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A Remotely Controlled Siphon System for Dynamic Water Storage Management

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ABSTRACT

Previous research has concluded that upland wetlands could be effective to control small floods, yet for large floods, their value may be greatly reduced as their storage capacity may be exceeded. A potential solution could be to release water from wetlands ahead of (e.g., few days before) a heavy rainfall event that is forecasted to produce flooding. In this case, the wetlands would be partially empty when this rainfall occurs. This work is part of a long-term project that aims at developing a decision support system (DSS) that will determine optimal flooding scenarios with dynamic management of wetlands using siphons. This DSS will incorporate simulation and optimization models with the aim of minimizing flooding losses. The success of this project hinges on the automation of a siphon that can be fully controlled (opened and closed) remotely and that can initiate the flow regardless of the opening time of the valve. To make possible the remote and dynamic release of water from wetlands, we designed and built a siphon system that can be remotely operated by a SCADA-type control. In practice, flood control managers would remotely open and close hundreds or thousands of this type of siphon simultaneously or in arrays. This first paper presents an experimental, numerical (3D), and analytical study of the initiation of siphon flows regulated with a downstream ball valve for rapid and slow valve openings. Three initial water depths in the upstream tank, four different final opening positions for the valve, and three opening times of the valve were investigated. The rate of depletion of the water surface in the upstream tank obtained numerically and analytically agreed well with the experimental results. Furthermore, the proposed siphon system was found to initiate the flow regardless of the opening time of the valve. Overall, the proposed siphon system could be an effective and inexpensive method to dynamically manage the storage of ponds and wetlands for flood control.

Keywords: *Experiments, Flood Control, Ponds, Simulation, Siphon, Storage Management, Wetlands*

1. INTRODUCTION

In recent decades, the significant and rapid increase of impervious surfaces has increased the risk of flooding. The effects of flooding on the environment are extensive and significant, resulting in an increase of loss of lives and damage to property and crops (NHC, 1997; NWS, 2013). The National Weather Service NWS (2013) reported that direct freshwater flood damages in the U.S. in 2011 and 2012 were $3.9 and $0.5 billion, respectively. There are two common approaches for reducing flood damages: structural and nonstructural measures. The traditional approach (structural measures) can reduce inundation of floodplains in several ways. For instance, reservoirs reduce downstream peak flow rates, levees and flood walls confine the flow of the rivers, and floodways help divert excess flow (ICE, 2002; De Bruijn et al., 2008; Breckpot et al., 2010). Although structural measures can be effective in reducing floods, they have a limited capacity to mitigate floods since only small parts of the watersheds (river and floodplains) are used for flood management.

Since flooding impacts have increased in frequency and severity, there is a new emphasis on evaluating nonstructural and watershed management approaches to determine whether they are effective strategies for flood prediction, prevention, and mitigation (e.g., Breckpot et al., 2010). A report from the Environmental Protection Agency (EPA, 1996) concluded that watershed approaches are the most effective approaches to address water resource challenges. This approach can help to maintain and mimic the natural hydrologic system (Buss, 2005).

Within a watershed, ponds and wetlands can play an important role in flood reduction, increasing water quality, and creating habitats for fauna (Hey and Philippi, 1995; Mitsch and Day, 2006). Ponds and wetlands could also increase flood storage by storing, holding, and percolating water (Costanza et al., 1989; Cole et al., 1997; Godschalk et al., 1999; Erwin, 2009). A study demonstrated that wetlands are able to absorb and hold greater amounts of floodwater than previously thought (Godschalk et al., 1999). A report of the United Nations (UNDP and UNISDR 2006) concluded that upland wetlands could be effective for small floods, but for large floods, their value may be greatly reduced as their storage capacity may be exceeded. In fact, during rainy seasons, mild to heavy rainfall events may occur continuously for days or weeks. In these situations, the benefit of wetlands and ponds for flood mitigation is limited because they may be full of water when a heavy rainfall that is forecasted to produce flooding occurs. One strategy for reducing flooding could be to release part of the water from wetlands and ponds ahead of (e.g., few days before) this heavy rainfall so that some storage is made available for the heavy rainfall.

To make possible the remote and dynamic release of water from ponds and wetlands, we designed and built a siphon system that can be remotely operated (Figure 1). This system (1) requires a simple anchoring of the siphon pipe; (2) can be remotely operated using a SCADA-type control, and can be activated through direct radio, via satellite, wireless radio, or a combination of these communications channels; and (3) does not need significant energy except for keeping the siphon pipe full and for actuating (opening and closing) the downstream valve. For this small requirement of energy, a small solar panel could be used. In practice, hundreds or thousands of these siphons could be operated simultaneously.

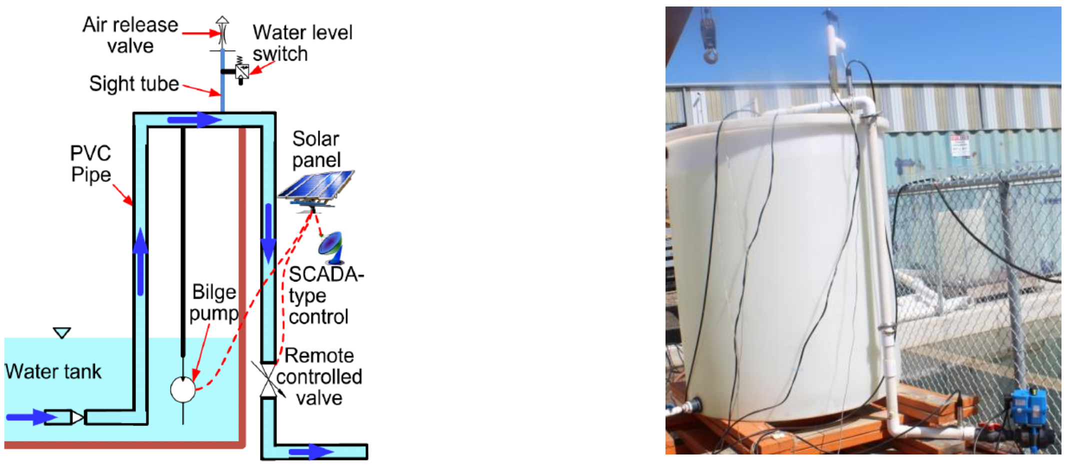


Figure 1. Left (schematic of siphon), Right (Laboratory setup). A video of our automated siphon in action can be seen at https://www.youtube.com/watch?v=LvdyFJlMwZI.

1.1. Siphon Flows

Siphons have been known since early times as simple and inexpensive devices for transferring water using gravitational force (Potter and Barnes, 1971; Garrett, 1991; Hughes, 2010). Siphons work due to the difference in pressure between the atmospheric pressure at the upper reservoir and the top of the siphon (negative gage pressure). This device can effectively remove water from reservoirs and ponds in remote locations. When set up properly, siphons usually require minimal oversight. One important characteristic of siphons is that, once the flow is started, a siphon requires no electricity to keep the liquid flowing up and out of the pond. The siphon will draw liquid out of the pond until the level falls below the intake, allowing air to break the siphon flow, or until the outlet of the siphon equals the level of the pond, whichever comes first. In addition to atmospheric pressure, the density of the liquid, and gravity, the maximum height of the crest in practical siphons is limited by the vapour pressure of the liquid. When the liquid pressure in the siphon drops below the liquid's vapor pressure, tiny vapor bubbles will begin to form at the siphon top, which may stop the flow. Overall, there is a limit for the height of the siphon pipe above the pond water surface elevation. For water at standard atmospheric pressure, the maximum siphon height is approximately 10.3 m, which is the definition of standard pressure. This equals the maximum height of a suction pump, which operates by the same principle. In practice, the maximum height should be smaller than 10.3 m due to head losses and because water will already evaporate as steam before the pressure drops to vacuum pressure (Garrett, 1991).

Considerable research has been conducted on siphons (Potter and Barnes, 1971; Garrett, 1991; Hughes, 2010; Binder and Richert, 2011). Cambiaghi and Schuster (1989) and Govi (1989) introduced a system using siphon principles as an emergency drainage treatment for landslides. Bryant and Jewell (1996) tested the hydraulic performance of a siphon system used to drain a small earthen dam, where comparisons were made between theoretical siphon hydraulic performance and actual field performance. Leumas (1998) discussed the variables that should be considered in designing siphons and repairs to existing dams. Recently, siphon drainage combined with electropneumatic drainage has been the method for discharging ground water in Europe, especially in France (Mrvik and Bomont, 2011). More recently, Mrvik (2013), Cai et al. (2014), and Boatwright (2014) focused on maintenance and management requirements of siphons. Although there is vast research on siphon flows, the regulation of siphon flows using valves have not been fully explored yet.

This paper aims to investigate the performance of the proposed siphon system when regulated with a valve. In particular, we aim to investigate the reliability of this system to initiate the flow under various conditions. This paper is divided as follows. First, the experimental work is presented. Second, the numerical work is briefly described. Third, the analytical model is briefly introduced. Fourth, the results are presented and discussed. Finally, the key results are summarized in the conclusion.

2. EXPERIMENTAL WORK

The experimental setup consisted of eight components as shown in Figure 2: (1) an upstream tank with a diameter of 1.05 m and a height of 1.6 m; (2) 0.038 m diameter and 4.34 m long PVC pipe; (3) a check valve at the pipe inlet; (4) a submersible pump (200 gallons per hour (GPH)) used to prime the pipe, if necessary; (5) an air valve used to release the air from the system when priming the pipe; (6) an actuator valve used to control the opening/closing of the downstream valve. The actuator and submersible pump are operated using a solar panel (7). The operation of the actuated valve and the air valve and data collection are accomplished using a LabVIEW system (8). Figure 3 shows the dimensions of the tank and siphon pipe. Three pressure transducers (UNIK 5000) with a resolution of ±3.2 mm were installed at three different locations indicated in Figure 4. The sampling rate for the pressure transducers was set to 36 Hz.

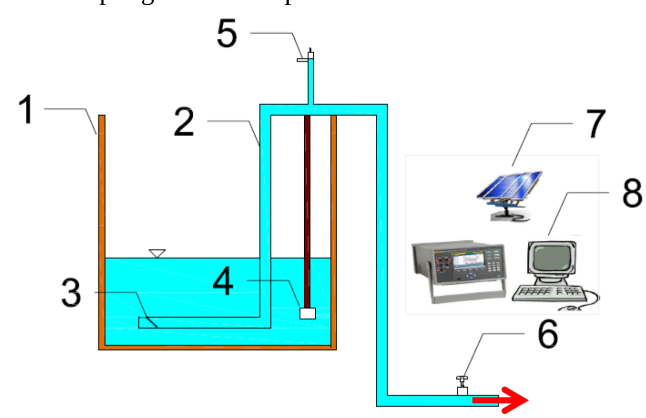
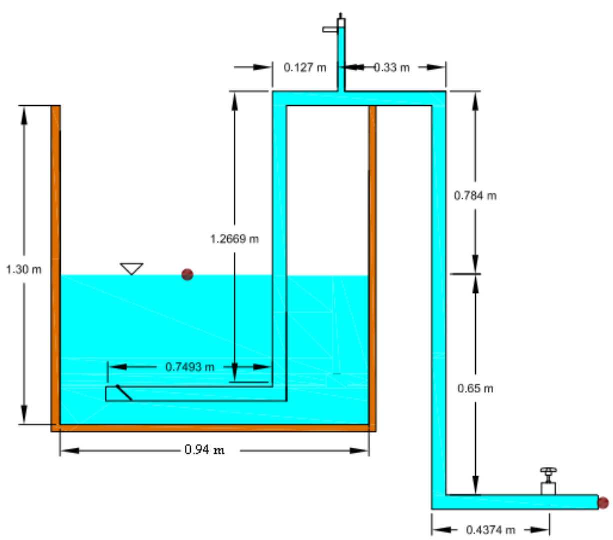


Figure 2. Experimental components: (1) upstream tank; (2) PVC pipe; (3) check valve ; (4) small submersible pump (for priming only); (5) air valve; (6) actuated valve; (7) solar panel (energy); (8) data acquisition system.



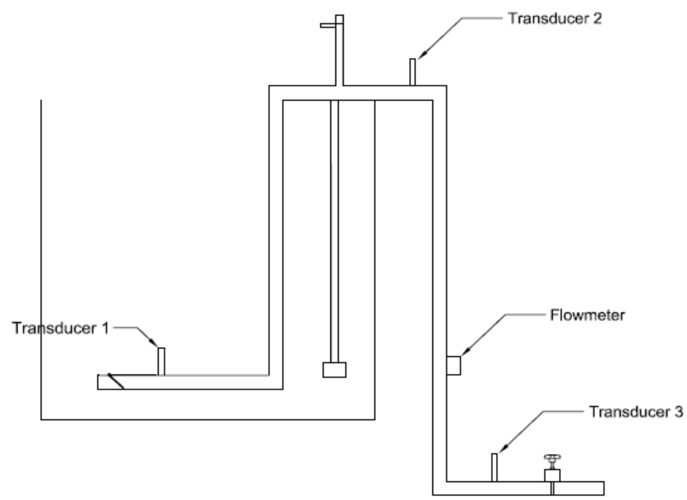


Figure 3. Dimensions of the tank and siphon pipe

Figure 4. Locations of pressure transducers and flowmeter

2.1. Measurement Conditions

The experiments were conducted for three initial water depths in the tank, $H_{A=}$1.14m, H_B=0.60m, and H_C=0.30m (see Figure 5). For each water depth, four different final opening positions for the valve were tested (25%, 50%, 75%, and 100% (fully-open)). The percentages of valve opening refer to the ratio of opening area to the cross-sectional area of the pipe. For instance, a 25% opening means that the area of opening is 25% of the pipe's cross-sectional area. Additionally, three opening times of the valve were tested. The first opening time was 0.1s, which corresponds to a fast opening. The second and third opening times were 30 and 60s, which correspond to a slow opening. Finally, pressure measurements were made for each experiment. Every experiment was repeated at least four times to ensure consistency of results.

2.2. Signal Filtering

Filters of some sort are essential in data acquisition systems to remove selected frequencies from an incoming signal and minimize noise (Holloway, 1958). In this paper, a low pass filter was used to smooth noisy data. The low pass filter removes the corrupting high frequency noises in the data. In order to eliminate unwanted response, the pressure data acquired at 36Hz was filtered using a Chebyshev low-pass filter (MATLAB), which effectively removed frequencies above 4 Hz. An example of the original time series and filtered data is shown in Figure 6. It is pointed out that all experimental figures after Figure 6 display filtered data only.

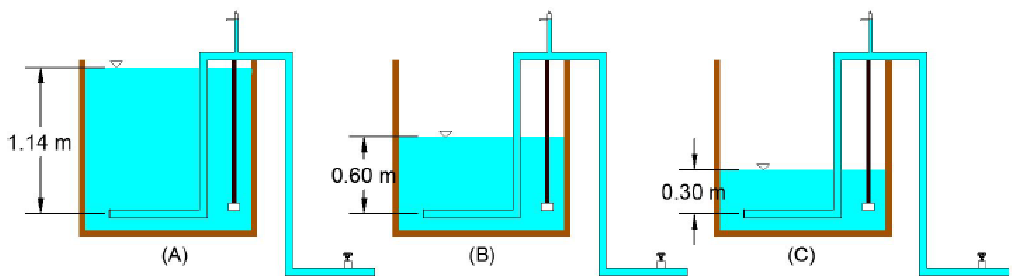


Figure 5. Initial water depths tested: (A) tank near full; (B) tank near half full; (C) tank near 1/3 full

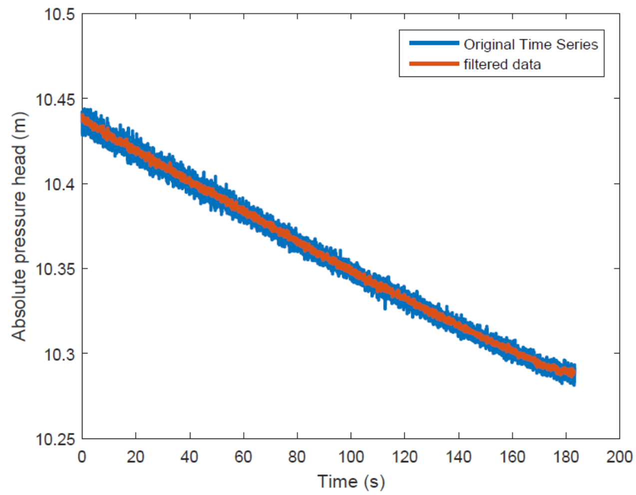


Figure 6. Filtered and unfiltered absolute pressure head versus time for H = 0.3m, 25% valve opening and opening time = 0.1s.

3. THREE-DIMENSIONAL NUMERICAL MODELING

The numerical modelling was performed using the 3D Computational Fluid Dynamics (CFD) model Star-CCM+ v7.0. The overall process to simulate the siphon flow consisted of (1) using 3D-CAD model to create a 3D solid geometry; (2) building the mesh; (3) selecting appropriate boundary conditions; (4) selecting the numerical model and parameters of the simulation; (5) ensuring grid convergence; and (6) visualizing the results. A brief discussion of the 3D numerical model is presented next.

To account for the air and water phases, the Volume of Fluid (VOF) method was used. The VOF method solves a single set of momentum equations for both phases. The realizable k-ε model was used to simulate the turbulent flow. As shown in Figure 7, the computational domain of the numerical experiment involved two cylindrical tanks with diameters of 1.06 m (upstream tank) and 0.80 m (downstream tank). The computational domain was extended beyond the outlet of the siphon represented by the second tank. This extension was made to avoid specifying a boundary condition at the outlet of the pipe. To represent the opening of the downstream ball valve in the physical experiment, various valve positions at intermediate times were specified in Star-CCM+. Furthermore, the mesh size was refined around the pipe inlet, outlet, and elbows. A surface wrapper was used to refine the intersecting parts of the system (e.g., the siphon pipe with the downstream valve).

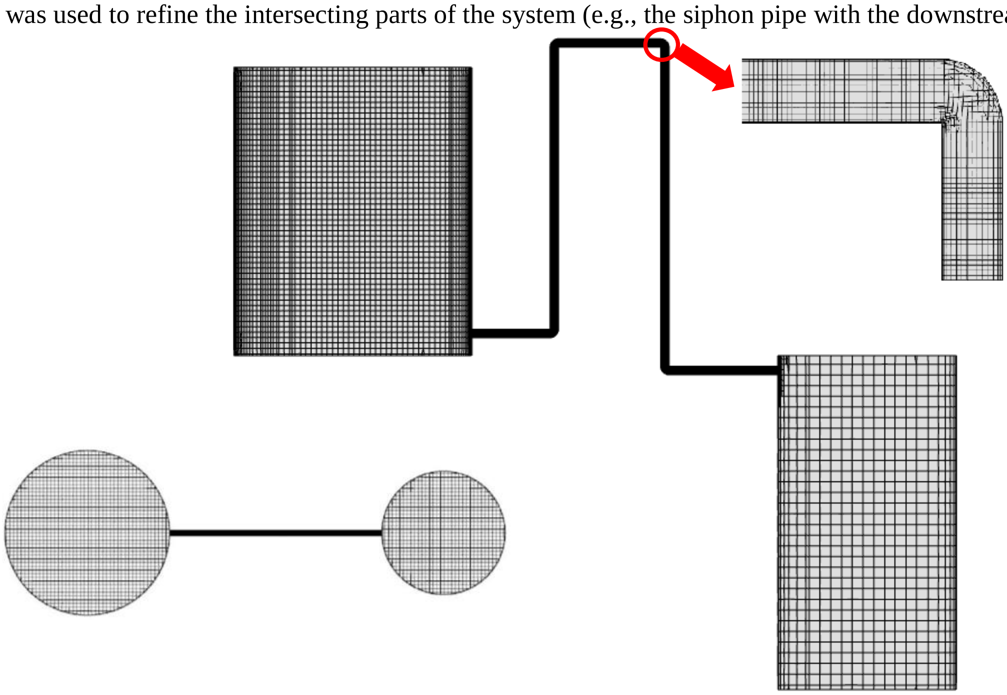


Figure 7. Plan- and side view of computational mesh

For the boundary conditions, the non-slip wall boundary condition was imposed at the pipe wall. Also, the pressure at the top surface of both cylindrical tanks was set to atmospheric pressure. As shown in Figure 8, the pipe was initially primed (e.g., filled with stagnant water), and the initial water surface elevation at the downstream tank was below the elevation of the pipe outlet. The latter was to avoid interfering with the flow at the siphon outlet. The downstream valve was initially closed and started to operate to the desired position (e.g., open) at t (time) = 0.

Due to space limitations, only two snapshots of pressure and velocity for the inlet and outlet regions of the siphon at t = 500 s for H = 0.3 m, opening time = 0.1 s, and O = 25% are shown in Figures 9 and 10. As can be observed in Figures 9 and 10, the flow is pretty much one-dimensional except at the bends and around the inlet and outlet regions. This may explain why the one-dimensional analytical model agrees very well with the 3D model and the experiments, as will be shown later.

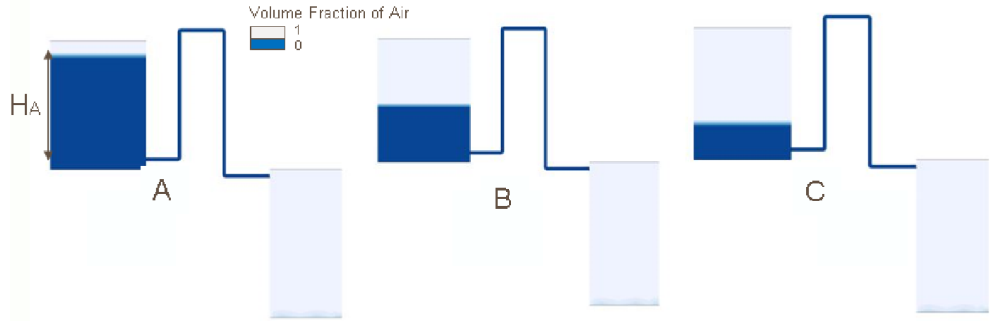


Figure 8. Initial water levels in the tanks used in CFD model

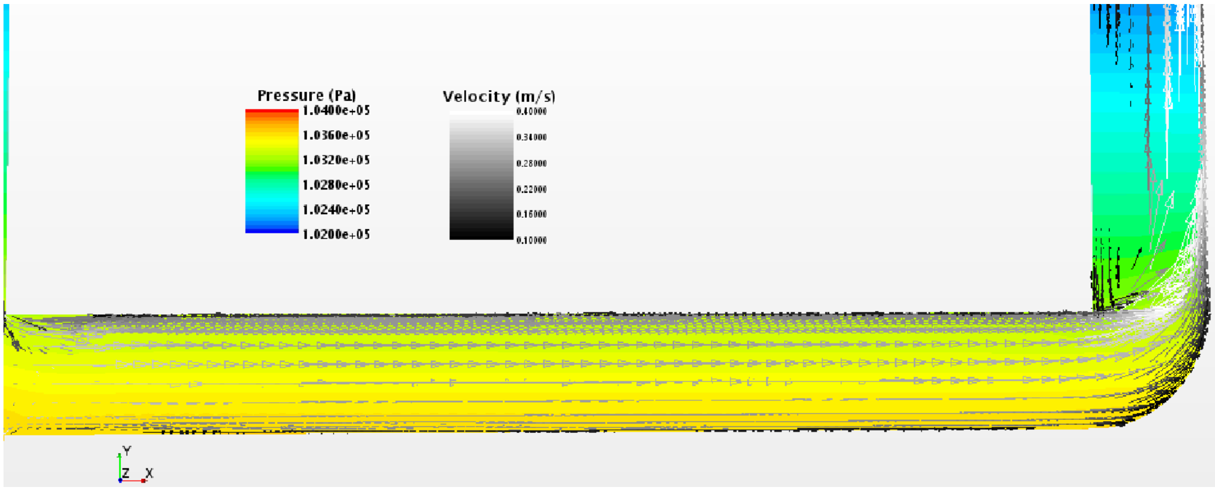


Figure 9. Snapshot of pressure and velocity at the siphon inlet at t = 500 s (H = 0.3 m, opening time = 0.1 s, and O = 25%)

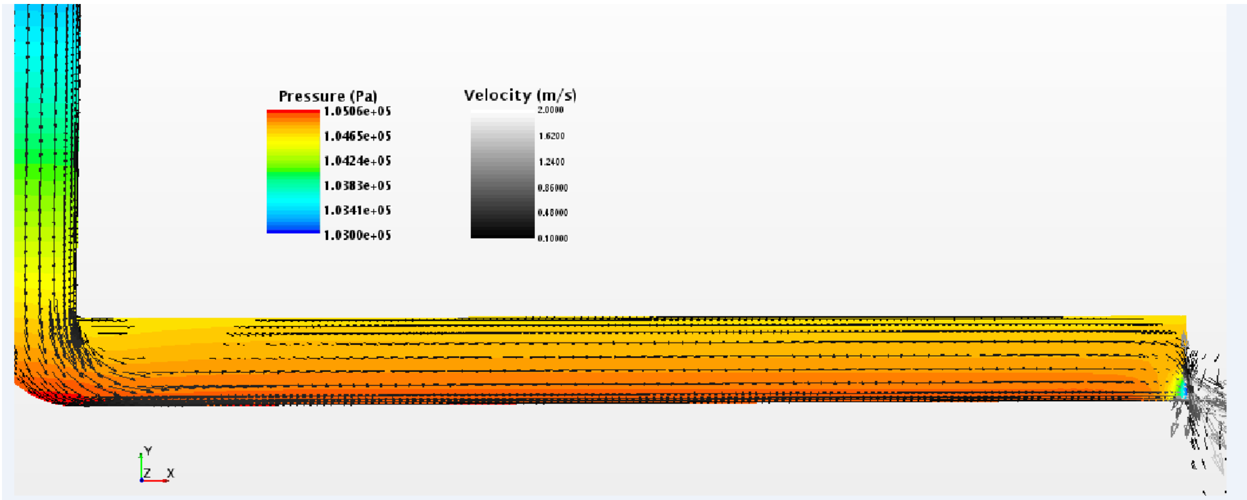


Figure 10. Snapshot of pressure and velocity at the siphon outlet at t = 500 s (H = 0.3 m, opening time = 0.1 s, and O = 25%)

4. ANALYTICAL SOLUTION

Siphon flows can be analyzed using the energy equation, which is given by the following equation:

$$Z_a + \frac{P_a}{\gamma} + \frac{V_a{}^2}{2g} = Z_b + \frac{P_b}{\gamma} + \frac{V_b{}^2}{2g} + h_f + h_m \tag{1}$$

where, Z_a is the elevation of the pond water surface (point "a"), Z_b is the elevation of the pipe centerline at the outlet (point "b"), P_a is the pressure at the pond water surface, P_b is the pressure at point "b", V_a is the velocity at the pond water surface, V_b is the velocity at point "b", γ is the specific weight of water, g is the gravitational acceleration, h_f is the total head loss due to pipe friction, and h_m is the sum of local head losses. Because the velocity head at point "a" is relatively small, the velocity at the outlet (point "b") can be written as

$$V_b = \sqrt{2g\left(Z_a - Z_b - h_f - h_m\right)} \tag{2}$$

To estimate the friction losses, the Darcy-Weisbach formula was used:

$$h_f = \frac{fLV^2}{2gD} \tag{3}$$

where f is the pipe friction factor, L is the pipe length, V is the pipe cross-sectional averaged flow velocity and D is the diameter of the pipe. The local head losses are estimated as

$$h_m = \sum k_i \frac{V^2}{2g} \tag{4}$$

where k is the head loss coefficient for the particular pipe fitting (i.e., elbows, check valve, ball valve).

5. RESULTS AND DISCUSSION

5.1. Experimental work

A total of 144 tests were conducted considering three different initial water depths (H), four different final opening positions for the valve (O), and three opening times of the valve. Each experimental condition was repeated at least four times. Fig. 11 shows the measured absolute pressure head versus time at the locations indicated in Figure 4 when the initial water depth in the tank was 0.3m, the final position for the valve opening was 25%, and the opening time was 0.1 s (fast opening). As can be observed in this figure, the pressure at the inlet is higher than that in the outlet at all times. Also note in this figure that the absolute pressure in the siphon top remains below atmospheric pressure (~ 10.3 m of water head) at all times. Thus, the gage pressure at the siphon top is negative at all times. Fig. 12, 13, and 14 show traces of the absolute pressure head at the siphon top, siphon inlet, and siphon outlet for an initial water depth in the tank of 0.3 m, fast valve opening (0.1s) and various final positions for the valve opening. As expected, the greater the final opening area of the valve, the smaller the pressure head at all locations. The latter is because the greater is the hydraulic area, the greater is the flow discharge (and head losses), and hence the smaller is the pressure head at all locations.

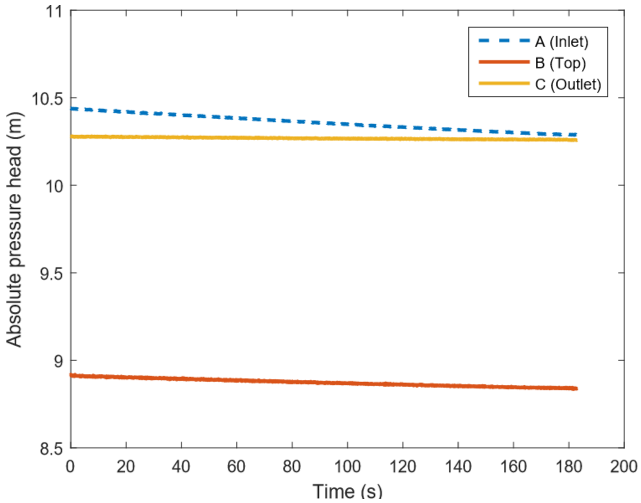


Figure 11. Absolute pressure head versus time for H = 0.3 m, O = 25%, opening time = 0.1 s

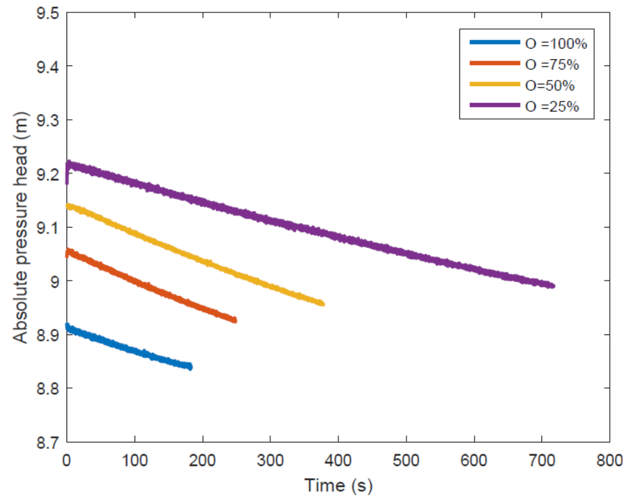


Figure 12. Absolute pressure head versus time at siphon top for H = 0.3 m, opening time = 0.1 s and four final positions for the valve opening (O)

Figures 15 and 16 show traces of absolute pressure head at siphon top and siphon outlet for slow openings (30 and 60 s). The initial water depth in the tank was 0.3 m, and the final position for the valve opening was 100% open (fully-open valve). As can be seen in these figures, the pressure decreases with time, indicating that the siphon still initiates the flow for slow openings. We have also tested the siphon for opening times of 5 minutes (not reported here), and the siphon still initiates the flow. Overall, the siphon initiates the flow regardless of the opening time of the valve.

5.2. Comparison between Analytical, Numerical and Experimental Results

Due to space limitations, only the comparison for the absolute pressure head trace at the siphon top for H = 0.3m, opening time = 0.1 s, and O = 75% is shown in Figure 17. As observed in Figure 17, the drainage rate obtained analytically and numerically agrees very well with the experimental results. The results (not shown here) are similar for other conditions. The reader may notice in this figure that the results of the 3D numerical model display a large fluctuation of the pressure right after the siphon flow is started. This relatively large pressure fluctuation, which lasts for few seconds, occurs due to the sudden increase or decrease of the velocity (e.g., Leon et al., 2007, 2008). As shown earlier for the CFD model (Figures 9 and 10), the flow in the siphon is pretty much one-dimensional except at the bends and around the inlet and outlet regions. This may explain why the one-dimensional analytical model agrees very well with the 3D model and the experiments. Thus, a one-dimensional analytical model can be used for predicting the draining rate of ponds with very good accuracy.

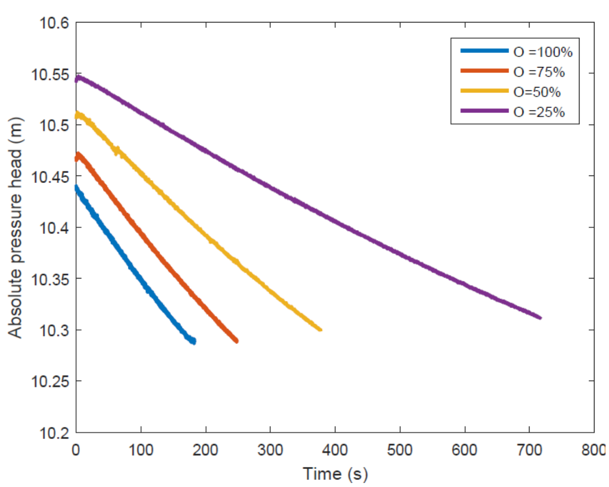


Figure 13. Absolute pressure head versus time at siphon inlet for H = 0.3 m, opening time = 0.1 s and four final positions for the valve opening (O)

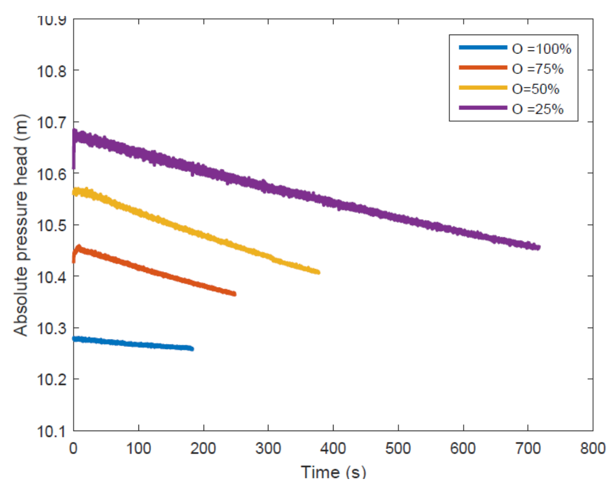


Figure 14. Absolute pressure head versus time at siphon outlet for H = 0.3 m, opening time = 0.1 s and four final positions for the valve opening (O)

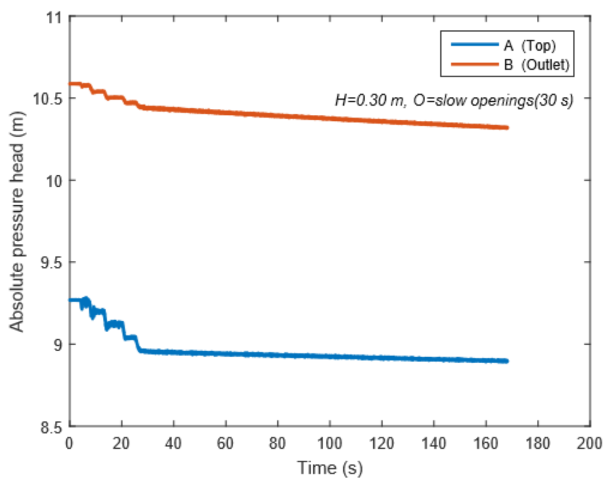


Figure 15. Absolute pressure head traces at siphon top and outlet when the valve is fully opened in 30 s (H = 0.3 m).

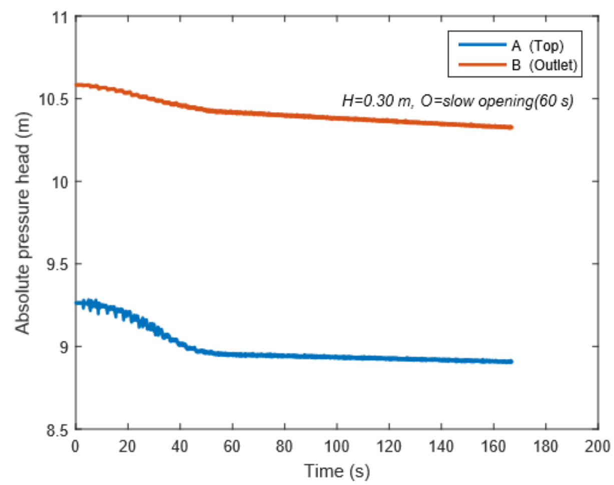


Figure 16. Absolute pressure head traces at siphon top and outlet when the valve is fully opened in 60 s (H = 0.3 m).

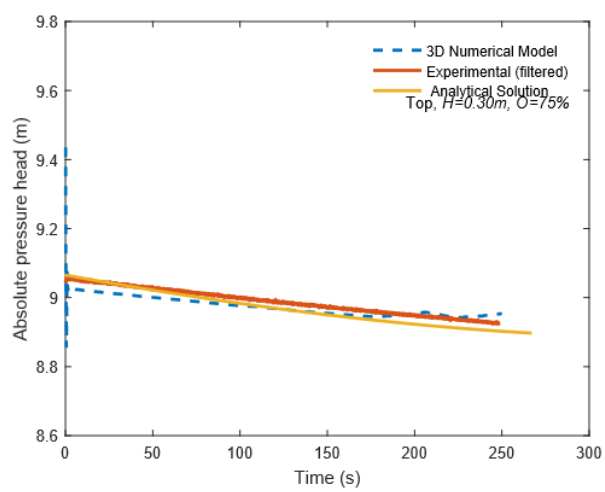


Figure 17. Comparison between numerical, experimental and analytical results of absolute pressure head traces at the siphon top (H = 0.3m, opening time = 0.1 s, and O = 75%)

6. CONCLUSION

The initiation of siphon flows regulated with a downstream ball valve for rapid and slow valve openings were investigated analytically, numerically, and experimentally. Three initial water depths in the upstream tank, four different final opening positions for the valve, and three opening times of the valve were investigated. The key results are as follows:

- The rate of depletion of the water surface in the upstream tank obtained numerically and analytically agreed well with the experimental results.
- The flow in the siphon is pretty much one-dimensional except at the bends and around the inlet and outlet regions. This may explain why the one-dimensional analytical model does a very good job predicting the drainage rate.
- The remotely-controlled siphon system was found to initiate the flow regardless of the opening time of the valve. However, small leaks in the pipe may depressurize the siphon pipe and stop the flow.

Overall, the proposed siphon system could be an effective and inexpensive method to dynamically manage the storage of ponds and wetlands for flood control. However, each project site may have specific challenges that need to be considered. For example, the inlet of a siphon must be designed to prevent sediments from entering the pipe.

7. REFERENCES

Binder, P-M. and Richert, A. (2011). The explicit siphon. Physics Education, 46(6):710-711.

Boatwright, J. D. (2014). Air-regulated siphon spillways: Performance, modeling, design, and construction., M.S. Thesis Clemson University, 74 pages.

Breckpot, M., Blanco, T. B., and De Moor, B. (2010). Flood control of rivers with nonlinear model predictive control and moving horizon estimation. *In Proceedings of 49th IEEE Conference on Decision and Control, Atlanta, GA,* pages 6107-6112.

Bryant, S. (1996) and Jewell C.D. Analysis of siphon lake drain performance for a small earthen dam. *In Proceedings of Dam Safety, Seattle, Washington*, Page 12.

Buss, L. S. (2005). Nonstructural flood damage reduction within the US Army Corps of Engineers. Journal of Contemporary Water Research & Education, 130:26-30.

Cai, Y.-L., Sun, H.-Y., Shang, Y.-Q., and Xiong, X.-L. (2014). An investigation of flow characteristics in slope siphon drains. Journal of Zhejiang University SCIENCE A, 15(1):22-30.

Cambiaghi, A. and Schuster, R. (1989). Landslide damming and environmental protection - a case study from northern Italy. *In Proceedings of 2nd International Symposium on Environmental Geotechnology*, *Shanghai, China,* volume 1, pages 381-385.

Cole, C. A., Brooks, R. P., and Wardrop, D. H. (1997). Wetland hydrology as a function of hydrogeomorphic (HGM) subclass. Wetlands, 17(4):456-467.

Costanza, R., Farber, S. C., and Maxwell, J. (1989). Valuation and management of wetland ecosystems. Ecological economics, 1(4):335-361.

De Bruijn, K., Klijn, F., McGahey, C., Mens, M., and Wolfert, H. (2008). Long-term strategies for flood risk management: scenario definition and strategic alternative design. *FLOODsite Consortium*, T14 08 01.

EPA (1996). Why watersheds? Technical report, Environmental Protection Agency. EPA800-F-96-001, February 1996.

Erwin, K. L. (2009). Wetlands and global climate change: the role of wetland restoration in a changing world. Wetlands Ecology and management, 17(1):71-84.

Garrett, R. E. (1991). Principles of siphons. Journal of the World Aquaculture Society, 22(1):1-9.

Godschalk, D., T. Beatley, P. Berke, D. Brower, and E. Kaiser (1999). Natural hazard mitigation: Recasting disaster policy and planning. Island Press, s, Washington, DC.

Govi, M. (1989). The 1987 landslide on Mount Zandila in the Val-tellina, Northern Italy. *Landslide News*, 3:1-3.

Hey, D. L. and Philippi, N. S. (1995). Flood reduction through wetland restoration: The upper Mississippi river basin as a case history. Restoration Ecology, 3(1):4-17.

Holloway, J. L. (1958). Smoothing and filtering of time series and space fields. Advances in geophysics, 4:351-389.

Hughes, S. W. (2010). A practical example of a siphon at work. Physics Education, 45(2):162-166.

ICE (2002). Learning to live with rivers. Report, Institution of Civil Engineers (ICE), London, UK.

Leon, A. S., Ghidaoui, M. S., Schmidt, A. R., and García, M. H. (2007). “An efficient finite-volume scheme for modeling water hammer flows." *Contemporary Modeling of Urban Water Systems*, Monograph 15, W. James (Editor in Chief).

Leon, A. S., Ghidaoui, M. S., Schmidt, A. R. and Garcia, M. H. (2008) “An efficient second-order accurate shock-capturing scheme for modeling one and two-phase water hammer flows.” *Journal of Hydraulic Engineering*, 134(7), 970-983.

Leumas, J. (1998). To siphon or not to siphon: That is the question (among others) - A repair history of the Crossgate Dam, ASDSO Annual Conference, Las Vegas, 1998.

Mrvik (2013). Experience with drainage and ground stabilisation by siphon drains in Slovakia. In Proceedings of the 5th International Young Geotechnical Engineers' Conference, volume 2, pages 36-39.

Mrvik, O. and Bomont, S. (2011). Experience with treatment of road structure landslides by innovative methods of deep drainage. *Landslides*, pages 79-90.

Mitsch, W. J. and Day, J. W. (2006). Restoration of wetlands in the Mississippi-Ohio-Missouri (MOM) river basin: Experience and needed research. Ecological Engineering, 26(1):55-69.

NHC (1997). Assessing losses and costs over the last 20 years. Report, National Hurricane Center (NHC).

NWS (2013). May 201, Oklahoma tornadoes and flash flooding. Report, National Weather Service (NWS), Silver Spring, Maryland.

Potter, A. and Barnes, F. H. (1971). The siphon. Physics Education, 6(5), pages 362-366.

UNDP and UNISDR (2006). Integrating disaster risk reduction and climate change adaptation into ecosystem management of coastal and marine areas in south Asia. Technical report, UNDP.