{A_{(b,o,i,e)} \sqrt{2gh}} \quad (23)$$

The computations were carried out in Maple (Maple, 2010), with h/d varying from 0.5 to 20 and d/D with values of 0.125, 0.25, 0.5, 0.75, and 1.

Early during the experimental testing, we noted that the cross-sectional shape of the *vena contracta* was often not circular. To document this effect, the *vena contractas* were photographed horizontally and vertically to allow for an approximate measurement of their free-jet height and width, respectively. These photographs required constructing four equally sized half risers with varying sized orifices that discharged water out the side of the tank (Figure 5). The half risers had a diameter of 10.2 cm, with orifice sizes corresponding to d/D values of 0.125, 0.25, 0.5, and 0.75.

Results and Discussion

Differences between the four orifice area definitions are compared in Figures 6 and 7. Figure 6 illustrates the four orifice area definitions flattened onto a 2D plane for d/D values of 0.5, 0.75, and 1.0. Visually, it is evident that the four areas differ just slightly at $d/D = 0.5$. For larger values of d/D , the A_o , A_i , and A_e increase significantly compared to A_b . Figure 7 quantifies the differences with a dimensionless plot of A_o , A_i , and A_e relative to A_b as a function of d/D . At $d/D = 0.25$ there is a slight divergence, where $A_o/A_b \approx A_i/A_b \approx A_e/A_b = 1.01$. At $d/D = 0.75$, A_o and A_i are 9% larger than A_b , and A_e is 13% larger than A_b . As d/D approaches unity, A_o is 27% larger, A_i is 41% larger, and A_e is 57% larger than A_b . These trends suggest that assuming the orifice area is equal

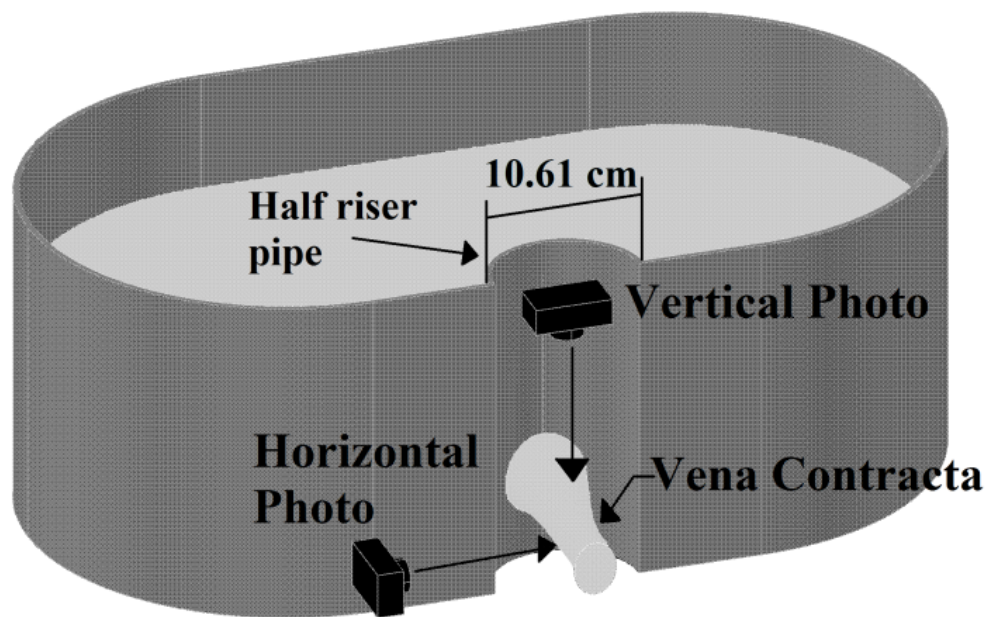


Figure 5. Setup for photographic examination of the *vena contracta*

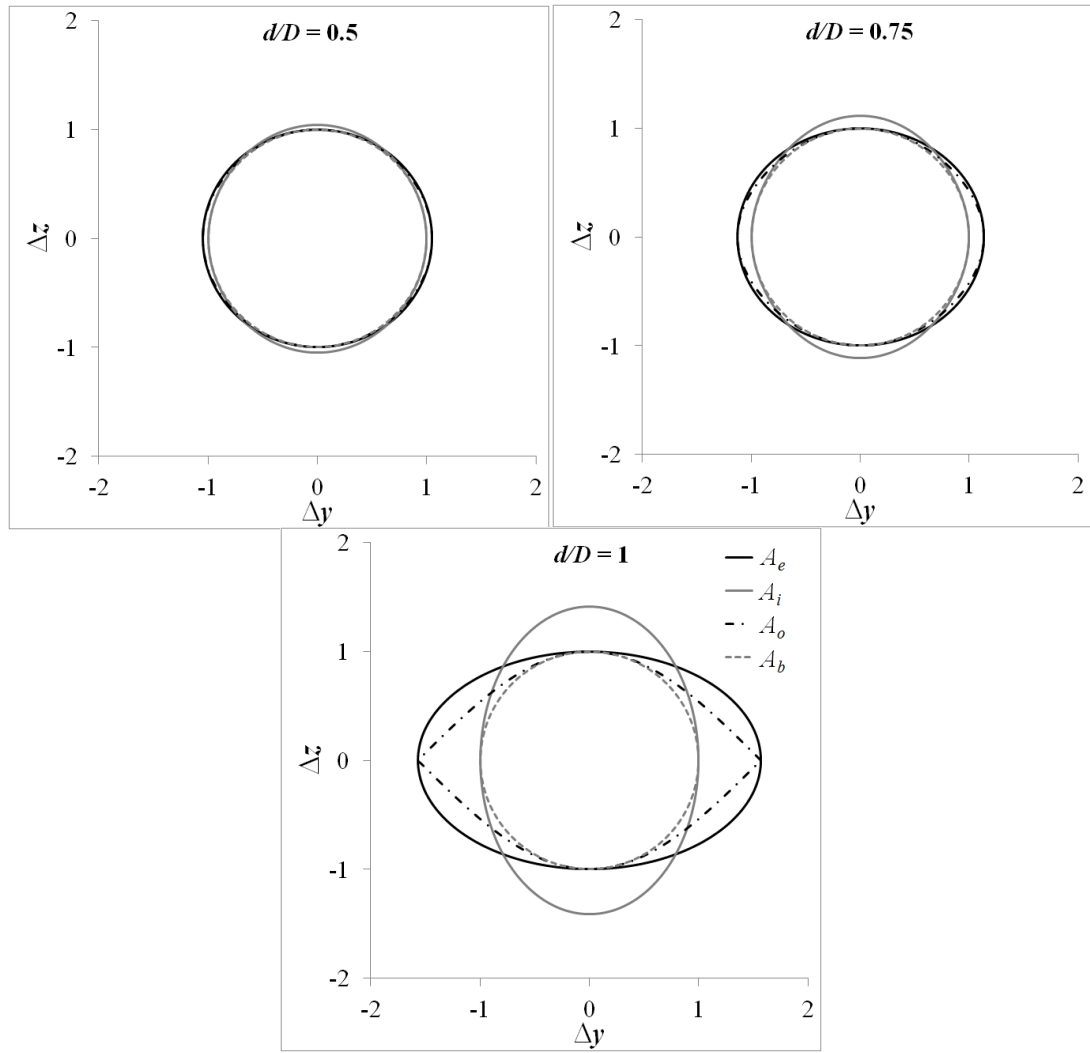


Figure 6. 2D plane comparison of A_b , A_o , A_i , and A_e for d/D of 0.5, 0.75, and 1

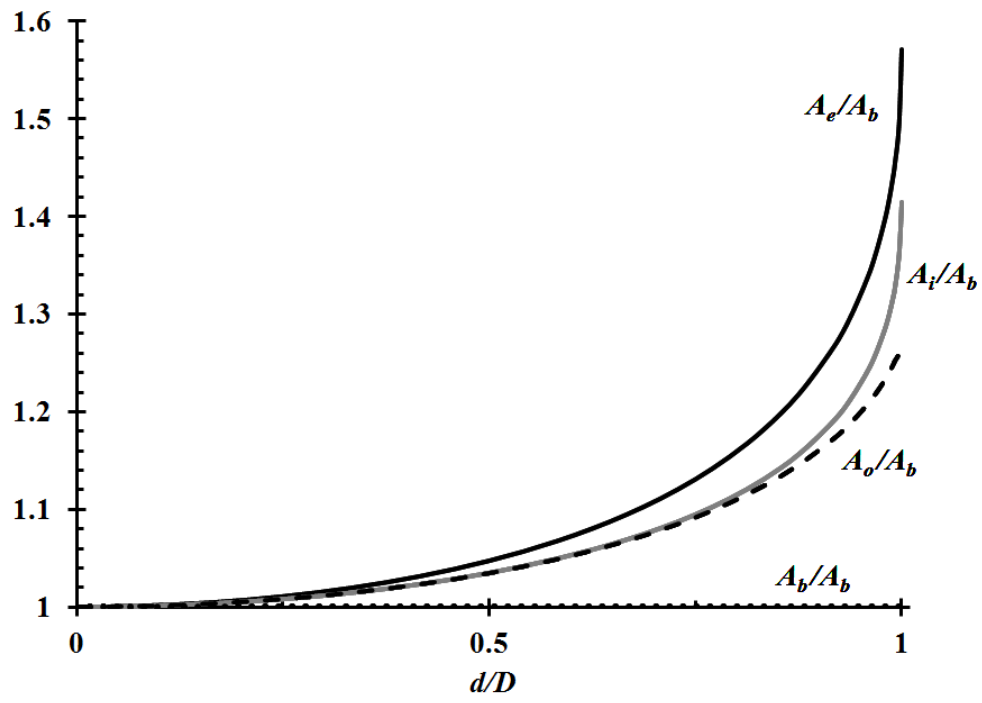


Figure 7. A_b , A_o , A_i , and A_e dimensionless comparison

to A_b may cause significant error as d/D increases.

Measured data from a single discharge experiment ($d=2.54$ cm and $D=5.08$ cm) is presented in Figure 8. Figure 9 shows plots of C_d versus h/d for various d/D , while letting area be described by A_b . The general trends are similar, with smaller C_d 's as d/D increases, and to a lesser extent as h/d increases. Figure 10 is similar to Figure 9 and shows similar trends, but this is with the area described by A_e . The differences between Figures 9 and 10 are small, but can be seen visually as d/D increases where C_d calculated from A_e is lower than C_d for A_b . Similar plots were constructed for A_o and A_i (not shown), both showed decreasing C_d with increasing d/D and an increased C_d at low head. A series of single- and multi-parameter empirical equations were developed and fit to predict C_d from the data presented in Figures 9 and 10, and the similar plots from A_i and A_o , with the best two equations shown in Table 2. Based on R^2 and RMSE, A_e provides the best fit, followed by A_i and A_o , which produced similar values. This is a fortuitous result, given that the mathematical expressions describing A_e are simpler than those for A_o and A_i . A_b consistently produced the poorest results. The best fit line for A_b and A_e are also shown on Figures 9 and 10, respectively. The overall best fit relationship includes d/D , h/d , and z_o/d , and explains 89.5% of the variation with a RMSE of 0.027. However, it appears that adding the z_o/d term was of little benefit, since the first equation (Table 2, grey box) does not reference z_o , but still has R^2 and RMSE values almost identical to those of the overall best fit. We therefore suggest that the most useful equation is the first one in Table 2, using A_e for area. Fitted with the correct constants, this equation becomes

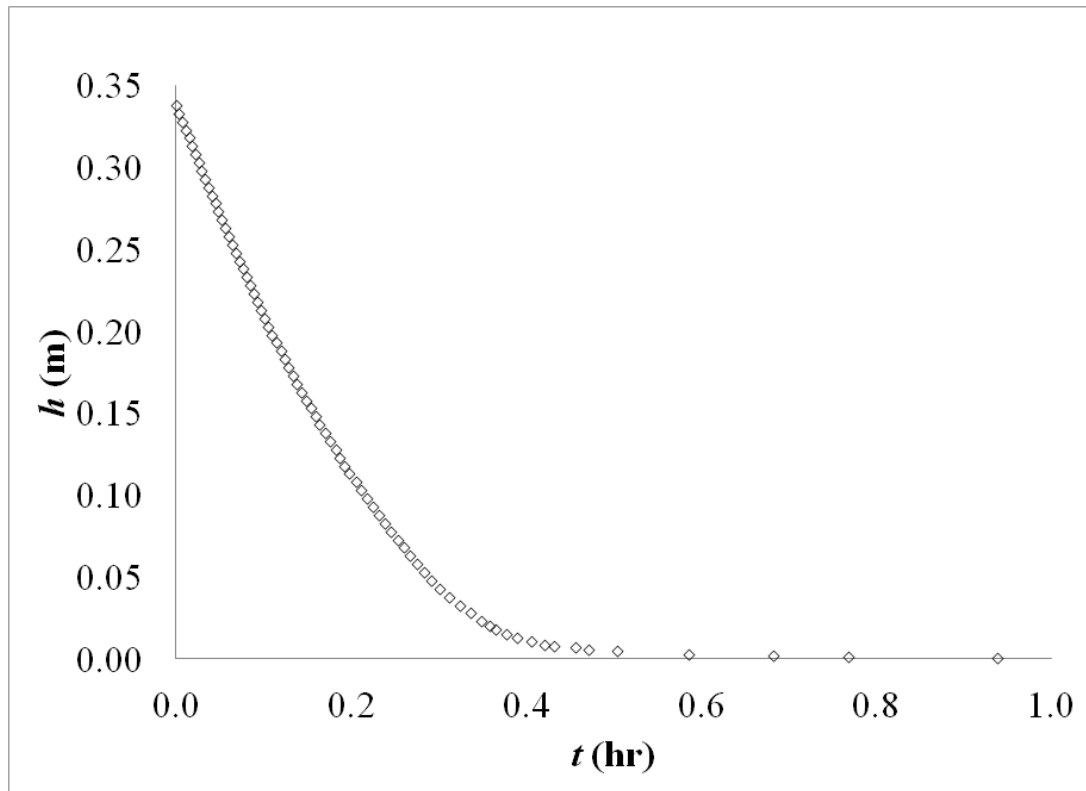


Figure 8. Collected h (m) versus t (hr) data for $d=2.54$ cm and $D=5.08$ cm

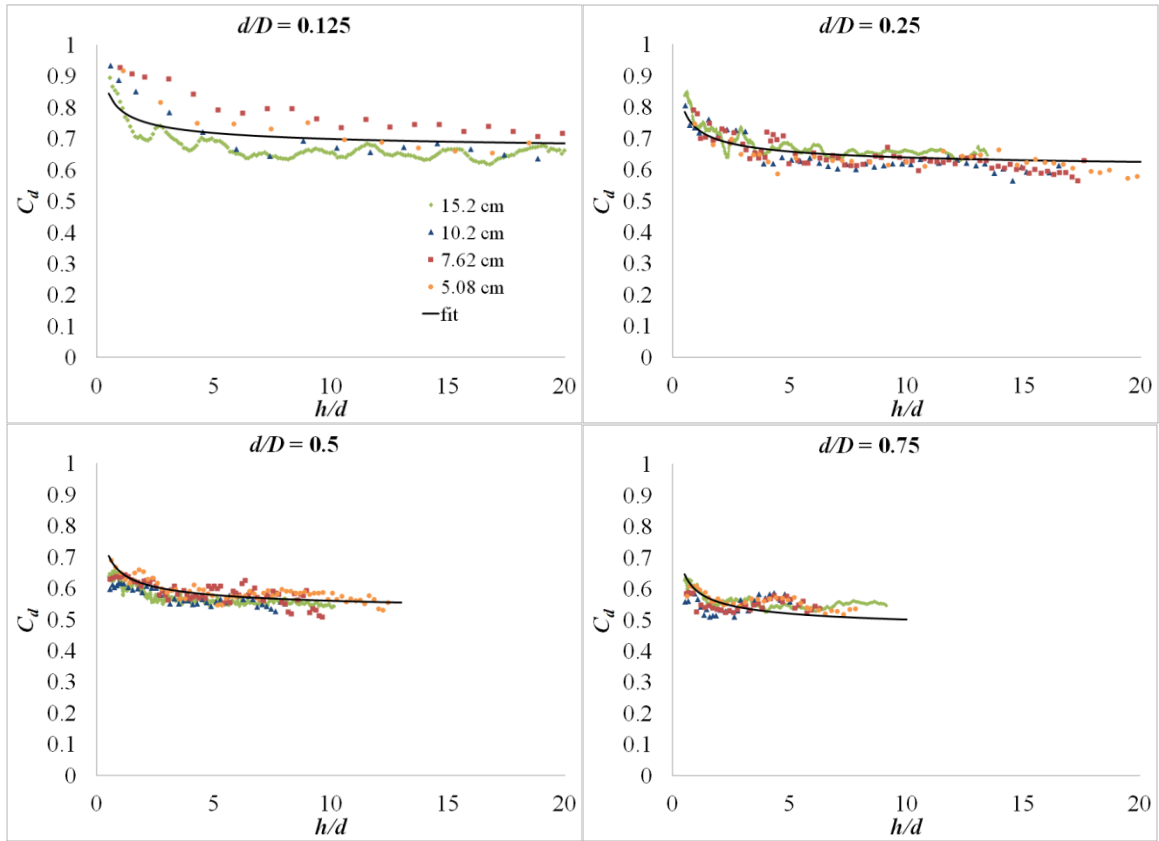


Figure 9. C_d data versus h/d for $d/D = 0.125, 0.25, 0.5$, and 0.75 where $A = A_b$, with A_b best fit line

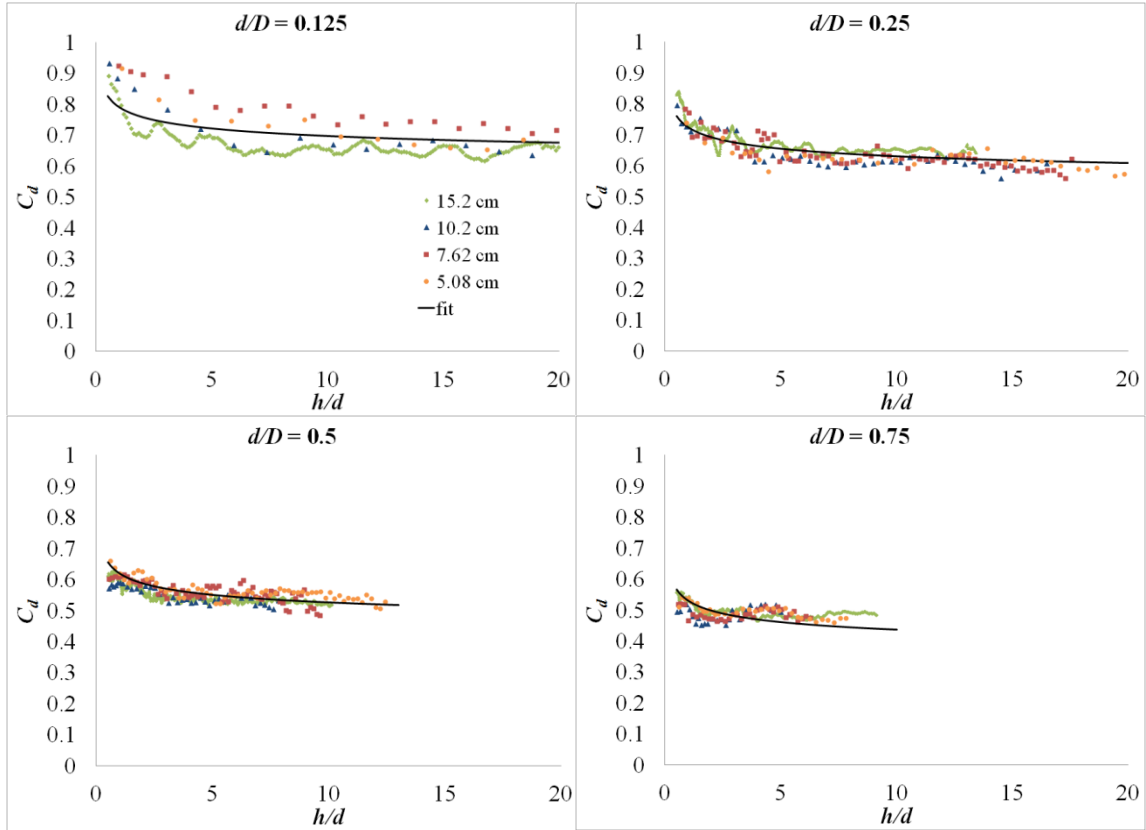


Figure 10. C_d data versus h/d for $d/D = 0.125, 0.25, 0.5$, and 0.75 where $A = A_e$, with A_e best fit line (Eq. (22))

Table 2. R^2 and RMSE values of selected fit equations for measured data with all area definitions.

<i>Fit parameters (R^2, RMSE)</i>				
<u>Equation form</u>	<u>A_b data</u>	<u>A_o data</u>	<u>A_i data</u>	<u>A_e data</u>
$C_d = 0.61 + a\left(\frac{d}{D}\right)^p + b\left(\frac{h}{d}\right)^q$	0.818, 0.030	0.875, 0.028	0.879, 0.028	0.891, 0.028
$C_d = 0.61 + a\left(\frac{d}{D}\right)^p + b\left(\frac{h}{d}\right)^q + c\left(\frac{z_o}{d}\right)^s$	0.820, 0.029	0.880, 0.028	0.881, 0.028	0.895, 0.027

$$C_d = 0.610 - 0.449 \left(\frac{d}{D} \right)^{0.677} + 0.289 \left(\frac{h}{d} \right)^{-0.168} \quad (24)$$

At least one discharge experiment for each orifice and riser combination was conducted to produce the data points presented in Figures 9 and 10 and develop the best fit equation. Variability among replicated experiments was measured by fitting a line through each replicate data set and determining the average absolute difference between the fit lines. The fitted lines were developed for each replication independently, while assuming A_e for A , to produce a consistent measure of C_d for changing h/d . Figure 11 illustrates the C_d data and fitted lines for the smallest D with the smallest d , 5.08 and 0.635 cm respectively. The fitting process was repeated for five experiments, each having two replicates, with variability measurements provided in Table 3. The greatest variability, 0.022 and 0.017, occurred between replicates of the 5.08 cm riser and 0.125 d/D , and 15.2 cm riser and 0.75 d/D . These results suggest that variability is greatest at the extremes orifice and riser combinations studied and can expect variability among non-replicated experiments to be less than or equal to that measured for the extreme cases.

In an attempt to explain the increasing C_d with decreasing h/d , we compared the difference in predicted flow assuming a single head across an entire orifice compared to vertical integration of the orifice equation with changing head (Eqs. (17-20)). Figure 12 shows the results of Eq. (23) for each area definition and for d/D values of 0.125, 0.25, 0.5, 0.75, and 1. Only the A_b line is presented because the resulting curves from the examination of the four area definitions differed at most by 0.5%. The shape of Figure

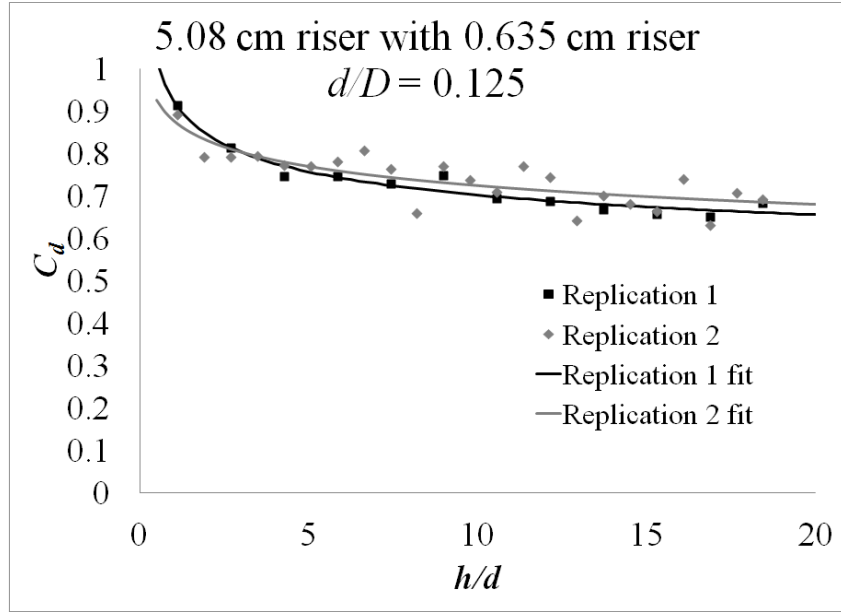


Figure 11. Replicate C_d plots with replication fit lines

Table 3. Average absolute difference of two replications for the C_d data

d/D ratio	Riser pipe diameters (cm)	Average absolute difference	Average difference
0.125	5.08	0.022	0.013
0.125	10.2	0.011	0.011
0.250	15.2	0.009	0.007
0.500	15.2	0.002	0.002
0.750	15.2	0.017	0.010

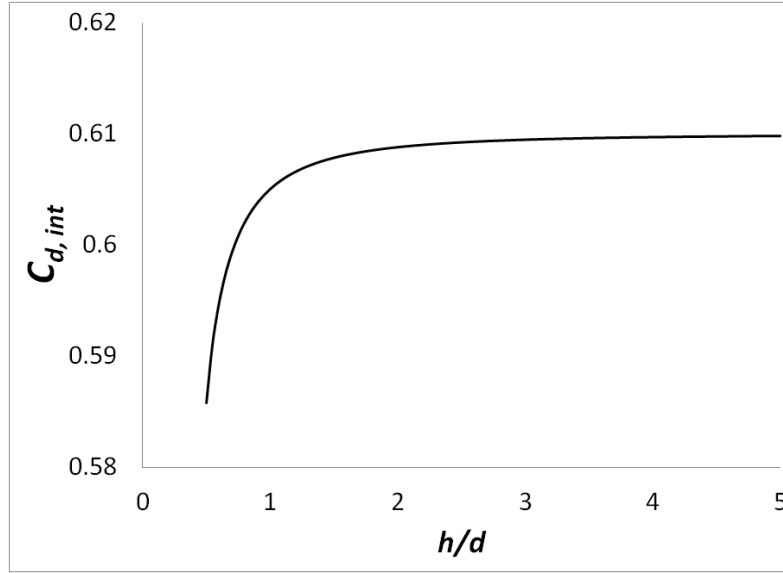


Figure 12. Approximation of $C_{d,int}$ (Eq. (21)) for with $A = A_b$ for d/D of 0.125, 0.25, 0.5, 0.75, and 1

12 shows that as h/d decreases below a value of 5, Eq. (4) overestimates discharge with an error of approximately 4% at $h/d = 0.5$. The decreasing C_d suggests the opposite of the finding from the discharge experiment, which show that C_d increases as h/d decrease. In other words, the increase in C_d as h/d decreases is not due to the assumption of a single h value, so there must be some other explanation.

While performing the visual examination of orifice discharge, we noted that the discharge jet fanned out vertically from an orifice placed in a vertical pipe (Figure 13). After photographing the jets in the horizontal and vertical plane, the width (w_{vc}) and height (l_{vc}) of 1.27, 2.54, 5.08, and 7.62 cm orifice diameters were measured photographically to the nearest 0.3 cm. The cross-sectional shape of the flow jet in the *vena contracta* appeared elliptical, so the basic form of the ellipse equation was applied for A_{vc} :

$$A_{vc} = \frac{\pi}{4} (l_{vc} \cdot w_{vc}) \quad (25)$$

Then Eqs. (8 and 25) were substituted into Eq. (7) to solve for the C_c , and C_d was calculated (Eq. (5)) assuming that C_v is a constant 0.98. Measurements of w_{vc} and h_{vc} were collected for $h/d > 5d$, allowing for the prediction of C_d (Table 4). Results indicate that C_c decreases with increased d/D and increases with decreasing h/d . These two visually-established trends help explain the results shown in Figures 9 and 10. We theorize that the greater h/d values cause the lateral flow coming around the curved surface of the riser to accelerate, driving the *vena contracta* to become thin in the horizontal direction but tall in the vertical direction (Figure. 14). This curvature effect



Figure 13. *Vena contracta* visual assessment, $D = 10.2$ cm and $d = 7.62$ cm. The width of the jet was 3.07cm and the height was 10.6cm at a distance 5.1cm from the orifice

Table 4. Averaged visual measurements of C_d for each orifice size on a 10.2 cm riser when $h/d \geq 5$

d/D	w_{vc} (cm)	h_{vc} (cm)	A_{vc} (cm ²)	A_b (cm ²)	C_c	C_d
0.125	0.794	1.27	0.792	1.27	0.625	0.613
0.25	1.53	2.54	3.06	5.07	0.604	0.592
0.5	2.94	5.08	11.7	20.3	0.578	0.567
0.75	3.07	10.6	25.5	45.6	0.559	0.548

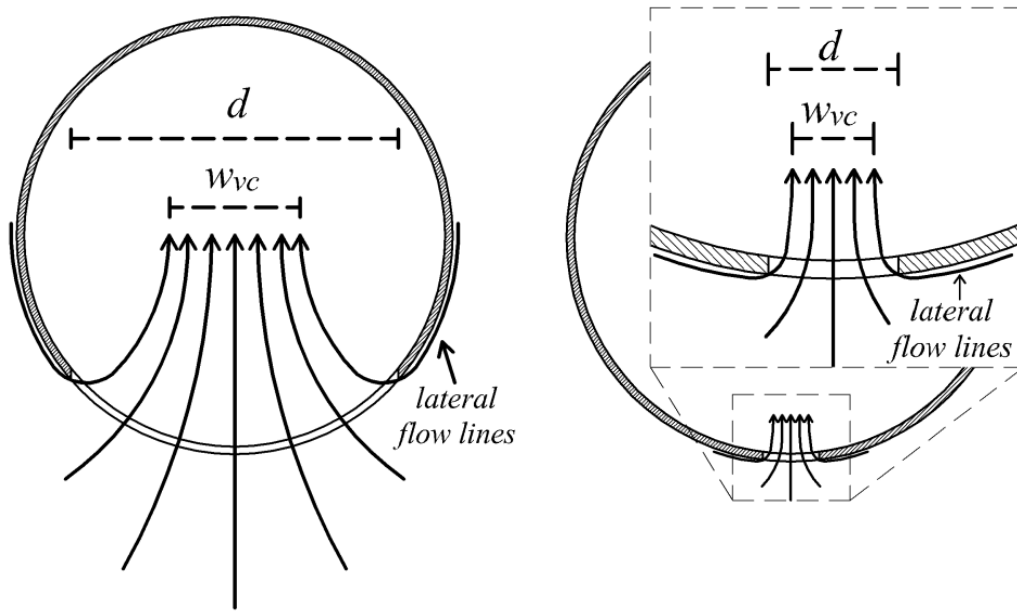


Figure 14. Theorized flow lines for $d/D = 0.75$ (left) and 0.125 (right)

reduces the area of the *vena contracta* beyond what normally occurs for an orifice on a flat plate. The velocity slows when h approaches the orifice, reducing the compression effect and allowing the *vena contracta* area to increase. This increased *vena contracta* area equates to more flow exiting through the orifice, explaining why the C_d increases at low h . This effect is greater than the error associated with an assumed constant h , and explains why the decreasing C_d noted in the examination of the integration correction was not present in the discharge data.

Conclusion

Four definitions of A were presented and compared to illustrate the effect of the riser pipe curvature on the orifice area. Discharge experiments were conducted in the lab for four riser pipes, each with four orifices corresponding to d/D ratios of 0.125, 0.25, 0.5, and 0.75. Data from the lab experiments were used to determine C_d . Error associated with an assumed h across the entire orifice was analyzed by comparing the normally applied orifice equation (Eq. 4) to the integral form (Eq. (16)), while considering the four definitions of A . Additionally, the *vena contract* was photographed to visually explain the findings of the discharge experiments and the assumed h analysis.

The major trend evident in the measured data is increasing C_d values with decreasing d/D and to a lesser extent with decreasing h/d . Several empirical equations were fitted to the measured C_d data and the most applicable fitted model, Eq. (24), indicates that h/d and

d/D with area defined by A_e can explain 89.1% of the variation in the measures data with a RMSE of 0.028. It was determined from the integral comparison that C_d should decrease as h/d decreases, which is the opposite of the measured results. In an attempt to explain this contradiction, the *vena contracta* was visually assessed and measured. We believe the C_d decrease as d/D increases is caused by the flow streams bending sharply around the curved surface of the riser and forcing the *vena contracta* to become thinner in the vertical plane. We also noted from the visual assessment that as h reduces, the *vena contracta* area increases. This is what causes C_d to increase at low h/d values and why the error associated with assumed h is not evident in the measured discharge data.

Notation

These symbols are used in this chapter:

$a, b, c, p, q,$ and s = generic fit coefficient

A = orifice area (generic)

A_b = bit area

A_e = ellipse area

A_i = inner area

A_o = outer area

A_t = tank area

A_{vc} = vena contracta area

$C_{d(b,o,i,e)}$ = measured coefficient of contraction for each area definition

C_c = coefficient of contraction

C_d = orifice discharge coefficient

$C_{d,int}$ = integral orifice discharge coefficient

$C_{d,model}$ = model orifice discharge coefficient

C_v = coefficient of velocity

d = orifice diameter

D = riser diameter

g = acceleration due to gravity

h = head above center of orifice

L = arc length of orifice cut along curved riser pipe

l_{vc} = measure vena contracta height

Q = orifice flow rate

$Q_{b,o,i,e}$ = integral form of the orifice equation for each area definition

Q_{int} = basic integral form of the orifice equation

Q_{meas} = measured flow rate

t = time

v = actual velocity

v_i = ideal velocity

w_{vc} = measured vena contracta width

$x, y,$ and z = coordinate definitions

z_o = height of the orifice center above the tank bed

θ = angle relative to positive z around the orifice cut

References

- Davis, C. V., and K. E. Sorensen. 1969. *Handbook of applied hydraulics*. 3rd ed. New York, NY: McGraw-Hill.
- Finnemore, E. J., and J. B. Franzini. 2002. *Fluid mechanics with engineering applications*. 10th ed. New York, NY: McGraw-Hill.
- Gregg, W. B., D. E. Werth, and C. Frizzell. 2004. Determination of discharge coefficients for hydraulic sparger design. *ASME J. Pressure Vessel Technol.* 126(3), 354–359.
- HOB0. 2011. Product specification for the U20-001-04. Bourne, MA.: Onset. Available at: <http://www.onsetcomp.com/callback/show-specs?n=2373>. Accessed 12 December 2011.
- Jarrett, A. R. 1993. Design of perforated risers to control dewatering of sedimentation basins. *Appl. Eng. Agric.*, 9(1), 37–42.
- Maple. 2010. *Maple for Windows*. Ver. 15. Waterloo, ON.: Maplesoft.
- McLemore, A. J., J. S. Tyner, and D. C. Yoder. 2011. Discussion of “Investigation of flow through orifices in riser pipes” by P. D. Prohaska, A. A. Khan, and N. B. Kaye. *J. of Irrigation and Drainage Eng.*, 137(9), 632-633.
- Prohaska, P. D., A. A. Khan, and N.B. Kaye. 2010. Investigation of flow through orifices in riser pipes. *J. of Irrigation and Drainage Eng.*, 136(5), 340-347.
- Stockie, John M. 1998. The geometry of intersecting tubes applied to controlling a robotic welding torch. *MapleTech* (Special Issue on Maple in Industry), 5(2-3), 58–66.

- Encyclopædia Britannica. 2012. Torricelli's theorem. Chicago, IL.: Encyclopædia Britannica, Inc. Available at: <http://www.britannica.com/EBchecked/topic/600154/Torricellis-theorem>. Accessed 19 April 2012.
- Visser, K. K., J. M. Steichen, B. M. McEnroe, and J. Hua. 1988. Hydraulics of perforated terrace inlet risers. *American Society of Agric. Eng.* 31(5), 1451-1454.

CHAPTER III

OPTIMIZATION OF THE SOILD STATE SKIMMER

Abstract

This research focuses on development and optimization of the Solid State Skimmer (SSS) as an outlet control device for a sediment retention basin. Sediment basins on construction sites help retain sediment on-site so it cannot enter creeks, streams, rivers, and other waterways. The basin sediment trapping efficiency can be increased by using a skimmer outlet such as the SSS, as it extracts from the top of the basin water from which the sediment has already been removed by settling. A modified overflow basin design method is herein presented to quantify the efficiency of the SSS based on its ability to increase top water discharge. The new method takes into account the elevation of the exiting water. A program is presented that utilizes this modified overflow method to optimize the design of the SSS for a multi-storm sediment basin. A SSS was successfully modeled to meet peak flows and a minimum retention time for six storm events on a site whose management varied from natural vegetation to bare soil. The SSS increased efficiencies by 12.0, 41.7, and 36.0% for a single storm simulation and 0.0178, 14.9, and 31.4% for a multiple storm simulation. The analyzed particles were a sand, silt, and clay, respectively.

Introduction

The Environmental Protection Agency (EPA) is mandated by the Clean Water Act to protect our waterways (EPA, 2007). According to the EPA (2007), one of the major issues is that 35-45 tons of sediment per acre each year may be lost due to erosion

from construction sites, and ultimately a portion of it enters our streams, rivers, lakes, and estuaries, where the pollutant can reduce hydraulic capacity, convey toxic materials, decrease habitat quality, and increase drinking water cost (EPA, 2007). To combat this issue, the EPA has set requirements for erosion and sediment control. The implementation of a sediment retention basin is one of the requirements for construction sites having a drainage area of 10 or more acres (NPDES, 2011). Peak discharge rates from construction sites are often regulated to mitigate flooding in Municipal Separate Storm Sewer System as specified by state, city, town, village, or other public entity (NPDES, 2011). A stormwater detention basin comprised of storage and an outlet structure can be used to regulate peak discharge rate. In many cases, the functions of sediment retention basin and stormwater detention basin are designed into a single basin, though the outlet control may differ for the two purposes.

Studies indicate that perforated risers and floating skimmers can increase a sediment basin's trapping efficiency. Jarrett (2001) examined eight studies and summarized that a perforated riser on average is able to retain 82.0% of incoming sediment mass, while a floating skimmer increases the efficiency to 91.1% of the total incoming sediment load for a Hagerstown silt loam "A" horizon soil. McCaleb and McLaughlin (2008) conducted a study comparing traditional rock dams, normal and oversized basin configurations with a chemical flocculent additive, and a floating skimmer. Normal basins were sized to attenuate a 10-yr Type II 24 hr storm event and the oversized basins were sized for a 25-yr Type II 24 hr storm event. Their findings

indicate that traditional rock dams—with and without a larger than normal basin and silt fence baffles—retained less than 45% of the entering sediment. They found that a design with a floating skimmer, larger basin, porous baffles, and stable sides was able to retain 99% of the total sediment that entered the basin over 33 storm events. They did report, however, that the floating skimmer became stuck in the mud and submerged at the bottom the basin, which greatly decreased efficiency.

Pilon (2010) discusses a recently developed outlet structure that uses no moving parts but still combines the depth-related flow rates of a perforated riser with the skimming effect of a floating skimmer outlet; this device is referred to as the Solid State Skimmer (SSS). The SSS consists of two perforated risers—one inside the other—which are designed to maintain during discharge a water height within a chamber between the two pipes slightly lower than the height of water in the basin. The difference in height between the basin and the water level within the chamber defines the *differential head* on the submerged orifices of the outer pipe. The SSS is designed to have increasing orifice area as elevation increases, therefore a small *differential head* equates to less flow through the bottom submerged orifices compared to the upper submerged orifices. Pilon's (2010) initial proof of concept study of the SSS determined that the flow characteristics can be modeled and implemented with reasonable accuracy. He also found that the SSS, on average, reduced turbidity by 10% compared to a traditional perforated riser, which is similar to the reported performance of floating skimmers. The proof of concept study validated the hydraulics and illustrated the retention benefits, but

little consideration was provided as to how the design could be optimized for a sediment retention basin on a specific site.

Sediment basins are commonly designed using the overflow method, which assumes the stormwater moves through the basin as plug flow, the suspended sediment settles according to Stokes' law, and the incoming sediment is evenly distributed throughout the height of the water column (Fifield, 2001). By applying those assumptions, the amount of sediment retained can be determined for a given flow rate, basin geometry, and sediment distribution, or conversely a basin's size can be determined so as to meet a specific retention requirement. Fifield (2010) presents a basin geometry efficiency parameter for a rectangular basin that functions as a mixing correction factor, referred to as the apparent effectiveness:

$$A_{eff} = 20(l:w) - (l:w)^2 \quad (26)$$

valid for $l:w$ (*length:width*) values less than 10, and where the effectiveness A_{eff} is a percentage. This relationship indicates that A_{eff} is assumed to be 100% effective when the basin has a *length:width* ($l:w$) of 10. The net sediment trapping efficiency (N_{eff}) then becomes the product of the theoretical percent mass of sediment retained and the apparent effectiveness

$$N_{eff} = PEG \cdot A_{eff} \quad (27)$$

where PEG is the mass Percent Equal to or Greater than the smallest particle size that will settle in a given basin configuration at a given flow rate based on stokes law. N_{eff} as defined by the overflow method does not increase if the outlet is a skimming device.

Therefore, the overflow method does not consider whether the water discharges from near the top or bottom of the basin, or can alternatively be defined as assuming that all discharging water has an even concentration of the unsettled sediment and leaves evenly across the vertical distribution of the water column.

The goal of this project is to develop an automated optimization process for peak performance of the Solid State Skimmer (SSS) in a sediment basin. To achieve this goal, the overflow method was investigated and a modified approach is proposed to account for the location, quantity, and quality of water discharging from the basin. The modified approach of the overflow method can be used to track sediment movement in the basin and define a basin's efficiency. The basin efficiency process is presented including a software version coded in MATLAB for automated optimization. A multi-storm basin was simulated with the MATLAB program to compare efficiencies between a traditional riser and the SSS.

Methods

The first task was to modify the overflow method to account for the location, quantity, and quality of the discharging water such that a skimmer increases a basin's efficiency and an outlet draining solely from the basin bottom decreases efficiency, while an even vertical distribution of outflow results in efficiencies similar to the standard overflow method. The location of unsettled particles in the water column at the basin outlet can be determined by tracking the distance the particles fall as they travel from the basin inlet to the outlet. This is supported by the findings of Jarrett (2001) and McCaleb

and McLaughlin (2008), who found that floating skimmers increase sediment trapping efficiency.

To determine the percentage of sediment retained in a basin during a single storm event, the movement of the particles through the basin will be modeled assuming ideal conditions (i.e., plug flow with no mixing). It is assumed that particles are initially evenly mixed in the plug, and particles settle according to Stokes' law (Fifield, 2001). To account for mixing, the A_{eff} factor developed for the overflow method will be used as a correction factor (Fifield, 2001). The modified approach determines efficiency for each plug of water that passes through the basin independently based on the volume of water discharge during a set time interval. And each particle size in the plug of water is examined independently and expressed as a percentage of the total mass of particles in a given plug of water. Thus the efficiency for each plug of water is determined by accounting for the percent mass of each particle size that settles before reaching the outlet and the percent mass of each particle size that settles at the outlet because of outlet design. Then the efficiency of the basin for the storm event is a function of the efficiency for each discharging water volume (i.e., plug of water) and the corresponding discharged volume averaged by the total volume of the storm event.

The retention of single particle size in a plug of water that passes through the basin is defined in Figure 15. Figure 15 illustrates a plug of water moving horizontally through the basin and the vertical movement of a single particle size distributed throughout the plug, where z_c is the contaminated water boundary height from the bottom

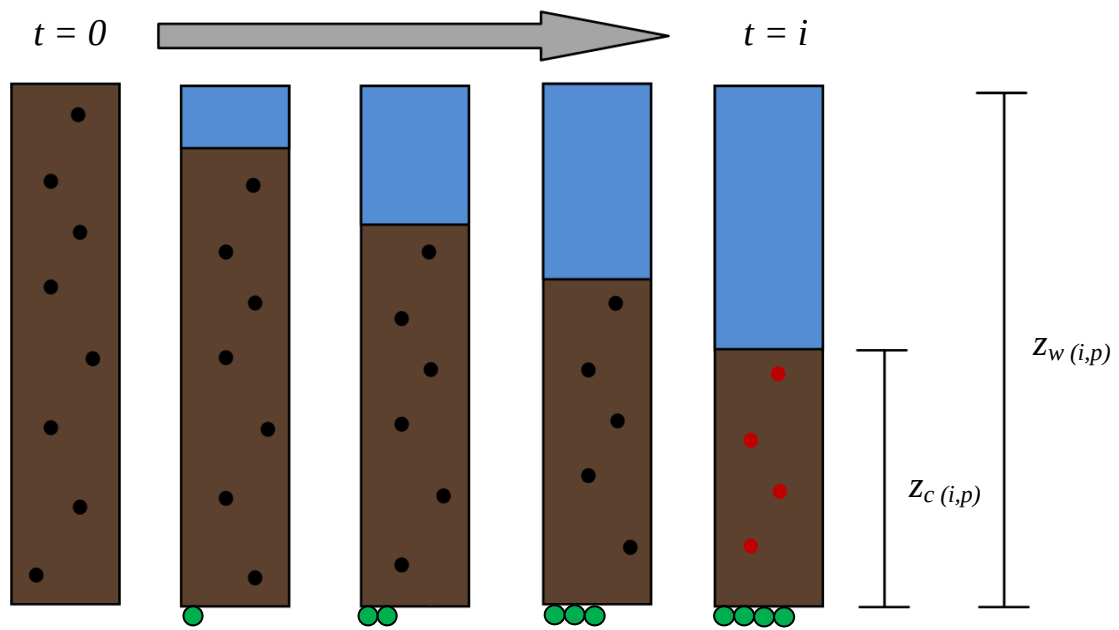


Figure 15. Sediment distribution from the inlet, $t = 0$, and to the outlet, $t = i$. **Green** particles are retained while **red** particles are subject to discharged.

of the basin, z_w is the total height of the plug of water, t is the time increment, i defines the time step when the plug of water reaches the outlet during the storm event, and p defines the particles size being analyzed. As time progresses, the particles begin to settle to the basin floor, illustrated in green. The green particles signify the percent mass of a single particle size, out of the total sediment mass in the plug, which settles before reaching the outlet, defined as M_s . This is quantified by relating the clean water mass to the total water mass

$$M_{s(i,p)} = M_{(i,p)} \left(1 - \frac{Z_c(i,p)}{Z_w(i,p)} \right) \quad (28)$$

where M is the initial percent mass of a single particle size, out of the total incoming sediment mass, in the plug of water. The particle's percent mass at the outlet, M_o , is illustrated as red particles in Figure15 and is quantified as:

$$M_{o(i,p)} = M_{(i,p)} \left(\frac{Z_c(i,p)}{Z_w(i,p)} \right) \quad (29)$$

The description above indicates the percent mass for a single particle size suspended in the plug of water at the outlet. The actual percent mass for a given particles size discharged is a function of the elevation and quantity of discharge, which is controlled by the outlet type. An outlet correction factor is introduced to defined the fraction of discharging water that does not contain the given particle size

$$Q_{eff}(i,p) = \left(1 - \frac{Q_{contaminated}(i,p)}{Q_{total}(i,p)} \right) \quad (30)$$

where Q_{eff} is the outlet correction factor, $Q_{contaminated}$ is the discharge containing the given particle size, and Q_{total} the total discharge at time i . As Q_{eff} approaches 1, the outlet discharges only water absent of the given particle size, but $Q_{eff} = 0$ when all the discharging water is contaminated with the given particle size. The product of M_o and Q_{eff} define the percent mass of a single particle retained from the exiting plug at the outlet as a result of the outlet design. Thus, the percent mass retained, M_r , for a single particle size from a plug of water that discharges the basin at time i is defined as:

$$M_{r(i,p)} = M_{s(i,p)} + M_{o(i,p)} \cdot Q_{eff}(i,p) \quad (31)$$

Substituting Eq. (28-30) into Eq. (31) yields:

$$M_{r(i,p)} = M_{(i,p)} \left(1 - \frac{Z_c(i,p)}{Z_w(i)} \frac{Q_{contaminated}(i,p)}{Q_{total}(i)} \right) \quad (32)$$

The total percent mass retained from the discharging plug of water is define as

$$M_{r(i)} = \sum_{p=1}^n M_{r(i,p)} \quad (33)$$

where n represents the number of particle sizes examined. N_{eff} for the plug of water is the product of the percent mass retained for the plug of water, (Eq. (33)), and apparent effectiveness, (Eq. (26)), defined as:

$$N_{eff}(i) = M_{r(i)} \cdot A_{eff} \quad (34)$$

assuming a constant A_{eff} . The retention efficiency for the entire storm is determined as a volume discharge weighted efficiency, defined as:

$$N_{eff} = \frac{\sum_{i=1}^m (Vol_{out(i)} \cdot N_{eff(i)})}{Vol_{tot}} \quad (35)$$

where Vol_{out} is the volume of water discharged, (i.e., volume of plug) at time i and Vol_{tot} is the total discharge volume. Figure 16 is comprised of three steps outlining the information and processes required to determine the efficiency for a known basin and outlet configuration, and one incoming storm. Step one of Figure 16 lists required information about the outlet, basin, and storm need for routing and efficiency. Routing the storm through the basin is defined in Step 2. In Step 3, the information from Step 2 is utilized to determine N_{eff} as defined by Eq. (35).

The Efficiency Method was utilized in MATLAB to automatically solve for the best SSS configuration that produces a maximize efficiency as defined by Eq. (35). Several design simulations were conducted with the MATLAB program to determine the sensitivity of the model to various inputs. The sensitivity analyses involved simulating the design of a SSS and sizing a basin to attenuate peak flows to pre-construction condition for a single storm event basin compared to multiple storms events basin. The simulations were conducted assuming a 12 acre site went from bushy-grassy land use to 8 acres of ½ acre residential lots and 4 acres of open fair-condition grass in Knoxville, Tenn. The single storm simulation involved routing the 10-yr 24-hr return period storm event, while the multiple storm simulation involved routing the 2, 5, 10, 25, 50, and 100

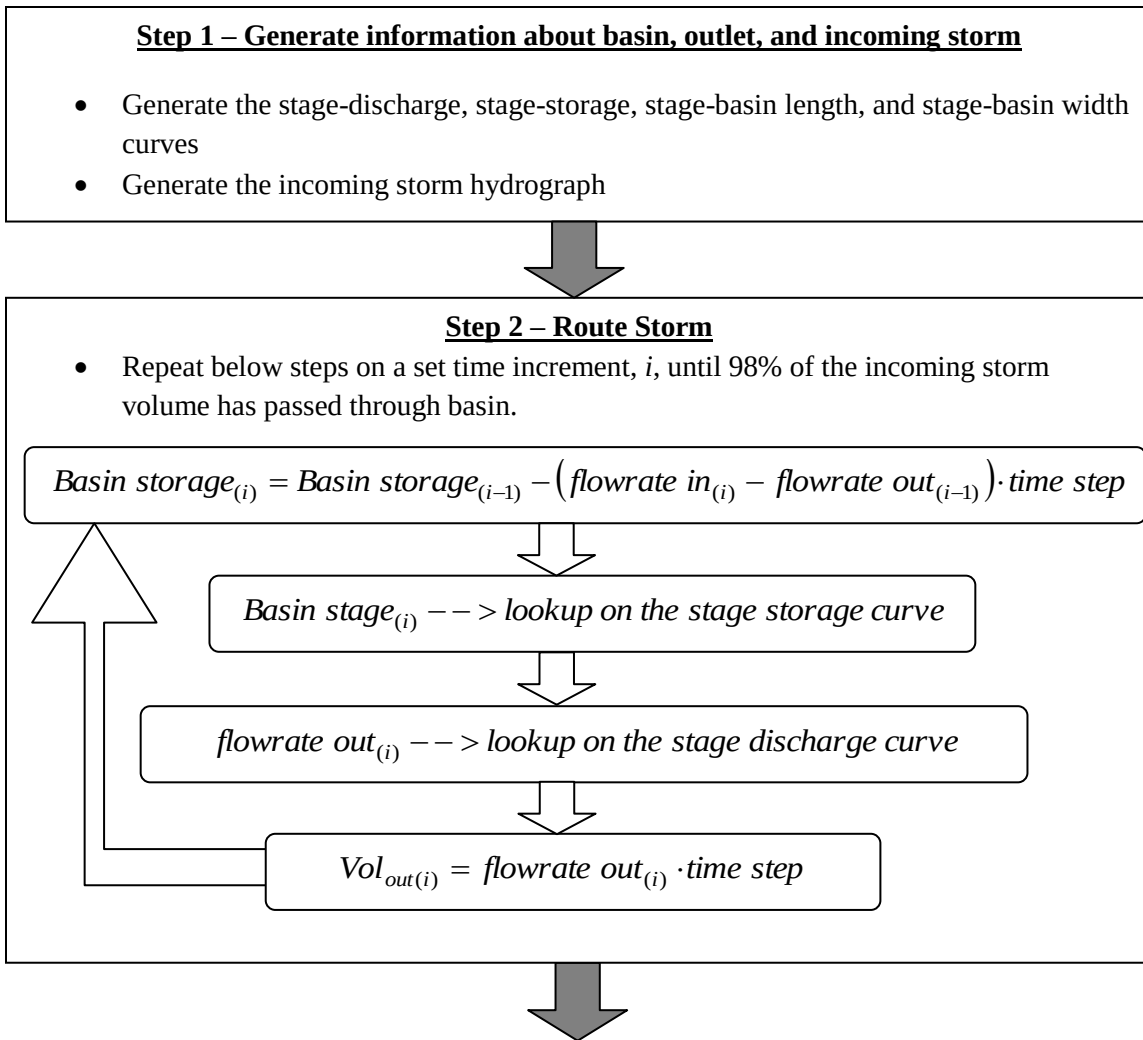


Figure 16. Efficiency and storm routing flowchart

Step 3 – Efficiency

- Repeat below steps for the length of time, i , required to route storm and number of particle sizes, p

$$residence\ time_{(i)} = \frac{basin\ area_{(i)} \cdot basin\ stage_{(i)}}{flowrate\ out_{(i)}}$$

$$\text{if } \left(\frac{particle\ settling\ velocity_{(p)}}{residence\ time_{(i)}} \right) < basin\ stage_{(i)}$$

$$z_{c(i,p)} = basin\ stage_{(i,p)} - \frac{particle\ settling\ veloc}{residence\ time_{(i)}}$$

else

$$z_{c(i,p)} = basin\ stage_{(i)}$$

$$Q_{contaminated\ (i,p)} \rightarrow \text{calculate amount of flow below } z_{c(i,p)}$$

$$M_{r(i,p)} = M_{(i,p)} \left(1 - \frac{z_{c(i,p)}}{basin\ stage_{(i)}} \frac{Q_{contaminated(i,p)}}{Q_{out(i)}} \right)$$

$$A_{eff(i)} = 20 \left(\frac{basin\ length_{(i)}}{basin\ width_{(i)}} \right) - \left(\frac{basin\ length_{(i)}}{basin\ width_{(i)}} \right)^2$$

$$N_{eff(i)} = M_{r(i)} \cdot A_{eff(i)}$$

$$M_{r(i)} = \sum_{p=1}^n M_{r(i,p)}$$

$$N_{eff} = \frac{\sum_{i=1}^m (Vol_{out(i)} \cdot N_{eff(i)})}{Vol_{tot}}$$

Figure 16. Continued

year 24-hour return period storm events. A Type-II storm distribution was assumed for all events. Storm depths and the time of concentration information was obtained from Win TR-55 for both the pre- and post-construction and storm hydrographs were generated by HydroCAD with the SCS unit hydrograph runoff method (Win TR-55, 2009; HydroCAD, 2012; Viessman and Lewis, 2003). The basin and SSS were required to attenuate peak discharge rates from post-construction state to be less than or equal to peak discharge rates from pre-construction. Each simulation was analyzed with an assumed constant addition of sediment evenly distributed into the incoming water column. Because efficiencies for each sediment type/distribution are determined independently, clay, silt, and sand were analyzed separately for each simulation. For modeling purposes, the clay, silt, and sand were assumed to be spherical and have particle diameters of 0.002, 0.02, and 0.2 mm, respectively. These values were selected for the analysis because of their relative sizes and use in Fifield (2001). A_{eff} was assumed to be 100%, which meant assuming a $l:w$ (*length:width*) of 10. The basin walls were assumed vertical with a maximum depth of 8 ft.

The simulations modeled the SSS with a weirs rather than discrete orifices as was done in the study by Pilon (2010). Weirs require fewer variables and ultimately are easier to model. For the single storm event simulation, the outlet of the SSS is set as a rectangular weir, so its geometry is defined by a single variable, a_{out} , that describes the weir width, and the flow rate is defined as the weir equation:

$$Q_{out} = \frac{2}{3} C_d a_{out} \sqrt{2g} h_c^{1.5} \quad (36)$$

where C_d is the discharge coefficient, g is the gravitational constant, and h_c is the head in the SSS chamber above the bottom of the weir (Finnemore and Franzini, 2002). The inlet weir needs to increase in area with increasing height, so its shape is defined as a width, a_{in} , and a slope, b_{in} . Inflow to the SSS is the sum of the submerged flow and the non-submerged flow.

$$Q_{sub} = C_d \left(a_{in} h_c + b_{in} h_c^2 \right) \sqrt{2g} dh \quad (37)$$

$$Q_{non-sub} = C_d \left(\frac{2}{3} a_{in} + \frac{8}{15} b_{in} h_b + \frac{4}{5} b_{in} h_c \right) \sqrt{2g} dh^{1.5} \quad (38)$$

where h_b is the head in the basin above the bottom of the weir and dh is difference between h_b and h_c (Pilon, 2010). Figure 17 is an illustration of a SSS designed with weirs and references the portions of flow through inlet weir defined by Q_{sub} and $Q_{non-sub}$. The multiple storm event simulation requires the inflow and outflow weir to have more degrees of freedom to achieve optimal skimmer, thus additional terms were added to Eqs. (36-38). Outflow from the skimmer for the multiple storm simulation was defined as:

$$Q_{out} = C_d \left(\frac{2}{3} a_{out} h_c^{1.5} + \frac{8}{15} b_{out,1} h_c^{2.5} + \frac{16}{35} b_{out,2} h_c^{3.5} \right) \sqrt{2g} \quad (39)$$

where $b_{out,2}$ is the addition geometric term. Inflow to SSS was defined as:

$$Q_{sub} = C_d \left(a_{in} h_c + b_{in,1} h_c^2 + b_{in,2} h_c^3 \right) \sqrt{2g} dh \quad (40)$$

$$Q_{non-sub} = C_d \frac{2}{105} \left(35 a_{in} + 28 b_{in,1} h_b + 24 b_{in,2} h_b + 42 b_{in,1} h_c + 36 b_{in,2} h_c h_b + 45 b_{in,2} h_c^2 \right) \sqrt{2g} dh^{1.5} \quad (41)$$

where $b_{in,2}$ is the addition geometric term.

The resulting efficiencies from the SSS and basin design simulations were compared to efficiencies from the same basin but using a traditional perforated riser. The tradition riser was simulated to have an equivalent stage discharge curve as the SSS. Flow through the traditional riser, modeled as a weir, for the single storm simulation was defined as:

$$Q_{trad\ weir} = C_d \left(\frac{2}{3}a + \frac{8}{15}b h_b \right) \sqrt{2g} h_b^{1.5} \quad (42)$$

where a and b are the parameters that define the weir shape. Similar to the SSS multiple storm simulation, the traditional weir required addition parameters. The traditional weir for the multiple storm simulation was defined as: simulation was defined as:

$$Q_{trad\ weir} = C_d \left(\frac{2}{3}a + \frac{8}{15}b h_b + \frac{16}{35}b_2 h_b^{2.5} \right) \sqrt{2g} h_b^{1.5} \quad (43)$$

where b_2 is the addition term. The equivalent stage discharge curve was determined by solving for the geometer parameters that produce the least sum of square error between discharge rates. To quantify how flow per elevation differs between the SSS and traditional weir for a given stage, flow rates per elevation for the multiple storm simulation were compared at multiple stages.

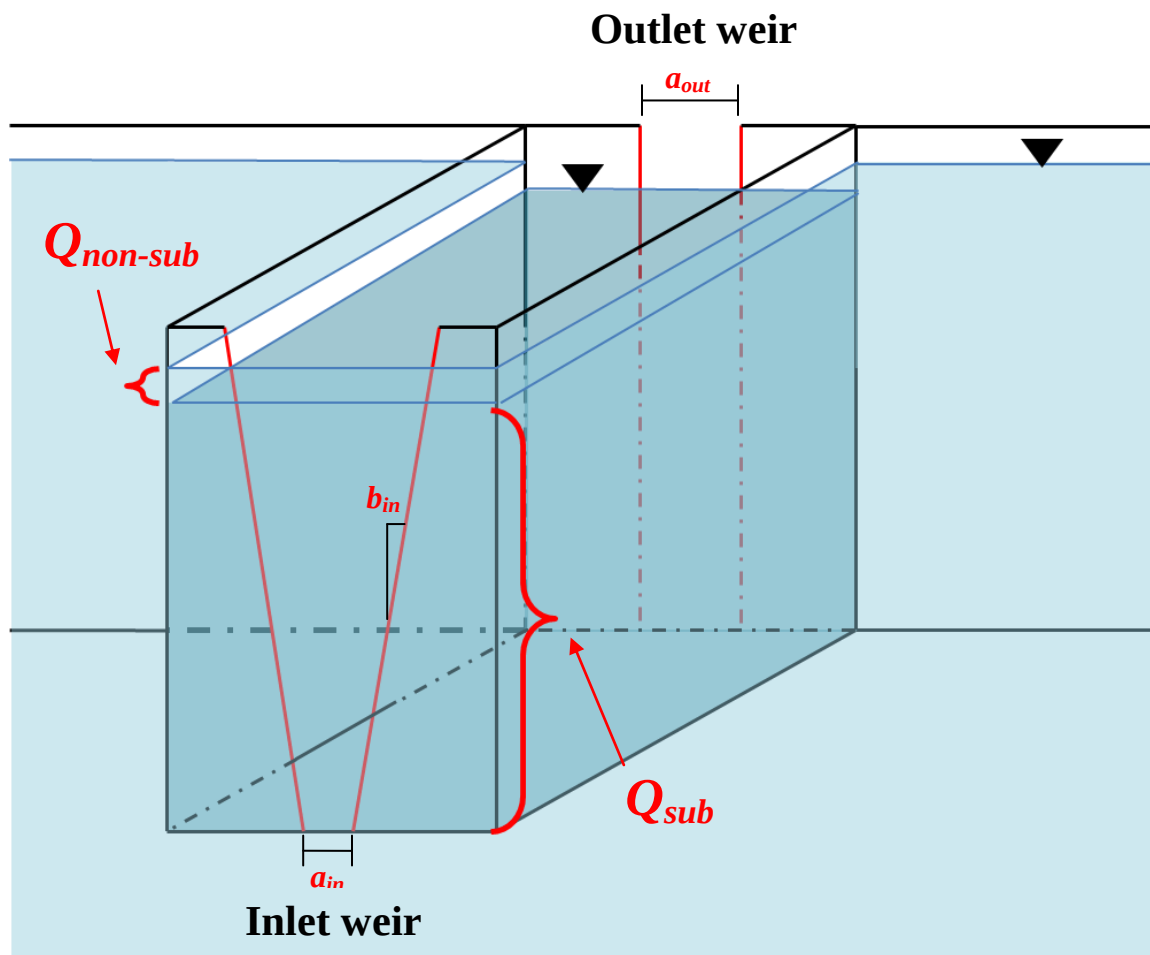


Figure 17. SSS weir configuration

Results and Discussion

MATLAB program

Design of the SSS for use in a sediment basin is optimized by maximizing N_{eff} for a set basin configuration through a multi-step process. This process is outlined in Figure 18, and has three main components; the input and variable initialization, optimization looping, and output. Due to the complexity of the optimization process, MATLAB functions are utilized to automate variable adjustments, repetition, and optimization (MATLAB, 2011). The MATLAB controlled functions are those located in the *Optimization Loop* of Figure 18.

The entire process was coded within eight MATLAB files. These eight files can be broken down into three groups; setup/initialization, control processes, and process files. Setup/initialization of the program is one file that handles the details on the left side of Figure 18 (Appendixes 1.1). Input variables for the optimization include the geometric parameters of the SSS and 20 points to define the dh curve. The initial shape of the dh curve was defined by 20 values because this proved to be a good combination of resolution and speed. The inclusion of the basin area as an optimization variable is left to the user because testing indicated that the additional variable overwhelmed the optimization function and no solution could be found. Therefore, to achieve an optimal design it is up to the user to make an “educated guess” for the basin area and then iteratively change the value over several optimization runs until a minimum area and/or efficiency is met while meeting constraints.

The MATLAB function *fmincon* automates the optimization process. This function works by minimizing an objective value while meeting constraints. The *SQP* optimization algorithm was chosen as the variable selection gradient because it was described as the appropriate algorithm for the number of inputs size and constraints required for the optimization. Objective and constraint functions call the process files and generate the inputs for *fmincon*, thus they are the control process files (Appendix 1.2). The process files include the subroutines that generate the stage discharge curve, interpolate the *dh* curve, calculate the distribution of discharge for a each stage, route storms, and calculate efficiency (Appendix 1.3).

The objective file is organized to first generate the stage discharge curve. Then, a spline function is fit to the 20 *dh* points to produce a continuous *dh* curve. This high-resolution *dh* curve is used to develop a discharge distribution matrix and stage discharge curve. The stage discharge curve is used by the routing routine to determine the discharge rates and the corresponding stage at each time step for the duration of each storm event. The discharge distribution matrix includes the incremental flow per unit of height (i.e., numerical integration) for each stage in the basin. Lastly, this matrix along with the discharge rates and the corresponding stage at each time step for the duration of the storm events are used by the efficiency routine to calculate $N_{eff, total}$. The efficiency routine first determines $N_{eff, total}$ for each storm event and then combines them into one value by calculating a storm event frequency weighted efficiency based on a 100 year period.

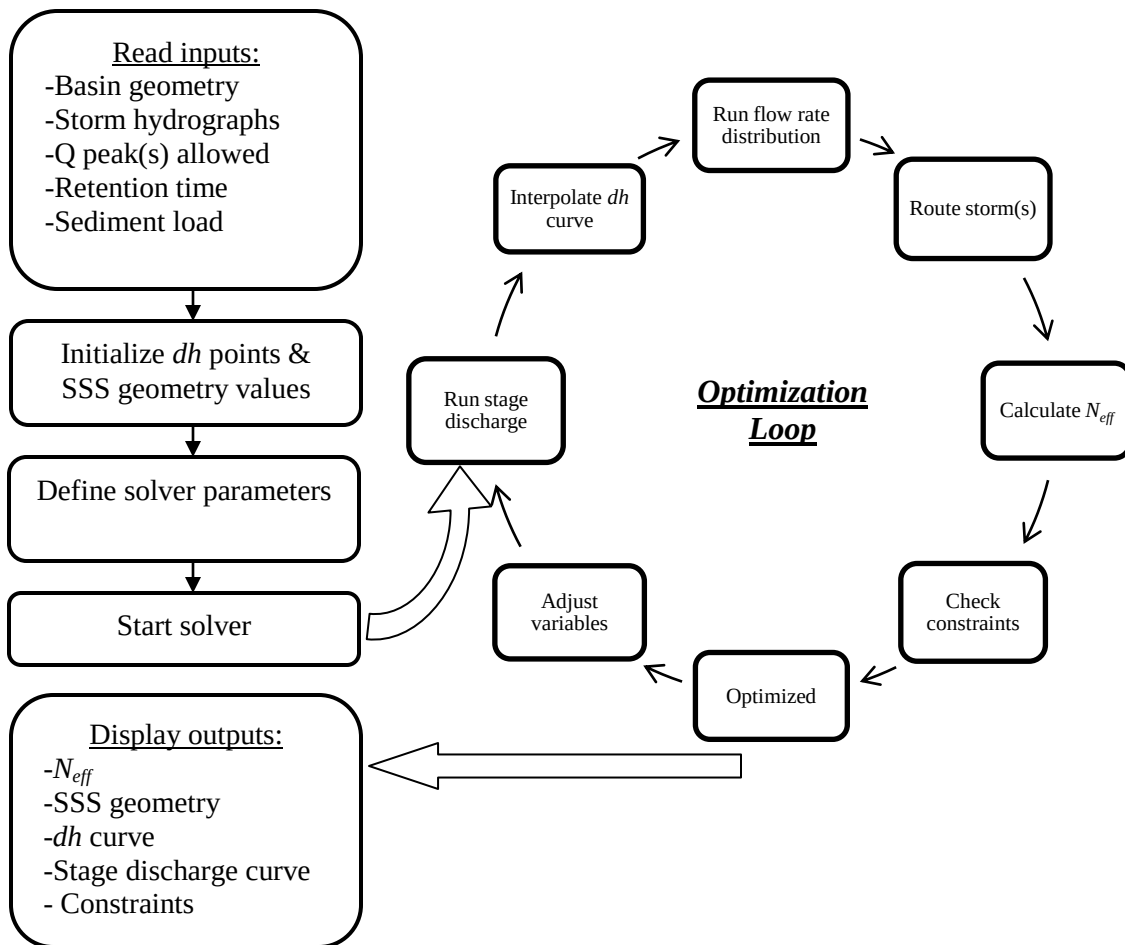


Figure 18. Optimization flowchart

$$N_{eff (mult \ storms)} = \frac{\sum_{m=1}^j N_{eff (m)} \cdot k_{(m)}}{\sum_{m=1}^j k_{(m)}} \quad (44)$$

where k is the number of occurrences during a given time span of the m defined storm event and $N_{eff (m)}$ is the efficiency of the m defined storm event, for j number of storm events. The multiple storm efficiency is set as a negative value because the objective is to have the maximum efficiency and $fmincon$ minimizes the objective value.

The constraint function first calculates the difference between the inflow and outflow rates of the SSS for each stage to ensure that they are equal. This constraint is calculated in the stage discharge routine. Additionally, the stage discharge routine generates a constraint that indicates if the peak discharge at the maximum basin stage is less than or equal to the peak allowable.

The final constraints come from the routing subroutine. These include peak discharges and percent of the storms that route through the basin in the allowed maximum retention time. For this study, a storm is defined as fully drained when 98% of the total storm volume has passed through the basin.

Sensitivity analysis

The optimal parameters of the SSS for the single storm were $a_{in} = 0.1384$ ft, $b_{in} = 0.1123$ and $a_{out} = 0.1384$ ft and the traditional riser parameters were $a = 0.1304$ ft and $b = 0.0010$. The basin area was 3400 ft^2 with a constant depth of 8 ft. Figure 19 illustrates

the stage discharge curves for the SSS and traditional riser and dh for the SSS. Figure 20 is the incoming storm hydrograph—in this case for a 10-yr Type-II 24 hr storm—and the outflow hydrograph for the SSS and traditional riser. It is evident in both Figures 19 and 20 that the traditional riser has a similar stage discharge curve and routing discharge values to the SSS. Table 5 displays the trapping efficiencies for the single storm analysis. The SSS increase the efficiencies an average 29.9% for clay, silt, and sand, with the greatest efficiency increase of 41.7% for silt. Even though the efficiencies increased when the SSS is employed, the overall percent of clay retained is still relatively low, especially if compared to sand and silt.

For the multiple storm simulation, the SSS parameters were optimal when $a_{in} = 0$ ft, $b_{in,1} = 0.4471$, $b_{in,2} = -0.0287$, $a_{out} = 0.0669$ ft, $b_{out,1} = 0.0834$, and $b_{in,2} = -6.016 \text{ E-3}$. The traditional riser parameters were $a = 0.0557$ ft, $b_1 = 0.0852$, and $b_2 = -6.370 \text{ E-3}$ for an equivalent stage discharge curve. The minimum basin area that produced results capable of meeting all constraints was 6260 ft^2 with a constant basin depth of 8 ft. It took the MATLAB program approximately 1.3 hours on a 2.9 Ghz dual-core PC with 2 GB of RAM to determine the optimal SSS parameters. The stage discharge curves for the SSS and traditional riser are shown in Figure 21 along with the dh curve for the SSS. The smaller storm events—more frequently occurring—force the dh curve to have the lowest values at small *head*. Table 6 lists the pre-construction peak discharges and post-construction peak discharges from the basin for the SSS and traditional riser outlet. The peak discharges differ slightly—mainly at high *head*—where an average absolute

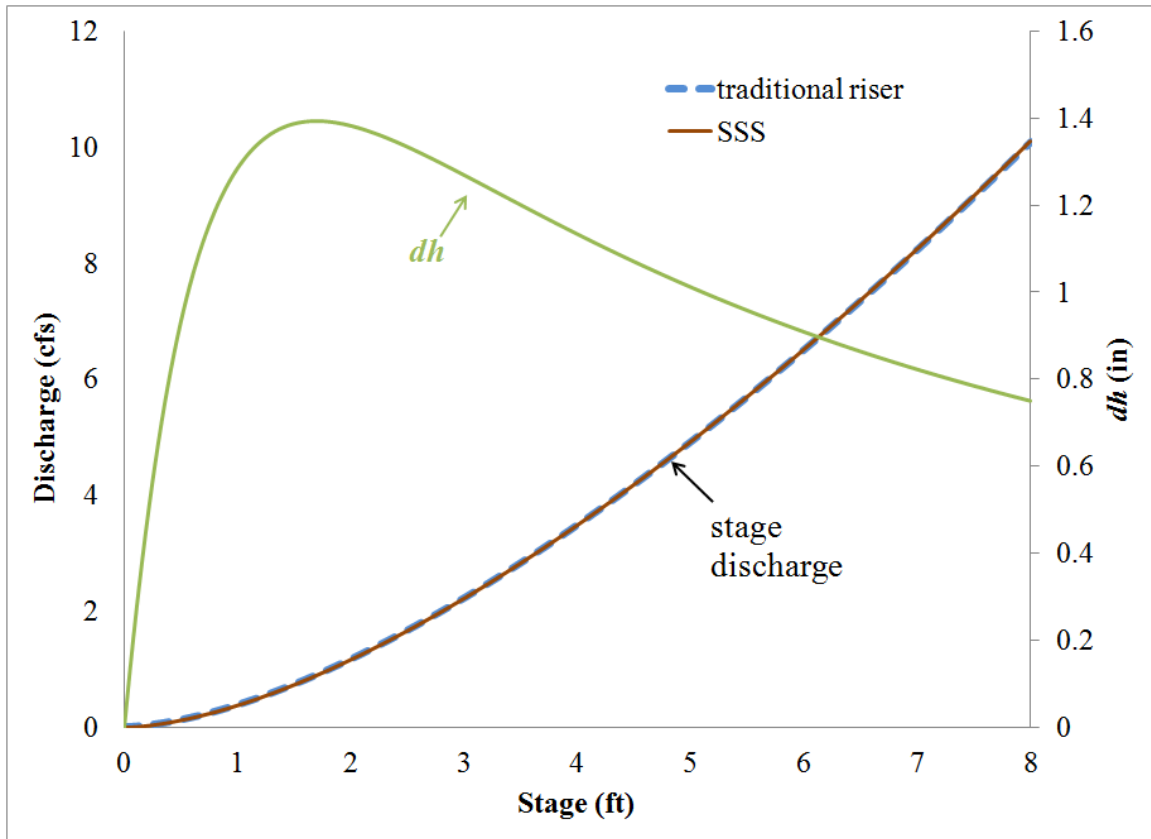


Figure 19. Single storm simulation stage discharge and dh curve

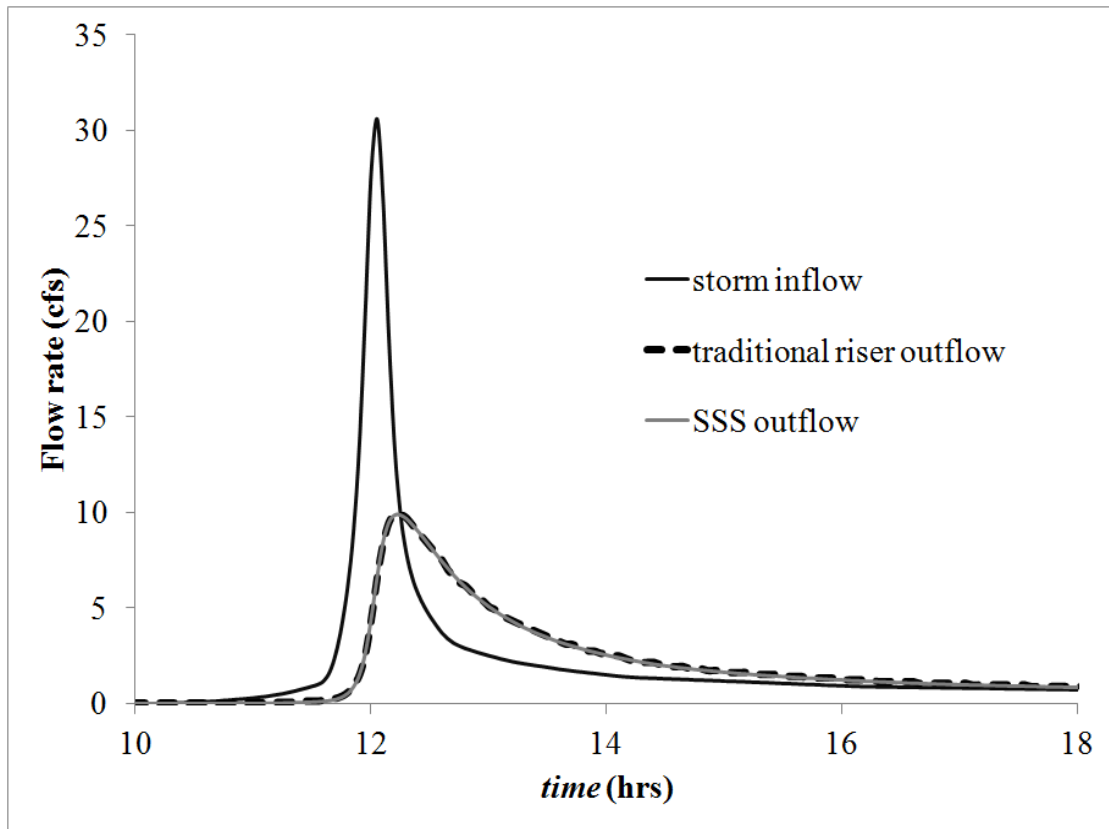


Figure 20. Single storm simulation inflow and outflow hydrographs

Table 5. Single storm simulation sediment trapping efficiencies (%)

	Trad. riser	SSS	% increase
Sand	75.8	84.8	12.0
Silt	21.4	30.3	41.7
Clay	2.97	4.04	36.0

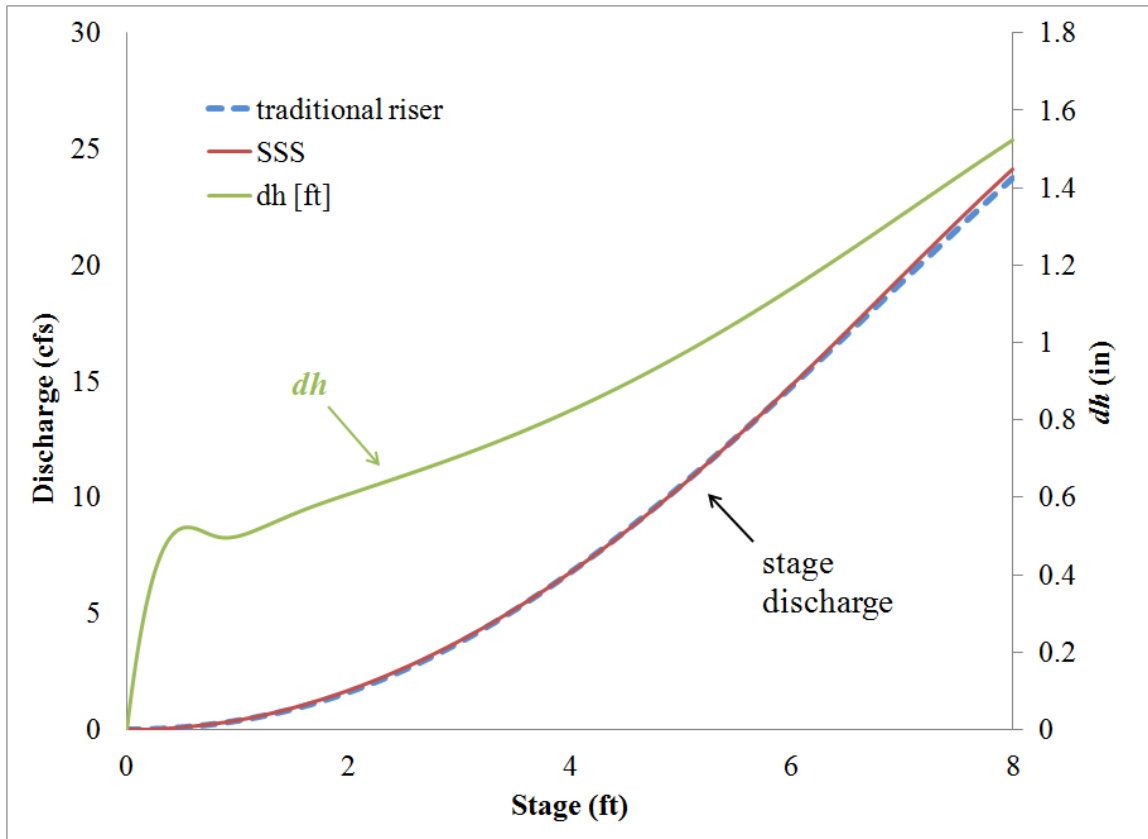


Figure 21. Multiple storm simulation stage discharge and dh curves

Table 6. Peak flow rates (cfs) for 2, 5, 10, 25, 50, and 100-yr storm events

<i>Storm</i>	<u>2-yr</u>	<u>5-yr</u>	<u>10-yr</u>	<u>25-yr</u>	<u>50-yr</u>	<u>100-yr</u>
	Q	Q	Q	Q	Q	Q
Pre	2.20	6.80	10.1	16.2	22.2	24.8
Trad. riser	2.12	5.89	8.91	14.8	20.4	22.8
SSS	2.18	5.88	8.90	14.9	20.7	23.1

difference of 0.094 ft³/sec was measured between the stage discharge curves.

Efficiencies for the multiple storm simulation are located in Tables 7. The SSS improved efficiency for each storm event and sediment range, except for sand during the 2-yr storm event. This is most likely the cause of slightly better performance from the traditional riser at very low *head*, but the percent difference is negligible at only a 0.521% decrease. The percent increase in efficiency for sand and silt increased as the storm event size increased, but efficiency increases for clay were almost constant for each storm event. When analyzing the basin and outlets over a 100 year period (storm event frequency weighted average), the SSS increased efficiency by 0.418% for sand, 14.0% for silt, and 36.3% for clay. These results indicate that the outlet design has little effect on retention of sand. Sand efficiencies are high for both outlets because the majority settles before reaching the outlet. It should be noted that the increased efficiencies for clay are optimistic because modeling the movement of clay in the basin with Stokes' law is a greatly simplified approach for such a small particles. Additionally, the relatively low efficiencies of clay—especially for the larger storm events—indicates that the clay is in theory is only slightly below the surface of the exiting water column. The possibility for mixing, especially near the top of the water column, would eliminate any increase in efficiency for any outlet type, even floating skimmers.

Overall the SSS is more sensitive to retaining silt. This is evident in both the single and multiple storm simulations, where the percent increase of efficiency varies from 10.3% to 26.1% for the multiple storm event simulation and is the greatest for the

Table 7. Multiple storm retention efficiencies for the Traditional and SSS riser

Multiple storm retention efficiencies									
storm event (yr)	<u>Sand</u>			<u>Silt</u>			<u>Clay</u>		
	<i>Trad.</i>	<i>SSS</i>	<i>% inc.</i>	<i>Trad.</i>	<i>SSS</i>	<i>% inc.</i>	<i>Trad.</i>	<i>SSS</i>	<i>% inc.</i>
2	96.9	96.4	-0.521	68.7	75.8	10.3	14.1	19.2	35.8
5	96.9	97.1	0.158	48.3	56.4	16.8	8.71	11.9	36.9
10	92.7	94.6	2.02	40.9	48.9	19.5	7.10	9.73	37.2
25	83.3	87.4	4.84	32.6	40.1	22.9	5.44	7.45	36.9
50	75.8	80.7	6.45	27.6	34.6	25.2	4.51	6.17	36.9
100	73.1	78.1	6.78	25.9	32.7	26.1	4.19	5.74	36.8
Weighted*	95.1	95.4	0.418	57.7	65.1	14.0	11.4	15.5	36.3

*frequency weighted over 100-yr period

single storm event simulation, 41.7% increase. The greater increase of efficiency noted for the single storm event simulation suggests that the SSS is better suited to increase retention efficiency for fewer storm events.

Figure 22 illustrates the discharge per elevation for the resulting SSS and traditional riser from the multiple storm simulation at 8, 4.5, and 1 ft. For comparison, the elevation with 50% flow above and 50% flow below is 4.7 ft for the SSS and 3.6 ft for the traditional riser at an elevation of 8 ft and is 3.0 ft for the SSS and 2.3 ft for the traditional riser at an elevation of 4.5 ft. At 1 ft of elevation, 50% flow above and 50% flow below is at 0.69 ft for the SSS and 0.49 ft for the traditional riser. These results are reflective of the dh curve in Figure 21, better skimming at low dh values—low *head*—while less skimming at high dh values—high *head*.

Many factors must be considered when implementing the modified overflow method to quantify retention efficiencies. This method relies on several models, many of which rely on other models, to determine efficiency, which can result in compounding error. Additionally, many of the models are simplified to increase speed and reduce the need for complex formulas, such as the mixing coefficient, A_{eff} . The mixing parameter is a sole term designed to account for the basin shape. It does not account for the entrance type or other basin attributes such as baffles, both of which can alter trapping efficiencies. Another simplification is the assumed plug flow for the horizontal movement in the basin. This assumption becomes less accurate near the entrance and exit of the basin. Assumed plug flow at the outlet is not always accurate because each of the outlets drain

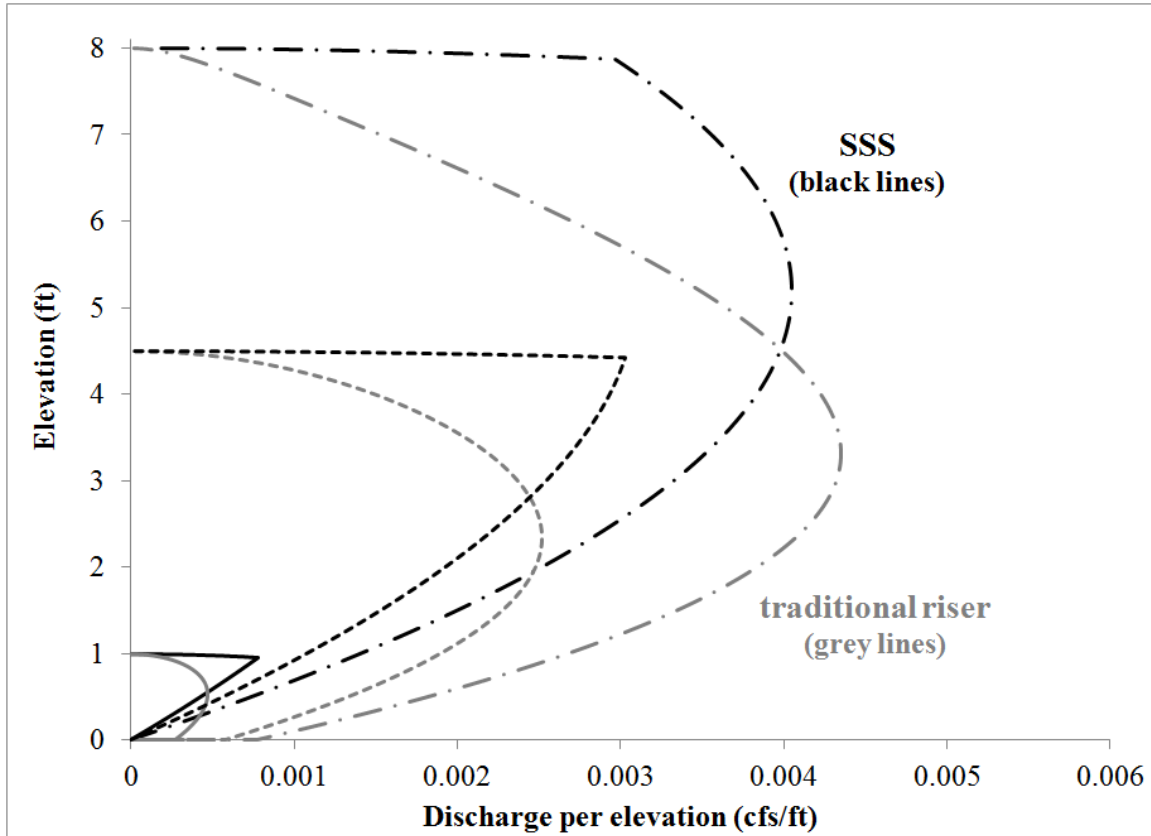


Figure 22. Discharge per elevation at max stage for the multiple storm simulation

differently along the elevation of the exiting water plug. This is especially true for a floating skimmer, because all of discharge is theoretically from the top, but in reality, the discharging water will come from near the top. An additional term may be needed to accurately model and compare a floating skimming outlet to outlets discharging along the entire column, such as the SSS and tradition riser.

Conclusion

It is evident that the use of skimmers in sediment basin can improve sediment retention. The SSS, a new type of skimmer, proved in an initial study that it can remove the cleaner upper basin water and thereby reduce turbidity with less complexity and no moving parts. Further investigation and refinement of the design is needed to maximize the sediment trapping efficiency of the SSS. The overflow method is commonly practiced method to determine retention efficiency, but lacks a method to account for the outlet elevation. A modification to the overflow method was developed that tracks the sediment to the outlet and quantifies the location and quantity of the discharging water so as to determine its sediment load.

MATLAB was utilized as a means to automate the design of a SSS for basin. The program includes a setup file that initializes the *fmincon* MATLAB function. The *fmincon* function then takes control by iterating between the objective and constraint routines while changing the SSS geometric parameters and the *dh* values. Subroutines are utilized by the objective and constraint functions to perform tasks such as generating a stage discharge curve, routing storms, and calculating efficiency. Multiple simulations

were conducted with MATLAB program to analyze the sensitivity of the efficiency model. The SSS increases storm event weighted trapping efficiencies from 95.1% to 95.4% for clay, 57.7% to 62.1% for silt, and 11.4% to 15.5% for clay for the multiple storm event simulation. The SSS, for the single storm simulation, increased efficiencies from 75.8% to 84.8% for sand, 21.4% to 30.3% for silt, and 2.97% to 4.04% for clay, indicating that the SSS is more beneficial when designed for fewer storm events. The SSS was more sensitive to the retention of silt. Percent retention increases for silt ranged from 10.3% to 26.1% for the multiple storm event simulation and was the largest increase for the single storm event simulation at 41.7%.

References

- EPA. 2007. Developing your stormwater pollution prevention plan: a guide for construction sites. EPA-833-R-06-004. Washington, DC.: Environmental Protection Agency.
- Fifield, J. S. 2001. *Designing for effective sediment and erosion control on construction sites*. Santa Barbara, CA: Forester Communications.
- HydroCAD. 2012. *HydroCAD for Windows*. Ver. 10.00-4. Tamworth, NH.: HydroCAD Software Solutions LLC.
- Jarrett, A.R. 2001. Designing sedimentation basins for better sediment capture. Soil Erosion Research for the 21st Century. ASAE: 701P0007.
- MATLAB. 2011. *MATLAB for Windows*. Ver. 2011a. Natick, MA.: MathWorks.
- McCaleb, M. M., and R. A. McLaughlin. 2008. Sediment trapping by five different sediment detention devices on construction sites. Trans. ASABE 51(5): 1613-1621.
- National Pollutant Discharge Elimination System (NPDES). 2011. Local ordinances for construction site runoff control. Available at:
http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=factsheet_results&view=specific&bmp=66. Accessed 15 December 2011.
- Pilon, B. S. 2010. Stormwater best management practices: improvement and evaluation. M. S. thesis. Knoxville, TN: Univ. of Tennessee, Department of Biosystems Engineering.

Viessman, Jr. W., and G. L. Lewis. 2003. *Introduction to Hydrology*. 5th ed. Upper Saddle River, NJ.: Pearson Education, Inc.

Win TR-55. 2009. *Win TR-55 for Windows*. Ver. 1.00.09. Washington DC.: Natural Resource Conservation Service.

CONCLUSION

Sediment retention basins are thought to be an effective way to reduce the amount of sediment from construction sites that enters our creeks, streams, rivers, and other waterways. The design of a basin has become more complex with the requirement of the basin to perform multiple functions such as limit peak flows, drain within a set time limit, and trapping efficiency. Thus, the design approach and modeling of a basin's various parameters require greater accuracy. Two independent but relevant issues related to design aspects of a sediment basin were studied. First, I examined the flow through circular orifices on round riser pipe, such as those often used on perforated riser in sediment basins, with mathematical models and laboratory experiments. Secondly, I developed a design process and MATLAB program to optimize the efficiency of a sediment basin with a SSS outlet device.

From the orifice study, the true area that is formed when a circular bit cuts an orifice into the side of a round riser was found to differ. Typically, the area is assumed to be equal to bit area, but we defined two distinct areas, outer and inner area, that are formed by the cut. Both areas increase as the bit diameter approaches the size of the riser diameter. When the bit diameter is half the size of the riser diameter, both areas are 1.09 times the bit area. When the bit and riser have equal diameters, the outer area is 1.27 times the bit area and the inner area is 1.41 times the bit area. The orifice area was also approximated as an ellipse because the ellipse equation is more applicable and follows the increasing area with increasing diameter that the outer and inner areas follow.

Laboratory experiments indicated that flow rate predictions with the orifice equation, assuming 0.61 for the coefficient of discharge, overestimated flow as the bit diameter increased for a constant riser diameter and was unable to explain the variation of flow when the head was low. Multiple empirical equations of the coefficient of discharge were developed to model the variation. The fit equations indicate that flow rate decreases per unit area as the bit diameter approaches the size of the riser diameter, but increases slightly when the head is low. The best fit equation explained 89.1% of the variation in the measured data with a RMSE of 0.028 when the orifice area is approximated as an ellipsis.

The SSS optimization for a sediment retention basin began with an examination of the overflow method, a commonly practiced design and efficiency estimation method. A modified approach was presented to account for the location and quantity of the discharging water. The modified overflow method models the sediment movement the same as the standard overflow method but uses the final height of the upper most particle, the particle that started at the top of the water column at time zero, to define a break between clean and contaminated water. This assumes that the incoming particles were evenly distributed at time zero. With this information, the efficiency for a given outlet is defined by the amount of clean water discharged compared to the contaminated discharge for particles that reach the outlet combined with particles that settle before reaching the outlet.

A MATLAB program developed to optimize a SSS for a sediment basin based on the efficiency defined by the modified overflow method. MATLAB was selected because of the diverse mathematical library and optimization functions. Several simulations were conducted with the MATLAB program. The SSS increased efficiencies for both a single storm design and multiple storm design. Based on a multiple storm simulation, the SSS increases storm event weighted trapping efficiencies from 95.1% to 95.4% for clay, 57.7% to 62.1% for silt, and 11.4% to 15.5% for clay. The single storm event simulation had increased efficiencies from 75.8% to 84.8% for sand, 21.4% to 30.3% for silt, and 2.97% to 4.04% for clay. These results suggest that the SSS increases efficiencies best for fewer storm events.

Using the coefficient of discharge equation while approximating of the orifice area with an ellipse when designing a perforated riser will increase flow rate prediction accuracy and sediment trapping efficiencies. Implementation of the modified overflow method can provide a more representative efficiency by considering the hydraulics of the outlet device. More specifically, the design program applies the modified overflow method to generate an optimal design for a SSS in a sediment basin to achieve improved sediment trapping. Ultimately, the equations and methods presented can help minimize sediment polluted stormwater and its negative effects.

BIBLIOGRAPHY

- Brandes, D., W. T. Barlow, and B. Hendrickson. 2010. An experimental study of stage-discharge relationships for thick-walled concrete orifices. *World Env. And Water Res. Congress 2010: Challenges of Change. ASCE*. 3329-3338.
- Bryant, D. B., A. A. Khan, and N. M. Aziz. 2008. Investigation of flow upstream of orifices. *J. of Hyd. Eng. ASCE*, Jan. 98-104.
- Chow, V. T. 1959. *Open-Channel Hydraulics*. New York, NY.: MacGraw-Hill Company, Inc.
- Davis, C. V., and K. E. Sorensen. 1969. *Handbook of Applied Hydraulics*. 3rd ed. New York, NY: McGraw-Hill.
- Encyclopædia Britannica. 2012. Torricelli's theorem. Chicago, IL.: Encyclopædia Britannica, Inc. Available at: <http://www.britannica.com/EBchecked/topic/600154/Torricellis-theorem>. Accessed 19 April 2012.
- EPA. 2009. National Water Quality Inventory: Report to Congress, 2004 Reporting Cycle. EPA-841-R08-001. Washington, DC.: Environmental Protection Agency.
- EPA. 2007. Developing your stormwater pollution prevention plan: a guide for construction sites. EPA-833-R-06-004. Washington, DC.: Environmental Protection Agency.
- Fangmeier, D. D., W. J. Eliot, S. R. Workman, R. L. Huffman, and G. O. Schwab. 2006. *Soil and Water Conservation Engineering*. 5th ed. Clifton Park, NY.: Thomas Delmar Learning.

- Fennessey, L. A. and A. R. Jarrett. 1997. Influence of principal spillway geometry and permanent pool depth on sediment retention of sedimentation basins. *Trans. of the ASAE*, 40(1), 53-59.
- Fifield, J. S. 2001. *Designing for effective sediment and erosion control on construction sites*. Santa Barbara, CA: Forester Communications.
- Finnemore, E. J., and J. B. Franzini. 2002. *Fluid Mechanics with Engineering Applications*. 10th ed. New York, NY: McGraw-Hill.
- Goldman, S. J., K. Jackson, and T. A. Bursztynsky. 1986. *Erosion and Sediment Control Handbook*. New York, NY.: McGraw-Hill, Inc.
- Gregg, W. B., D. E. Werth, and C. Frizzell. 2004. Determination of discharge coefficients for hydraulic sparger design. *ASME J. Pressure Vessel Technol.* 126(3), 354–359.
- Haan, C. T., B. J. Barfield, and J. C. Hayes. 1994. *Design Hydrology and Sedimentology for Small Catchments*. San Diego, CA.: Academic Press, Inc.
- Haestad Methods Inc. and S. R. Durrans. 2007. *Stormwater Conveyance Modeling and Design*. Exton, PA.: Bentley Institute Press.
- HOB0. 2011. Product specification for the U20-001-04. Bourne, MA.: Onset. Available at: <http://www.onsetcomp.com/callback/show-specs?n=2373>. Accessed 12 December 2011.
- HydroCAD. 2012. *HydroCAD for Windows*. Ver. 10.00-4. Tamworth, NH.: HydroCAD Software Solutions LLC.

- Jarrett, A.R. 2001. Designing sedimentation basins for better sediment capture. Soil Erosion Research for the 21st Century. ASAE: 701P0007.
- Jarrett, A. R. 1993. Design of perforated risers to control dewatering of sedimentation basins. *Appl. Eng. Agric.*, 9(1), 37–42.
- Maple. 2010. *Maple for Windows*. Ver. 15. Waterloo, ON.: Maplesoft.
- MATLAB. 2011. *MATLAB for Windows*. Ver. 2011a. Natick, MA.: MathWorks.
- McCaleb, M. M., and R. A. McLaughlin. 2008. Sediment trapping by five different sediment detention devices on construction sites. *Trans. ASABE* 51(5): 1613-1621.
- McEnroe, B. M., J. M. Steichen, R. M. Schweiger. 1988. Hydraulics of perforated riser inlets for underground-outlet terraces. *Trans. of the ASAE*, 31(4), 1082-1085.
- McLaughlin, R. A., S. A. Hayes, D. L. Clinton, M. S. McCaleb, and G. D. Jennings. 2009. Water quality improvements using modified sediment control systems on construction sites. *Trans. of the ASABE*, 52(6), 1859-1867.
- McLemore, A. J., J. S. Tyner, and D. C. Yoder. 2011. Discussion of “Investigation of flow through orifices in riser pipes” by P. D. Prohaska, A. A. Khan, and N. B. Kaye. *J. of Irrigation and Drainage Eng.*, 137(9), 632-633.
- Millen, J. A., A. R. Jarrett, and J. W. Faircloth. 1997. Experimental evaluation of sedimentation basin performance for alternative dewatering systems. *Trans. of the ASAE*, 40(4), 1087-1095.

- National Pollutant Discharge Elimination System (NPDES). 2011. Local ordinances for construction site runoff control. Available at: http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=factsheet_results&view=specific&bmp=66. Accessed 15 December 2011.
- Pilon, B. S. 2010. Stormwater best management practices: improvement and evaluation. M. S. thesis. Knoxville, TN: Univ. of Tennessee, Department of Biosystems Engineering.
- Prohaska, P. D., A. A. Khan, and N.B. Kaye. 2010. Investigation of flow through orifices in riser pipes. *J. of Irrigation and Drainage Eng.*, 136(5), 340-347.
- Win TR-55. 2009. *Win TR-55 for Windows*. Ver. 1.00.09. Washington DC.: Natural Resource Conservation Service.
- Tyner, J., D. C. Yoder, and B. Pilon. 2011. Sediment and detention basin drainage system and method. U.S. Patent No. US 2011/0278212 A1.
- Stockie, John M. 1998. The geometry of intersecting tubes applied to controlling a robotic welding torch. *MappleTech* (Special Issue on Maple in Industry), 5(2-3), 58-66.
- Viessman, Jr. W., and G. L. Lewis. 2003. *Introduction to Hydrology*. 5th ed. Upper Saddle River, NJ.: Pearson Education, Inc.
- Visser, K. K., J. M. Steichen, B. M. McEnroe, and J. Hua. 1988. Hydraulics of perforated terrace inlet risers. *American Society of Agric. Eng.* 31(5), 1451-1454.

APPENDIX

Appendix 1.1

Solver setup:

```
% Solver setup -- Alex McLemore

% Reset workspace
clc
clear

%% Inputs
basin_area = 6250; % user guesses
hb_max = 8; %[ft] max basin height
Q_peaks_allowed = [24.8,22.2,16.2,10.1,6.8,2.2]'; %[cfs] peak outflows
Q_peaks_storm = [54.5,50.4,41.0,30.6,24.5,14.2]'; %[cfs] peak inflows
t_ret_allowed = 48; %[hr] max retention time

% storm hydrographs
time_step = 0.05;
time = (0:time_step:t_ret_allowed)'; % [hr]
Qin_hydr = zeros(length(time),length(Q_peaks_allowed));
storm_vol = Qin_hydr;
total_storm_vol = zeros(size(Q_peaks_allowed));

% storm hydrograps removed to conserve space

% storm volumes
for m = 1:length(Q_peaks_allowed)
    for n = 1:length(Qin_hydr)
        storm_vol(n,m) = Qin_hydr(n,m)*time_step*3600;
    end
total_storm_vol(m) = sum(storm_vol(:,m));
end

%efficiency inputs
l_w = 10; % set by user
SPM = [0.33,0.33,0.33]; %percent soil distribution
V_s = [0.2,0.02,0.002]; %soil settling velocity [mm/s]
V_s = V_s./10/2.54/12; %soil settling velocity [ft/s]

% combined inputs to pass through solver
var = [Q_peaks_allowed(1);hb_max;t_ret_allowed;basin_area;l_w];

%% Solver
% Solver intial points
increments = 20; % dh increments (i.e. the resolution of dh curve)
dh(1:increments) = 0;
x0 = [1;1;1;dh'];
ub(1:increments) = hb_max/2;
```

```

ub = [10;10;10;ub'];
lb = zeros(1,increments);
lb(increments) = 0.75/12;
lb = [0;0;0;lb'];

% set solver options
opts = optimset('Algorithm','SQP','LargeScale','on',...
    'PlotFcns',@optimplotx,'FunValCheck','on'); %,...
    %'MaxFunEvals',100000,'MaxIter',10000);
% create solver problem
problem = createOptimProblem('fmincon',...
    'x0',x0,'objective',@(x)objfun(x,var,Qin_hydr,SPM,V_s,...
    Q_peaks_allowed,total_storm_vol),'nonlcon',@(x)confun(x,var,...
    Qin_hydr,SPM,V_s,Q_peaks_allowed,total_storm_vol),'lb',lb,...
    'ub',ub,'options',opts);

% Solver options

% x = ktrlink(@(x)objfun(x,var,Qin_hydr,SPM,V_s,type),x0,[],[],...
%     [],[],lb,ub, @(x)confun(x,var,Qin_hydr,SPM,V_s,type))
[x fval] = fmincon(problem) % local min solver
% ms = MultiStart('Display','iter','StartPointsToRun','bounds'); %
multiple start random solver
% [x,fval,eflag,output,solutions] = run(ms,problem,10)
% gs = GlobalSearch('Display','iter'); % iterative start point solver
% [x fval eflag,output solutions] = run(gs,problem)

% display constraint values
[c,ceq] =
confun(x,var,Qin_hydr,SPM,V_s,type,Q_peaks_allowed,total_storm_vol)

```

Appendix 1.2

Objective function:

```
function [obj] =  
objfun(x,var,Qin_hydr,SPM,V_s,type,Q_peaks_allowed,total_storm_vol)  
% Objective function  
  
basin_area = var(4);  
  
%increase dh resolution  
[dh_hi_res] = SSS_increase_resolution(x,var);  
  
%routing  
SSS_par = [x(1),x(2),x(3)];  
[Q_hb,Q_dis] = SSS_Q_distribution(dh_hi_res,var,SSS_par);  
[c2,ceq,Qout_storm,stage,dis_vol] = routing(basin_area,var,...  
      Q_hb,Qin_hydr,Q_peaks_allowed,total_storm_vol);  
  
%efficiency  
[Neff] = efficiency(x,var,SPM,V_s,Q_dis,Qout_storm,stage,...  
      dis_vol,basin_area,total_storm_vol);  
obj=Neff;
```

Constraint function:

```
function [c,ceq] =  
confun(x,var,Qin_hydr,SPM,V_s,type,Q_peaks_allowed,total_storm_vol)  
% Constraint function  
  
basin_area = var(4);  
%stage discharge  
[c1,ceq1] = SSS_stage_discharge(x,var);  
  
%increase dh resolution  
[dh_hi_res] = SSS_increase_resolution(x,var);  
  
%routing  
SSS_par = [x(1),x(2),x(3)];  
[Q_hb,Q_dis] = SSS_Q_distribution(dh_hi_res,var,SSS_par);  
[c2,ceq2] =  
routing(basin_area,var,Q_hb,Qin_hydr,Q_peaks_allowed,total_storm_vol);  
c = [c1;c2];  
ceq = [ceq1;ceq2];
```

Appendix 1.3

Stage discharge routine:

```
function [c,ceq] = SSS_stage_discharge(x2,var)
% Stage discharge routine

%confun_v1 --> the constraints function that works with all v1 solvers
%c --> are the inequality constraints
%   c(x) <= 0
%   **variables requiring constraint**
%       hc>=0
%       hb>=hc
%
%ceq --> are the equality constraints
%   ceq(x) = 0
%   **variables requiring constraint**
%       Qout(max)=Qmax_allowed
%       Qout=Qin_total

%% Run SSS function
% var = [Qpeak_allowed;hb_max;t_ret_allowed;basin_area;l_w]
%Variables
% constants
g = 32.2; %gravity [ft/s^2]
Cd = 0.61; %orifice discharge coefficient []
% variables
Qmax = var(1); %Defining the max flow, assumed to be at max depth [gpm]
height = var(2); %input hb height [in]
step = height/(20); %insuring matrices match up
hb = (step:step:height)'; %setting height increments
dh = x2(length(x2)-19:length(x2)); %use 19 to find first dh point,
assuming 20 dh points
hc = hb-dh; %solving for height in chamber
Aout = x2(1); %extracting Aout from x
Ain = x2(2); %extracting Ain from x
Bin = x2(3); %extracting Bin from x

%% Flow calculations
%Preallocating flow variables
Qout = zeros(1,length(hb))'; %SSS outflow (i.e. inner weir)
Qin_sub = Qout; %SSS inflow, submerged flow regime
Qin_free = Qout; %SSS inflow, free to atm flow regime
Qin_total = Qin_sub+Qin_free; %total inflow (i.e. outer weir)

% Q for inner riser (i.e., outflow)
for n = (1:length(hb))
    Qout(n) = (2/3*Cd*Aout*(2*g)^0.5*hc(n)^1.5); %[ft^3/s]
end
```

```

% Q for outer riser (i.e., inflow)
for n = (1:length(hb))
    Qin_free(n) =
    (Cd*(2*g)^0.5*(2/3*Ain+8/15*Bin*hb(n)+4/5*Bin*hc(n))*dh(n)^1.5);
    %[ft^3/s]
    Qin_sub(n) = (Cd*(2*g)^0.5*(Ain*hc(n)+Bin*hc(n)^2)*dh(n)^0.5);
    %[ft^3/s]
    Qin_total(n) = Qin_sub(n)+Qin_free(n);
end

%% Build c vector
dQmax = abs(Qout(length(Qout))-Qmax); %forcing Qtrad at highest head to
equal Qmax
c = [Ain-Aout; (-hc)];

%% Build ceq vector
dQ2 = abs(Qout-Qin_total); % insures inflow and outflow are equal
ceq = [dQmax;dQ2];

```

Interpolate dh curve routine:

```

function [dh_hi_res] = SSS_increase_resolution(x,var)
% Interpolate dh curve routine

% setup
hb_max = var(2);
dh = x(length(x)-19:length(x));
hb = (0:hb_max/length(dh):hb_max)';
dh = [0;dh];
spline_fit = csapi(hb,dh); %spline fit equation

% create high resolution vectors
hb_hi_res = (0:0.01:hb_max)';
dh_hi_res = (fnval(spline_fit,hb_hi_res));
dh_hi_res(dh_hi_res < 0) = 0;
hc_hi_res = hb_hi_res-dh_hi_res;

% to check spline fit if needed
subplot(2,1,2); plot(hb_hi_res,dh_hi_res);

```

Flow rate distribution routine:

```

function [Qin_total,Q] = SSS_Q_distribution(dh,var,SSS_par)
% Flow rate distribution routine

% var = [Qpeak_allowed;hb_max;t_ret_allowed;basin_area;l_w] for refence

```

```

%% Variables
% constraints
g = 32.2; %gravity [ft/s^2]
Cd = 0.61; %orifice discharge coefficient []
% variables
height = var(2); %input hb height [in]
Ain = SSS_par(2); %extracting Ain from x
Bin = SSS_par(3); %extracting Bin from x
step = height/(length(dh)-1); %insuring matrices match up
hb = (0:step:height)'; %setting height increments
hc = hb-dh;
head = 0:0.001:height;
Q = zeros(length(head),length(hb));
Qin_total = zeros(size(dh));
Q_sum = zeros(size(dh));

% building Q_distribution curve
for m = 1:length(dh)
    for n = 1:length(head)
        if (head(n)<=0) % head below or at zero
            Q(n,m) = 0;
        elseif head(n)>0 && head(n)<=hc(m) % head between zero and hc
            Q_bottom1 = 0.61*(2*32.2)^0.5*(Ain*head(n-1)+Bin*head(n-1)^2)*dh(m)^0.5;
            Q_top1 = 0.61*(2*32.2)^0.5*(Ain*head(n)+Bin*head(n)^2)*dh(m)^0.5;
            Q(n,m)=Q_top1-Q_bottom1;
        elseif head(n)>hc(m) && head(n-1)<=hc(m) && hc(m)>0 && head(n)<=hb(m) % head above hc but previous head is below hc
            Q_bottom2 = 0.61*(2*32.2)^0.5*(Ain*head(n-1)+Bin*head(n-1)^2)*dh(m)^0.5;
            Q_sub1 = 0.61*(2*32.2)^0.5*(Ain*hc(m)+Bin*hc(m)^2)*dh(m)^0.5;
            Q_free1 = 0.61*(2*32.2)^0.5*((2/3)*(hb(m)-hc(m))^(3/2)*Ain+(8/15)*...
                (hb(m)-hc(m))^(3/2)*Bin*hb(m)+(4/5)*(hb(m)-hc(m))^(3/2)*Bin*hc(m)-...
                (2/3)*(hb(m)-head(n))^(3/2)*Ain-(8/15)*(hb(m)-head(n))^(3/2)*...
                Bin*hb(m)-(4/5)*(hb(m)-head(n))^(3/2)*Bin*head(n));
            Q_top2 = Q_sub1+Q_free1;
            Q(n,m)=Q_top2-Q_bottom2;
        elseif head(n)>hc(m) && head(n)<=hb(m) % head blow hb and above hc
            Q_sub3 = 0.61*(2*32.2)^0.5*(Ain*hc(m)+Bin*hc(m)^2)*dh(m)^0.5;
            Q_free3 = 0.61*(2*32.2)^0.5*((2/3)*(hb(m)-hc(m))^(3/2)*Ain+(8/15)*...
                (hb(m)-hc(m))^(3/2)*Bin*hb(m)+(4/5)*(hb(m)-hc(m))^(3/2)*Bin*hc(m)-...

```

```

        (2/3)*(hb(m)-head(n-1))^(3/2)*Ain-(8/15)*(hb(m)-head(n-
1))^(3/2)*...
        Bin*hb(m)-(4/5)*(hb(m)-head(n-1))^(3/2)*Bin*head(n-1));
        Q_bottom3 = Q_sub3+Q_free3;
        Q_sub4 =
0.61*(2*32.2)^0.5*(Ain*hc(m)+Bin*hc(m)^2)*dh(m)^0.5;
        Q_free4 = 0.61*(2*32.2)^0.5*((2/3)*(hb(m)-
hc(m))^(3/2)*Ain+(8/15)*...
        (hb(m)-hc(m))^(3/2)*Bin*hb(m)+(4/5)*(hb(m)-
hc(m))^(3/2)*Bin*hc(m)-...
        (2/3)*(hb(m)-head(n))^(3/2)*Ain-(8/15)*(hb(m)-
head(n))^(3/2)*...
        Bin*hb(m)-(4/5)*(hb(m)-head(n))^(3/2)*Bin*head(n));
        Q_top3 = Q_sub4+Q_free4;
        Q(n,m)=Q_top3-Q_bottom3;
elseif head(n)>hb(m) % head above stage
        Q(n,m)=0;
end
end
Q_sum(m) = sum(Q(:,m));
% check with closed form equations below
Qin_free =
(Cd*(2*g)^0.5*(2/3*Ain+8/15*Bin*hb(m)+4/5*Bin*hc(m))*dh(m)^1.5);
%[ft^3/s]
Qin_sub = (Cd*(2*g)^0.5*(Ain*hc(m)+Bin*hc(m)^2)*dh(m)^0.5); %[ft^3/s]
Qin_total(m) = Qin_sub+Qin_free;
end

```

Routing routine:

```

function [c,ceq,Qout_storm,stage_rounded,dis_vol]=
routing(basin_area,var,Q_hb,Qin_hydr,Q_peaks_allowed,total_storm_vol)
% Routing routine

% var = [Qpeak_allowed;hb_max;t_ret_allowed;basin_area;l_w]; for
reference

%% Variables
hb_max = var(2); %input hb height [in]
t_retention_allowed = var(3); %max retention time [hr]
step = hb_max/(length(Q_hb)-1); %insuring matrices match up
hb = (0:step:hb_max)'; %setting height increments

%% Routing/particle tracking
% Initialize matrices
Qout = Q_hb;
time_step = 0.05;
time = (0:time_step:t_retention_allowed)'; % [hr]
Qout_storm = zeros(size(Qin_hydr)); basin_storage =
zeros(size(Qin_hydr)); basin_stage = zeros(size(Qin_hydr));
dis_vol = zeros(size(Qin_hydr)); stage_rounded = zeros(size(Qin_hydr));

```

```

percent_dis = zeros(size(Q_peaks_allowed));
Q_peaks_act = zeros(size(Q_peaks_allowed));

% routing process
for n = 1:length(Q_peaks_allowed)
    for i = 2:length(time)
        basin_storage(i,n) = basin_storage(i-1,n)+((Qin_hydr(i,n)-
Qout_storm(i-1,n))*time_step*3600); %[ft^3]
        basin_stage(i,n) = basin_storage(i,n)/basin_area; %basin stage
[ft]
        stage_rounded(i,n) = roundn(basin_stage(i,n),-3); % -3 rounds
to nearest 100th, i.e. resolution of hb
        if stage_rounded(i,n)< 0 % all water drained
            m = 1;
            error = 1;
        elseif (stage_rounded(i,n)+hb(2)/2)>max(hb) % overflow
            error = 2;
            m = 1;
        else
            [m]=find(stage_rounded(i,n)-hb(2)/2+0.000000001<hb &
hb<stage_rounded(i,n)+hb(2)/2+0.000000001); %find location of current
stage in hb array
            if isempty(m)
                m = 1;
                error = 3;
            end
        end
        Qout_storm(i,n) = Qout(m); % Get flowrate values
        dis_vol(i,n) = Qout_storm(i,n)*time_step*3600; %[cf]
    end
    total_dis_vol = sum(dis_vol(:,n));
    percent_dis(n) = total_dis_vol/total_storm_vol(n);
    Q_peaks_act(n) = max(Qout_storm(:,n));
end

%% Build constraint vectors
% c vector
storm_drained = 98-(percent_dis.*100); % solving for retention time,
assumed to be at 98% of storm discharged
stage_constraint2 = max(max(stage_rounded))-hb_max; % prevents overflow
Q_peaks_con = Q_peaks_act-Q_peaks_allowed; % insures allowable peak
flow are meet
c = [stage_constraint2;Q_peaks_con;storm_drained];

% ceq vector
ceq = [];

```

Efficiency routine:

```

function [Neff_total] =
efficiency(x,var,SPM,V_s,Q_dis,Qout_storm,stage,dis_vol,basin_area,tota
l_storm_vol)
% Efficiency routine

% var = [Qpeak_allowed;hb_max;t_ret_allowed;basin_area;l_w]; for
reference

height = var(2);
l_w = 10;
Q_dirty =
zeros(length(Qout_storm),length(V_s),length(total_storm_vol));
%preallocating Q_z
z_p = Q_dirty; Neff = Q_dirty; SPM_eff = Q_dirty;
Neff_i = zeros(length(Qout_storm),length(total_storm_vol));
basin_width = (basin_area/l_w)^0.5; %basin width [ft]
l = basin_width*l_w; %basin length [ft]
Aeff = 20*l_w-l_w^2; %effective area
size_Q_dis = size(Q_dis); %returns x(down) then y(right)
z = (0:height/(size_Q_dis(1)-1):height)'; % makes the "down length" the
size from Q_dis
hb = (0:height/(size_Q_dis(2)-1):height)'; % makes the "right length"
the size from Q_dis
Neff_storm = zeros(size(total_storm_vol));

%Particle tracking loop
for m = 1:length(total_storm_vol);
    for i = 1:length(Qout_storm)
        if Qout_storm(i,m)==0
            SPM_eff(i,:,m) = 0;
        else
            V_hor = Qout_storm(i,m)/(basin_width*stage(i,m));
%horizontal water movement in basin [ft/s]
            t_r = l/V_hor; %residence time [sec]
            drop = V_s.*t_r; %distance particle drops [ft]
            z_p(i,:,m) = stage(i,m)-drop; %particle break location from
basin floor [ft]
            for n=1:length(V_s)
                if (z_p(i,n,m)<=0)
                    Q_dirty(i,n,m) = 0;
                    SPM_eff(i,n,m) = SPM(n); %prevents necative z_p(i)
values to creat false SMP_eff values
                else
                    [s]=find(z_p(i,n,m)-z(2)/2+0.000000001<z &
z<z_p(i,n,m)+z(2)/2+0.000000001); %find location of current z_p in z
array
                    if isempty(s)
                        s = 1;
                        error = 2;
                    end
                end
            end
        end
    end
end

```

```

[r]=find(stage(i,m)-hb(2)/2+0.000000001<hb &
hb<stage(i,m)+hb(2)/2+0.000000001); %find location of current stage in
hb array
    if isempty(r)
        r = 1;
        error = 1;
    end
    Q_dirty(i,n,m) = sum(Q_dis(1:s,r));
    SPM_eff(i,n,m) = SPM(n)*(1-
((z_p(i,n,m)/stage(i,m))*(Q_dirty(i,n,m)/Qout_storm(i,m))));
        end
    end
    Neff(i,:,m) = Aeff*SPM_eff(i,:,m);
    Neff_i(i,m) = sum(Neff(i,:,m))*dis_vol(i,m)/total_storm_vol(m);
end
Neff_storm(m) = sum(Neff_i(:,m))*storm_freq(m)/sum(storm_freq);
Neff_storms(m) = sum(Neff_i(:,m));
end
Neff_total = -sum(Neff_storm); % weight for larger vol storms not
frequency

```

VITA

Alex McLemore was born in Knoxville, Tennessee, on September 6, 1987. He grew up in Knoxville, Tennessee, where he graduated from South-Doyle High School in 2006. In 2010 he graduated with a B.S. in Biosystems Engineering and a minor in Environmental Engineering from the University of Tennessee. He will graduate in August 2012 with a M.S. in Biosystems Engineering.