Towards Smart and Green Flood Control: Remote and Optimal Operation of Control Structures in a Network of Storage Systems for Mitigating Floods

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ABSTRACT

Increasing flood frequency and intensity is leading to a new emphasis on utilizing nonstructural approaches for flood mitigation and in integrating nonstructural and structural approaches for the same objective. Within a watershed, wetlands, detention ponds, and reservoirs play a vital role in mitigating floods. However, in many cases, the effectiveness of these storage systems appears to be limited because they are often not operated in a coordinated manner besides storage limitations. We claim that improved flood mitigation at the watershed scale could be achieved by using all watershed storage systems in a coordinated manner and in response to forecasted storm events. The aim of this work is to present a software and hardware architecture for the optimal and coordinated operation of an array of storage systems such as reservoirs, detention ponds, and wetlands for mitigating floods. This approach will enable adaptive release of water from wetlands hours or days ahead of rainfall events, thereby maximizing storage capacity and mitigating floods. As part of this framework we have developed a modular hardware/software platform for interfacing automated siphons/gates, water level sensors, and sensor control/communication to enable remote operation of an array of actuated water releasing hardware in wetlands, detention ponds, and reservoirs. The remote operation is performed using 3G/4G cellular connection. The DSS combines modules of hydrological modeling, inundation modeling, robust optimization, and ecological and operational constraints. The remotely-controlled system is a relatively inexpensive method for flood mitigation. A low-cost way to manipulate the storage in wetlands, detention ponds, and other storage systems could open the doors to a new cost-efficient method for flood control and other objectives.

INTRODUCTION

Floods are natural disasters that often cause large economic losses and human suffering (Cheng, 2004; Uccellini, 2014). For instance, in Texas, Hurricane Harvey alone had killed 82 people during August 25-August 30, 2017 and caused economic losses in an amount of $ 180 billion (Moravec, 2017; Morris et al., 2017). Increasing flood frequency and intensity is leading to a new emphasis on utilizing nonstructural approaches for flood mitigation (Schijndel, 2005; Breckpot et al., 2010). Within a watershed, wetlands can play an important role in flood mitigation, improving water quality, providing ecological habitats, and creating opportunities for public appreciation and recreation (Lee et al., 2012; Mitsch et al., 2015; Kadlec, 2016; Skagen et al., 2016). Several studies have shown the effectiveness of using wetlands for flood mitigation (Bekele & Nicklow, 2007). 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 ahead (e.g. a few hours or a few days before) of a heavy rainfall that is forecasted to produce flooding.

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 hydroperiod, so their function is not necessarily reduced by partial draining (Babbitt, 2005). 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 low water levels 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 (Leon et al., 2018). 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 (Leon et al., 2018).

It is clear that each watershed prone to flooding may have specific challenges and different topographical conditions, however in general, most of these watersheds have inline storage systems (e.g., reservoirs) and off-line storage systems (e.g., detention ponds, wetlands). To make possible the optimal and coordinated operation of storage systems for flood control, it would be necessary to add or retrofit actuated water releasing hardware (e.g., siphons and valves/gates) at each storage system so they can discharge most of the water stored in a pre-determined time. It is worth mentioning that a siphon flow (uphill flow followed by a downhill flow) or a pure downhill flow are gravity-driven flows which require a hydraulic gradient between the water surface level in the storage system and the discharge point (e.g., natural or artificial drainage ditch). In many instances, even near flat land can be engineered to create a storage system and achieve a hydraulic gradient of at least 0.6 or 0.9 m, which would still give significant flow velocities exceeding 1 m/s. In addition, remote operation of water releasing hardware is necessary because very often wetlands, detention ponds and reservoirs are located in remote areas far away from urban areas. The remote operation could be achieved using the classical Supervisory control and data acquisition (SCADA) system or using latest and cheaper technologies such as those presented in Li et al. (2018).

This paper presents a framework for the coordinated and optimal operation of storage systems for mitigating floods. This paper is organized as follows: (1) the architecture of the proposed water releasing hardware is presented; (2) a brief overview of the decision support system (DSS) for guiding the optimal schedule of water release is presented; and (3) preliminary prototype tests are briefly described. Finally, the key results are summarized in the conclusion.

ARCHITECTURE OF REMOTELY-OPERATED HARDWARE FOR WATER RELEASE

Overview of Architecture

The overall architecture of the remotely operated hardware for water release is shown in Fig. 1. As shown in Fig. 1, the architecture of the remotely operated water releasing hardware can be divided into four layers: Client station and software application, Virtual Private Network (VPN) router, Programmable Logic Controller (PLC) and hardware deployed in the field. The first layer consists of the sensor control software, which is used to control the actuated devices (e.g., bilge pump, air vent, valve/gate). The second layer consists of the VPN router, which is used for the communication between the control software and PLCs. This communication is currently performed using the fourth generation (4G) of the mobile phone communication system, however, this can be easily replaced with satellite links if higher reliability in communication is needed. The third layer consists of the PLC, which connects directly to the hardware deployed in the field (e.g. actuated gates). The user sends commands to each PLC for opening/closing the actuated gates/valves. The PLC also performs a diagnostic of the system by collecting information on the status of the sensors and electrical devices. This information would be used by the user for scheduling repairs and maintenance of the system. The fourth layer includes the water releasing hardware deployed in the field.

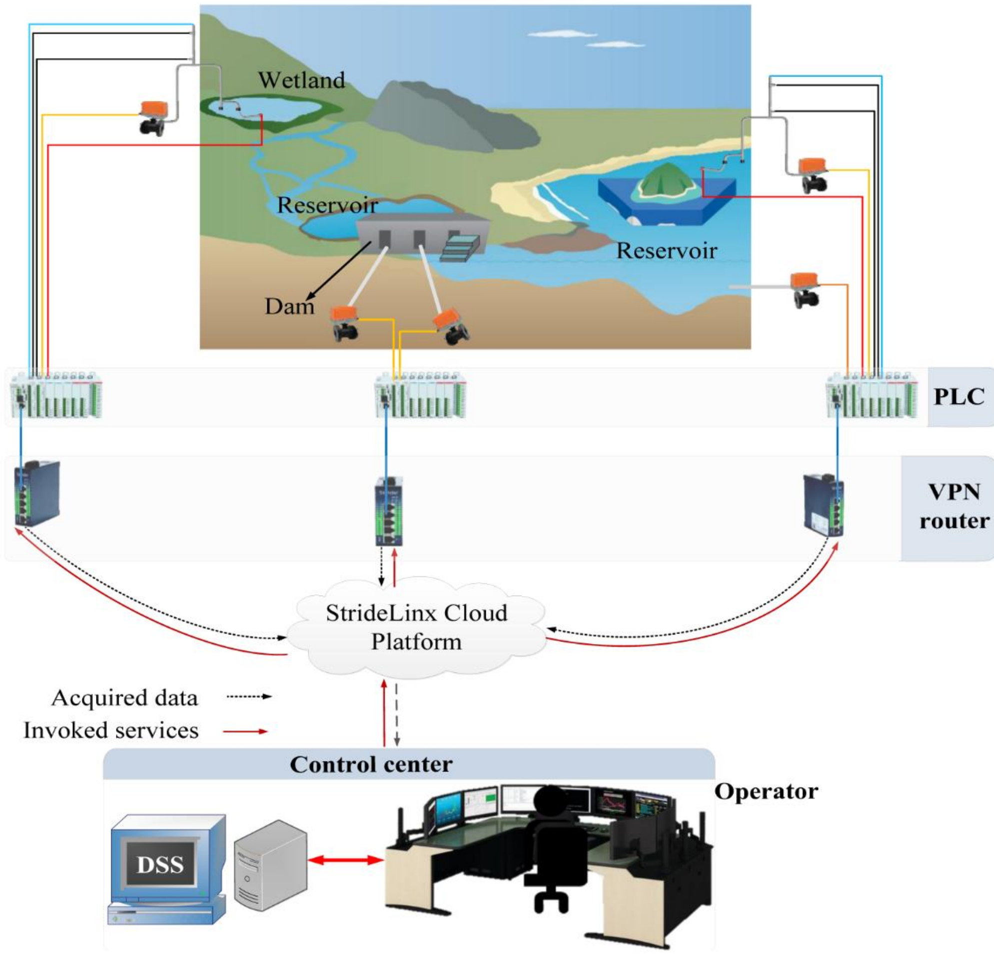


Fig. 1. Overview of the architecture of our remotely operated hardware for water release

Hardware for water release

Two types of hardware are used. The first hardware is simply an actuated gate in a downward pipe. The second hardware is a siphon system, which is shown in Fig. 2. This siphon is equipped with 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, which is driven by gravity, 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 setup is designed to maintain the pipe primed at all times when the siphon is not in operation and when the 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 two types of hardware are powered using two 12V batteries, which are recharged using solar power.

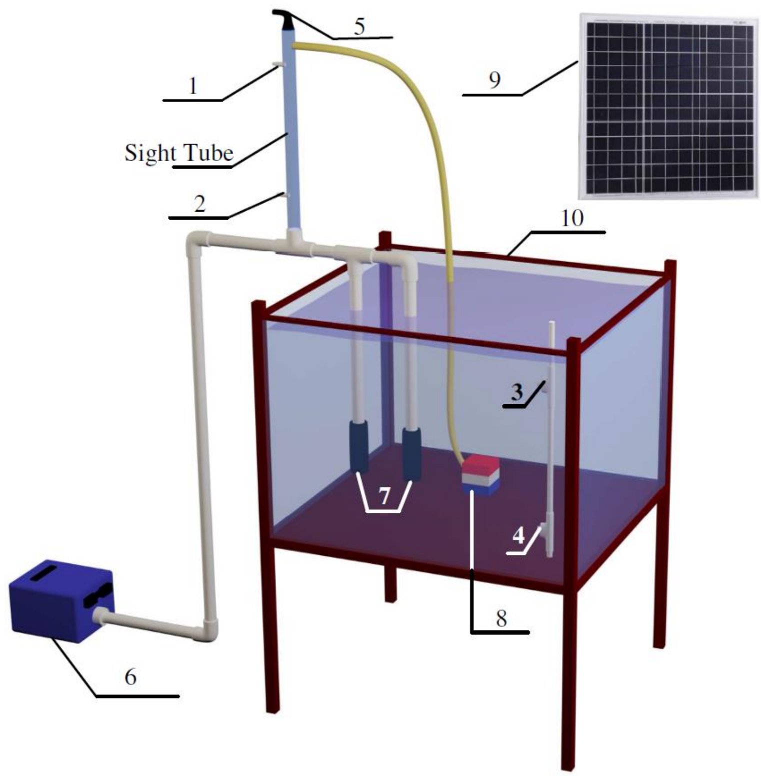


Fig. 2. Schematic of the hardware of the siphon system: (1-4) level switches; (5) air vent; (6) actuated valve; (7) check valves; (8) bilge pump; (9) solar panel; and (10) wetland.

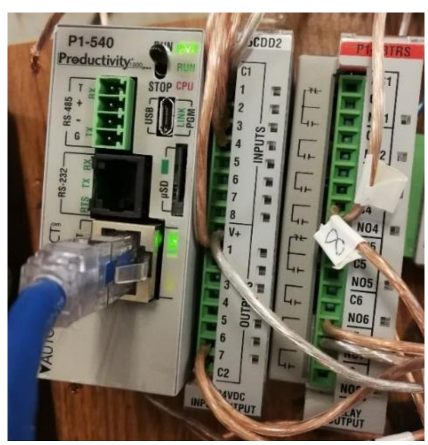


Fig. 3. Photo of the PLC physical connections

Communication

The communication between the user and the water releasing hardware involves a Programmable Logic Controller (PLC) and a Virtual Private Network (VPN). A Programmable Logic Controller (PLC) is a miniature computer that contains hardware and software used for the automation of electromechanical processes, such as control of various types of machinery. A

PLC consists of a Central Processing Unit (CPU), memory, and a set of input and output modules (Bayindir & Cetinceviz, 2011). The input/output system is physically connected to the water releasing hardware and provides the interface between the CPU and its information providers (user) and controllable devices (e.g., actuated gate, bilge pump). Fig. 3 shows a photo of the actual physical connections of the PLC for one of our prototype tests, which are described later.

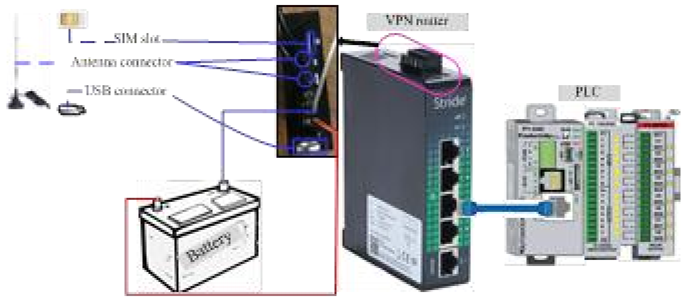


Fig. 4. Schematic of connection between VPN, PLC, and power

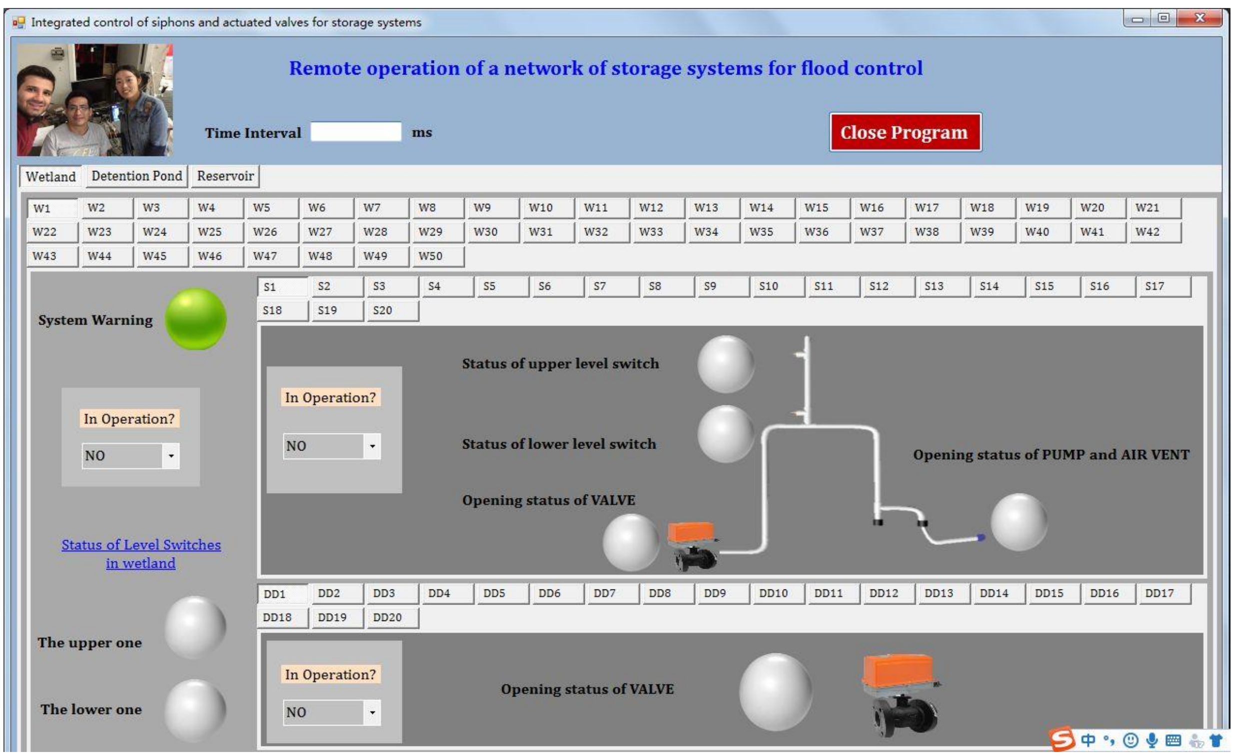


Fig. 5. Interface of Control Software

For establishing the connection between the user and the PLC controller, the StrideLinx's VPN router (SE-SL3011-4G, Automationdirect) was used in this study. The connection between the VPN router and the PLC is through an Ethernet cable, as shown in Fig. 4. 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 presence of extreme storm events. In those cases and when a higher reliability in communication are needed, the 4G cellular connection can be replaced with a satellite link. If redundancy and higher reliability are needed, both, 4G cellular and satellite connection can be used.

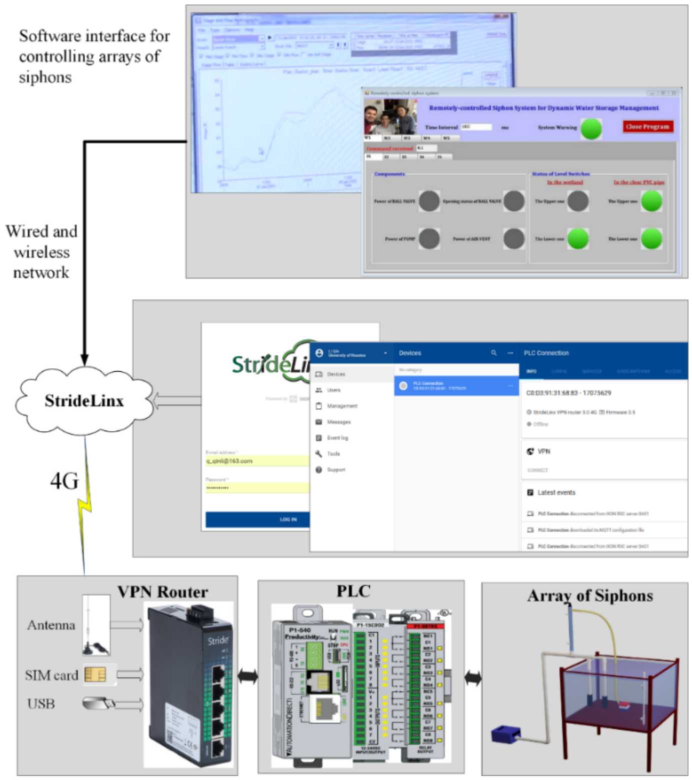


Fig. 6. Schematic of the integration of the control software, communication, and the water releasing hardware

Power

All hardware devices that require energy (e.g., PLC, 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.

Software for Controlling an Array of Actuated Gates and other Devices

The software for controlling an array of our remotely operated hardware for water release was developed in Visual C# (pronounced "C sharp") language of Microsoft Visual Studio 2010, which provides various features, such as object-oriented, automatic memory management, rich library, structured programming language, scalable, and easy to be made modular (Wei et al., 2014). Fig. 5 shows the software interface for controlling an array of actuated water releasing hardware in multiple wetlands, detention ponds and reservoirs. In Fig. 5, *W1* indicates wetland 1, *W2* indicates wetland 2, and so on. Likewise, *S1* indicates siphon 1, *S2* indicates siphon 2, and so on. Also, *Time Interval* is the time step at which a set of commands is sent to the hardware. This time interval is also the time step at which the status of the sensors is collected. The set of commands received consist of 0s and 1s, where 0 indicates valve closing and 1 indicates valve opening. In addition, all actuated water releasing hardware for a given storage system have the same operation. For instance, the command "0,1,0" indicates to close all gates from storage 1, open all gates from storage 2 and close all gates from storage 3. The button of *system warning* turns red color when the internet gets disconnected or there are any problems with the sensors or other components of the system. Whenever there is a malfunction or problem with a particular water release hardware, the corresponding actuated gate/valve is automatically closed using the power provided by the battery.

Integration of Control Software, Communication, and Water Releasing Hardware

Fig. 6 depicts the schematic of the integration of the control software, communication, and water releasing hardware. The sensors and actuated devices of the water releasing hardware (e.g. level switches, actuated gate) 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 actuated components from a PC or Laptop. For the first type of water releasing hardware (actuated gate in a downward pipe), it is required 4 hardware input and output (I/O) points (2 level switches and an actuated valve, which needs two I/O points). For the second type of water releasing hardware (siphon), it is required 8 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 PLC has a maximum of 128 hardware I/O points. If more I/O points are necessary, PLC extensions can be added.

DECISION SUPPORT SYSTEM

The coordinated and optimal operation of storage systems for flood control requires a computational framework that integrates hydrologic and hydraulic models within an optimization framework. There is a vast array of hydrologic, hydraulic and optimization models available in the literature. The present framework combines widely used software within the MATLAB platform for forecasting optimal flow releases in a multi-storage system for flood control. The present framework combines four models namely, The U.S. Army Corps of Engineers' Hydrologic Modeling System (HEC-HMS), The U.S. Army Corps of Engineers' Hydrologic Engineering Center's River Analysis System (HEC-RAS), the MATLAB Genetic Algorithm (GA) Toolbox, and The U.S. Army Corps of Engineers' HEC-DSSVue. The version of the models used herein are: HEC-HMS 4.2.1, HEC-RAS 5.0.5, MATLAB R2018b and HEC-DSSVue 2.0.1.

Following we present a brief overview of a case study, which involves the operation of a hypothetical eight wetland system in the Cypress Creek watershed in Houston, Texas. Figure 7 depicts the geographical location of this watershed. The Cypress Creek watershed is located in northern Houston and it experiences about two to three flooding events per year on average. The Cypress Creek watershed also experienced devastating floods during Hurricane Harvey in August 2017.

The hydrologic model of the Cypress Creek watershed was created in HEC-HMS. The HEC-HMS model of the Cypress Creek watershed was divided into 23 sub-basins, as shown in Fig. 8. As shown in this figure, the watershed was divided into three portions, upstream, midstream and downstream. To help in flood mitigation, eight hypothetical wetlands (i.e., reservoirs in HEC-HMS) are placed in the midstream portion of the watershed, which are displayed as yellow clouds in Fig. 8. The reason to implement wetlands in midstream is that most of the natural wetlands and abandoned rice farms are located within this region. Figure 9 shows typical hourly gridded precipitation used as input to the HMS model. The schedule of optimal flow releases for managing the wetlands are determined by the optimization model.

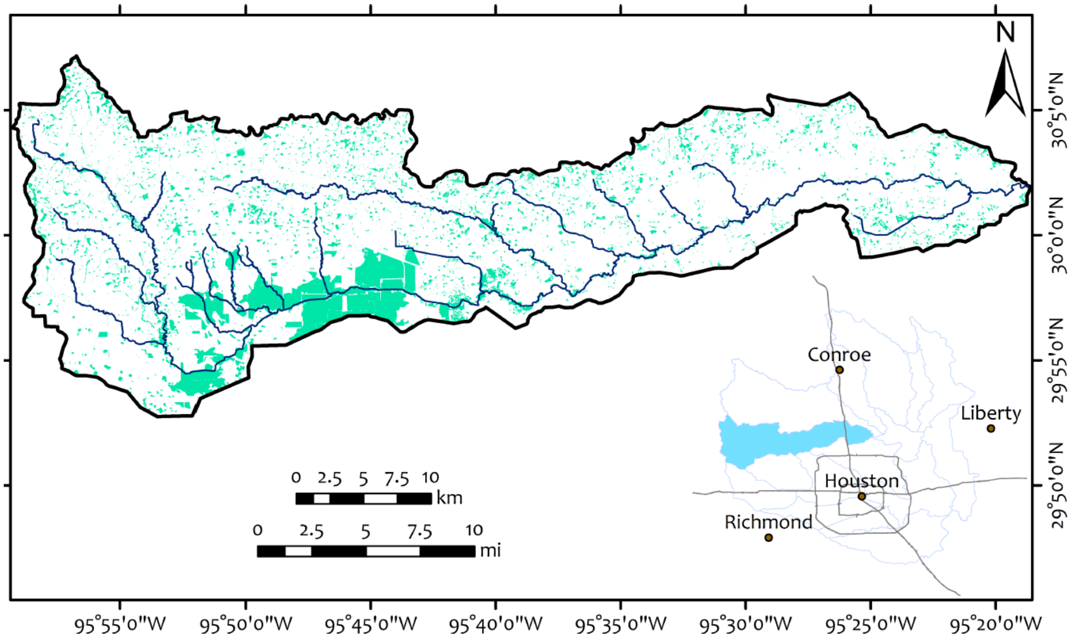
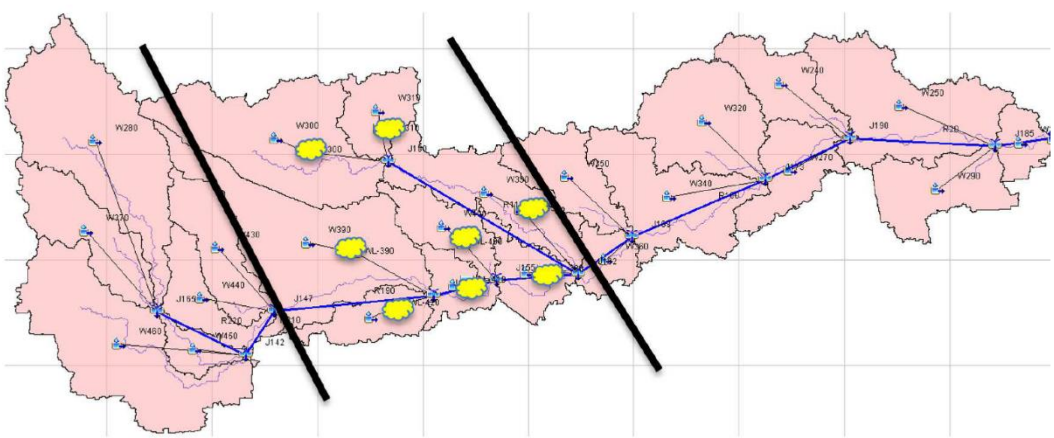


Fig. 7. Geographical location of Cypress Creek watershed, TX



Upstream **Middle-stream** **Downstream**

Fig. 8. Screenshot of the HEC-HMS model for Cypress Creek watershed, TX along with schematics of eight hypothetical wetlands in midstream, displayed as yellow clouds.

The HEC-RAS model of the major streams of Cypress Creek watershed was built using the HEC-GeoRAS tool within ArcGIS. Typical flooding scenarios for various wetland sizes (as a percentage of watershed area) in the Cypress Creek are shown in Fig. 10. The HEC-RAS model is used to simulate inundation in the watershed. The inflow data for the HEC-RAS model is provided by the HEC-HMS model. The total outflows from the wetlands (optimization derived outflows and spill flows) are routed through the respective downstream reaches and enter the main streams in HEC-RAS as lateral flows. Thus, the HEC-RAS model consists of eight lateral flows that change at every generation during the optimization. All other inflows to HEC-RAS are also provided by HEC-HMS but they are not changed during the optimization. To speed up the computations, all HEC-RAS simulations are performed in parallel using the scripts presented in Leon and Goodell (2016).

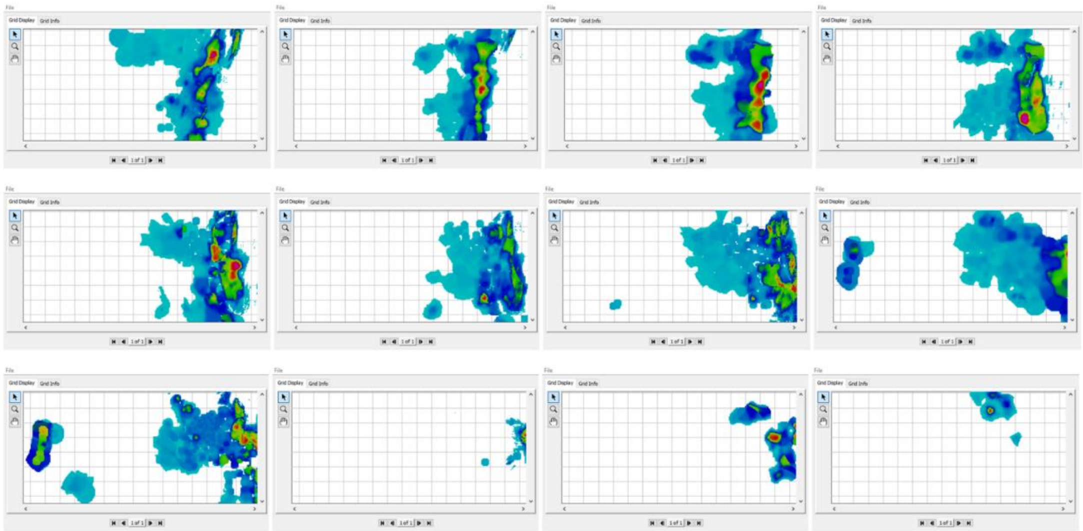


Fig. 9. Typical hourly gridded precipitation used as input to our DSS

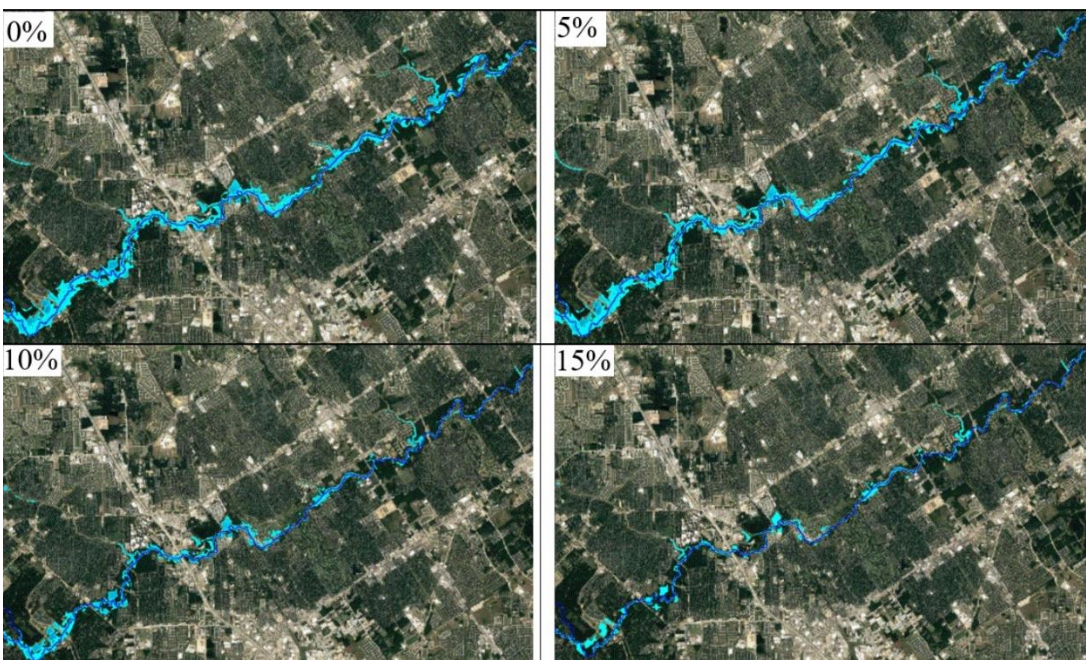


Fig. 10. Typical flooding scenarios for various wetland sizes (as a percentage of watershed area) in the Cypress Creek, Texas.

Once the HEC-HMS and HEC-RAS models are constructed and validated, the GA optimization model creates an initial population of schedules of flow releases at the eight wetlands. These release flows, as well as the wetland overflows, if there is any, are routed to the reaches downstream of the respective wetlands by HEC-HMS. The routed flows from the wetlands together with the unmanaged flows (sub-basins without wetlands) enter the HEC-RAS model to simulate inundation at the watershed scale. Then, the optimization model calculates the objective function to determine the new population of schedules of flow releases at the eight wetlands. This procedure is repeated until the optimization stopping criteria is satisfied. The screenshot of a typical convergence process of the optimization is shown in Fig. 11. After the optimization stopping criteria is satisfied, the plots for the optimal schedule of outflows at all wetlands are automatically generated. Each plot includes the time trace of the water surface elevation, storage, total inflow, spill flow and total outflow. A typical graph produced for one managed wetland is shown in Fig. 12. As shown in Fig. 12, the optimization tends to release part of the water from the wetland ahead of the inflow hydrograph to provide extra water storage during a heavy storm event. In the present exercise, the minimum ecological water depth was set to 0.5 ft and the model tried to keep the water level in the wetland above this value.

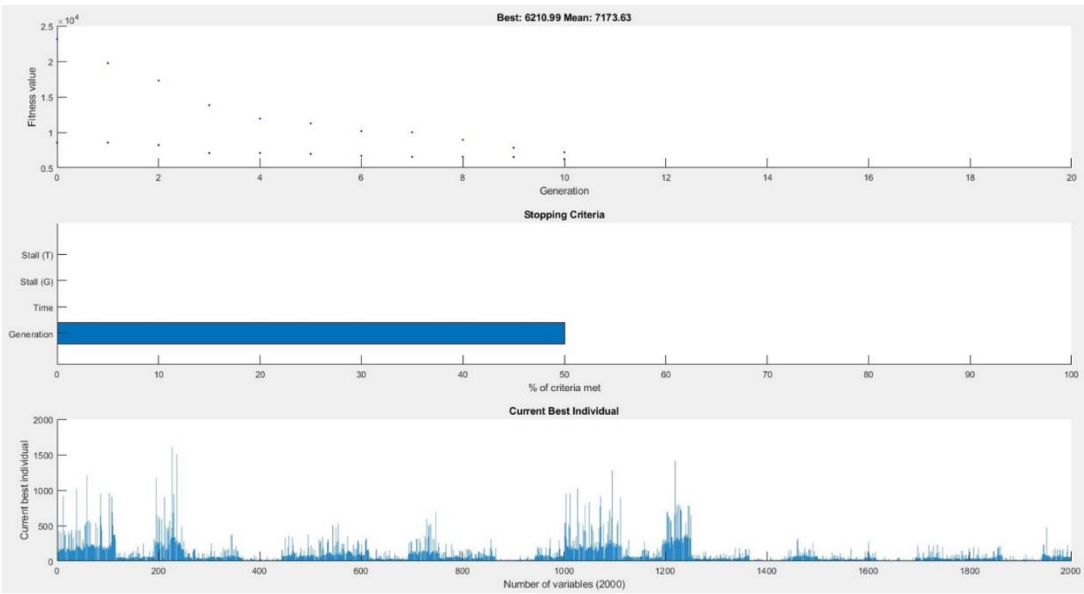


Fig. 11. Screenshot of a typical convergence process for optimal schedule of wetland outflows

PROTOTYPE TESTS

Prototype tests using 1.5 and 6 in-diameter siphons were performed. Fig. 13 shows a photo of our 6-in diameter siphon system along the 1.5-in diameter siphon. A video of the operation of the 6-in diameter siphon can be seen at https://youtu.be/Zw_2hCd0G9o. The total actual cost of the 6” siphon system was about 4200$ (November, 2018). The estimated cost of a 12” diameter siphon system would be about $5500.

To increase the flow discharge in the siphon, tests were performed using one, two, three and four check valves. No significant flow discharge difference was found between these four configurations. Thus, a single inlet would be needed in practice. Power tests were also performed. It was found that the aforementioned batteries could fulfill the power needs of up to 2 siphons. For safety factor considerations, a battery should be used for each siphon. With regard to the solar panel, after a 25-year period, a single solar panel could still fulfill the recharge needs of a battery. It is noted that the battery, which life usage is between 3 and 5 years according to the manufacturer, would need to be replaced multiple times during the life time of the project, which is estimated to be at least 25 years.

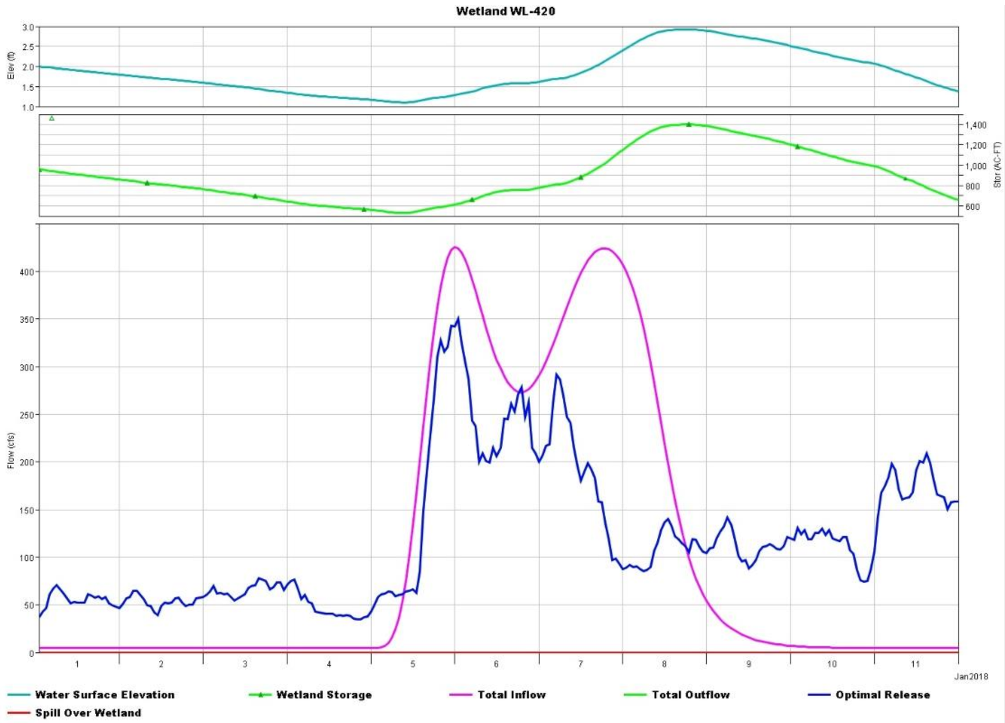


Fig. 12. Screenshot of typical optimal schedule of outflows for one managed wetland

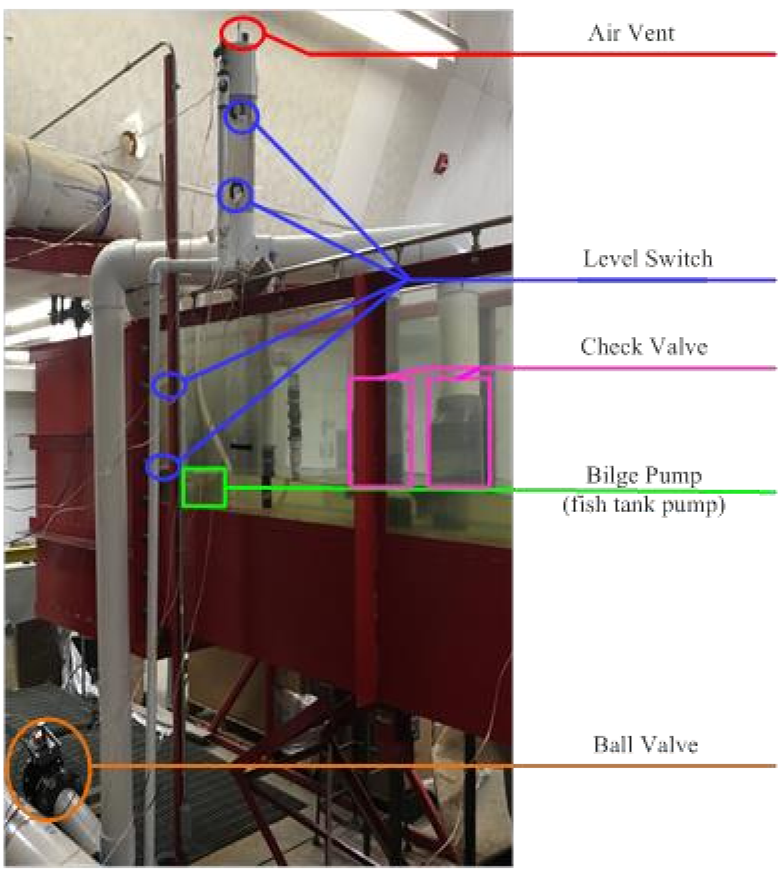


Fig. 13. A photograph of our 6″- and 1.5″-diameter siphons tested in the lab

CONCLUSIONS

This paper presents a framework for the coordinated and optimal operation of a network of storage systems to mitigate floods in response to forecasted storm events. This approach aims to enable adaptive release of water from wetlands, detention ponds and reservoirs hours or days ahead of rainfall events, thereby maximizing storage capacity and mitigating floods. As part of this framework, we developed a modular hardware/software platform for interfacing water releasing hardware, water level sensors and sensor control/communication. The remote operation of water releasing hardware is performed using 3G/4G cellular connection. The Decision Support System (DSS) for guiding the optimal flow release combines modules of hydrological modeling, inundation modeling, robust optimization, and ecological and operational constraints.

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