Impact of Dynamic Storage Management of Wetlands and Shallow Ponds on Watershed-scale Flood Control

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Abstract

This paper presents a case study on the impact of dynamic management of wetland storage on downstream flood control at the Cypress Creek Watershed in Houston, Texas. Dynamic storage management is performed by optimizing the schedule of flow releases from managed wetlands for minimizing downstream inundation. The main objective of this study is to compare the extent of downstream flood inundation with and without dynamic management of wetland storage. This study used HEC-HMS for the overland flows and the level pool routing in the wetlands and HEC-RAS for simulating river inundation. Wetlands were implemented in the midstream region of the watershed. The schedule of optimal wetland flow releases were determined using the MATLAB Genetic Algorithm toolbox. The optimization results indicate that, when wetland size exceeds a fairly low threshold, dynamic storage management of wetlands can significantly reduce flood area, flood depth and flood duration at the downstream region of the watershed compared with the case without dynamic storage management.

Keywords: Wetland, Flood Control, Flow regulation, Flood management, Optimization, Cypress Creek Watershed

1. Introduction

Wetlands serve in flood mitigation by retaining excess stormwater/snowmelt water and thus reducing the peak and volume of flows going into rivers in downstream (Berlin and Handley 2007). Abundant literature over the past few decades asserts that wetlands can help to reduce floods and thus bring significant flood mitigation benefits to the human society. For example, based on an experiment that involved constructing wetlands along the Des Plaines River in Illinois, it was found that a marsh of only 5.7 acres could retain the natural

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run-off of a 410 acre watershed. This study estimated that only 13 million acres of wetlands (3% of the upper Mississippi watershed) would have been needed to prevent the catastrophic flood of 1993 (Godschalk et al. 1999). Another study conducted by Barbier et al. (2013) estimated the protection values of wetlands in Southeast Louisana from Hurricane storm surges and concluded that coastal wetlands present a significant effect on storm surge level reduction. Their regression analysis showed that a 0.1 increase in wetland continuity (defined as the ratio of wetland to water along the analyzed transect in the Caernarvon Basin , i.e., 0 means open water, 1 means solid marsh) per meter reduces flood loss by \$99 - \$133 in the study area. Similarly, Watson et al. (2016) performed a wetland value study in Middlebury, Vermont and estimated that the annual flood mitigation value that the Otter Creek floodplains and wetlands brought to Middlebury, VT ranged from \$126,000 to \$450, 000 annually. In addition, Rizzo et al. (2018) studied the effects of constructed wetlands on combined sewer overflow (CSO) reduction and proposed that the constructed wetlands reduced 86.2% of the peak flow for a CSO event with a return period of 10 years.

Nonetheless, a report of the United Nations (UNDP and UNISDR 2006) suggested that upland wetlands could be effective for small floods, but for large floods, their value may be significantly reduced as their storage capacity may be exceeded. Glenn and Woo (1997) and Quinton and Roulet (1998) reported that more significant floods occurred when the water table of some Canadian peatlands exceeded the depression storage capacity while smaller floods were observed when pools became disconnected into separate micro-catchments. In other words, the capacity of wetlands in alleviating floods is dependent on the available storage capacity, which may be limited for many natural wetlands depending on local weather and hydrologic conditions. For instance, research by Holden and Burt (2003a) on blanket bogs on the English Pennines showed that the water table was within 40 cm of the surface for 80% of the year and concluded that when it rained there was little space for water storage. Likewise, in the case of our study area (Cypress Creek Watershed, Houston, TX), the flood control District of Harris County has chosen not to use extensive areas of abandoned rice fields for flood control because there is no guarantee that the rice ponds would be empty when a flood-producing storm approaches.

Past research about the flood mitigation effect of wetlands mainly focused on how the natural storage capacity of the wetlands affects flood peak and volume, and the natural available storage capacity may become more limited for some areas in rainy seasons when mild to heavy rainfall events occur continuously for days or weeks. The novelty of this study is to find a strategy to increase the available storage capacity of wetlands on a watershed scale and thus improve their performance on flood control. This can be achieved by enabling dynamic storage management of a wetland system, which means water can be released from wetlands ahead of, and/or in the middle of, heavy rainfall events that are forecasted to produce flooding so that increased storage can be made available. Such a wetland system can be operated through remotely controlled gates and siphons such as those presented in Qin et al. (2019). This approach can substantially increase the available storage capacity of wetlands so that more flows from hillslopes can be captured and attenuated through the wetland system, which then helps to further mitigate flooding.

This study presents a framework for the optimal wetland storage management for watershed-scale flood control. This paper is the second of a two paper series exploring the impact of wetlands on watershed-scale flood control. The scope of this paper is limited to the impact of the dynamic management of water storage in a system of wetlands on downstream flood mitigation.

2. Methodology

To investigate how dynamic management of water storage in a system of wetlands affect downstream flooding, this study assumes hypothetical upland wetlands with drainage pipes and remotely operated gates to control the flow releases from these wetlands. The goal is to release as much water as possible from the wetland system and deliver the flows out of the watershed using the full conveyance capacity of the rivers during the simulation period. Such an objective was set based on the needs of minimizing flooding area while at the same time maximizing the usable storage capacity of wetlands in case of continuous large rainfall events that last several days or weeks.

The modeling framework can be divided into four major parts: 1) hydrologic modeling of the watershed, which is performed in the Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS), 2) hydraulic modeling of rivers, which is performed in the Hydrologic Engineering Center - River Analysis System (HEC-RAS), 3) wetland storage routing, which is performed using the reservoir module in HEC-HMS, and 4) optimization of wetland flow releases, which is performed using the MATLAB genetic algorithm (GA) toolbox. These four parts are integrated as shown Fig. 1.

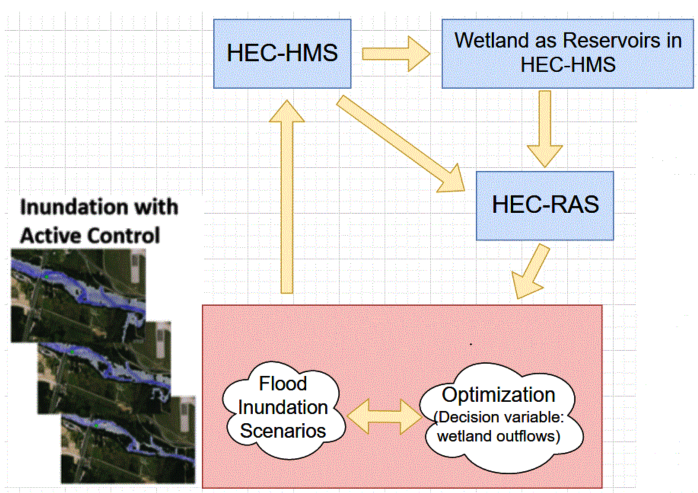


Figure 1. Overall structure of the modeling framework

The HEC-HMS model simulates the rainfall-runoff process of the watershed and produces the outflow hydrograph from each sub-basin. The outflows from each sub-basin are the inflows to the wetlands. The wetlands are simulated as reservoirs in the HEC-HMS model with flow release (if specified) and overflow. The total outflow from each wetland (flow release + overflow) is then routed downstream until they arrive at the river or creek. The flow in the river is modeled in HEC-RAS, which computes water surface profiles along the river and then generates inundation mapping, which shows the magnitude of flooding in terms of flood area, flood depth, and flood duration. The flow release feature of reservoirs in HEC-HMS needs to be enabled for studying the dynamic management of wetland storage.

Fig. 2 shows the flow chart of the methodology used in this study. The general process can be divided in two parts. (a) Model preparation and (b) Model execution. In the model preparation, the hydrologic (HEC-HMS) and hydraulic models (HEC-RAS) were built, calibrated and validated for the Cypress creek watershed. Then, the wetlands were set up in the HEC-HMS model. As mention above, the flow release feature of reservoirs in HEC-HMS model needs to be enabled for studying the dynamic management of wetland storage. For the model execution, the following procedure was followed: (1) set up initial GA population (wetland flow release schedule), (2) run HEC-HMS for each population and transfer flow results data to HEC-RAS, (3) run HEC-RAS for each population, (4) compute objective function and determine if the optimization convergence criteria is met. If not, update GA population and repeat steps 2 to 4. Once the optimization convergence criteria is met, plot optimal schedule of wetland outflows and inundation map.

2.1. *Study Area: Hydrologic modeling, Hydraulic Modeling, Design Rainfall Event*

Cypress Creek Watershed (Houston, TX) was used as the study area to investigate the impact of dynamic management of wetland storage on downstream inundation. A 100yr 72hr design rainfall event was developed for all simulations in this study based on a Texas empirical hyetograph study (Williams-Sether et al. 2004). A hydrological model for the watershed was built in HEC-HMS and a hydraulic model for the major rivers within the watershed was built in HEC-RAS. The HEC-HMS and HEC-RAS models were coupled through Hydrologic Engineering Center - Data Storage System (HEC-DSS). For more details of the construction, calibration, validation, and coupling of the above-mentioned models, as well as the development of the design rainfall event, the reader is referred to the first paper of this series (Tang et al. 2019a).

2.2. *Wetland Modeling*

The wetlands are modeled as reservoirs in the HEC-HMS model enabling the flow release and overflow modules. The flow release module in HEC-HMS is essential for the implementation of dynamic storage management of the wetland system. The flow release module in HEC-HMS consists of a schedule of

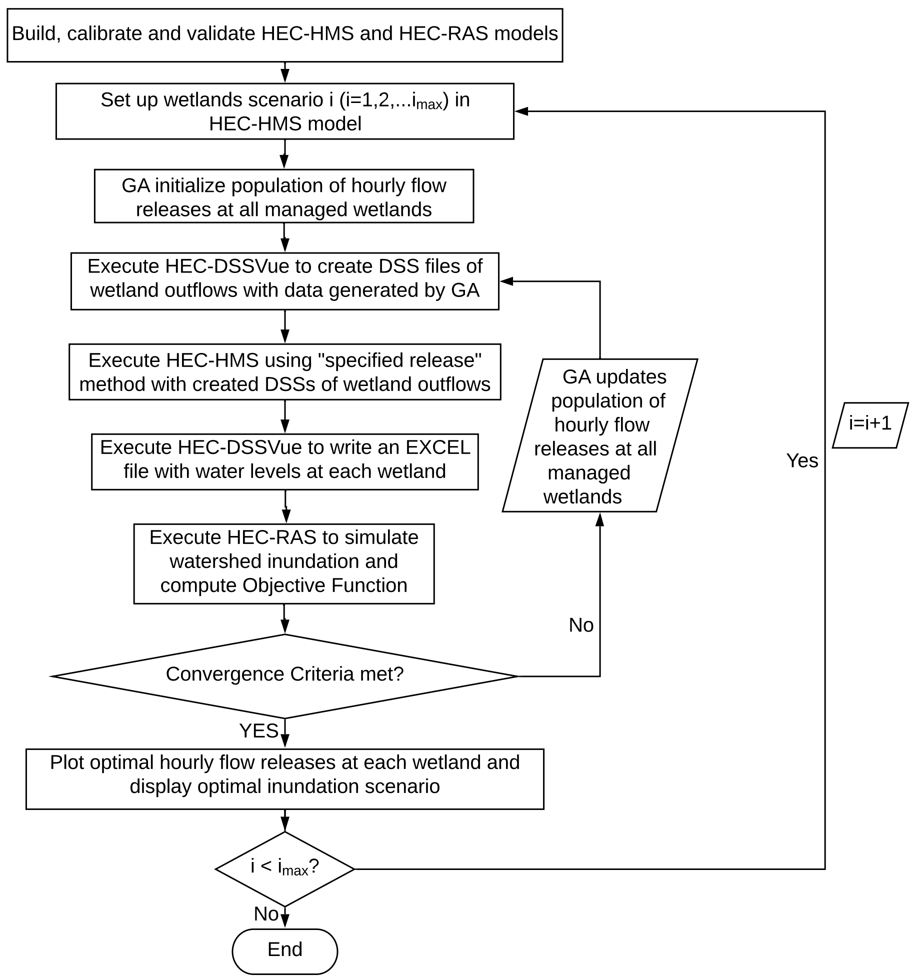


Figure 2. Flow chart of the methodology

outflows at a given time step (e.g., hourly). The schedule of flow releases will be continuously modified by the optimization algorithm until the convergence criteria is met. The wetland overflow is approximated as the broad-crested weir flow, using equation 1.

$$Q = CLH^{3/2} \tag{1}$$

where Q is discharge, C is discharge coefficient, L is weir length, H is hydraulic head.

2.3. Optimization

The schedule of flow releases from the managed wetlands, other than overflows, are determined by the optimization algorithm. Depending on the population density, economic importance, and/or other social, industrial factors, decision-makers can set a series of control cross-sections along the river, and assign a maximum allowable water level at each of these cross-sections. To use the full conveyance capacity of the river, the water levels in the pre-determined cross-sections need to be maintained near their specified maximum levels.

To protect an area of interest, a control cross-section should be set based on preliminary hydraulic simulations to determine the impact range of the water elevation. For instance, for the Cypress Creek river, which flows in subcritical flow conditions, the water level at a control section can significantly impact the water levels up to about 20km upstream of the control cross-section (e.g., backwater effects) and about 10km downstream. Beyond this range, the control cross-section does not exert significant influence. Because the urban area in the Cypress Creek Watershed extends for about 40km along the Cypress Creek, to protect the whole area from flooding, two control cross-sections were set along this area as shown in Fig. 3. The maximum allowable water level was set at around 0.3m (1ft) below the bank elevation at each control cross-section.

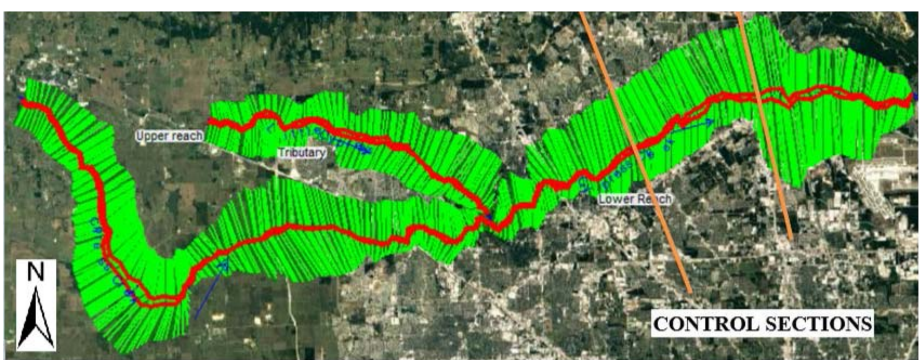


Figure 3. Location of the two control cross-sections within the Cypress Creek watershed

The objective function is written as the squared difference of the maximum allowable water level and the computed water level with a couple of penalty coefficients, as shown in equation 2. The objective is minimized during the optimization process based on a penalized approach.

$$Obj = \sum_{i=1}^{n} \sum_{j=1}^{m} p_{wl} p_{ed} (y_{i_j} - y_{i_{max}})^2 \tag{2}$$

where i is the index of the control cross-sections, j is the index of the time series of the flow data, n is the total number of control cross-sections, m is the total number of flow releases at each wetland during the optimization period, y_{i_j} is the computed water level at time j at cross-section i, $y_{i_{max}}$ is the maximum allowable water level at cross-section i, p_{wl} is a penalty coefficient imposed at the control cross-section depending on whether the water level has exceeded or not the maximum specified water level, p_{ed} is a penalty coefficient for draining wetlands below ecological water depth.

In the case study, the penalty coefficient p_{wl} was set to 100 for water levels exceeding $y_{i_{max}}$ (indicating flooding), and as 1 for water levels 0.9m (3ft) below $y_{i_{max}}$ (indicating not conveying water at the full channel capacity). For water levels within the buffer zone from the maximum allowable water level to 0.9m (3ft) beneath, the penalty coefficient was set to 0, which means the optimization aims to convey water within the channel's full capacity without causing flooding. It is possible that under a heavy rainfall event, optimization of wetland outflows cannot necessarily eliminate flooding totally, but the objective function will minimize the flood area at all times.

The penalty coefficient p_{ed} is introduced in the objective function to exclude the possibility of draining wetlands below the minimum water level required to sustain the ecological function of the wetlands, like supporting local hydro-habitat and biodiversity. This minimum water depth is considered as the ecological water depth of the wetlands. In our case study, the ecological water depth of wetlands was assumed to be 0.15m (0.5ft). During the optimization, high flow release may randomly be chosen at a given generation and cause the water depth to drop below the ecological water depth. However, by setting the penalty coefficient p_{ed} to a large number (e.g., 50000 in the case study) when water depth in wetlands drops below the ecological water depth, it is ensured that such scenario will be discarded in the optimization process. p_{ed} is set to 1 in all other cases.

Optimization in this study uses the non-dominated sorting genetic algorithm (NSGA-II) as a solver, which is one of the most popular optimization algorithms and follows the main principles of classical GA. First, a set of candidate solutions (population) is initialized based on the problem range and constraints. This is the first generation, and a sorting process based on non-domination criteria will be performed on the population. Based on individual fitness, the high-ranked individuals will be selected to produce children (next generation) by using crossover and mutation operators. The offspring generation will be ranked and selected again to produce the next generation. This evolution process continues until a stopping criterion is met. In the present study, the stopping criteria are when the average improvement in the objective drops below a small number close to 0 (e.g., 0.01), or when the maximum number of generations is reached. A diagram of the genetic algorithm is shown in Fig. 4.

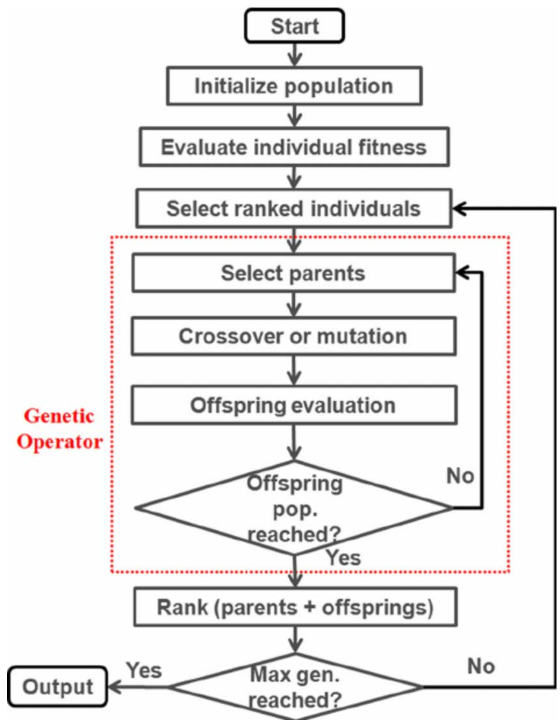


Figure 4. Flow chart of the genetic algorithm (Chang et al. 2015)

2.4. Coupling of Optimization, HEC-HMS and HEC-RAS model

The coupling of the HEC-HMS and HEC-RAS models is made through Hydrologic Engineering Center - Data Storage System (HEC-DSS) files. One may question whether backwater effects from the hydraulic routing may affect the wetland outflows. However, the authors believe this would not constitute a limitation for the coupling as the wetland flow releases will be performed when the water levels in the creeks and bayous are relatively low. In addition, the wetlands would be generally located at higher elevations than the river floodplains.

A set of scripts for the integration of HEC-HMS, HEC-RAS, HEC-DSS and the optimization model were developed in MATLAB. The scripts include parallel computations, the automated coupling between models and visualization. Detailed description of these scripts can be found in Leon et al. (2019). The basic procedure of the set of scripts is summarized as follows: 1) the GA optimization first generates a population of schedules of flow releases at the managed wetlands or storage systems; 2) HEC-HMS routes the flows through managed and unmanaged sub-basins; 3) the outflows of the managed and unmanaged sub-basins enter HEC-RAS to simulate inundation at the watershed scale; 4) the GA optimization calculates the objective function to determine the new population of flow releases at all managed wetlands; 5) repeat step 1-4 until the optimization stopping criteria is satisfied.

2.5. Simulated Scenarios

Based on the spatial geographic and landscape features, the Cypress Creek Watershed was divided into three regions: upstream, midstream, and downstream, as shown in Fig. 5. The total area of the sub-basins that are located in the upstream, midstream, and downstream regions of the watershed are $2.55 \times 10^8 \mathrm{m}^2, 2.88 \times 10^8 \mathrm{m}^2, 2.9 \times 10^8 \mathrm{m}^2$, respectively. The upstream and midstream region of the Cypress Creek Watershed are mostly natural and agricultural areas, and the downstream region is mainly urban area. The authors are mainly interested in urban flooding, which often causes the most significant losses.

To analyze the effects of dynamic management of wetlands storage, wetlands of different sizes were implemented in the midstream region of the watershed as most of the natural wetlands are located within this region. Wetlands implementation was not in a lumped format, but rather distributed in each sub-basin within the midstream region, because sub-basin is the basic hydrologic response unit within HEC-HMS. As such, wetland size was represented by the percentage area of each sub-basin in which the wetlands were implemented. The maximum allowable depth of water to be stored in the wetlands was assumed to be 0.9m (3ft), and the minimum water depth for ecological purposes was assumed to be 0.15m (0.5ft). The initial water depth in the wetlands was also assumed to be 0.15m (0.5ft).

A total of 8 scenarios were analyzed in this study, in which 2% to 16% of each midstream sub-basin were assumed to be used as wetlands, with an increment of 2%. These midstream sub-basins include sub-basin W300, W310, W330, W380, W390, W400, W410, and W420, as shown in Fig. 5. The flood area in this study is defined as the maximum inundation area minus the area of the rivers as well as other water body bodies like ponds. Flood areas between scenarios of the same size of wetlands with and without dynamic storage management were compared. The difference in the flood areas indicates the impact of wetland storage management on flooding in the downstream region.

3. Results

The present case study was performed using a population of 72 in the genetic algorithm optimization. In general, around 40 to 50 generations were needed to meet the convergence tolerance of the optimization, which was set to 0.01. As an example, Fig. 6 shows the convergence process for a scenario with 10% wetland implemented in each midstream sub-basin (which in total is around 3.5% of the whole watershed area).

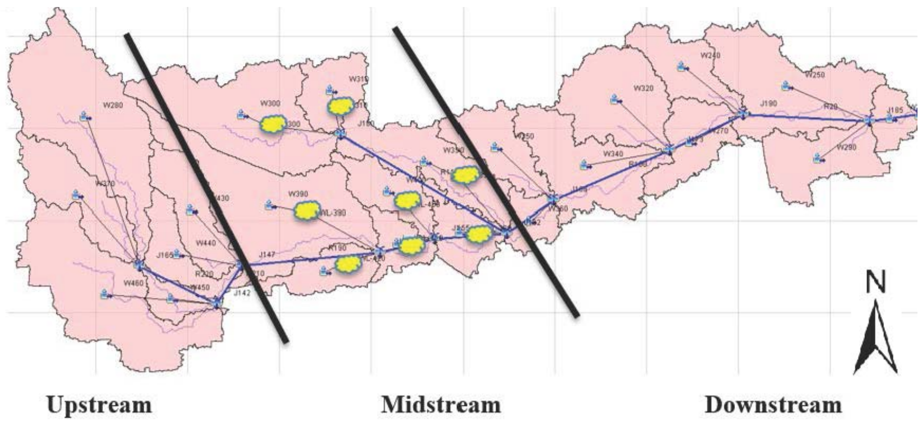


Figure 5. Implementation of different sizes of wetlands (2% - 16%) in the midstream region of the Cypress Creek Watershed

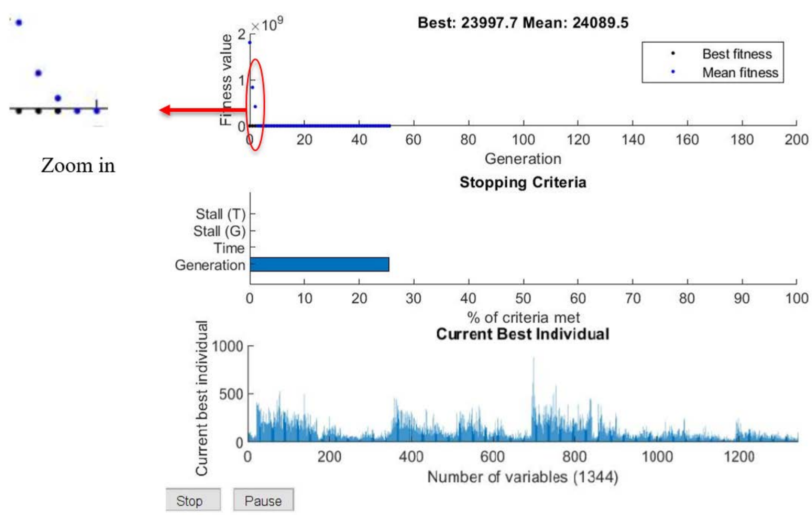


Figure 6. Convergence process for wetland optimal outflows for 10% of wetland implementation

Optimization results indicate that dynamic storage management of wetlands can further attenuate hillslope flows. For instance, Fig. 7 shows the flow attenuation from sub-basin W390 with 10% of wetlands implemented with and without dynamic storage management. It can be seen that the optimization of wetland outflows tries to maintain a low flow release at around 8.5cms (300cfs) until the wetland becomes full, and then the flow release combined with the overflow makes the total outflow of wetlands rise to a peak of around 34cms (1,200cfs). Nonetheless, it is still significantly lower than the peak 48.1cms (1700cfs) in the scenario of the same size of wetlands implementation but without storage management.

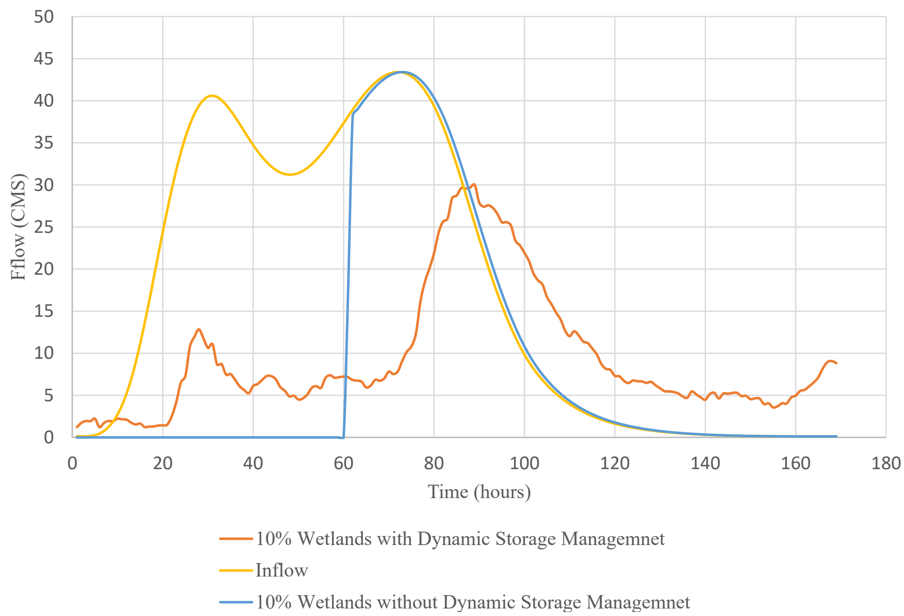


Figure 7. Comparison of hillslope flow attenuation for 10% of wetland implementation with and without dynamic storage management for wetland in subbasin W390

Fig. 8 shows the time series of inflows, outflows, water surface elevation (considering the wetland bottom elevation as 0 m) and storage for the wetland in sub-basin W390 for the case of 10% of wetland implementation with dynamic storage management. As shown in this figure, the framework starts to release water before the heavy rainfall arrives at the wetland. After a certain time period, the wetland is filled and then overflow occurs. The results for all other managed wetlands show similar characteristics to wetland in sub-basin W390. One may question why the optimization does not increase flow release to avoid the overflow from wetlands. This is because the optimization process uses combined wetland outflow (release + overflow) for flood modeling, which means it does not differentiate wetland flow release from overflow. When a wetland becomes full, the optimization will not increase the release rate to avoid overflow because the total outflow will not change. If decision-makers prefer no overflow from wetlands, they can simply increase the release rate to the total outflow to avoid wetland overflow.

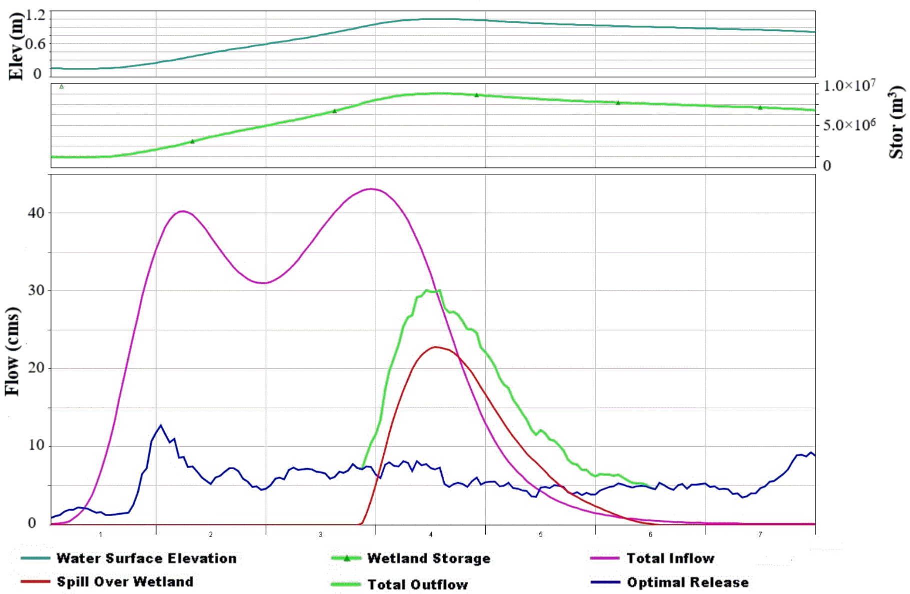


Figure 8. Time traces of water storage, water level, optimal release, total inflow and total outflow for wetland W390 for 10% of wetland implementation in midstream region (3.5% of total watershed area)

The same optimization procedure was performed for each scenario with 2% to 16% of wetlands implementation in each sub-basin within the midstream region of the watershed. Inundation extent at the downstream urban area is plotted in Fig. 9. It can be seen that flood areas at the downstream region decrease when the wetland size increases. When around 14% of the area of each sub-basin within the midstream region (which in total is around 4.8% of the whole Cypress Creek Watershed area) is used as wetlands and when the storage of these wetlands are dynamically managed, the flood conditions at the downstream region can be generally eliminated.

Flood areas for various wetland implementations are summarized in Table 1. The total equivalent wetland percentage areas in terms of the entire watershed are also presented in this table. A sensitivity analysis was performed between the flood area at the downstream region and the size of wetlands located in each sub-basin within the midstream region. This sensitivity curve was compared with the case when the wetland storage was not managed (presented in the first paper of this series (Tang et al. 2019a)), as shown in Fig. 10. Results indicate that when the wetland size is below 4% of each sub-basin within the midstream region (which in total is around 1.4% of the whole watershed area),

Wetland Area	Downstream Inundation Area
No wetlands	
4%	
10%	
14%	

Figure 9. Downstream inundation areas with different sizes of wetlands implementation in the midstream region of the watershed and with dynamic storage management

there is no visible impact from the dynamic storage management. Wetlands fill up quickly at the beginning of the design rainfall event, and then behave like unmanaged wetlands, where flows are released through overflows only. However, when wetlands sizes are above 4% of each sub-basin within the midstream region (1.4% of total watershed area), with the same size of wetlands, dynamic storage management can further reduce the downstream region's flood area. In addition, 6% of wetland area (2.1% of total watershed area) with dynamic storage management can almost achieve the same flood control effect as 10% of wetlands implementation (3.5% of total watershed area) without dynamic storage management. 10% wetlands (3.5% of total watershed area) with dynamic storage management can eliminate the flooded area by around 75%. In practice, the lands available to be used as wetlands in an urbanized watershed are more likely to be limited. Therefore, when there are not enough land available to be used as wetlands, dynamic storage management can play an important role in further reducing flood areas.

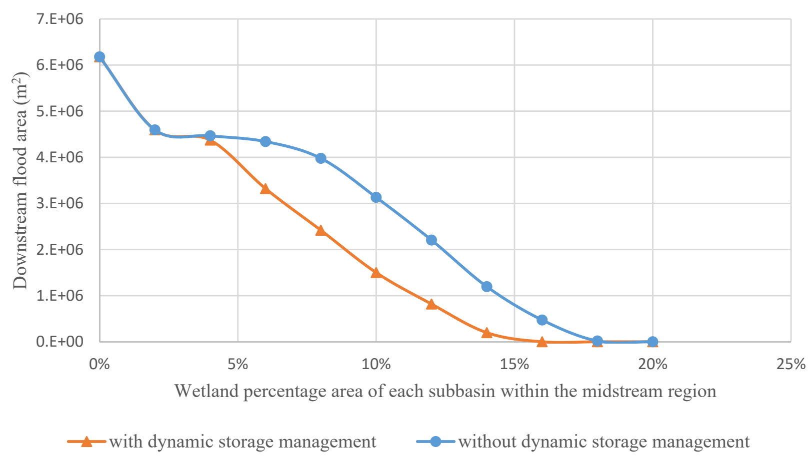
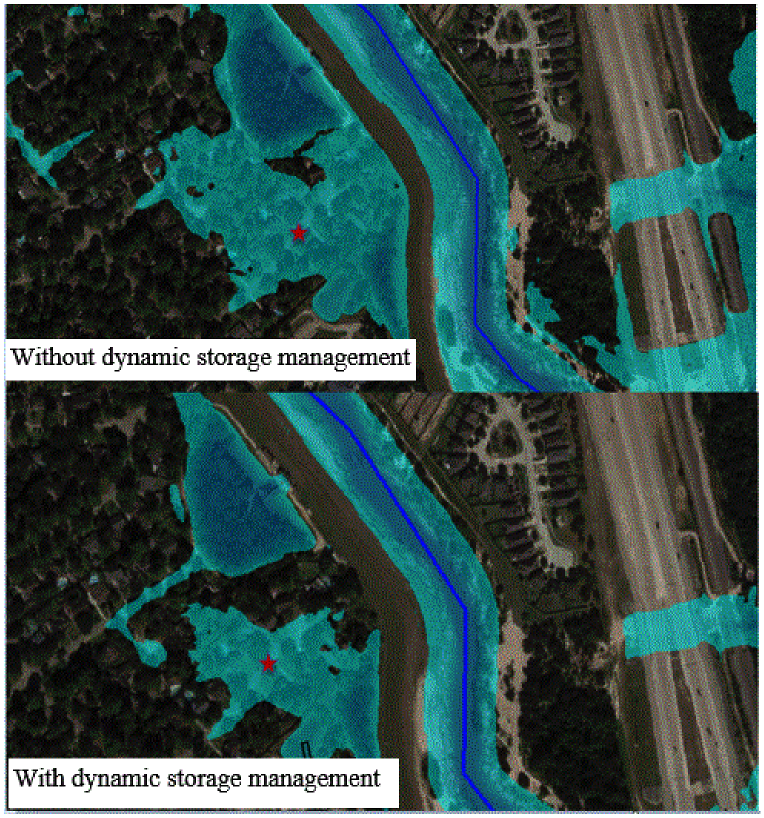


Figure 10. Sensitivity of inundation area to wetland size with and without dynamic storage management

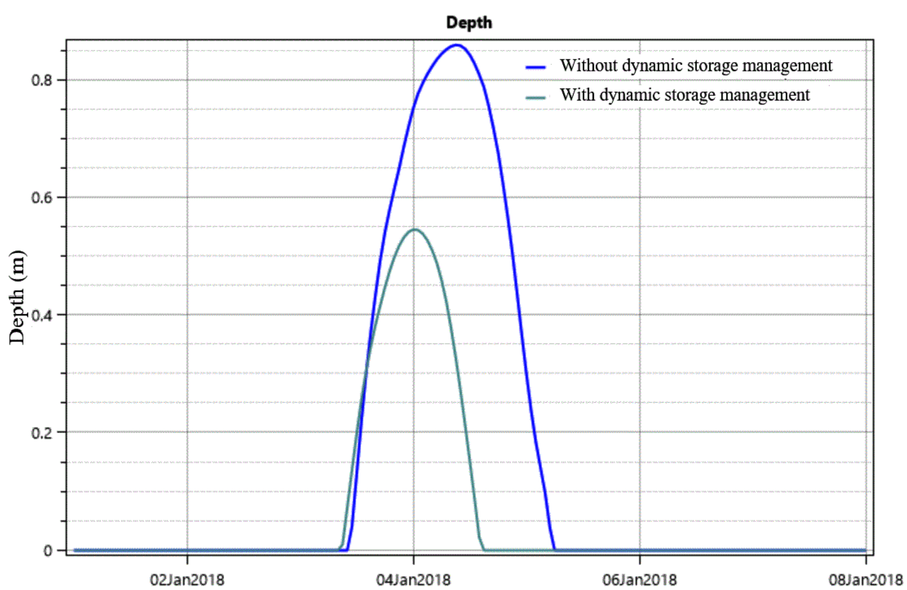
Besides the reduction of the inundation area, results also indicate that dynamic storage management of wetlands can decrease flood depth and flood duration. Fig. 11 shows the maximum inundation extent at the Kenchester Park neighborhood, as well as the time trace of inundation depth at a house in the neighborhood (specific location labeled as a red star) with 10% of wetlands implementation in each sub-basin within the midstream region (3.5% of the total watershed area) with and without dynamic storage management. It can be seen that the maximum inundation extent reduced significantly when the wetlands storage was dynamically managed; in addition, the maximum inundation depth and inundation period with dynamic storage management decreased about 35% with respect to the case without dynamic storage management.

Table 1. Downstream flood area for different sizes of wetland implementation with and without dynamic storage management

Wetland Percentage Area of each sub-basin within the midstream region	Wetland total equivalent percentage area of the whole watershed	Down stream flood area without storage management (m^2)	Down stream flood area with storage management (m^2)
0%	0.0%	6.18E+06	6.18E+06
2%	0.7%	4.59E+06	4.59E+06
4%	1.4%	4.47E+06	4.37E+06
6%	2.1%	4.34E+06	3.32E+06
8%	2.8%	3.98E+06	2.42E+06
10%	3.5%	3.13E+06	1.50E+06
12%	4.1%	2.21E+06	8.18E+05
14%	4.8%	1.20E+06	1.98E+05
16%	5.5%	4.72E+05	0.00E+00
18%	6.2%	1.79E+04	0.00E+00
20%	6.9%	0.00E+00	0.00E+00



(a) Inundation area



(b) Time trace of inundation depth

Figure 11. Inundation area, depth, and period at the Kenchester Park Neighborhood with 10% of wetlands implementation with and without dynamic storage management

4. Discussion

The results above were summarized based on the case study of the Cypress Creek Watershed, which is a fairly small watershed with a relatively sequential river geometry. Further analysis should include a case study with a larger and more complex river branching. Complex branching may alter the flow conveyance which in turn may influence downstream flooding.

In addition, the objective function in this study was only developed to satisfy the needs of flood control. However, wetlands are frequently used for multiple purposes and decision-makers may need to consider different aspects when operating wetlands.

5. Conclusions

The present work illustrates a case study of optimal management of wetland storage in order to mitigate floods at the watershed scale. The key findings are as follows:

1. As expected, the downstream flood area, flood depth, and flood duration decrease as the size (storage capacity) of the wetlands increases, regardless of the management of the wetlands.
2. When the wetland size (storage capacity) is relatively small (below 1.4% of the total watershed area in this case study assuming maximum water storage depth to be 0.9m), dynamic storage management does not have a visible impact as wetlands fill up quickly at the beginning of the rainfall event and then behave like unmanaged wetlands, where flows are released through overflows only. However, when wetland size exceeds 1.4% of the total watershed area, dynamic storage management plays a significant role in further reducing flooding. For example, 2.1% of wetlands with dynamic storage management can almost achieve the same flood control effect as 3.5% of wetlands implementation without dynamic storage management. This is particularly important when not enough land is available for wetland implementation.

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