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A Remotely-Operated Siphon System for Water Release From Wetlands and Shallow Ponds

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ABSTRACT The early release from wetlands and shallow ponds could provide extra water storage during heavy rainfall, thus mitigating floods. In this paper, a remotely operated integrated siphon system intended to release water from wetlands/shallow ponds ahead of (a few hours or a few days before) a heavy rainfall that is forecasted to produce flooding is proposed. Siphons work under the pull of gravity and are limited to pond berm heights below about 6 m. An array (e.g. hundreds) of the proposed siphon system can be controlled remotely by an operator or by a Decision Support System. A self-operating and remotely controlled siphon system could open the doors for managing wetlands and shallow ponds for multiple purposes, including flood control and improvement of aquatic habitat. Laboratory tests using 4 and 15 cm-diameter siphons were performed in this study. The results showed that the integrated control system is technically feasible and economically viable.

INDEX TERMS Flood mitigation, remote control, smart wetland, water storage management system.

I. INTRODUCTION

Floods are natural disasters that often cause large economic losses and human suffering [1], [2]. Only in the United States, 4,586 people died from 1959 to 2005 due to flash flooding [3] while economic losses averaged nearly 8 billion dollars per year (in 2011 dollars) between 1981 and 2011 [4]. Because 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 mitigation [5], [6]. Within a watershed, wetlands and ponds can play an important role in flood mitigation, improving water quality, providing ecological habitats, and creating opportunities for public appreciation and recreation [7]–[10]. Several studies have shown the effectiveness of using wetlands for flood mitigation [11]. However, their limited storage capacity limits their effectiveness and the fact that part or all of this capacity may be occupied when a flood is imminent. A way to minimize this problem could be to release part of the water from wetlands/ponds ahead (e.g. a few hours or a few days before) of a heavy rainfall that is forecasted to produce flooding.

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It is well known that wetlands provide habitat for a wide variety and number of wildlife and plants. However, many wetlands naturally have a variable hydro-period, so their function is not necessarily reduced by partial draining [12]. If the wetland is completely drained, however, species that require standing water, such as fish, will be eliminated. Moreover, if a wetland is drained to a low water level in anticipation of a storm and the storm does not materialize, the wetland will be at risk of drying out completely in the following days due to natural evapotranspiration [13]. Thus, draining involves some risks, which can be minimized by not draining the wetlands fully, and by draining only when the certainty of rain events is very high, which may be achieved in the best of the cases a few hours or days in advance of a predicted storm.

The main objective of this study is to present the architecture of a self-operating and remotely-controlled siphon system to release water from wetlands and shallow ponds ahead of a large rainfall storm that is forecasted to produce flooding. The present study builds upon the preliminary work

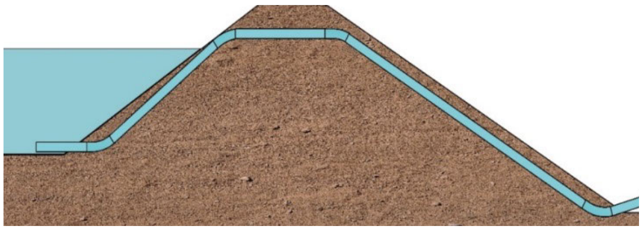

FIGURE 1. Schematic of a siphon system.

in Leon and Alnahit [14]. Apart from the introduction the paper is structured along three sections. The second section is devoted to the presentation of the components of the architecture and software of the integrated system. The third section is devoted to the laboratory tests and corresponding discussion. Finally, the key results are summarized in the conclusion section.

II. MATERIALS AND METHODS

A. TRADITIONAL SIPHON

A siphon (Fig. 1) is an inverted U shape tube or pipe that, under the pull of gravity, flows upward in the tube and then downwards to discharge at a lower level. Siphons have been known since early times as a simple and inexpensive device for transferring water using gravitational force [15]–[17]. The maximum height of the crest in practical siphons is limited by the vapor pressure of the liquid. When the liquid pressure in the siphon drops below the liquid's vapor pressure, small vapor bubbles will begin to form at the siphon top, which will eventually stop the flow [16]. In general, there is a limit for the height of the siphon pipe above a pond water surface elevation. For water at standard atmospheric pressure, the maximum siphon height is approximately 10.3 m (34 feet) [18]. In practice, the maximum height should be smaller than about 6 m due to head losses and because water will already evaporate as steam before the pressure drops to vacuum pressure.

Considerable research has been conducted on siphon flows in the last few decades. Cambiaghi and Schuster [19] presented a system using siphon principles as an emergency drainage treatment for landslides. Bryant and Jewell [20] studied the hydraulic performance of the siphon system intended to drain a small earthen dam, where comparisons were made between theoretical siphon hydraulic performance and actual field performance. Leumas [21] analyzed the variables that should be considered in designing siphons and repairs to existing dams. Recently, siphon drainage combined with electro-pneumatic drainage has been the method for discharging groundwater in Europe, especially in France [22]. More recently, few studies [23]–[25] focused on the management and maintenance requirements of siphons. Although there is vast research on siphon flows, the self-operating and remote-operation of siphons have not been fully explored yet.

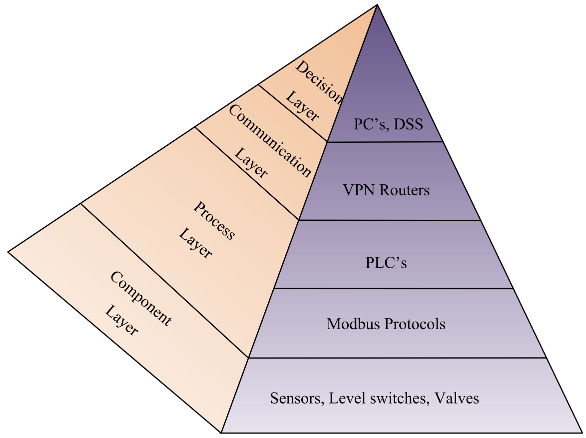

FIGURE 2. Integrated system pyramid.

B. PROPOSED INTEGRATED SIPHON SYSTEM

1) BACKGROUND

The overall hierarchy in our integrated siphon system is presented in Fig. 2. Data exchange takes place between and within different layers [26]. As shown in Fig. 2, the integrated siphon system can be divided into four layers, includes:

- Component layer: This layer consists of the sensors, level switches, actuated valves, air vents, bilge pumps and other accessories.
- Process layer: A Programmable Logic Controller (PLC) is an electromechanical process control system based on a set of input and output modules that connect directly to the hardware. The PLC also performs a diagnostic of the system by collecting information on the status of the sensors and electrical devices.
- Communication layer: A Virtual Private Network (VPN) router is used for the communication between the decision and process layers. This communication is currently performed using 4G cellular network (e.g., AT&T).
- Decision layer: This layer consists of the computational framework for scheduling the optimal flow releases (Decision Supporting System) and the software for the remote control of the siphon system.

2) HARDWARE OF CONTROLLED SIPHON

Fig. 3 depicts the schematic of the hardware of the proposed siphon system. The hardware includes four level switches (components 1, 2, 3 and 4), check valves (component 7), a bilge pump (component 8), an actuated valve (component 6), an air vent with solenoid (component 5) and a solar panel (component 9). The bilge pump is only used to prime the pipe (i.e., fill the pipe with water) before the siphon operation. During siphon operation, the bilge pump is kept turned off. The level switches in the sight tube (components 1 and 2) are used for deciding when to prime the siphon (e.g., refilling the pipe). The system is designed to maintain the pipe primed at all times when the siphon is not in operation and when the

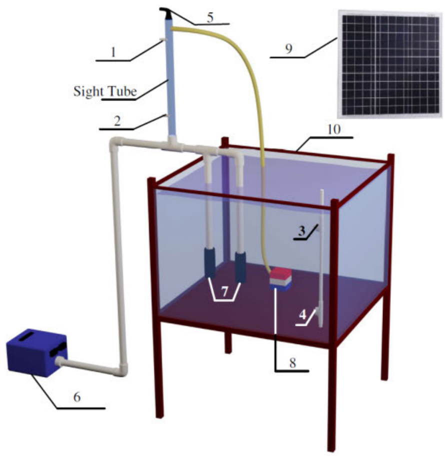

FIGURE 3. Schematic of the hardware of the siphon system: (1-4) level switches; (5) air vent; (6) actuated valve; (7) check valves; (8) bilge pump; (9) solar panel; and (10) wetland.

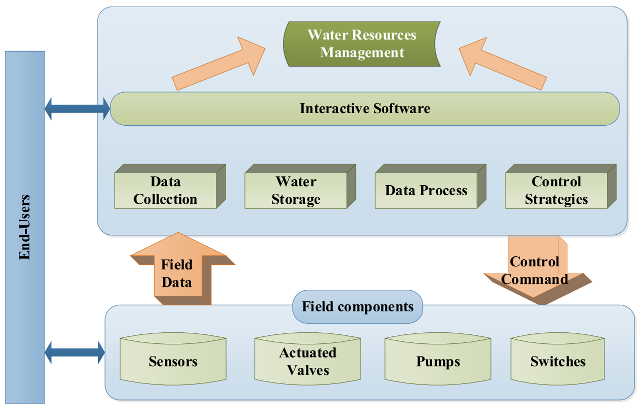

FIGURE 4. The interactive software's architecture.

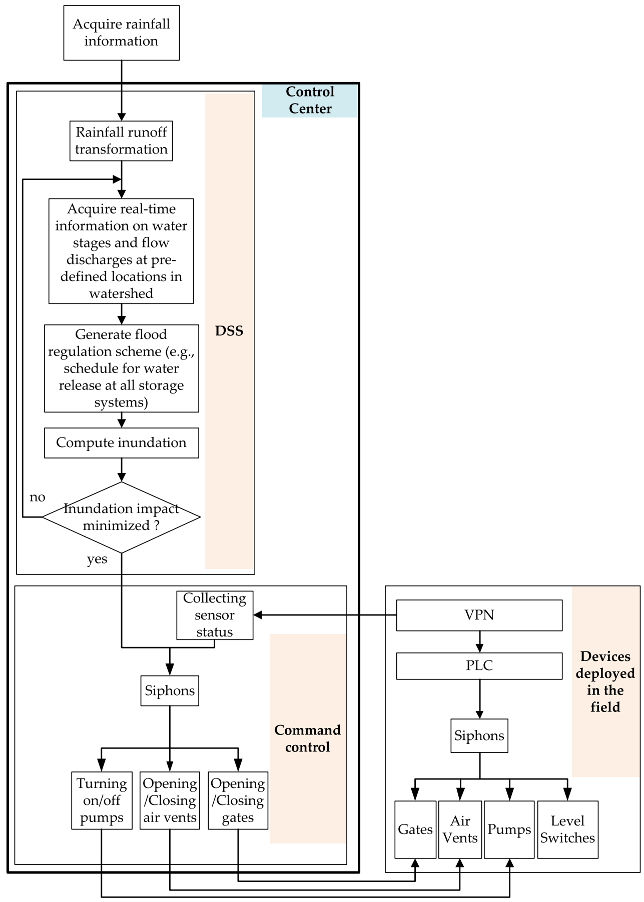

FIGURE 5. Flowchart of the decision making and flood control operation.

water level in the wetland is above level switch 4, which is the minimum wetland water level for ecological requirements. In this way, the siphon system can be always ready to receive an order for opening/closing the outlet valve. The two-level switches in the wetland (components 3 and 4) inform the user if the wetland is about to dry or overflow. The outlet valve will automatically close if the wetland water level is below level switch 4. Conversely, the outlet valve will automatically open if the wetland water level is above level switch 3. The siphon system is powered using two 12V batteries, which are recharged using solar power.

3) SOFTWARE OF CONTROLLED SIPHON

The interactive software serves the development of a graphical user interface (GUI), which was developed in the widely used language "C sharp" (C#). Fig. 4 shows the software architecture. Software end-users can manage the sensor's data and control the operation of an array of siphons.

The flowchart schematic of the decision making and flood control management system is presented in Fig. 5.

As observed in Fig. 5, the DSS module first acquires the rainfall information, then the rainfall-runoff transformation is computed. The DSS also acquires real-time information on water stages and flow discharges at pre-defined locations in the watershed. Then the DSS combines an optimization model, the real-time information of water stages and flow discharges, and an inundation model to generate the optimal schedule of wetland flow releases for minimizing inundation damage. Then, the schedule for the opening/closing of gates is determined based on the required flow releases. Finally, the control software sends the opening/closing commands to the devices deployed in the field.

III. RESULTS AND DISCUSSION

A. DEMONSTRATION OF THE PROPOSED ARCHITECTURE

The schematic of the integration of the control software, communication, and siphon hardware is shown in Figure 6. It can be seen that the level switches and all controlled devices of the siphon hardware (e.g. outlet valve, bilge pump) are directly connected to the PLC unit through physical cables. The PLC module is connected to the VPN router through an Ethernet cable and the VPN router is connected to the StrideLinx platform through the fourth generation (4G) of broadband cellular network mobile communication system. After the communication has been established, the user can monitor and control the sensors and components of the siphon from a PC or Laptop.

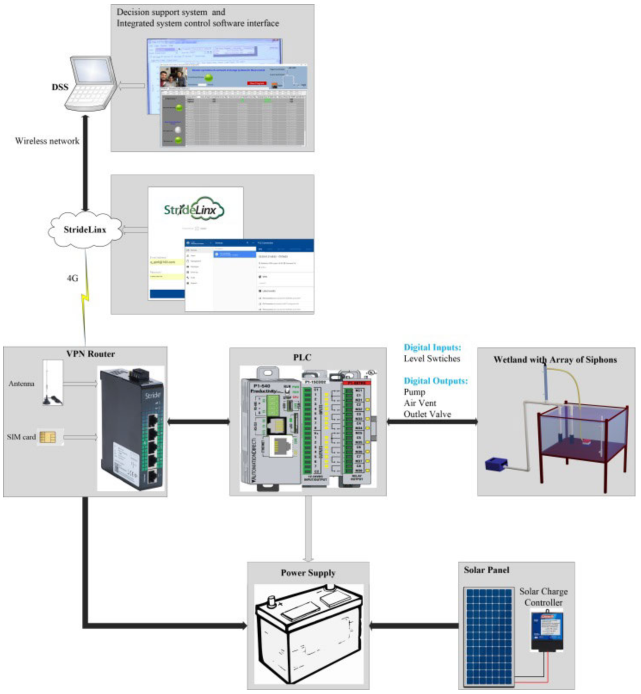

FIGURE 6. **Schematic of the integration of the control software, communication, and siphon hardware.**

A description of the components of the siphon architecture is presented below:

- PLC: The Productivity 1000 PLC system consists of a CPU (P1-540), a discrete combo input/ output module (P1-15CDD2) and an isolated relay module (P1-08TRS). The P1-540 CPU includes four communications ports (USB, Ethernet, RS-232, and RS-485) and uses a 24VDC ± 2% power supply @ 5W plus 1.25 W per additional I/O module. In this study, the Ethernet communication port was used. The P1-15CDD2 has eight 12-24 VDC inputs, and seven 12-24 VDC outputs that source up to 1A per output. The P1-08TRS offers eight, 3A surge protected outputs. The productivity suite programming software for basic configuration is available at https://support.automationdirect.com/products/p3000.html.
  - The first siphon in a wetland requires 8 hardware input and output (I/O) points (4 level switches, an air vent, a bilge pump and an actuated valve, which needs two I/O points). The second, third and successive siphons in the same wetland only require 6 hardware I/O points as the information provided by the level switches in the wetland (i.e. not in the siphon pipe) are the same as those of the first siphon.
  - Each CPU has a maximum of 128 hardware I/O points. Thus, one PLC can connect at least 16 (128/8 = 16) siphons at the same time. If more siphons are necessary at a wetland, PLC extensions can be added.
- VPN router: The StrideLinx's VPN router (SE-SL3011-4G, Automationdirect) is used to establish the connection between the user and the PLC controller. The VPN router requires a 12 to 24 VDC power supply. The VPN router enables 24/7 secure access to the StrideLinx server from anywhere in the world. Once the VPN router is connected to the StrideLinx server network, the user can link to the remote sensors through a secure VPN connection. In some areas, the 4G cellular connection is not reliable and even more in the presence of extreme storm events. In those cases and when higher reliability in communication is needed, the 4G cellular connection can be replaced with a satellite link. If redundancy and higher reliability are needed, both, 4G cellular and satellite connections can be used.
- Battery: All siphon devices that require energy (e.g., PLC, bilge pump, actuated valve) are powered using two 12-Volt batteries (model: Chrome Battery- 12V35AH), each of which is continuously recharged with a 50W 12V solar panel. These two batteries are connected in series to produce 24-volts, which is the voltage required for the PLC.
- Solar panel: This is used in conjunction with a charger controller. A charger controller regulates the voltage and current from a solar array to the battery and thus extends the life of the battery.

For illustration purposes and due to budget limitations, the proposed architecture has been tested using two relatively small-diameter siphons (4 cm and 15 cm). The interface for the integrated control software is shown in Fig. 7. In this figure, the overall system warning indicates the status of the whole system and will turn to red color if there is any problem with the system such as when the internet gets disconnected or if there is a general malfunction, otherwise the light will be green. A text box on the top left corner of the interface displays the time interval at which a set of commands is sent to the controlled siphons. This time interval is also the frequency at which the status of the devices deployed in the field is collected. The schematic of the siphon system is shown on the top right corner of the interface.

As can be seen in Fig. 7, the software interface is designed for a network of wetlands, each with an array of automated siphons. In this figure, W1 indicates wetland 1, W2 indicates wetland 2, and so on. Pre-defined wetlands are displayed in black. Otherwise, they are displayed in gray. Structure warning indicates the status of hardware connections (siphons) in the corresponding storage system (e.g., wetland) and will turn to red color if the connections are malfunctioning; otherwise, the light will be green. There are two level-switches in each storage system (components 3 and 4 in Fig. 3), which aims to check if the water level has exceeded or not some pre-defined levels (e.g., near dry and about to overflow levels). The green color button indicates that the water level exceeded the switch level while a gray color button indicates that the water level is lower than the level switch. For the upper level-switch in the wetland (lower left side in Fig. 7), the green color will

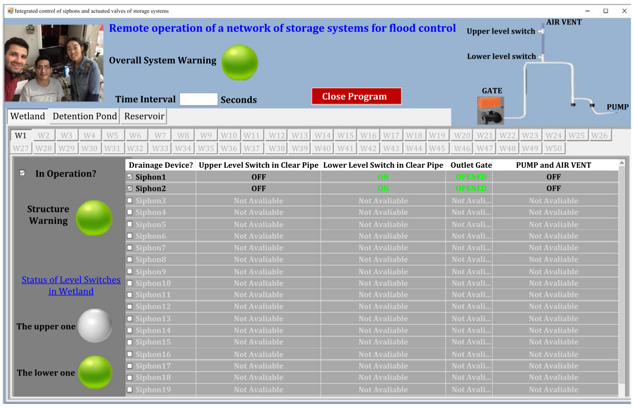

FIGURE 7. Interface of the control software.

automatically open the gate to avoid the overflowing of the wetland; gray color does not result in any action and the system is ready to accept the order of the user or DSS. For the lower level-switch in the wetland, the green color does not result in any action and the system is ready to accept the order of the user or DSS; the gray color indicates that the water level is at or below the level switch, which is the user-minimum water level for the wetland. In this condition, the gate is kept closed and no water release is allowed. This minimizes the impact to aquatic habitat present in the wetland. Currently, each storage system is limited to a maximum of 20 siphon systems, however this could be easily increased if necessary. The end-user needs to define the siphons deployed in each wetland. As an illustration, two siphons were defined for wetland 1 in Fig. 7. For each pre-defined siphon system, there are two states for the upper/lower level switch in the clear pipe, ON and OFF. The ON state indicates that the water level in the clear pipe has exceeded the level switch while OFF indicates that the water level in the clear pipe is lower than the level switch. There are two states for the outlet gates, OPENED and CLOSED. The OPENED state indicates that the outlet gate is fully opened while the CLOSED state indicates that the outlet gate is fully closed. Likewise, there are two states for pumps and air vents, ON and OFF. The ON state indicates that the power of the pump and air vent is turned on while OFF indicates that the power is turned off.

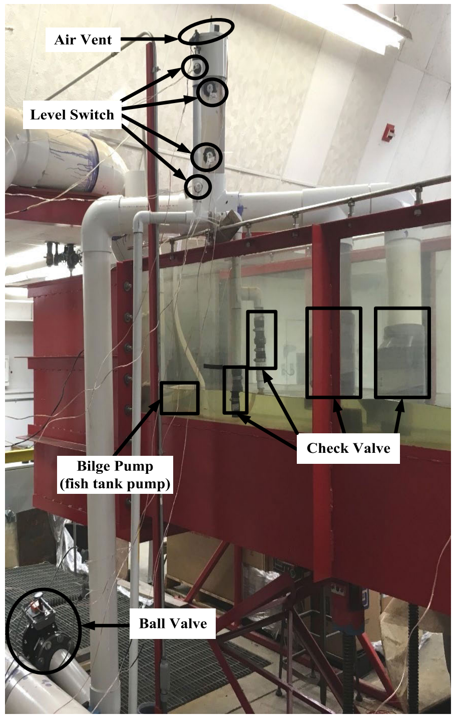

FIGURE 8. A photograph of our 15 cm- and 4 cm-diameter siphons tested in the lab.

TABLE 1. Budget detail for the 4 cm diameter siphon hardware.

Item (4 cm)	Cost=Unit × Quantities
Liquid Level Switch	\$ 56.76 = 14.19×4
Bilge pump	\$ 30.97 = 30.97×1
Air vent with solenoid	\$ 11 = 11×1
PVC Swing Check Valve	\$ 4.33 = 4.33×1
Actuated Ball Valve	\$ 480.5 = 480.5×1
Solid PVC Schedule 40 Pipe	\$ 13.7 = 4.56 /m ×3 m
Clear PVC Schedule 40 Pipe	\$ 3.36 = 5.6 /m × 0.6 m
40 PVC 90 Elbow Socket	\$ 19.96 = 4.99 × 4
40 PVC Tee Socket	\$ 3.96 = 1.98 ×2
PVC Drain Cap	\$ 1.42 = 1.42 ×1
40 PVC Coupling Socket	\$ 0.41 = 0.41 ×1
40 PVC Van Stone Flange Socket	\$ 3.76 = 3.76 ×1
Bilge pump	\$ 30.97 = 30.97×1
Total	\$ 661

B. SIPHON PROTOTYPE TESTS

Laboratory tests using 4 and 15 cm-diameter siphons were performed. Fig. 8 shows a photo of our 15 cm diameter siphon system along with the 4 cm diameter siphon. The itemized budget for the 4 and 15 cm-diameter siphons is shown in Tab. 1 and Tab. 2, respectively. As shown in Tab. 1 and Tab. 2, the total cost of the siphon hardware for a 4 cm diameter siphon is \$661, and \$2,483 for a 15 cm diameter. The cost of the communication and power components, which are independent of the diameter of the siphon, is shown in Tab. 3. As shown in the Tab. 1-3, the total cost of a siphon system is relatively low (e.g., about 3,500 for a 15 cm siphon diameter).

As shown in Fig. 9, an ultrasonic flow meter and a water level sensor were used in the experiments to measure the flow rate and water level, respectively. Typical data collected in an experimental test for water level (cm) and flow rate (m^3/h) are shown in Fig. 10.

As observed in Fig. 10, the valve is fully opened in approximately 150 seconds after receiving the opening command. Around this time, the flow rate reached a maximum value of 83 m^3/h. If a shorter openings time is desired, a faster actuated gate can be used.

C. SIPHON DRAINING VOLUMES

In actual applications, the diameter of the siphon and the number of siphons to use would depend on the desired period to release the water from the wetland. For illustration purposes, we assumed a wetland surface area of 4,000 m^2 with a

TABLE 2. Budget detail for the 15 cm diameter siphon hardware.

Item (15 cm)	Cost=Unit × Quantities
Liquid Level Switch	\$ 56.76 = 14.19×4
Bilge pump	\$ 30.97 = 30.97×1
Air vent with solenoid	\$ 11 = 11×1
PVC Swing Check Valve	\$ 105.14 = 105.14×1
Actuated Ball Valve	\$ 1950 = 1950×1
Solid PVC Schedule 40 Pipe	\$ 18.8 = 6.27 /m ×3 m
Clear PVC Schedule 40 Pipe	\$ 75.4 = 125.66 /m × 0.6 m
40 PVC 90 Elbow Socket	\$ 81.68 = 20.42 ×4
40 PVC Tee Socket	\$ 62.82 = 31.41 ×2
PVC Drain Cap	\$ 4.89 = 4.89 ×1
40 PVC Coupling Socket	\$ 9.32 = 9.32 ×1
40 PVC Van Stone Flange Socket	\$ 19.81 = 19.81 ×1
Bilge pump	\$ 56.76 = 14.19×4
Total	\$ 2483

TABLE 3. Budget of the communication and power components.

Item	Cost=Unit × Quantities
P1-540	\$ 171 = 171×1
P1-15CDD2	\$ 58 = 58×1
P1-08TRS	\$ 44 = 44×1
VPN Router	\$ 640 = 640×1
Solar panel	\$ 62.99 = 62.99 ×1
Rechargeable battery	\$ 69.8 = 69.8 ×1
Total	\$ 1046

(a) (b)

FIGURE 9. Sensors used in the measurements (a) Ultrasonic flow meter (Model FDT-47); (b) Ultrasonic level.

maximum water depth of 3 m. For this wetland, the maximum storage volume is 12,000 m^3. The calculations were done assuming an initial water depth of 3 m, a siphon diameter of 30 cm (12''), a siphon length of 20 m and considering 2, 5, 10, 15 and 20 siphons. Figs. 11 and 12 show the water depth and drained volume as a function of time for the above number of siphons.

Assuming a minimum water depth in the wetland of 1m (e.g., for ecological purposes), it is observed from Fig. 11 that the wetland could be drained to this depth in about 0.8, 0.9, 1.3, 2.6 and 6.2 hours when using 20, 15, 10, 5 and 2 30 cm-diameter siphons, respectively. Finally, as observed in Fig. 12, to fully drain the 12,000 m^3 wetland, it will require about 1.4, 2, 3 and 5.7 hours when using 20, 15, 10 and 5 30 cm-diameter siphons, respectively.

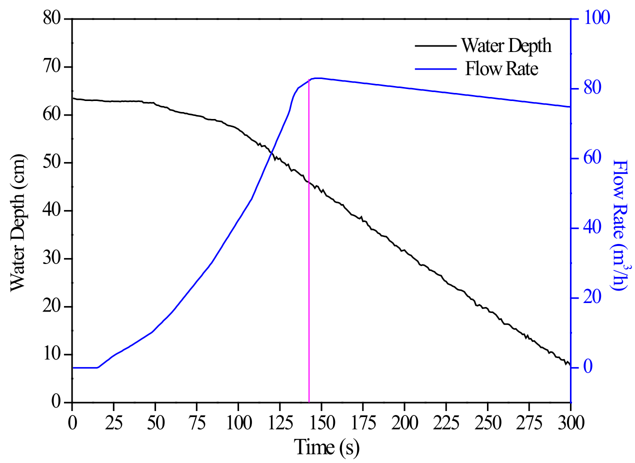

FIGURE 10. Traces of flow rate and water level for an experimental test.

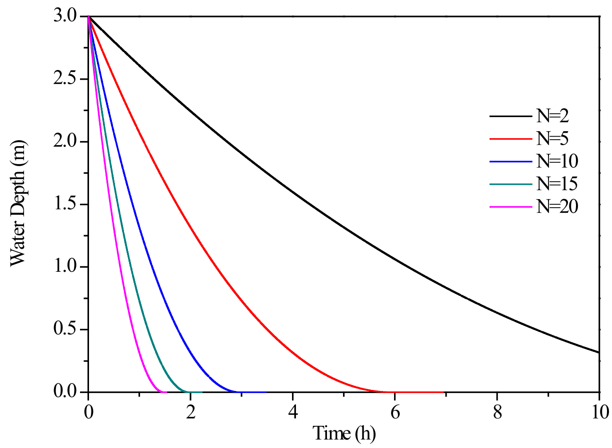

FIGURE 11. Wetland water depth as a function of time for various numbers of 30 cm-diameter siphons.

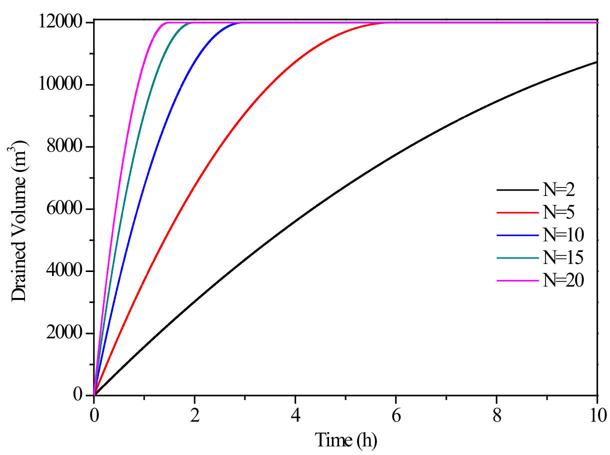

FIGURE 12. Drained volume as a function of time for various numbers of30 cm-diameter siphon.

D. FAILURE RISKS

Adopting a network of siphon systems for flood control involves potential risks that need to be minimized in an actual implementation of this framework. Below, some potential failure risks are identified and strategies to minimize them are discussed.

1) SIPHON PIPE DAMAGE

There is a potential risk that the siphon pipe could rupture due to vandalism or due to inclement weather conditions such as low temperatures that may freeze the water inside the pipe and cause the pipe bursting. Additional problems may include excessive leaks around the fittings due to faulty connections or due to worn out pipes/fittings. The pipe rupture or significant leak may occur when the actuated valve is open (e.g., siphon is in operation) or when the actuated valve is closed. If the actuated valve is initially opened, the pipe rupture or significant leak will depressurize the system and will stop the siphon flow. If the actuated valve is initially closed, the pipe rupture or significant leak will decrease rapidly the water level in the sight tube below the bottom level switch (component 2 in Fig. 3). This, in turn, will lead to the opening of the air vent and turning on of the bilge pump to try to fill the siphon pipe above the top-level switch in the sight tube (component 1 in Fig. 3). Because the pipe rupture will prevent filling the sight tube in less than a Δt, the PLC will identify this problem and send this information to the client software/user. As mentioned earlier, the PLC performs a diagnostic of the system at each operation interval (Δt). During this diagnostic, the PLC collects information on the status of the level sensors and all electrical devices. This information can be used for scheduling repairs and maintenance of the system.

2) ACTUATED VALVE

There is a potential risk that the actuated valve could malfunction while it is opening or closing. In both cases, the flow release will continue until the siphoning effect is lost (e.g., air enters the siphon pipe). To eliminate the siphoning effect and thus, stop the siphon flow, the air vent could be opened. In any case, the PLC will detect the malfunction of the actuated valve during the aforementioned diagnostic and will send this information to the user.

3) POWER

As mentioned earlier, the siphon system is powered using two 12V batteries, which are recharged using solar power. There is a potential risk that one or both batteries could malfunction while the siphon is in operation (i.e., valve is open) or when the actuated valve is closed. If the siphon is in operation (e.g., valve is open), the siphon flow cannot be stopped because there is no power for closing the actuated valve or opening the air vent. In this case, the siphon flow will continue until the siphoning effect is lost due to the lowering of the water level in the wetland below the invert of the intake pipe. If the actuated valve is initially closed, the valve will remain closed. In any case, the PLC will detect the power issues during the aforementioned diagnostic and will send this information to the user.

4) CELLULAR COMMUNICATION

There is a potential risk that cellular service could be interrupted during flow release (i.e., valve is open) or when the actuated valve is closed. If the signal is lost when the actuated valve is open, the valve will automatically close using the power of the battery. If the signal is lost when the actuated valve is initially closed, the valve will remain closed. This means that in the event of cellular service interruption, the siphon will not release water from the wetland. If the cellular connection is not reliable in presence of extreme storm events or if higher reliability in communication is needed, the 4G cellular connection can be replaced with a satellite link. If redundancy and higher reliability are desired, both, 4G cellular and satellite connection can be used.

IV. CONCLUSION

An integrated remotely operated-siphon system was proposed to dynamically manage the water storage in wetlands. The siphon system can be easily installed in wetlands as only anchoring over the berms of wetlands would be necessary. Siphons are modular, and they can be easily added to a wetland if a larger flow discharge is desired. The proposed siphon system could open the doors for managing wetlands for multiple purposes, including flood control and improvement of aquatic habitat.

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