

Hydraulic structure and stream vegetation induced backwater
effects on wetland flood reduction

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Abstract

In this study, we present a case study to assess backwater effects induced by hydraulic structures and restored stream vegetation on wetland flood reduction (peak discharge attenuation and peak time delay). A coupled surface-groundwater model, HydroGeoSphere, is applied for the subwatershed including the Yahara River, Cherokee Marsh and downstream Lake Mendota, where the Tenney dam and the Highway 113 bridge constriction are located. The effects with and without hydraulic structures on hydrological connectivity and flood storage capacity are compared. Furthermore, we examine the potential benefit of flood reduction for a large scale stream vegetation restoration at the study site. Results show that hydraulic structures and restored stream vegetation induced backwater can increase hydrological connectivity between river and wetlands. The total flood storage capacity dramatically increases for the integrated backwater wetland system. Overall it is suggested that the backwater wetland provide an optimal flood reduction by keeping the hydraulic structures and restoring the stream vegetation.

Key words: *wetland, flood reduction, hydraulic structure, backwater, channel restoration*

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1. INTRODUCTION

Flood reduction is one of the critical hydrological functions provided by wetlands (Trenberth, 1998; EPA, 2006; Acreman and Holden, 2013). The function is achieved when the wetlands in river system could act like a “sponge” that temporarily retains flood waters and slowly releases excess water downstream as flooding subsides (Price, 1992; Bullock and Acreman, 2003, Jones et al., 2014). As a result, the peak flood rate is attenuated and the peak time is delayed (Junk et al., 1989; Bullock and Acreman, 2003). The US Corps of Engineers (1972) and Doyle (1987) calculated that, 3800 ha of wetland storage on the Charles River, Eastern Massachusetts leads to 50% of peak flow attenuation and 40 days of peak time delay during extreme flood events. The flood reduction function provided by wetlands is altered by backwater effects, which are created by introducing hydraulic structures and implementing stream restoration on surface waterways nowadays (Petts 1984; Naiman et al., 1997; Johansson and Nilsson 2002). The uncertainty in wetland performance causes challenges and questions regarding the benefit of wetland restoration in flood reduction (Brookes, 1988; Surian et al., 2011).

Backwater is a part of a river in which there is less river currents and higher river stage, which may significantly alter water movement during flood events (Ward and Stanford 1995; Tsai and Yen, 2004; Jones et al., 2014). In order to predict flood reduction function of the wetland affected by backwater (also called backwater wetland), several physical processes need to be considered, such as longitudinal river flow propagation under backwater effect (Wu et al., 1999; Tsai and Yen, 2004; Ozcelik and Dogan, 2009), transverse water exchange between river, wetland and alluvial aquifer in a backwater wetland system (Ward and Stanford 1995; Poole et al, 2002; Ward et al., 2013), and the implicit internal water exchange and energy loss (Kingsford, 2000; Frazier and Page, 2006; Ward et al., 2013). These processes cannot be quantified precisely

if studies fail to treat backwater wetland as an integrated system framework. The failure of quantification would hinder us to calculate transvers connection between river, wetland and alluvial aquifer, and impede us to determine how much flood volume can be stored by the backwater wetland system under backwater effects. The transvers connection can be described by introducing concept “hydrological connectivity”, and the ability to store flood can be described by using concept “flood storage capacity”.

“Hydrological connectivity”, defined in this paper mainly as surface water exchange potential between a channel and adjacent riparian wetlands, is suggested to be affected by backwater effects (Poole et al, 2002; Frazier and Page, 2006; Jones et al., 2014). Hydrological connectivity increases, i.e. flood in the channel is easier to overflow to the riparian zone, when the elevation difference between the river and riparian wetland surface decreases due to backwater (Stanford and Ward, 1993; Bates et al., 2000; Jones et al., 2014). Previous field observations show increasing hydrological connectivity allows wetlands to provide more surface area to store flood volume (Junk et al., 1989; Acreman et al., 2003; Hammersmark et al., 2008). While the effects of hydrological connectivity on flood reduction function is conceptually understood, the explicit hydrological connectivity and responses across channel-wetland-aquifer continuum under backwater effects cannot be considered by using general hydrodynamic-based (e.g. HEC-RAS) and hydrologic-based simulations (e.g. SWAT) (Liu et al., 2008; Ward et al., 2013). Without accounting for altered hydrological connectivity induced internal water exchange, these models cannot precisely quantify the amount of flood stored by wetlands under backwater effects (Junk et al., 1989; Wondzell and Swanson, 1996; Ward et al., 2013).

“Flood storage capacity”, defined as flood volume retained by channel, wetland surface and wetland subsurface, functions to reduce floods. Previous researches have confirmed that water exchange processes between these storage components are determined by geomorphic

surface topography (Brookes, 1988; Stanford and Ward, 1993; Rosgen, 1996), geological subsurface properties (Wondzel and Swanson, 1999; Hammersmark et al., 2008; Loheide and Booth, 2011), and antecedent water level and soil moisture (Price, 1992; Potter, 1994; Burt, 1995). Nevertheless, the influence of backwater on the flood storage capacity has not been examined carefully. The channel storage capacity decreases as backwater occupies part of this storage. Concurrently, the wetland subsurface storage capacity may also decrease, as elevated surface water level may act as strong boundary condition to increase regional subsurface saturation (Burt, 1995; Devito et al., 1996; Loheide and Booth, 2011). However, the wetland surface storage capacity is likely to increase due to the increasing hydrological connectivity. The magnitude of these changes will impact total flood storage capacity. Therefore, each storage capacity term must be precisely quantified to determine total flood storage capacity under backwater effects.

Hydraulic structures and stream vegetation restoration can limit discharge and elevates upstream water level, creating backwater (Fithi-Maghadam and Kouwen, 1997; Rahmeyer, 1998; Wu et al., 1999; Fremling et al., 1976; Wilen and Warren, 1983; Thomas and Nisbet, 2006). Previous studies have examined the upstream hydraulic structures, such as dams and channel constrictions, have altered river flow regime (Dynesius and Nilsson, 1994; Kingsford, 2000), affecting wetland inundation regimes (Ward and Stanford, 1995; Frazier and Page, 2006), thus altering downstream wetland functions. Relatively few studies have investigated how backwater from downstream hydraulic structures affects flood reduction in upstream wetlands (Tsai and Yen, 2004). Thomas and Nisbet (2006) found wooded wetlands in a reach of the River Cary in England with a high roughness value slowed down flood progression, and resulted in flood peak delay as large as 140 minutes. Harvey et al. (2009) observed flood velocity reduction of up to 29 percent in the densely vegetated Everglades located in Florida, USA. Very few studies have

examined how restored stream vegetation induced backwater can have effects on flood reduction function provided by riparian wetlands (Frazier and Page, 2006; Acreman and Holden, 2013; Ward et al., 2013).

The objective of this paper is to evaluate backwater effects induced by hydraulic structures and restored stream vegetation on wetland function for reducing floods in an integrated channel-wetland-aquifer system. A three-dimensional, physically-based, coupled surface and groundwater model is calibrated for a backwater wetland system, where downstream dam and channel constriction currently existed downstream. We aim to quantify and compare the changes of hydrological connectivity and flood storage capacity due to backwater effects, thus evaluating flood reduction function.

2. METHODOLOGY

2.1 Study Site

The study site is in Cherokee Marsh, located upstream from Lake Mendota in Dane County, Wisconsin (Fig.2 a). The size of Cherokee marsh is 13 km², the largest wetland in the Cherokee Subwatershed of Yahara Watershed (Bedford et al. 1974). The width of the riparian wetland along the Upper Yahara River ranges from 100 m to greater than 2 km as the North Unit of Cherokee Marsh. The topographic change for North Unit is less than 40 cm (Kurtz et al, 2007), leading to potential massive water storage. The climate at the study area is humid continental. With prevailing weather patterns and winds from the west, the Cherokee Marsh experiences four distinct seasons with extreme variations in temperature and precipitation. Average annual precipitation is 1.07 m (Wisconsin State Climatology Office, 2008). The period from May through October have the highest rainfall totals with 60% of annual precipitation falling. Due to long time precipitation input, groundwater table in the wetland is approaching to the land surface,

or even higher at some places (WETS 2004). Geologically, the subsurface units at the study site are mainly glacial sediments deposited during the Wisconsin Glaciation (10,000-14,000 B.P.) as part of the Horicon Member of the Holy Hill Formation. The sediments include sand with plane-bedded and cross-bedded sand, plane-bedded silt and clay with some near-shore gravel, and some post-glacial peat (Clayton and Attig, 1997).

The waterway of the study site (Fig.2 a) starts from Upper Yahara River and meet the tributary Token Creek at North Unit of Cherokee Marsh. The slope of Upper Yahara River becomes flat and the width becomes wider. In the early 1960s as part of a residential development, the east side of the wetland was dredged and named as Cherokee River (Dane County Environmental Council, 2007). The river continuously flows southward through the Highway 113, where the channel cross section is the smallest, forming channel constriction, to Lake Mendota, which is the largest lake in the Yahara River chain of lakes. At the outlet of Lake Mendota, the Tenney Park Dam was constructed around 1847, resulting in the water level of Lake Mendota 5.5 ft higher than natural condition (Dane County Environmental Council, 2007).

2.2 Data

Meteorological, hydrogeological, and hydrological data are collected within this study site to construct and calibrate the numerical model. These data will be applied for establishing initial and transient simulation during 2008 June flooding period (100 year storm). The meteorological data includes rainfall and evapotranspiration (ET) rates; the hydrogeological data includes hydrostratigraphic unit properties and groundwater hydraulic head; the hydrological data includes stream flow and lake stage. Land use and site topography data will also be talked about.

Meteorological data are obtained from the National Climate Data Center (NCDC) station, located at 1 km southeast away of study subwatershed (Fig. 2 a). The time interval is fifteen minutes. This study site has a humid continental climate with severe winters, warm summers and no dry season. The relative humidity typically ranges from 42% to 95% over the year, and the temperature typically varies from -12 °C to 28 °C. The long-term average precipitation rate 0.95 m/year from 2007-2008 in this station are used to develop the initial condition for 2008 June storm. The long-term average evapotranspiration (ET) data is obtained from daily estimates of the potential ET using Priestly-Taylor formulae over the entire study area. The fifteen minutes precipitation rates during 2008 June are used to simulate the transient response of the numerical model.

Hydrogeological data consists of stratigraphy properties and groundwater hydraulic head. The stratigraphy distribution of Cherokee Marsh is shown in Fig. 2 b, as a comprehensive consideration of the field survey study done by Kurtz et al (2007), Laboratory grain-size study done by McDermott (2004) and numerical study of Dane County groundwater model at steady state done by Wisconsin Geological and Natural History Survey (Bradbury et al., 1999). Six main hydrogeological units are applied for simplification, corresponding to the observed subsurface stratigraphy by Kurtz et al. (2007): riverbed clay, wetland peat, sand with silt, silt loam, fine sand, and medium sand (Fig. 3 a). At the top of the wetland area, 0.5 m to 1.0 m of peat with varying texture, water content, and degree of decomposition. Beneath the peat underlies a 1.5-2.5 m layer, consisting of sand with silt unit (50-90% sand) adjacent to the river site, and silt loam unit (83% silt) near the inland site (Kurtz et al, 2007). The existence of this fine-grained layer inhibits the vertical water movement in the wetland area, promoting more surface inundation in comparison with the rest of the study site. Underlying the above layers, a thin layer of fine sand has a depth around 0.5 m. Below the fine sand layer, there is a 5~10 m

medium sand layer. Some layers may be absent in some of the area since the pre-glacial erosional surface scoured the bedrock down to the Mount Simon Sandstone within the Yahara River Valley (Clayton and Attig, 1997). Groundwater hydraulic head is initially abstracted from steady state Dane County Groundwater model by using average groundwater pumping rates between 2005 and 2010. Regional groundwater flow is set up by fixing groundwater hydraulic head at boundary (sided) faces. As a result, groundwater recharges to the Cherokee River and Cherokee Wetland from both north and south side of the subwatershed boundary, which matches with previous field survey and numerical study (Bradbury et al., 1999). The transient hydraulic head data are not available in this study site due to lack of observation wells in this study site, which would be one of the main uncertainty factors for later calibration.

Hydrological data for water level and discharge are obtained from USGS gauge stations (Fig. 2 a) and mathematical calculation. The USGS Gauge Station Windsor (USGS NO. 05427718, Latitude 43 °12'32", Longitude 89 °21'09" NAD27) records discharge and water level every five minutes at the Upper Yahara River, drained from 190.6 km² area of Yahara at Windsor Subwatershed. The average discharge is 1.2 cubic meters per second (cms) during non-flooding periods, and the discharge can reach to 93 cms during the flooding period. The other inflow stream Token Creek discharge is drained from a 70 km² area of Token Creek Watershed. There is currently no gauge station to measure Token Creek discharge but only historical inflow measurements from 1/1/1964 to 1/1/1981 are available. It is found that an apparent relationship exists between current and historical data. During non-flooding periods, discharge at the Token Creek is larger than that at the Windsor station; while during flooding periods, discharge at Token Creek is less than that at the Windsor station. In this study, multiple linear regression analysis is used to develop a relationship between the Token Creek station discharge Q_T and Windsor station discharge, i.e. $Q_T = 1.9 \times Q_s + 0.05 \times Q_b \dots [1]$, where Q_s is direct runoff and Q_b is

baseflow that is separated using the local minima method (Aksoy et al. 2009). The calculated surface water discharge for Token Creek discharge has a root-mean-square error (RMSE) of 0.24 cms and mean square error (MSE) of 0.15 cms. At the outlet of Cherokee River to Lake Mendota, water level and discharge are recorded every five minutes at USGS Gauge Station Hwy113 (USGS NO. 05427850, Latitude 43 °09'03", Longitude 89 °24'07" NAD27). In addition, downstream water level of Lake Mendota are recorded every fifteen minutes the USGS Tenney gage station (USGS NO. 05428000, Latitude 43 °05'42", Longitude 89 °22'12" NAD27).

Land use within the study site is based on the digital land-use map provided by the National Land Cover Database (NLCD), USA. Five main distinct land-use categories (14 sub-dis-land use) are identified in the map: water, urban (resident, industrial), forest, grass, and wetland. Topographic data is obtained from the LIDAR with a vertical root mean square error of 24.7 cm at 95% confidence interval. Bathymetry underwater is measured from an acoustic sub-bottom profiler with a vertical resolution of 1.8 cm. The average water depth for the waterway is around 1 m, while water depth is up to 1.8 m in the middle unit of the river. Further detailed will be discussed at the model set up section.

2.3 Model set up

2.3.1 HydroGeoSphere

In this study, HydroGeoSphere (HGS), a physically-based, finite element and groundwater-surface water integrated model (Therrien et al., 2006), is employed. The surface flow module is based on a modification of the Surface Water Flow Package of the MODHMS model. A two-dimensional diffusive-wave approximation of the St. Venant equations is used to present the unsteady shallow overland flow and channel flow, assuming the convection terms area negligible (Gottardi and Venntelli, 1993). Together with Manning's equation to compute

overland flow velocities, additional frictional resistance and small scale energy loss over obstruction surface are calculated (Panday and Huyakorn, 2004). The subsurface flow module for HGS is based upon FRAC3DVS code created by Rene Therrien (Therrien et al., 2006). A three-dimensional variably saturated form based on the Richards' equation is employed to describe the flow in subsurface medium (both unsaturated and saturated flow). Soil retention curves are derived from van Genuchten function (van Genuchten, 1980), which determines the effects of saturation on pressure head and soil conductivity. HGS can simulate dynamic hydrological processes including precipitation, surface runoff, channel flow, infiltration, lateral flow, groundwater discharge and regional groundwater flow. In addition, the integrated features allow HGS model to simulate reciprocal transport through infiltration and saturated-excess across wetland surface and subsurface storage. The way to calculate water exchange between surface and subsurface domain is 'dual node approach'. It requires surface nodes to coincide with top subsurface nodes, and assumes there is a thin porous media layer between surface and subsurface domain. Darcy exchange flux is then computed as a head difference between two domains by multiplied a first-order leakage factor, i.e. coupling length l_{exch} :

$$d_o \Gamma_o = \frac{K_r K_{zz}}{l_{exch}} (h - h_o) \quad [2]$$

where a positive Γ_o represents flow from the subsurface system to the surface system; K_r is the relative permeability for the exchange flux; K_{zz} is the vertical saturated hydraulic conductivity of the underlying porous medium; l_{exch} is the coupling length for fluid exchange; h is the subsurface water head, and h_o is the surface water head (Therrien et al., 2006).

2.3.2 Mesh, boundary conditions and calibrated properties

Meshes for the surface domain and the subsurface domain at the study site are shown in Fig. 3 a. Surface elevation for this subcatchment is from 290 m above sea level (NGVD29) along the stream at the northwest boundaries, to 258 m at the outlet of this subcatchment at the south boundaries. The mesh is created such that regions near the surface water bodies have smaller finite elements (~10 m in plan view), while finite elements further away from the stream are larger (~80 m). Fine discretization of river bed profile and water level under steady state along surface waterway longitudinally allows model to catch the flow hydraulic condition. Fig. 3 b shows the longitudinal discretization of thalweg from upstream Yahara River to downstream Lake Mendota (BB' line in Fig. 3 a) and its corresponding river profile. The river slope profile is steep (~0.001) at Yahara River but reach to flat at Cherokee River reach. To simulate subsurface flow, a 3-D triangular prism with an average depth of 10 m is under the 2-D surface mesh. The top of the 3-D mesh is identical with the 2-D surface mesh, so that the dual surface-subsurface interaction nodes exist at the land surface. Vertical discretization for this subsurface mesh is finer for the first four layers adjacent to the land surface, and becomes much bigger for the bottom six layers. This effort is to capture an accurate subsurface condition when the computational cost is satisfied. The total number of nodes for the surface and subsurface domain is equal to 7448 and 81928, respectively.

Boundary conditions are set up separately in surface and subsurface domains. The surface domain boundaries consist of a combination of specified-flux boundary at two north inflow channels, and specified-head boundary at the south lake outlet of the surficial domain. The specified-flux rate is achieved by two USGS Gauging Windsor and Token at each time step. Differences from typical way to treat downstream boundary condition as a free fall, a specified water head at downstream lake outlet can consider lake level constrain on the incoming river

flow. Surface outflow is only allowed to leave the domain through this south side segment. This discharge rate from river to lake would be captured by nodes formed as flagged hydrograph segment on the surficial 2D mesh, which coincides with USGS surface water gauging Hwy113. The subsurface domain boundaries consist of a combination of specified-head boundary at the south lake site, and no-flow boundary at the other sides and the bottom of the domain. The groundwater head set at the south lake bottom layers is the same as lake level, thus forming regional groundwater flow from sided of the domain to the river channel.

Calibrated subsurface properties (hydraulic conductivity, storage capacity and specific storage) are set cell by cell in order to simulate hydraulic head, groundwater flow and exchange flux between surface and subsurface flow. The distribution of hydraulic conductivity values (horizontal and vertical) for each hydrogeological unit are initially extracted from Dane County groundwater model built by Wisconsin Geological and Natural History Survey, and applied homogeneously to each unit. Porosity and specific storage for each unit are originally obtained from Freeze and Cherry (1979) and Kurtz et al. (2007) respectively. Soil retention curves are derived from van Geneuchten function, which consider the residual water saturation, capillary pressure and relative permeability parameters. Events for model calibration are storms in 2004 May and 2005 September. Each of the hydrogeological units is assumed to be homogenous throughout the study area, with the assigned properties reported in Table 1. Concurrently, calibrated surface properties (Manning's roughness, depression storage and obstruction storage height) are set cell by cell in order to simulate surface runoff, stream flow propagation and wetland inundation. The initial Manning's roughness values are from Chow (1959), and the depression storage and obstruction storage values are from Jones et al. (2006). The calibrated land properties for each land-use type are reported in Table 2. We assume these surface and subsurface properties are constant during the short simulation period.

Parameters that exhibit the largest degree of sensitivity are: porosity and vertical hydraulic conductivity for wetland peat, porosity and vertical hydraulic conductivity for silt loam, and Manning's roughness for open water (river bed). All the parameters that are adjusted remained within the range of literature reported parameters provided by Chow (1959), Freeze and Cherry (1979), Fetter (2001), Jones et al. (2006), and Kurtz et al. (2007). For porosity of wetland peat, the tested value ranges from **0.30** to **0.70**, and the outflow peak values between these two conditions are 3.7% difference. For the vertical hydraulic conductivity of wetland peat, the tested value ranges from 1×10^{-8} to 1×10^{-3} m/s, which are two extreme values for wetland soil. The corresponding peak values for 2008 June storm are 5.0% higher and 1.8% lower than current condition. For the porosity of silt loam, the tested value ranges from 0.30 to 0.50 m/s, and the corresponding peak values are 1.1% higher and 1.0% lower. For the vertical hydraulic conductivity of silt loam, the tested value ranges from 5×10^{-4} to 1×10^{-6} m/s, and the corresponding peak values are 5.1% higher and 1.1% lower. The Manning's n for open water ranges from 0.025 to $0.10 \text{ m}^{-1/3}$, with which the peak values are 2.5% higher and 6.2% lower, respectively.

2.3.3 The flood event set up

The flood in 2008 June (100 year storm) is chosen to be applied into the calibrated model. After the model is subjected to 2008 June rainfall data series, resulting discharge hydrographs are compared with the measured rainfall-runoff response at USGS surface gauge stations. The computed hydrodynamics response is next analyzed, in terms of temporal variations in the surface water inundation area, the groundwater-surface water (GW-SW) interaction, and the subsequent drainage phase. The 2008 June flooding, which is reported as the biggest flood event in American Midwest for decades, causes approximately \$48 million in 14 south Wisconsin

counties (Fitzpatrick et al, 2008). This floods event was aggravated by wet soil, caused by antecedent events (Fitzpatrick et al, 2008; WICCI, 2011).

The antecedent condition includes the information about regional groundwater table, soil saturation profile, and groundwater discharge distribution. They are required by physical-based numerical model before transient variably-saturated flow simulation. While the data sometimes may be available, the corresponding subsurface data are usually lacking. Observation well for groundwater table and soil saturation condition is not available within this study site. Therefore some other means need to be brought to set the initial condition for the following transient simulation. In collaboration with the ongoing research conducted by Wisconsin Geological and Natural History Survey, initially saturated system (i.e. initial total hydraulic head in this model domain) is obtained from the Dane County groundwater steady state model for each subsurface hydrogeological unit, by using average groundwater pumping rates between 2005 and 2010. To achieve wet antecedent condition, a 3×10^{-8} m/s rate of rainfall for one year (0.95 m/year) is chosen to apply on the top of the saturated system, until the system reached steady state equilibrium, resulting matching calculated and observed stream flow rate at USGS Gauging Hwy 113. Note that this rainfall rate has consider 40% evapotranspiration (ET) reduction caused by dense vegetation in wetland, which corresponds to what Cline (1965) concluded. The riparian wetland is absorbing rainfall and receiving groundwater discharge from underlying aquifer. As a result, some middle units of Cherokee wetland are even inundated in shallow water. In other area where the water table falls below the surface (not inundated), the soil is fairly wet. This initial condition is identical to the extremely wet soil and high groundwater table condition in study site. There is no available spatially-distributed unsaturated moisture data to calibrate the soil saturation profile, which is a vital factor to control the infiltration and recharge from the subsurface in this study site.

Once the antecedent condition is achieved, precipitation obtained from NCDC in fifteen minute intervals is uniformly applied on the top surface of the study site. The simulation period is from June 4th 2008 to June 25th 2008, when a big storm occurred in Dane County, WI (Fig. 4 a). In order to consider ET during this period, 13 % of the rainfall is been cut during the entire simulating period, making daily ET lost similar with the value used for getting the initial condition. The inflow rate of Windsor Stream data provided by USGS Gauging station for this storm period is shown in Fig. 4 b. The flow rate was around 0.85 cms before the flooding period, while it reaches as high as 95 cms on June 8th after the intense rain event. Token Creek inflow for this storm period was calculated by using empirical Eq. [1]. The baseflow of observed Windsor discharge was obtained using the base flow separation methods (Aksoy et al., 2009). The calculated corresponding Token Creek inflow is shown in Fig. 4 b. Downstream lake water level is recorded by USGS gauging station at the lower part of Lake Mendota. A slowly increased water level for this storm period is shown in Fig. 4 c.

3. RESULTS

3.1 The flood event results

The model performance under transient conditions was assessed by comparing the match between calculated and observed river outflow discharge hydrographs features and river level features, including: discharge/level peak value and time, shape of increasing and recession limbs, measure of error, and total discharge volume. As mentioned before, the Hwy 113 surface water gauge recorded both the outflow rates from the Cherokee River and river level stage during this simulated storm. The calculated and observed surface water discharge hydrograph can be seen in Fig. 4 b, and the calculated and observed surface water stage can be seen in Fig. 4 c. On the whole, the computed result agrees with the observed one very well during the flood period. The

model can precisely simulate the peaks of discharge and river stage. Because the calibration is mainly made in aim to catch the discharge rate and volume, the model underestimates river level for the first peak, and overestimates river level for the second peak. The measure of errors between the observed and calculated discharge and river stage are 1.35 cms and 0.02 m, respectively. The calculated accumulative discharge over this simulated period is $2.26 \times 10^7 \text{ m}^3$ which is 2 % lower than the observed accumulative discharge $2.30 \times 10^7 \text{ m}^3$. The model cannot simulate sever back flow during low flow periods with little precipitation. This difference may be caused by ignoring inertial term in momentum equation, and lacking wind shear stress consideration.

The misfits may be caused primarily by (1) simplistic way to consider the ET reduction during this period, ignoring the ET-induced soil moisture dynamics; (2) the uniform rainfall rate applied in this domain surface is taken at the station 1 km away from the study site, while rainfall is often variable spatially within a watershed as observed; (3) the hydrologic method based on historical observed data to estimate the Token Inflow is not correct, as both geomorphology and geo-structure condition have been changed over the past 30 years, which would have changed the relationship between Token and Windsor discharge.

Mechanism of the hydrologic process of river-wetland system has been mentioned in part **1** (Fig. 1). Under the integrated river system framework, “flood storage capacity” and “hydrological connectivity” are the two key concepts that explain hydrologic exchange processes under backwater effects. From the “flood storage capacity” perspective, input water into a river-wetland system (**I**) consists of precipitation and inflow from upstream during the flood period. The storage mechanism is the most important to consider flood reduction function by riparian wetlands (Potter, 1994). Channel storage (**C**), riparian wetland surface (**W1**) and subsurface storage (**W2**) are three main terms to temporarily store the input water before it gets downstream

as outflow (**Q**). Equation for the water budget of the river-wetland system is $(\mathbf{I}) - (\mathbf{Q}) = (\mathbf{W1}) + (\mathbf{W2}) + (\mathbf{C})$. Three storage terms **W1**, **W2** and **C** in a river-wetland system can store input water during the flooding period to affect the outflow rate, which further delays and attenuates flood peaks downstream in a short-term storm period (Potter, 1994). Be noted that, in long-term, flood volume may also be reduced by ET in wetland, especially in dry regions (Potter, 1994; Devito et al., 1996), and by infiltration into deeper groundwater system (Acreman and Holden, 2013). The existence of dam, constriction and stream vegetation induced backwater effects can affect these three storage terms by increasing “hydrological connectivity”. Backwater can induce higher hydrological connectivity, causing less absorption of floods and precipitation water into wetland subsurface during storm event, i.e. to reduce **W2** (Burt, 1995; Devito et al., 1996; Loheide and Booth, 2011). However, higher hydrological connectivity may cause more floods overflow to wetland surface during the storm event (i.e. to increase **W1**), allowing further infiltration into wetland subsurface **W2** after storm events (Junk et al., 1989; Acreman et al., 2003; Hammersmark et al., 2008).

To examine the hydrological connectivity of current condition with channel constriction and downstream dam, we compared the simulated surface water depth and flow velocity at initial time of the flood (Fig. 5 a) and at peak time of the flood (Fig. 5 b). Arrow length is proportional to surface flow velocity. Flow velocities for initial time range from 0.005-0.01 m/s in the middle Cherokee River. Flow velocities for peak time reach as high as 0.3 m/s in the middle of the Cherokee River, and gradually decreases towards the outer edge of the flood, generating low speed flow on the riparian wetland surface area due to the drag induce by vegetation (Thomas and Nisbet, 2006). The water depth approximately increases by 1 m in the channel, causing higher hydrological connectivity. Consequently, riparian wetlands are inundated by incoming flood flow at the peak time. Especially, most of the North Unit of Cherokee Marsh is inundated

by floods. The horizontal extent of the flooding is relatively unchanged in the south part of the Cherokee Marsh, due to topographical limit of there. Fig. 5 c is the surface water depth difference plot by subtracting initial surface water depth from peak surface water depth, indicating the flood stored in channel (**C**) and wetland surface (**W1**) between initial and peak time. A comparison of the average saturation from initial (Fig. 5 d) and peak time (Fig. 5 e) shows that higher riparian wetland saturation caused by higher river water level does not allow much precipitation and floods infiltrated into riparian wetland subsurface, although a portion of input water can be stored in the wetland subsurface, causing wetland more saturated. Fig. 5 f is the surface water depth difference plot by subtracting the initial surface water depth from the peak surface water depth, accounting for the subsurface storage capacity (**W2**) between initial and peak time.

Accumulated volume of three storage terms **C**, **W1** and **W2**, together with **I** and **Q** for current condition with channel constriction and downstream dam in each time step are calculated and shown in Fig. 6. During the flood peak on June 9th, the accumulated storage terms **W1**, **W2**, **C** can store 31%, 23% and 14% of input water (**I**), respectively as summary in Table 3. **C** and **W2** for floods are reduced due to backwater effects, while increasing hydrological connectivity causes flood flow easier to inundate riparian wetland surface, increasing **W1**. In general, wetland surface storage **W1** in this study site is more impactful to reduce the flood than subsurface storage. Two weeks following the storm events, if ignoring ET process, floods stored in the riparian surface area can leave in to two pathways (i.e. decrease **W1** after the storm): one is to infiltrate into subsurface area, the other one is back to the channel as return flow (Potter, 1994; Devito et al., 1996). As a result of infiltration, water flows to wetland subsurface storage slowly, causing **W2** to increase even after the storm.

3.2 Hydraulic structure scenarios: dam removal, constriction widening

Currently, hydraulic structures existing in this study site as mentioned before are (1) channel constriction near gauge station HWY113; (2) downstream dam construction at the outlet of Lake Mendota (Fig. 2). The water level in Cherokee River has been increased by 1.6 m due to introducing hydraulic structures. In order to assess the backwater effects of dam removal and channel widening at constriction location (i.e. to get rid of channel constriction) on flood propagation, scenarios are tested by using the calibrated and validated model. Case 2 and Case 3 are the management scenarios to remove dam and widen channel, respectively. Case 4 is the scenario to remove dam and widen channel concurrently. The case descriptions and outflow peak information are summarized in Table 3. Note that the downstream dam removal causes 1.6 m lake level drawdown; the channel at the constriction site is widened to 350 m, which is as wide as the average width of lower Cherokee River.

The subtraction plots for dam removal and constriction widening cases, similar to Fig. 5 c and f, are shown in Fig. 6, indicating flood volume that been stored in channel (**C**), wetland surface (**W1**) and subsurface storage capacity (**W2**) between initial and peak time. Fig. 6 a and b shows, since dam removal leads to smaller hydrological connectivity, wetlands provide less **W1**. Low stream level at initial time causes channel to provide more **C**. More infiltration caused by drier riparian zone after river level drawdown leads more **W2**. Fig. 6 b and e shows, both **W1** and **C** are reduced as widening constriction induced lower hydrological connectivity, which allows coming floods easier to pass through the wetland and channel system, without being stored. For **W2** perspective, widening constriction cannot alter river level, which can not affect riparian saturation condition before flood. Fig. 6 c and f shows, smallest hydrological connectivity results in less floods inundated to riparian zone, causing smallest **W1**.

Accumulated volume for three storage terms **C**, **W1** and **W2**, together with **I** and **Q** for each case in each time step are calculated and shown in Fig. 7. From June 7th to June 9th, the total

input water **I** is $1.5 \times 10^7 \text{ m}^3$. For Case 2 (dam removal), the accumulated storage terms **W1**, **W2**, **C** can store 23%, 26% and 20% of input water **I**, respectively. For Case 3 (constriction widening), 26%, 23% and 9% of input water are stored in **W1**, **W2** and **C**, respectively. Similar initial wetness content of the riparian zone makes the **W2** similar to Case 1 (current condition). For Case 4 (dam removal and constriction widening), the accumulated storage terms **W1**, **W2**, **C** can store 22%, 26% and 13% of input water **I**, respectively. The transient storage results reinforce the visualization results shown in Fig. 6.

These storage results for these cases explain the outflows shown in Fig.8 and Table 3. More total storage that the system can provide leads to more flood reduction at outlet. Removing dam can significantly reduce the river level and increase flow velocity; channel widening can increase peak flow rate, but reduce peak river level and flow velocity at the outlet of the river due to wider cross-section there. Overall, the existence of channel constriction reduces floods pronouncely, while the existence of dam only has minor impact on flood reduction. The contradictory to reduce floods by providing **W1** and **W2** indicates further discussion about the conflict with wetland maintenance of biodiversity is needed. For example, decreasing the backwater effect can cause more subsurface storage for floods, however, the lower river level can cause obvious riparian ecosystem degradation (Loheide and Booth, 2011), and less sediment, nutrient, and organic matter overflowing to feed wetlands (Tockner et al., 1999).

3.3 Stream vegetation restoration scenarios

The water level in Cherokee River has been increased by 1.6 m, causing stream losing vegetation. Restore the vegetation within the stream is proposed, from hydrological and ecological concerns (Wu, 1999; Kingsford, 2000). Case 5 is the scenario to create a 'stream vegetation restoration zone' within the channel in the establish model, when the restoration zone is shown in in Fig. 3. Note that, the restoration zone has the Manning's roughness of $0.2 \text{ s m}^{-1/3}$,

depression storage of 0.03 m, and obstruction storage height of 1 m. The Manning's roughness value (n) for restored in-stream wetland here is a compromise of values commonly used in hydrological models (Chow, 1959; Woltemade and Potter, 1994; Harvey et al, 2009) and previous model by using HGS (Jones, 2006; Therrien et al., 2006; Sciuto and Diekkruger, 2010). The model performances for this storm event are not sensitive to the depression storage and obstruction storage height, which represents surface evenness condition and plant height condition, respectively. Manning's roughness value in the channel is one of the parameter, as mentioned before, exhibits the largest degree of sensitivity. Restoring stream vegetation can cause higher hydraulic resistance with larger Manning's n . Highest n reported by Hall et al. (1994) can be up to $0.7 \text{ s m}^{-1/3}$. The sensitivity tests are done by using high n values: 0.1, 0.2, 0.3, 0.4 and $0.7 \text{ s m}^{-1/3}$, with which the peak reductions are 6.2, 13.4, 18.5, 20.5 and 20.5 %, respectively. $0.2 \text{ s m}^{-1/3}$ was chosen to be the n value represents the Manning's n value for the restored zone.

Stream vegetation, as shown in Case 5, can increase river level by 0.1 m, and this created backwater effect extended a distance of nearly 4000 m upstream of the Cherokee River. Results show 34%, 23% and 14% of input water can be stored in storage terms **W1**, **W2** and **C**. Wetland can provide the most substantial **W1** due to higher hydrological connectivity caused by the denser vegetation, together with constriction and dam. Overall, restoring stream vegetation increases the total flood storage capacity significantly. More total storage the system can provide leads to more floods at outlet reduction as shown in Table 3. Restoring stream vegetation leads outflow peak attenuated by 13 % and delayed by 12.7 hours.

The combined stream vegetation restoration together with dam removal and constriction widening scenarios are tested, and corresponding flood storage capacity and flood reduction information for Case 6, Case 7 and Case 8 are shown in Table 3. The stream revegetation can weaken the effects of dam removal and constriction widening, increasing **W1** (Case 6 V.S. Case

2, Case 7 V.S. Case3, Case 8 V.S. Case 4). The **W2** would not be altered after stream revegetation, as initial riparian wetness condition is not changed by denser vegetation in the stream. **C** is slightly increased owing to higher Manning's n in the stream, allowing flood propagating slowly in the stream. The peak reduction results (Table 3) show that removing dam but keeping constriction and restoring stream vegetation (Case 6) can most significantly reduce flood. Noted that the peak reduction caused by the dam removal and stream vegetation restoration (7.23 cms reduction) is smaller than direct superposition of the reduction results caused by dam removal and stream vegetation restoration individual (2.20 cms + 6.29 cms reduction).

4. DISCUSSIONS

4.1 Hydraulic structure

Removing hydraulic structures on surface water way is proposed to deal with flood problems from water manage perspectives (Junk et al., 1989; Hart and Poff, 2002; Frazier and Page 2006). Case 1, 2, 3, 4 are the scenarios to assess effects of dam removal and constriction widening on flood reduction function provided by wetland system. Based upon comparison results between Case 1 and Case 3, we demonstrated that widening constriction near Gauge HWY113 will increase outflow peak significantly as **W1** and **C** are decreased due to backwater effects weakening. Therefore, it is highly recommended to keep the constriction in this study site. Based upon comparisons between Case 1 and Case 2, however, more **C** and **W2** provided by dam removal condition are counteracted by less **W1** caused by less inundation zone in riparian wetland. Overall, dam removal can reduce the flood slightly in Case 2. Whether or not to remove the dam needs further consideration from the perspectives of hydrology and sustainability of the study region. Hydrologically, Case 2 can attenuate peak discharge by 5% and delay flowrate

peak by 5 hours in comparison with Case1. Sustainability of a region depends on interactions among ecological, economic and social/political factors, as stated by the Species Survival Commission of the World Conservation Union (IUCN) (Holling, 2001). Ecologically, keeping downstream dam can maintain high water level in Cherokee Marsh, allowing more wetland and channel erosion (City of Madison, 2008), but providing habitat for fish to lay eggs in flooded vegetation, especially for pike fish in this site (Friends of Cherokee Marsh, 1999). Economically, dam removal can cause visits for shoreline parks and entertainment decline, leading to corresponding job lost and tax revenue lost. Besides, shoreline house price will be also reduced (Dubash, 2011). Socially and politically, the debates are about equity, governance, justice and power issues that caused by altered river and use of natural resource, after installing or removing dams (Dubash, 2011). Removing current dam may provide opportunity for corruption, although current mainstream ideas tend to remove small scale dams for floods safety and environmental friend. In conclusion, keeping both dam and constriction in this study site is recommended.

The recommendation to keep hydraulic structures objects to previous studies, which showed removing human interruption can help to restore natural flow regime in the river and reduce flood (Junk et al., 1989; Hart and Poff, 2002; Frazier and Page 2006). However, these previous studies focused on upstream hydraulic structures on downstream wetland function, and analyzed surface water and groundwater processes alone or separately. Conversely, this study simulates channel-wetland-aquifer continuum under backwater effects, which can consider flux and energy exchange between channel-riparian wetland, and surface-subsurface flow interactions. In addition, the results of this study support the finding of Rahmeyer (1998), Wu et al. (1999) and Tsai and Yen (2004), who showed that backwater effects can reduce flood propagation in channel. Moreover, the results are consistent with the finding of Stanford and Ward (1993) and

Frazier and Page (2006), who showed that increasing hydrological connectivity can increase flood inundation that allows riparian wetland storing more floods.

4.2 Stream vegetation restoration

Restoring the stream vegetation does facilitated flood reduction in a backwater wetland zone by increasing river stage and decreasing flow velocity. Consequently, wetland surface storage for floods (**W1**) increases significantly. Thomas and Nisbet (2006) found similar woodland induced backwater effect in a 2.2 km reach of river in southwest England by using one and two-dimensional model. Wong and Laurenson (1984) and Frazier and Page (2006) found floods have longer duration with lower velocity with dense vegetated zone on surface water way. Frazier and Page (2006) also explain pulses of higher flow stage can increase the duration of riparian wetland inundation.

A synthesis diagram showing all possible scenarios results are provided in Fig. 9. Returning back to pre-settlement condition (Case 8) from current condition (Case 1), i.e. dam removal, channel widening and stream vegetation restoration, is the traditional restoration strategy (Junk et al., 1989; Hart and Poff, 2002; Frazier and Page 2006). However, based upon the calculated results of all scenarios (Table 3 and Fig. 9), Case 8 is not the most efficient scenario for flood reduction. Case 5 and Case 6, instead, are the two cases that can mostly attenuate flood. The main difference between Case 5 and Case 6 is whether removing downstream dam, meanwhile both of them keep the channel constriction and attempt to restore stream vegetation. Case 5 (keep dam, constriction and restore stream vegetation) is the suggested scenario, as discussed before, keeping dam is suggested from both hydrological and economical concern. Ecologically, greater river depth caused by dam requires more submerged vegetation to be planted in the stream. In considering of choosing the source of plants, the use of native seed bank is encouraged as a means to establish the local species (Zedler, 2000). But the constraints

on seeds dispersal and the viability compared with exotics requires further study (Zedler, 2000), as from long-term consideration, exotic species has high potential to dominate and persist to halt succession (Cole, 1999). In addition, planting matured vegetation directly can be an alternative way to achieve a mature community in a short time, based on previous wetland vegetation research in Wisconsin (Fassett, 1975; Gleason and Gronwuist, 1991; Chadde, 2002).

4.3 Channel restoration

Accelerated streambank erosion, land loss, aquatic habitat loss, land productivity reduction and downstream sedimentation are consequences of creating incised channel (Rosgen, 1996, 1997). To offset these adverse consequences, river improvement through restoration projects have been studied (Rosgen, 1997; Hammersmark, 2008; Loheide and Booth, 2011). An example of restoration in a low-gradient river-wetland system is made in a reach of Bear Breek in northeastern California (Hammersmark, 2008). The channel was re-meandered and the channel bottom elevation was raised for 3.6 km by filling peat which was got by cutting higher riparian peat. The channel bank was reshaped to gently slope to the water's edge. By doing these, water was easier to spread onto surrounding riparian wetland area during flood events, causing a 'increasing hydrological connectivity' process. Moving silt and other sediments in the flow will be deposited within the channel, which would begin to naturally fulfilled for long time. The marginal plant growth can be observed near new deposited area in the channel. Besides, other experiences (Brookes, 1988; Galatowitsch et al., 1999; Habersack and Piegay, 2007) also found the channel intervention can promote in-stream vegetation stability, further improve water quality of the stream.

A channel restoration scenario (Fig. 9 a, b) is tested in the established model by using before-incised morphology condition based on the area photo of Yahara River in 1964 (Fig. 9 c,

d). Returning the stream to its original elevation and the stream channel is intermittently filled with locally derived alluvial material. The restored channel was classified as C4 and E4 types of the Rosgen classification system (Rosgen, 1996). The result shows the outflow of restored channel is attenuated by 19 % and delayed by 13.9 hours (Table 3). Channel stores less water, as the channel capacity has been reduced due to restoration. Wetland subsurface stores more water, as more riparian zone was created. Wetland surface stores significant volume of water (**W1**) due to narrowing channel induced higher hydrological connectivity. This study results support previous channel restoration research (Rosgen, 1997; Bernhardt et al., 2007; Hammersmark, 2008), showing channel restoration has profound effects upon increasing wetland storage capacity for floods.

5. CONCLUSIONS AND IMPLICATIONS

This paper evaluates the effects of hydraulic structure and restored stream vegetation induced backwater on flood reduction function provide by wetlands at upstream of Lake Mendota, Dane County of Wisconsin. A three-dimensional, physically-based, surface water and groundwater fully-coupled model was established and calibrated to account for the riparian wetland function for reducing the floods of 2008 June. Results show the wetland subsurface storage decreases under the backwater wetland effects, especially caused by downstream dam. However, the wetland surface storage dramatically increases due to the enhanced hydrological connectivity under backwater effects caused by downstream hydraulic structures. Besides, restoring stream vegetation can facilitate backwater effects to increase hydraulic connectivity, causing more wetland surface storage. An optional restoration scenario based on the quantification result is provided. After synthesis hydrological analysis, subject to economic and

ecological constraints, keeping the downstream dam and channel constriction and meanwhile restoring stream vegetation is the most efficient way to manage this system.

Implications can be achieved from our quantification results for making strategies of hydraulic structures impoundment/removal, channel and wetland restoration in small scale. Nationally, the length of most dam removal, river and wetland restoration projects is on the order of 1-10 km for small-scale river-wetland systems (Bernhardt et al., 2007). Some hydraulic structures such as dam and constriction may be kept to enhance backwater effect, strengthening upstream wetland function to reduce floods. This is an update of traditional thinking towards hydraulic structure management, which suggesting removing the structures. Besides, the wetland ecosystem degradation across the country is mainly caused by worse hydrological connectivity. More than making geomorphologic change of channel and wetland surface, the restoring stream vegetation can be another option to restore the hydrological connectivity for the practitioner. It should be noted that, the function of wetland for floods reduction is a subsidiary support, as wetland cover a small percentage of most river basins.

6. TABLES

Table 1. Calibrated parameters in HGS model for subsurface hydrogeologic units

Hydrogeologic Units	Kx, Ky [m/s]	Kz [m/s]	Porosity	Ss [m⁻¹]
Riverbed Clay	1.058×10^{-6}	3.500×10^{-6}	0.65	9.8×10^{-4}
Wetland Peat	3.530×10^{-5}	5.050×10^{-6}	0.60	9.8×10^{-4}
Sand with Silt	8.950×10^{-5}	8.950×10^{-5}	0.55	2.3×10^{-4}
Silt Loam	1.764×10^{-5}	1.764×10^{-5}	0.40	5.0×10^{-4}
Fine Sand	1.058×10^{-4}	1.058×10^{-4}	0.35	1.6×10^{-4}
Medium Sand	1.230×10^{-4}	1.230×10^{-4}	0.31	1.6×10^{-4}

Table 2. Calibrated parameters in HGS model for surface land use

Land Use Type	Manning's Roughness	Depression Storage [m]	Obstruction Storage [m]
WATER	0.040	0.003	0.025
RESIDENT-LOW DENSITY	0.012	0.002	0.25
RESIDENT-MEDIUM DENSITY	0.012	0.002	0.25
RESIDENT-HIGH DENSITY	0.012	0.002	0.25
INDUSTRIAL	0.012	0.002	0.25
FOREST-DECIDUOUS	0.600	0.006	0.25
FOREST-EVERGREEN	0.600	0.006	0.25
FOREST-MIXED	0.600	0.006	0.25
RANGE-BRUSH	0.200	0.004	0.15
RANGE-GRASSES	0.200	0.0038	0.1
HAY	0.200	0.0038	0.1
SOUTHWESTERN ARID RANGE	0.200	0.002	0.25
WETLAND-FOREST	0.050	0.002	0.05
WETLAND-NON-FOREST	0.050	0.002	0.05

Table 3. Summary of backwater causes including downstream dam, channel constriction and in-stream wetland for each case, and corresponding backwater effect on flood peak condition including peak discharge, stage, velocity and time delay. Pay attention that the reference for peak flow delay is inflow peak from Windsor and Token gauge, which has a rate of 118.7 cms at June 9th 00:00.

management	causes			storage				outflow	
	Downstream dam	channel constriction	stream revegetation	wetland surface (W1/I)	wetland subsurface (W2/I)	channel (C/I)	total	Peak Q reduction (cms) *	lag time (h) *
1 current condition	✓	✓		31 %	23 %	14 %	68 %	0	0
2 dam removal		✓		23 %	26 %	20 %	69 %	-2.20	+5.0
3 constriction widening	✓			26 %	23 %	9 %	59 %	+19.68	-6.9
4 dam removal & constriction widening				22 %	26 %	13 %	61 %	+14.89	-3.7
5 stream revegetation	✓	✓	✓	34 %	23 %	14 %	71 %	-6.29	+12.7
6 dam removal & stream revegetation		✓	✓	26 %	26 %	20 %	72 %	-7.23	+16.8
7 constriction widening & stream revegetation	✓		✓	32 %	23 %	11 %	66 %	+1.47	-0.1
8 dam removal, constriction widening & stream revegetation			✓	30 %	23 %	15 %	68 %	-0.87	+9.7
9 channel restoration	✓	✓	✓	43 %	25 %	6 %	74 %	-8.92	+13.9

* Peak Q reduction is the peak rate difference between current condition and the specific case. Peak Q for Case 1 is 46.95 cms, so the reduction value for Case 1 is 0.

* Lag time: is the delay between the maximum rainfall amount and the peak discharge. The lag time for Case 1 is 21.3 hours, so the reference lag time for Case 1 is 0.

7. FIGURES

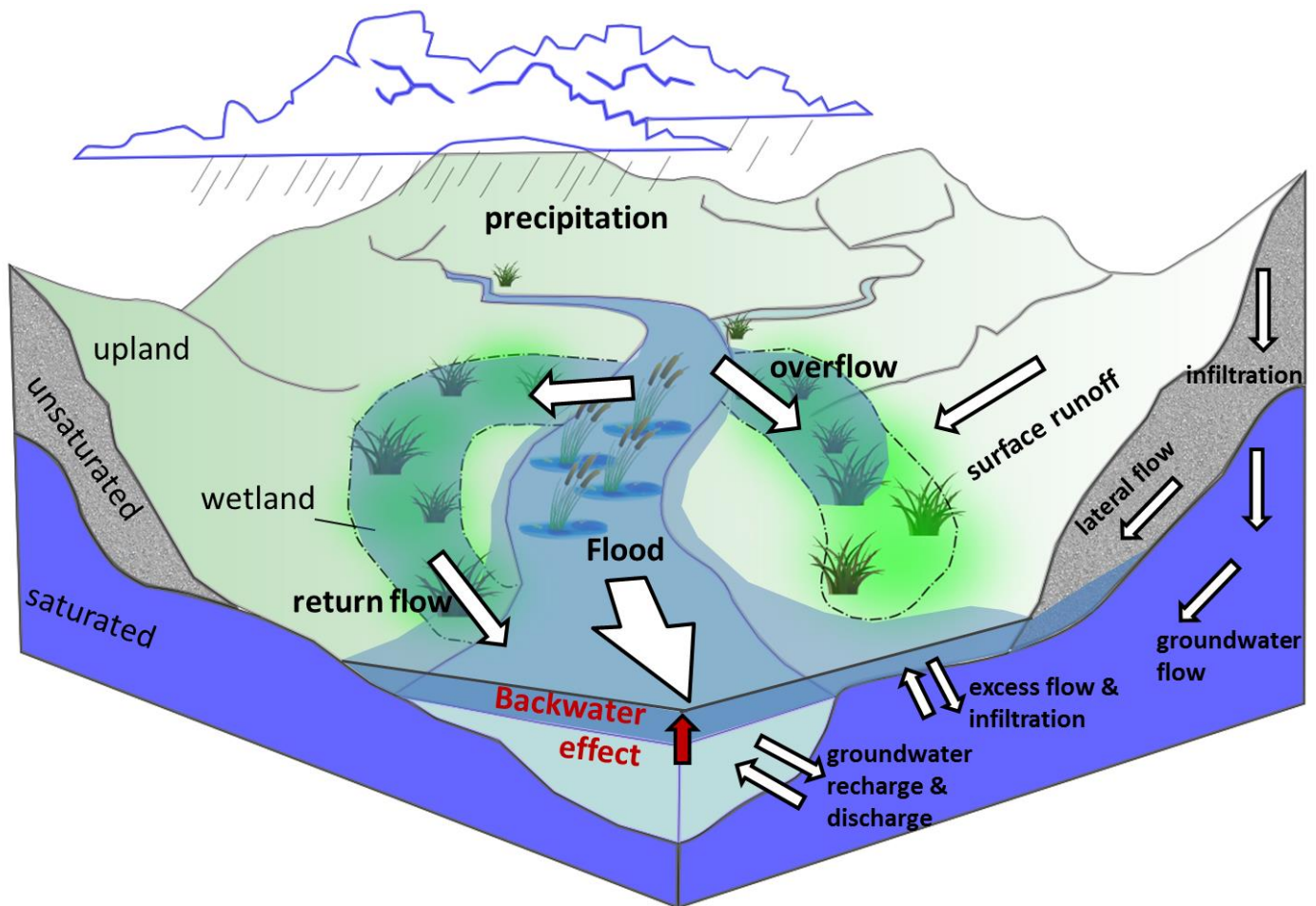


Fig 1. Schematic figure to show hydrologic process in a channel-riparian wetland system under backwater effects

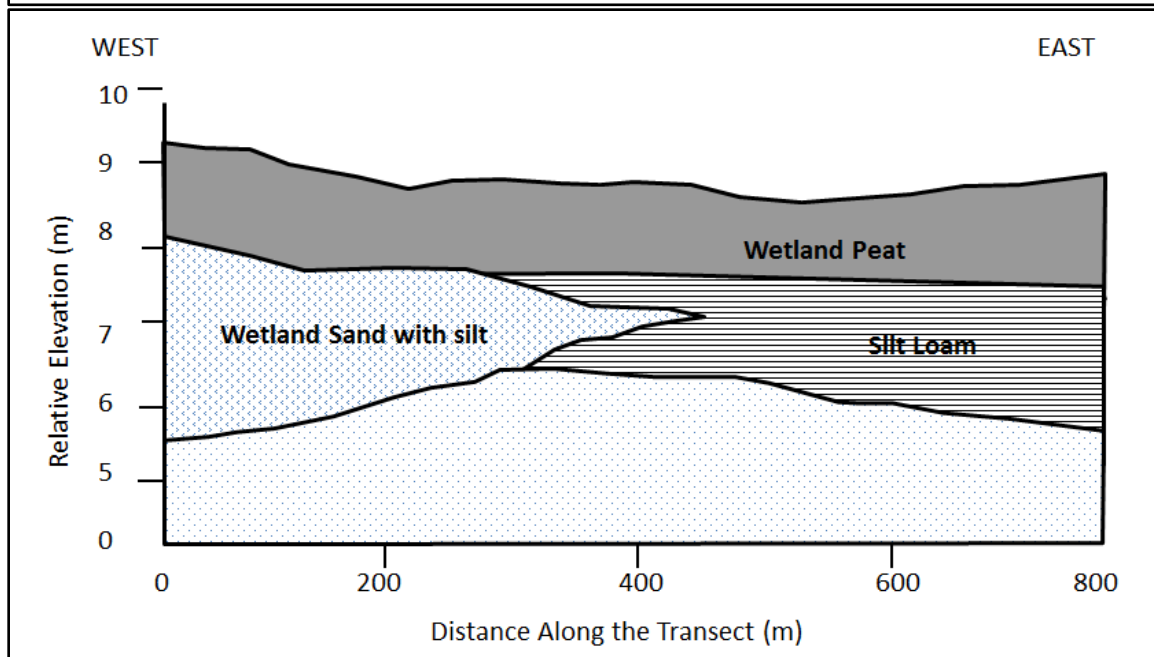
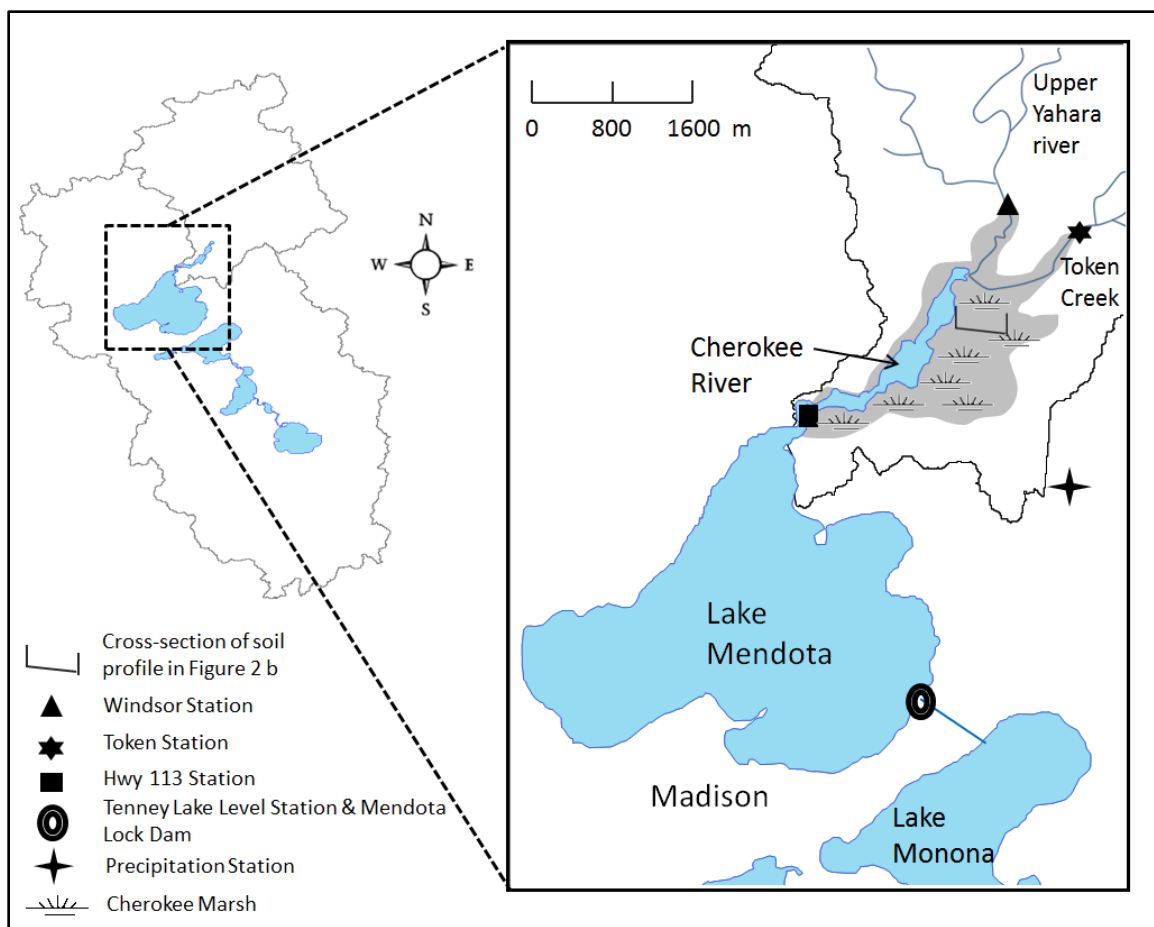


Fig 2. (a) Location of study site and gauge stations; (b) Soil profile of wetland cross-section.

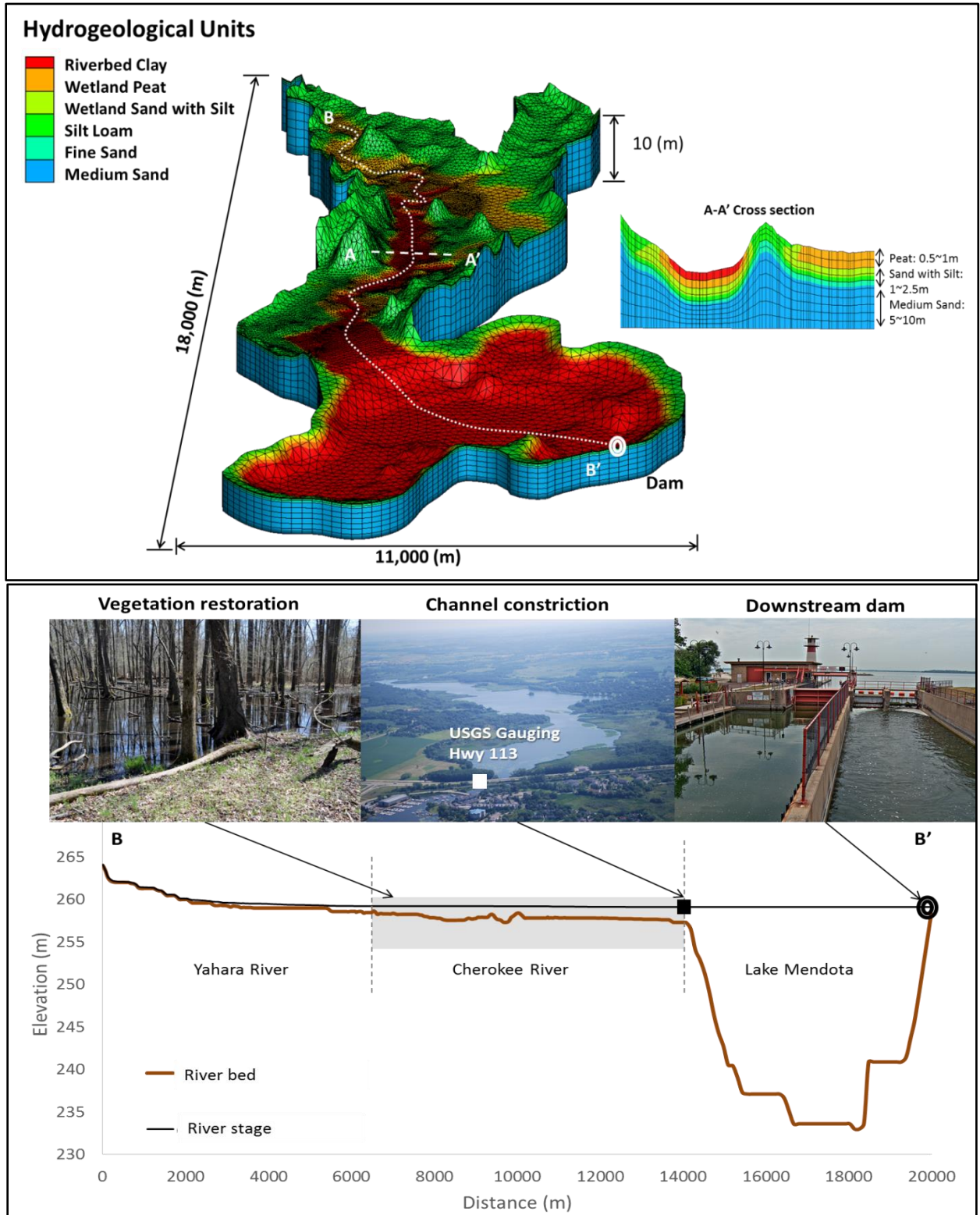


Fig 3. (a) Spatial discretization of the study site. The vertical exaggeration is 30 times; (b) Longitudinal discretization of thalweg from upstream to downstream lake (BB' line) and corresponding river profile.

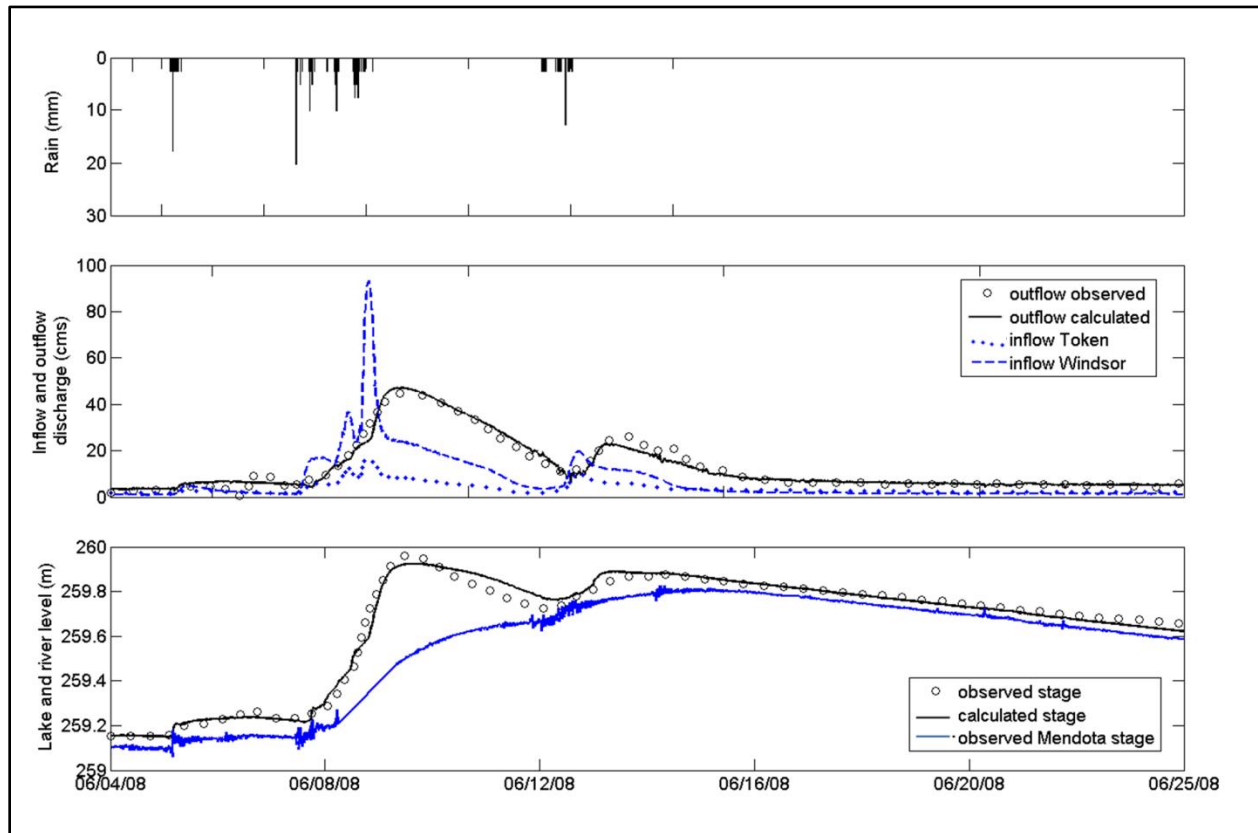


Fig 4. Input data and calibration results during 2008 June flood period: (a) rainfall depth; (b) stream inflow from Windsor River, stream inflow from Token Creek, observed outflow discharge at HWY113, calculated outflow discharge; (c) observed river stage at HWY113, calculated river stage at HWY113, and observed regulated downstream Lake Mendota stage.

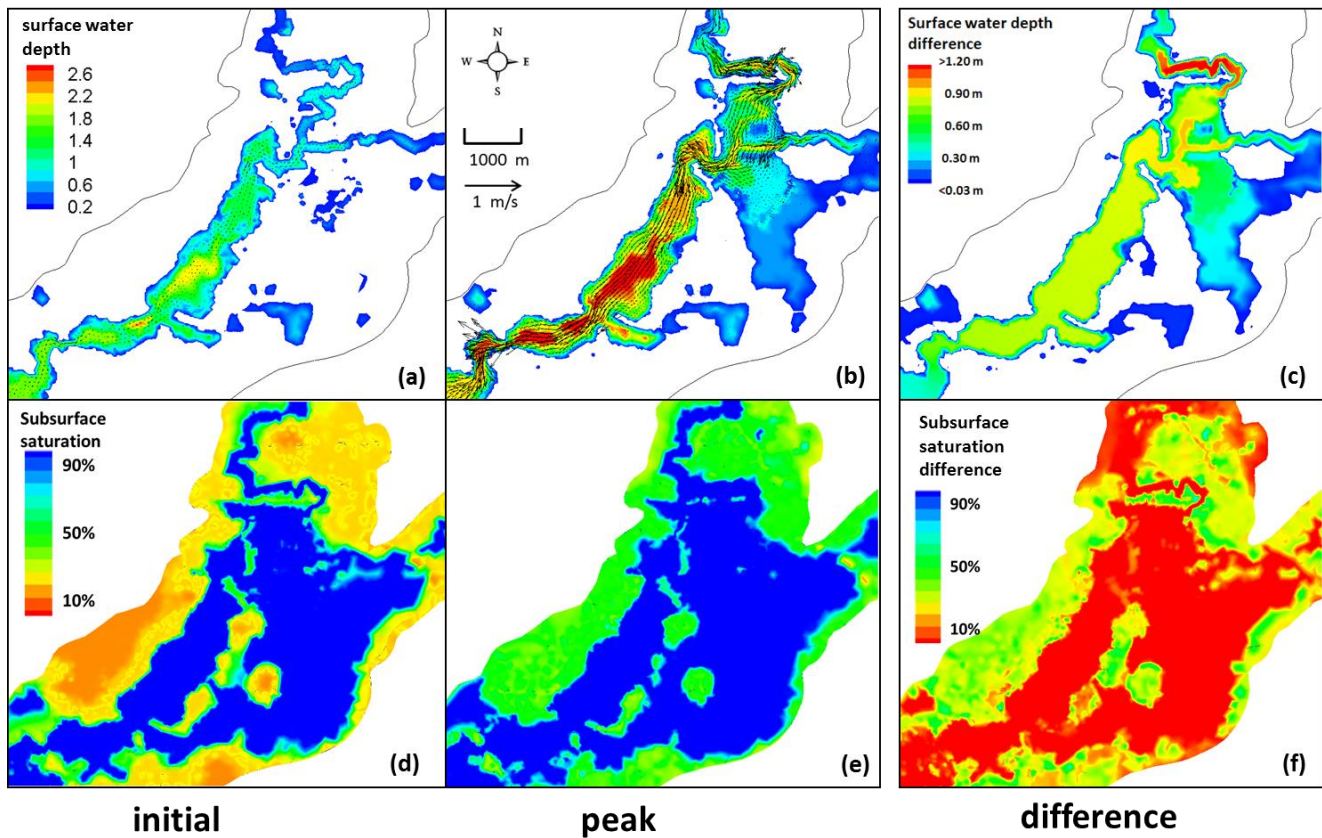


Fig 5. Simulated channel water depth, wetland inundation and flow velocity during peak flow of *Case 1*: (a) initial time of the flood, (b) peak of the flood, (c) difference plot between surface water depth before and after the storm; Subsurface saturation of *Case 1*: (d) initial time of the flood, (e) peak of the flood, (f) difference plot between subsurface saturation initial time and peak of the flood. (The flow vector length exaggeration is 1000 times to scale.)

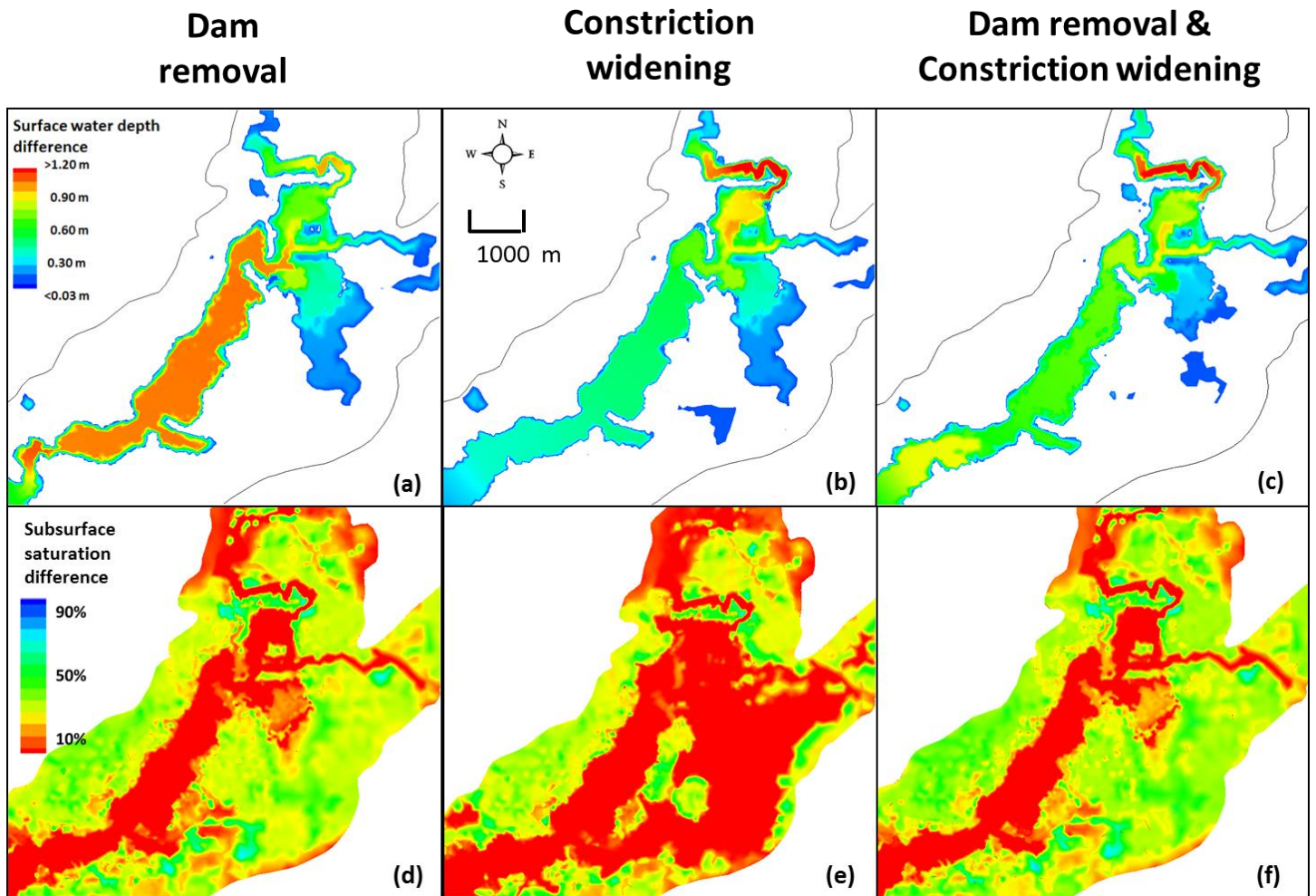


Fig 6. Subtraction of surface water depth between initial time and peak time of the flood to show wetland surface and channel storage for (a) Case 2; (b) Case 3; (c) Case 4; Subtraction of subsurface saturation between initial time and peak time of the flood to show wetland subsurface storage for (d) Case 2; (e) Case 3; (f) Case 4.

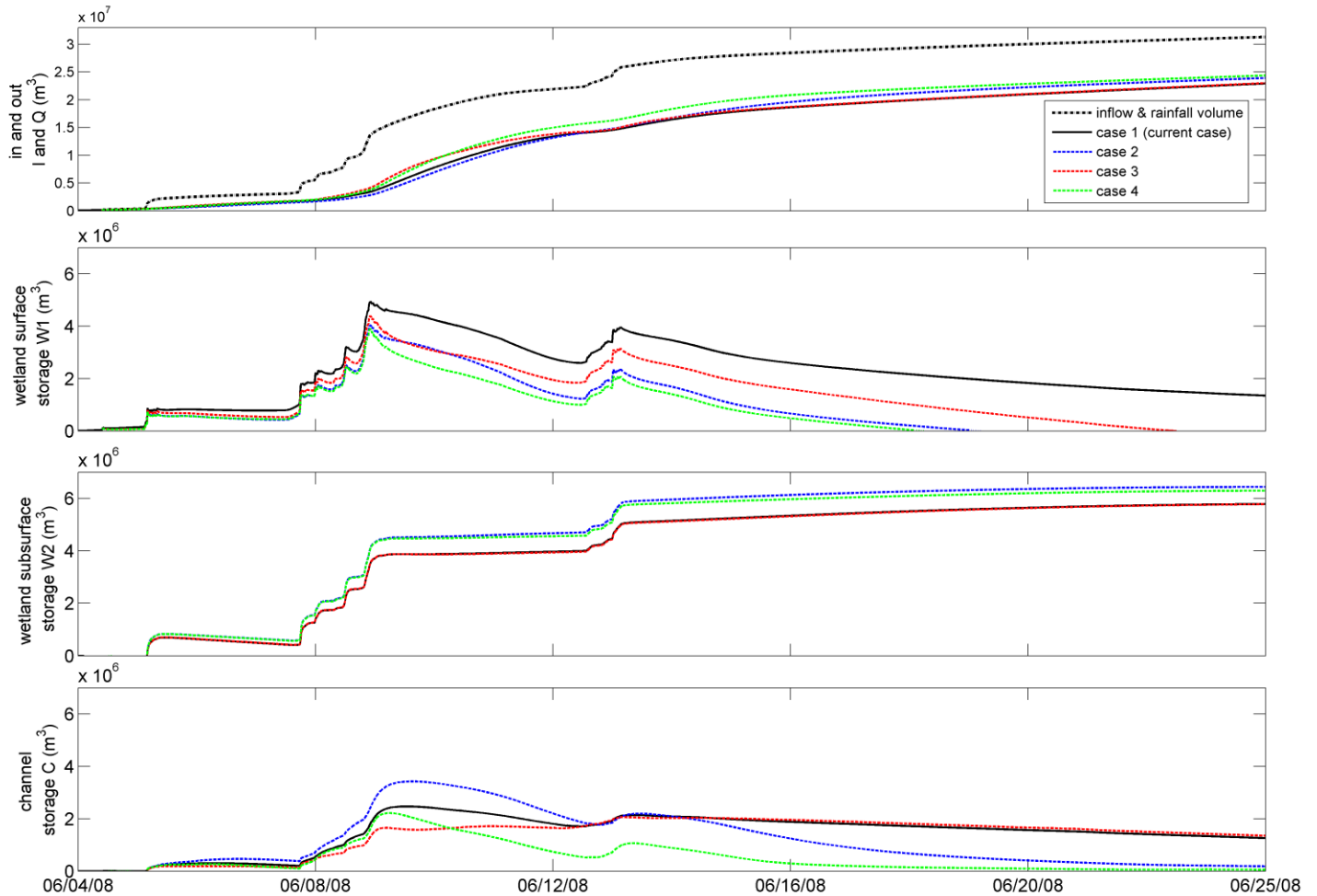


Fig 7. Accumulated volume results of Case 1(current condition), Case 2 (dam removal), Case 3 (constriction widening) and Case 4 (dam removal & constriction widening): (a) inflow and rain volume, outflow; (b) accumulated water stored by wetland surface area; (c) accumulated water stored by wetland subsurface area; (d) accumulated water stored by channel.

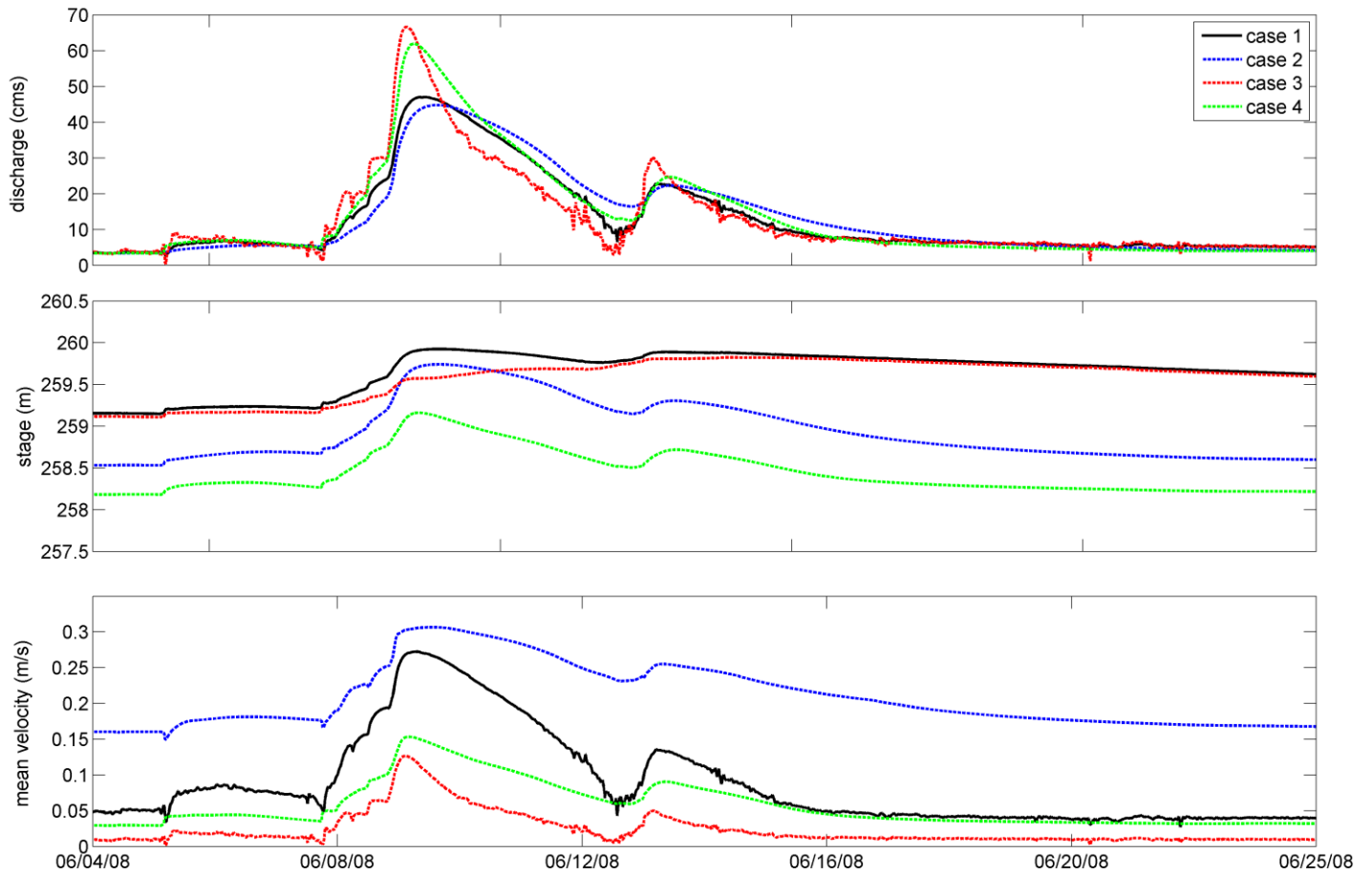


Fig 8. Transient rate results for Case 1, Case 2, Case 3 and Case 4: (a) outflow discharge; (b) river stage; (c) mean velocity through gauge HWY113.

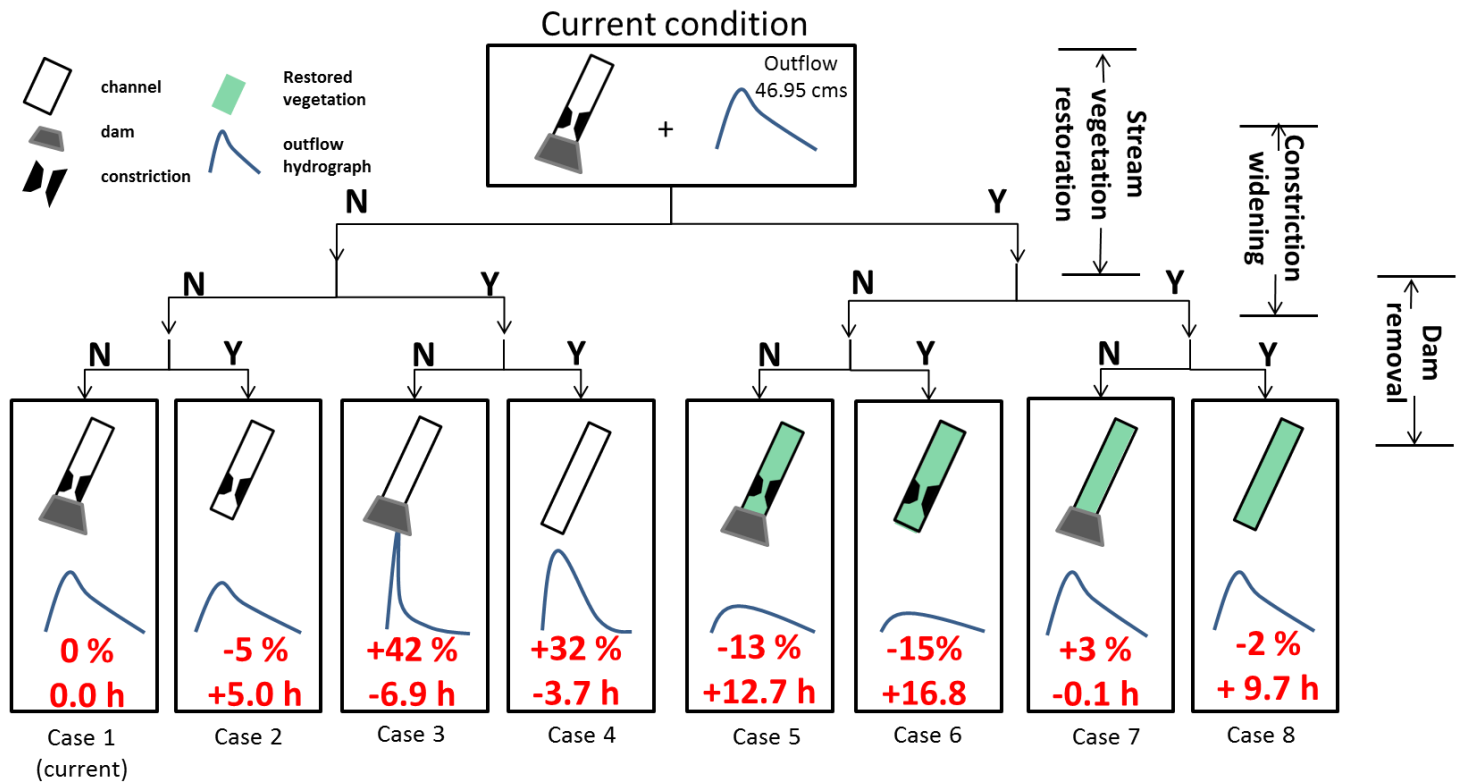


Fig 9. Synthesis diagram showing scenario results: peak rate reduction (being positive means peak rate reduction) and peak time delay (being positive means peak time delay) for each scenario are listed below each synthesis outflow hydrograph.

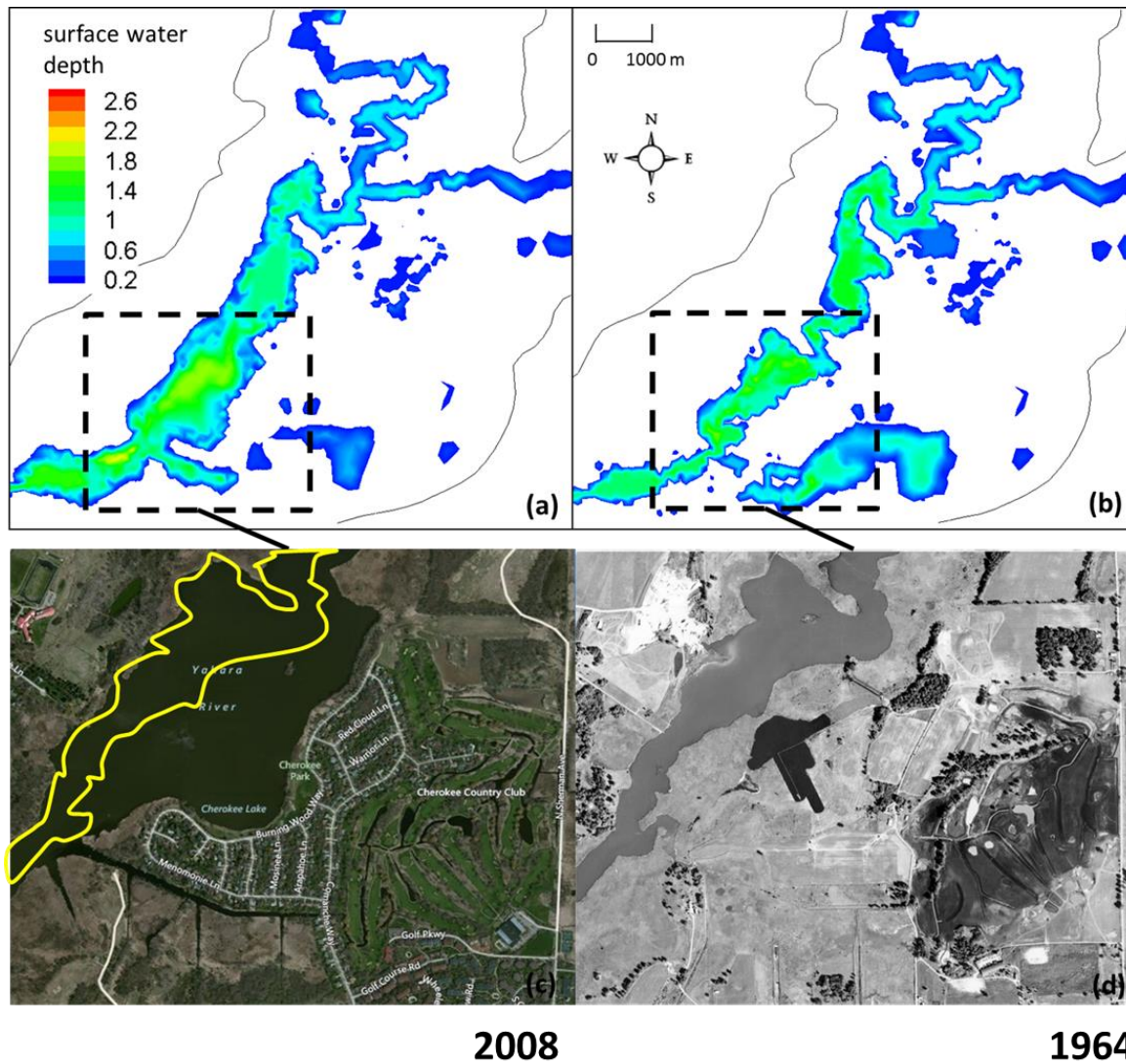


Fig 10. Channel restoration visualization: (a) simulated surface water depth distribution and (c) area photo of Yahara River in 2008; (b) simulated surface water depth distribution and (d) area photo of Yahara River in 1964.

7. CITATIONS

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