Modeling the main ~~inundation~~ channel-floodplain hydrodynamic interactions ~~of seasonally flooded wetlands~~ at the McCarran Ranch ~~on~~ in the Lower Truckee River, USA

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Abstract

This ~~paper~~ study ~~among the first presents the application and validation of a~~applied a two-dimensional hydrodynamic model AdH (Adaptive Hydraulics~~ model, AdH~~) ~~of~~ to a river reach ~~the McCarran ranch~~for complex floodplain hydrodynamic analysis. ~~We use~~ Using the AdH model with combined ~~topographic~~ bathymetry data and topographic data ~~by combining the DEM data~~ from USGS seamless server and ~~the ESRI tin data from~~ United States Army Corps of Engineers (USACE), we intended to ~~to~~ ~~predict~~ examine channel-floodplain ~~inundation~~ interaction on a~~for~~ 10km reach at ~~a river reach of~~ McCarran Ranch ~~~10km~~ located at lower Truckee river in Nevada~~-~~, USA~~state~~. After the calibration of the model, w~~W~~e tested the dependence of modeling results to mesh ~~independence~~density, ~~sensitivity of~~ input parameters and time steps, and ~~then~~ compared the modeling results to the existing gauged data (both the discharge and water stage heights). Results show that the accuracy of prediction from the AdH model ~~can~~ may decline slightly at higher discharges and water levels. The modeling results are much sensitive to the roughness coefficient of the main channel, suggesting that the model calibration should give priority to the main channel roughness. A d~~The simulation results~~etailed analysis of the flood water dynamics was then conducted using the modeling approach to examine the hydraulic linkage between the main channel and floodplains. It was found that~~ suggest that~~ large flood events could lead to a significantly higher proportion of total flow ~~that~~being routed through the floodplains. During peak discharges, a river channel ~~constriction~~ diverted as much as 65% of the ~~river’s 512.3 m^3/s~~total discharge into the floodplain. During the periods of overbank flow, the transboundary flux ratio ~~is~~ was about 5%~45% of the total river discharge, indicating substantial exchange between the main channel and floodplains. Results also showed that both the relations of the inundation area and volume ~~between~~ versus the discharge exhibit an apparent looped curve form, suggesting an areal hysteresis effect of flood routing on floodplains.

1. Introduction

Hydrodynamic characteristics of floods are highly concerned in hydraulics, fluvial geomorphology, and aquatic ecosystem due to its importance in flood control, river-bank erosion, sedimentation, restoration for freshwater habitat, and many related problems. In streams where large floodplains appear, floods may exhibit much more complex flow patterns since the overbank flow could be very different compared with the channel flow, and the hydraulic interaction between the floodplains and the main channel could be complicated. The dynamic channel-floodplain linkage during flood times may greatly affect the floodwaters, sediment transport, erosion, and deposition on floodplains with unsteady, non-uniform flow features (Amoros and Bornette, 2002; Antheunisse and Verhoeven, 2008; Bridge, 200~~2~~3; Thoms, 2003; Sheldon et al., 2002; Stanford and Ward, 1993). This linkage may not only affect flood conveyance and flood risks, but also influence water quality and ecological processes in the river system.

The pattern of flood inundation is of critical importance to the vegetation distribution in the floodplains in Lower Truckee River (Galat, 1990; McKenna et al., 1992). Temporal and spatial changes in flood inundation extent and water level have crucial role in maintaining the sustainable organic material/nutrients exchanges between the main channel and floodplains, yet are critical for understanding hydrological and biogeochemical processes in aquatical ecosystems (Bayley, 1995; Antheunisse and Verhoeven, 2008; Pettit et al., 2011). The ability to model potential flood inundation and map actual extent of inundation, timing, and intensity under different flood levels is central to understanding the dynamics of ecological interactions in the main channel-floodplain system.

Numerical models of channel-floodplain flows are important for understanding and predicting hydrodynamics and it environmental impacts in the channel-floodplain systems. As an increase in accuracy and reliability of flow and inundation predictions is desirable for better decisions concerning land use and water management, the development and improvement of methods for high-resolution hydrologic modeling has been increasingly committed (Neal et al, 2012;). Significant advances in flood ~~inundation~~ modeling have been achieved in the last decade through the use of a new generation of two-dimensional (2D) hydraulic numerical models (Leopardi et al., 2002; Hunter et al., 2007; Neal et al., 2011). These offer the potential to predict the local pattern and timing of flood depth and velocity, enabling informed flood risk zoning and improved emergency planning.

Suitable models for floodplain analysis must be capable of describing the interaction between floodplain topography and unsteady, non-uniform water flow and sediment transport. In particular, numerical models should be able to describe the effect of channel curvature on floodplain flow structure, and how they change in time over floods (Bridge, 2003). This means that the representation of flow field in the model should be two- or three-dimensional (2D or 3D). The US Army Corps of Engineers (USACE) AdH (Adaptive Hydraulics) model software is a 2D shallow water modeling tool capable for floodplain modeling studies (Gambucci, 2009). This tool is developed at the Coastal and Hydraulics Laboratory (CHL) and has been used to model hydrodynamics and sediment transport in sections of the Mississippi River, tidal conditions in southern California, and vessel traffic in the Houston Ship Channel, thus it is a suitable for channel-floodplain hydrodynamic interaction analysis.

~~This paper demonstrates the application of a 2D Adaptive Hydraulics model (AdH) with fine resolution, and the validation of the ability of such a code to simulate flood dynamics on a topographically complex floodplain. Also, the characterization of flow exchanges in channel-floodplains system and the inundation feature of the McCarran ranch were studied based on the modeling results.~~ The main objective of the present study was to investigate the hydrologic connectivity between floodplains and the main channel of a stream during floods. The 2D hydrodynamics model AdH used in this study allowed for detailed analysis of flood flow characteristics in the channel-floodplain system. Through the examination of several hydrodynamic aspects of the river-floodplain linkage, including the channel-floodplain flow rate partitioning, transboundary flux, and the inundation dynamics, the study aims to improve our understanding of the interaction between the two main geomorphic components of rivers. Results of this study may help advance the research of the exchange of nutrients and particulate matter in a dynamic river–floodplain ~~complex~~system and its potential impact on aquatic ecosystem.

2. Methodology

2.1 Study Site

We selected the McCarran Ranch reach of the Truckee River in Nevada, U.S. as our study site to investigate the hydrodynamics of main channel-floodplain system. The Truckee River flows through the U.S. states of California and Nevada. It is the second largest river in Nevada and the only outflow from Lake Tahoe. Roughly every ten years, the Truckee River generates a damaging flood. The 1997 inundation was a major event, putting downtown Reno under several feet of water and turning much of the Sparks industrial area into an inland sea. Although flooding is inevitable, progress is being made on flood control to make the area less prone to such risks (http://www.truckeeflood.us/). The use of satellite observations for evaluating the inundation extent and water level has been considered as an efficient way (Townsend and Walsh, 1998; Overton, 2005).However, currently available satellite observations of inundation extent and water level do not provide a solution as these are usually made using profiling altimeters with wide spacing between tracks (Birkett et al., 2002； Coe and Birkett, 2004), passive microwave instruments with good temporal but limited spatial resolution (Hamilton et al., 2002, 2004), or synthetic aperture radars with good spatial resolution but limited temporal coverage (Hess et al., 2003; Frappart et al., 2005). Whilst the regional significance of hydrology and biogeochemistry process in Truckee river floodplains is undisputed, flood risk analysis needs a higher accuracy at a much finer spatial and temporal resolutions.

2.~~1~~ 2 Governing equations and model settings

The 2D shallow water ~~module~~ model~~of~~ AdH solves the 2D nonlinear shallow water equations. These equations have proven successful in describing water surface and velocity fields in surface water modeling and accepted by many authors as it appears that most studies use 2D models (Abderrezzak et al., 2009; Mignot et al., 2006; Bates et al., 2010; deAlmeida et al., 2012).The equations are derived with the assumption that the vertical velocity component is negligible. Neglecting shear stress and fluid pressure at the free surface, the 2D shallow water equations as implemented within AdH are written as:

$$\frac{\partial Q}{\partial t}+\frac{\partial F_x}{\partial x}+\frac{\partial F_y}{\partial y}+H=0 \quad (1)$$

where,

$$Q=\begin{Bmatrix} h \\ uh \\ vh \end{Bmatrix} \quad (2)$$

$$F_x=\begin{Bmatrix} uh \\ u^2h+\frac{1}{2}gh^2-h\frac{\sigma_{xx}}{\rho} \\ uvh-h\frac{\sigma_{yx}}{\rho} \end{Bmatrix} \quad (3)$$

$$F_y=\begin{Bmatrix} vh \\ uvh-h\frac{\sigma_{yx}}{\rho} \\ v^2h+\frac{1}{2}gh^2-h\frac{\sigma_{yy}}{\rho} \end{Bmatrix} \quad (4)$$

$$H=\begin{Bmatrix} 0 \\ gh\frac{\partial z_b}{\partial x}+n^2g\frac{u\sqrt{u^2+v^2}}{h^{1/3}} \\ gh\frac{\partial z_b}{\partial y}+n^2g\frac{v\sqrt{u^2+v^2}}{h^{1/3}} \end{Bmatrix} \quad (5)$$

The Reynolds stresses are determined using the Boussinesq approach to the gradient in the mean currents,

$$\sigma_{xx} = 2\rho v_t \frac{\partial u}{\partial x} \quad (6)$$

$$\sigma_{yy} = 2\rho v_t \frac{\partial v}{\partial y} \quad (7)$$

$$\sigma_{xy} = \sigma_{yx} = 2\rho v_t \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \quad (8)$$

where, h is flow depth, u and v are velocities in x and y directions, g is gravitational accelerate, ρ is flow density, σ_{xx}, σ_{yy}, σ_{xy} and σ_{yx} are shear stresses, where the first subscript indicates the direction, and the second indicates the face on which the stress acts, are due to turbulence. z_b is the river bed elevation and n is Manning's friction coefficient. v_t is the kinematic eddy viscosity, which varies spatially where turbulence closure is achieved through the algebraic eddy viscosity formulation described by Rodi (1993).

The critical input data is the Digital Elevation Model (DEM) of sufficient resolution and vertical accuracy to capture floodplain topographic features relevant to flow development at the scale of interest and channel bathymetric information detailing the longitudinal slope. The channel bathymetry was ~~captured using the ESRI tin data~~ obtained from United States Army Corps of Engineers (USACE). The floodplain topology data was created from the 30 × 30m United States Geological Survey (USGS) Digital Elevation Model (DEM) obtained from the USGS seamless server (http://seamless.usgs.gov/) and it was integrated ~~into~~ with the bathymetry ~~ESRI tin~~ data ~~obtained from USACE~~. These data are ~~DEM is~~ necessary for delineating the study area and assigning elevation for individual grid cells (Bates and De Roo, 2000). The modeling area is depicted in Fig.1. The AdH model was developed for the river reach of approximately 10 km in length.

The other group of input parameters was the surface roughness. These parameters are generally associated with the land use information. The land use data was obtained from the webGIS website (http://www.webgis.com). It was used to determine the surface roughness with referenced data obtained from the tabular values in Chow (1988). Fine tuning of the roughness value was later on carried out in model calibration. The land use pattern within the AdH model boundary is shown in Fig. 2(a). Also, the estimated eddy viscosity function with a coefficient value of 0.5 was used for this study. As the element wetting and drying limits could cause model instabilities that require an elaborate adjustment (Gambucci, 2009; Karadogan and Willson, 2010). We set the values at 0.15 meters for both the wetting and drying limits. Results of testing models showed that changes in these values have very little impact on the hydrodynamic results.

There is only one gauging station (USGS 10350340) in the study reach. This gauge is located at the lower part of the study area (Fig. 1) and started operation from June, 1997. Data from this station were used for model validation. The nearest gauging station (USGS 10350000) is upstream to the study reach. It has record since January, 1995. Data from this station were used as inputs in a HEC-RAS simulation, and the output hydrograph was used as an upstream boundary condition of the study reach. Also, for flood events that happened before Jun, 1997, the outputs of HEC-RAS on the USGS gauging profile were used for validation. The river stage values also obtained from HEC-RAS simulation results was used for downstream boundary condition. The observed river flow was obtained from USGS NWIS (http://waterdata.usgs.gov/nwis/sw). It was used to compare the modeled flow with the observation.

2.3 Model

2.3.1 Model calibration

The model is designed to work in conjunction with the DoD Surface Water Modeling System (SMS) which can be used to create the mesh files directly for AdH setup. We used SMS to establish a finite element model for the chosen study area. ~~The~~

~~number of mesh grid is described in the case M2, and the initial time step size was set to 30s.~~Figure 2(b) represents the unstructured mesh domain. For a higher accuracy, the mesh adaptive technology was used for mesh refinement to get better results. Generally, the number of FEM nodes during the interaction ranged from 6307 to 7911. The devastating flood in early 1997 was chosen as a typical flood for model calibrations and validations. Due to the large inundation area during this flood event, it is more appropriate to analyze the impacts of floodplain roughness on the flood propagation. Roughness coefficient of main channel and floodplains were set separately for model calibration. In order to examine the model response to roughness coefficient, we ran a matrix of 25 simulations with values of n_c(Roughness coefficient for the main channel) varying from 0.036 to 0.041 in 0.001 increments and n_f (Roughness coefficient for the floodplains) varying from 0.044 to 0.05 in 0.002 increments.

Outputs of the model were compared with the observed values available at the gauging station near the outlet of the river reach. Here we calculated the time series discharge across the gauging profile based on the velocity magnitude and water depth value along the profile line (showing in Fig.1). The accuracy for all simulations was then calculated using the Nash–Sutcliffe efficiency criteria (Nash and Sutcliffe,1970), E_f:

$$E_f = 1 - \frac{\sum^n \left(\hat{Y}_i - Y_i\right)^2}{\sum^n \left(Y_i - \bar{Y}\right)^2} \qquad (9)$$

in which $\hat{Y}_i$ and Y_i are predicted and measured values of the criterion dependent variable Y, respectively; $\bar{Y}$ is the mean of the measured values of Y; and n is the sample size. E_f ranges between -∞ (where the observed mean is a better predictor than the model) to 1 (where observed and predicted values are identical). The Nash-Sutcliffe coefficient has been considered as a goodness of fit index to systemically assess effectiveness of hydrological models (Krause et al., 2005; McCuen et al.,2006). By calculating the E_f value for the 25 scenarios, it is found that the index value ranged from

0.770 with the lowest main channel roughness (n_c=0.036) to 0.937 with the roughness of main channel equals to 0.039. The change of roughness of floodplains makes less difference in the Nash-Sutcliffe index (for example, the E_f value ranges from 0.924 to 0.937 with the n_f gradually varying from 0.044 to 0.05, while keeping n_c with a constant value to 0.039), suggesting that the modeled flood discharge is much more sensitive to the main channel friction than the floodplain friction. Base on this understanding on the roughness impacts, the calibrated roughness coefficient of main channel was set to 0.039, while the roughness coefficients for other land use types are set to 0.048 (grass land), 0.05(crop land), 0.011(high way) and 0.05 (strip mines), respectively. The model was validated by using the adjusted roughness coefficients for the flood occurred in early January,1997. The corresponded E_f is equal to 0.933, showing a good goodness-of-fit.

2.3.2~~2 –~~ ~~mesh~~ Mesh dependence analysis

The adaptive numerical mesh within the AdH model can improve model accuracy without sacrificing efficiency. Before applying the adaptive mesh approach, a base level mesh needs to be generated first. The mesh was created in software Surface Modeling System (SMS) which can be used as a pre- and post-processing graphic user interface for AdH. Following mesh generation, the bathymetric data of the stream was interpolated onto the mesh nodes. Triangular elements were used to discrete the domain is shown in Fig.2 (b). Special care was taken to generate a fine mesh in the vicinity of the main channel. Since the simulation results depend on the mesh resolution and quality, several mesh resolutions were adopted for mesh dependence study (Table 1). To compare with the observation, the simulated velocity and water depth on the profile where the USGS gauging station located were extracted. Fig.3(a) and Fig.3(b) show the velocity and water depth corresponding to different element number on the peak flow stage for a high discharge flood happened in the early January in 1997. The time step (Δt) was set to 1s. Results show that the mesh size M2 and above were observed to be mesh independent.

2.~~3.~~3 Time step sensitivity ~~study~~

ADH is an implicit code and therefore, the time step size is not stability limited for the linear problem, however, nonlinear instability will occur if the time step is too large (Tate et al., 2009). Choosing a proper initial time step could reduce the turnaround time on time-critical simulations. Three different initial time step sizes were chosen for investigating the initial time step dependence (see table 2). Same as the mesh dependence analysis, the depth and velocity value along the gauging profile at the peak flow stage in the early January, 1997 were used for comparison. As showing in Fig. 4, both the velocity and depth along the gauging profile are plotted for particular time levels. From Fig.4 it can be note that the initial time step sizes of 30s is good enough to capture the physical properties of floods modeling results.

3. Results and discussion

3.1 Model ~~test~~application

~~We have established a finite element model for the chosen study area. The number of mesh grid is described in the caseM2, and the initial time step size was set to 30s. For a higher accuracy, the mesh adaptive technology was used for mesh refinement to get better results. Generally, the number of FEM nodes during the interaction ranged from 6307 to 7911. The devastating flood in early 1997 was chosen as a typical flood for model calibrations and validations. Due to the large inundation area during this flood event, it is more appropriate to analyze the impacts of floodplain roughness on the flood propagation. Roughness coefficient of main channel and floodplains were set separately for model calibration. In order to examine the model response to roughness coefficient, we ran a matrix of 25 simulations with values of~~ ~~n_c~~~~(Roughness coefficient for the main channel) varying from 0.036 to 0.041 in 0.001 increments and~~ ~~n_f~~ ~~(Roughness coefficient for the floodplains) varying from 0.044 to 0.05 in 0.002 increments. Outputs from the model were compared with the observed values available at the gauging station near the outlet of the river reach. Here we calculated the time series discharge across the~~

~~gauging profile based on the velocity magnitude and water depth value along the profile line (showing in Fig.1). The accuracy for all simulations was then calculated using the Nash–Sutcliffe efficiency criteria (Nash and Sutcliffe,1970), E_f:~~

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~~in which $\hat{Y}_i$ and Y_i are predicted and measured values of the criterion dependent variable Y, respectively; $\bar{Y}$ is the mean of the measured values of Y; and n is the sample size. E_f ranges between $-\infty$ (where the observed mean is a better predictor than the model) to 1 (where observed and predicted values are identical). The Nash-Sutcliffe coefficient has been considered as a goodness of fit index to systemically assess effectiveness of hydrological models (Krause et al., 2005; McCuen et al.,2006). By calculating the E_f value for the 25 scenarios, it is found that the index value ranged from 0.770 with the lowest main channel roughness (n_c=0.036) to 0.937 with the roughness of main channel equals to 0.039. The change of roughness of floodplains makes less difference in the Nash-Sutcliffe index (for example, the E_f value ranges from 0.924 to 0.937 with the n_f gradually varying from 0.044 to 0.05, while keeping n_c with a constant value to 0.039), suggesting that the modeled flood discharge is much more sensitive to the main channel friction than the floodplain friction. Base on this understanding on the roughness impacts, the calibrated roughness coefficient of main channel was set to 0.039, while the roughness coefficients for other land use types are set to 0.048 (grass land), 0.05(crop land), 0.011(high way) and 0.05 (strip mines), respectively. The model was validated by using the adjusted roughness coefficients for the flood occurred in early January,1997. The corresponded E_f is equal to 0.933, showing a good goodness-of-fit.~~

The calibrated model is further applied to simulate different flood events in order to examine the applicability and accuracy of simulation model in details. As shown in Fig.5, we chose six other flood events for testing cases in addition to the flood event in early 1997. These cases were sorted with index numbers according to the magnitude of peak flow. Comparison to the gauging station data (both the discharge and water level) for the 7 testing cases is shown in Fig. 6 and Fig. 7. The scatter plot comparison for all data is shown at the lower right corner in each figure. The commonly used accuracy measure RMSE (Root Mean Square Error) is calculated for each testing cases (shown in sub-figures in both Fig.6 and Fig.7). The overall RMSE for all testing cases to the discharge comparison throughout the simulation was 5.83 m^3/s. This was reduced to 3.06 m^3/s for discharge less than 100 m^3/s and increased to 6.94 m^3/s for discharge higher than 100 m^3/s. The model predicted the low flow much better (RMSE ranges 0.90 to 1.70 m^3/s for testing cases ①~③) and the model performance reduced during high flow (RMSE ranges 3.13 to 14.65 m^3/s for testing cases ④~⑦). Similar in Fig. 6, the overall RMSE of water depth for all testing cases throughout the simulation was 0.12 m. The accuracy of model predictions was higher for lower water levels (RMSE was 0.07 m for water depth less than 3 m and enlarged to 0.13m for water depth higher than 3 m).

For the relatively lower flow cases (testing cases ①~③), the RMSE ranged from 0.009 to 0.015m, showing a good accuracy of predictions at low water levels. The RMSE for relevant higher flow (testing cases ④~⑦) ranged from 0.05 to 0.22m, showing a less accuracy of predictions at high water levels. One main cause of the error for water level is likely due to the resolution of the topographic data. The vertical elevations of finite element mesh nodes were interpolated from the coarse DEM (30m) ~~and ESRI tin data~~on floodplains~~,~~; therefore errors may exist~~ed~~ ~~in the terrain data of study reach~~for floodplain delineation. Another source of the error may come from the vertical accuracy of the elevation/bathymetry data. Also, the zoning and spatial properties for each element of the whole modeling domain were primarily based on the land use data and led to temporally constant parameters, which may not reflect the real conditions. Flow roughness could be affected by this reason. Although the roughness coefficients had been calibrated for the modeling period, they probably cannot accurately represent the real friction factor of each land use type at all time (e.g. vegetation property would change seasonally). Also, treating the roughness coefficients as constant values independent of flow depth in AdH modeling would result in errors. In reality, flow roughness can change with the water levels over the floodplain (Domeneghetti et al., 2012). Moramarco and Singh (2010) evaluated the trend of Manning's coefficient for two river sites along the Tiber River and they highlighted that the *n* value decreases with increasing flow depth (and hence increasing discharge), showing an asymptotical behavior for high water levels. Furthermore, the neglecting of both the evaporation and infiltration would be another error factor. Despite modeling errors appearing in high flows, the model provides a much detailed view of floodplain hydraulics that can enhance our understanding of water interactions between main channel and floodplains.

3.2 Characterization of exchanges between main channel and floodplains

We assessed the hydrological connectivity between the main channel and its floodplains with two approaches. First, we examined the spatial variation in the flux distribution at 12 different locations (marked in Fig.1) along the focused river reach. We calculated the averaged longitudinal flux passing through the floodplains (Q_{fp}).The proportion of total flow that routed through the floodplains (α_{fp}) was then obtained by dividing Q_{fp} with total discharge. Second, we examined the transboundary flux of both river banks along the focused reach, which is defined as the flow flux penetrating the boundary between the main channel and floodplains along a selected reach. The transboundary flux ratio (β_{ex}) was then calculated by dividing the total transboundary flux with inflow discharge.

Quantifying the flux distribution is generally considered a good way to identify the river-floodplain exchange flux and connectivity (Thomaz et al., 2007; Heiler et al.,1995). Previous studies have shown that the lateral exchange can be considerably complicated and strongly depends on channel morphology, and both the magnitudes and direction of lateral flux are spatial-related variables. Such exchange cannot be simply described by a single flow quantity and needs to be examined in different aspect. The proportion of total flow routing through the floodplains (α_{fp}) is considered a useful indicator for flux distribution. Its magnitude and spatiotemporal change can disclose some details of the hydraulic role of the floodplains and the interaction between the main channel and the floodplains. For McCarran ranch, this ratio is calculated at each flux sampling location for 7 different discharges, carrying out 84 calculations in total.

~~The r~~Results of the analysis are plotted in Fig.8 (a). As shown, the error bars represent the spatial heterogeneity of the flux distribution in the river-floodplain system, and the mean values represent the averaged flux proportion that routing through the overall floodplains of the focused reach. The distribution of flux could have been caused by the flow pattern of the meandering channel. For example, since transects No. 6 and No. 11(Fig. 1) have stronger meandering feature comparing to other transects (e.g., transect No.2 locates at a much straighter reach), the flux on the adjacent floodplains at these transects can be 3.2~5.3 times of a straight reach while the peak discharge is 248.4m^3/s, with the rising of flux rate, the clout of meandering course is waning. The factor reduces to 2.3~4.1 when the discharge is as high as 521.3 m^3/s. Also, the lateral slope in terrain could be another cause to the flux distribution in main channel-floodplain system. Due to the relative higher slope of hill slopes at transect No.1, the α_{fp} always has the lowest value comparing to other transects.

The ratio α_{fp} increases with rising flow discharge. As shown in Fig.8 (a), the relation between the mean proportion and discharge can be fitted with a power-law function (a straight line in logarithmic scales with a slope of 1.5) with high goodness-of -fit (R^2=0.984). Despite this power law relationship for flood water exchange ratio was obtained from a specified study reach of Truckee river, and may not necessarily be applicable to other sites, it reveals the fact that the floods have a significant impact on the flux exchange in a river-floodplain system, and this would consequently affect the nutrients and organic matters transport.

The mean value of α_{fp} for McCarran ranch from year 1995 to 2000 is calculated by applying the power law function, shown in Fig. 8(b). Similar to the discharge trend, α_{fp} is seasonally fluctuated according to the floods. Generally, the proportion of flux routing through floodplains at McCarran ranch is less than 5% during base flow, and it can reach to 15%~30% during small flood events. During extreme high floods, this ratio can be as high as 65%, representing a much high proportion of total flow that routed through the floodplains. Our results are compatible to other results reported in literature. Similar research results have been reported in other river system studies. Richey et al (1989) used Muskingum routing of main channel flow and simple floodplain representation to estimate the flow volume exchanges in river-floodplain systems at Itapena of Amazon River, their research results showed that the ratio of exchanged flux was approximately 30%. Wilson et al (2007) updated this result based on 2-demensional modeling and found the ratio to be at least 40% between Itapeua and Manaus on Amazon River. Zurbrügg et al (2012) have estimated the river-floodplain exchange in Kafue Flats through high resolution measurements of discharge and tracers, and found this exchange ratio to be as much as 80% during peak discharge. This river-floodplain exchange flow could have a strong impact on river quality, and resulting in seasonally recurring sharp changes in dissolved oxygen levels or other quality objectives (Zurbrügg et al, 2012; Zurbrügg et al, 2013).

A more direct look of the river-floodplain exchange is the transboundary flux, which is defined as the flow discharge penetrating the boundary between the main channel and floodplains. The transboundary flux versus river discharge of two particular flood events was plotted in Fig. 9. The fluxes were used to determine the quantity of floodwater from the main channel to the floodplains. As shown in Fig. 9, the maximum transboundary flux occurred before the peak flow for each flood event. Generally, the transboundary flux ratio is approximately from 0.05 to 0.45, and the corresponded flux is $8m^3/s$ to $70m^3/s$. The variation of transboundary flux is mainly controlled by the magnitude of flood discharge, e.g. when the discharge is increased from $270m^3/s$ to $550m^3/s$, the total tranboundary flux is increased from $30m^3/s$ to $65m^3/s$ accordingly. The opposite flow across the river boundary at rising stage and receding stage leads to the loop curve relation between transbounday flux and discharge.

3.3 Flood inundation analysis

The prediction of flood inundation is crucial for risk control and water resources management. Both the inundation area and volume were numerically calculated from the AdH modeling results. A Matlab code was developed for the inundation area and volume calculation based on water depth values on mesh nodes (outputs of AdH) and the finite element mesh information (inputs of AdH). The extreme flood event occurred in early January in 1997 was set as an example for inundation analysis. The inundated area and volume were calculated at different discharges that chosen from the flood rising stage, peak flow stage and recession stage. Snapshots of the flood inundation maps were illustrated in Fig.10. Fig.~~10~~ 11 shows the scatter plots of inundated area and inundated volume. The maximum inundated area and volume can be as high as 1.3km^2 and 3.95×10^{6}m^3, respectively.

More interestingly, we found that both the inundated area-discharge relation and inundated volume-discharge relation show~~ing~~ a looped curve pattern. These looped curves indicate that the same flow discharge at different stages of a flood produced different inundated areas or volumes. This is similar to the looped rating curve for stage-discharge relation during flood events. Based on literatures survey, the looped curve pattern of the inundated area or volume-discharge relation has not been reported yet in the previous studies. This result has a great value in practice for flood risk mitigation, in improving the flood disaster assessment and risk estimation. Furthermore, the inundated area-discharge relation describes an areal result rather than at a station, i.e., an upscaled result of the point-scale stage-discharge relation. It shows that such hysteresis effect can appear not only at local scales, but also at large spatial scales. This result can help us further understand the flood regime and related biogeochemical processes.

4. Implications on riverine ecosystem and flood management

Our study reveals the hydrological connectivity property in the main channel-floodplain system of Truckee River during flood events. As discussed in the previous section that the channel divides a considerable portion of its inflow into the floodplains, and the laterally water exchanges between the main channel and floodplain is closely related to the discharge fluctuations, showing an intensive heterogeneity under different spatio-temporal scales. This high level of spatio-temporal heterogeneity has been proved for forming riverine floodplains as one of the most species-rich environments (Ward et al., 1999). We have analyzed the hydraulic roles of floodplains quantitatively through a set of characterized parameters (α_{fp} and β_{ex}), since the floodplain hydrodynamics from flooding play a dominate role in maintaining a diversity of lentic, lotic and semi-aquatic habitat types (Ward et al., 1999; Amoros and Bornette, 2002).

During the flood events, flood penetrate through the river bank while carrying large amounts of upstream sediment (organic or inorganic substance). When the hydraulic condition meets the appropriate water and sediment dynamic conditions, sediments would deposit on floodplains. This process provides conditions for the floodplain wetlands material recycling. In addition, the aquatic organisms (fishes, invertebrates, plankton etc.) would be entrained into the low-lying zones of floodplains, and eventually participate in the local food chain activities (Stanford and Ward, 1993; Tockner et al., 1999). Biochemical processes such as the metabolism activities happened on patches of floodplain would not change much until the next flood pulse (Thoms, 2003).

In addition, the ecological health of the river corridor relies not only on the surface water hydrological connection but is also reflected by the surface-subsurface water interactions (i.e., hyporheic exchanges). Although we have only discussed the flood hydrodynamic process on the Truckee River, we can still speculate that the intense flood inundations and transient fluctuations will certainly affect subsurface flow within the riparian zone. For instance, the lateral hyporheic flow patterns. Recent studies have shown that hyporheic exchanges within the river-floodplain system plays a key role in maintaining the health of fluvial systems due to its control of biogeochemical and ecological processes (Boulton and Hancock, 2006; Boulton et al., 1998; Brunke and Gonser, 1997; Findlay, 1995). The flood will cause a much more inundation area. This implies that the hyporheic exchanged zone will extend to a larger configuration according to the inundation. Therefore, it will affect the biogeochemical processes in the riverbed and floodplain, for example, the nitrification processes in downwelling area and denitrification processes in upwelling zone (Findlay, 1995).

Our results also indicated an interesting hysteresis pattern to flood inundation behavior. The largest inundation area/volume occurred behind the peak discharge. Generally, due to the unsteady fluctuation rate, backwaters in bend area, heterogeneity of lateral exchanges and other factors, the flood propagation shows a strong nonlinear dynamics. The fact is that the maximum loss that caused by a certain flood event will lag behind the peak discharge. This implies that when we are facing in an evaluation of a disaster flood, it is more appropriate to bring the hysteresis pattern into mind.

54. Conclusions

The use of the hydrodynamic model (AdH) is an effective method for delineating flood inundation in areas of subtle topographic relief. This model was applied for modeling the seasonally flood river at McCarran ranch on Truckee River with a much finer mesh grids. The model was calibrated with gauge data and the validated model performed well in representing the flood hydrographs of various magnitudes. Although the accuracy of prediction is declined slightly at higher discharge and water stage, the raw output of depth and velocity magnitudes from a 2-demensional form of AdH appears adequate to produce reasonable results.

Results show that the proportion of flow that routed through floodplains is much higher during extreme flood events. Since the river-floodplain exchange plays a crucial role in maintaining ecosystem, estimating the exchange ratio through a modeling approach could be useful for river restoration and river landscape design, or even be used as a global index for river ecological assessment. However, field measurements are still recommended for further verification of AdH modeling results.

The inundation area (or volume)-discharge relation at McCarran Ranch on Truckee River was found to be a loop curve pattern, showing hysteresis of flood inundation exists in large spatial scales. Despite this result was obtained from a specific river reach, it will be potentially useful for flood risk assessment and water resources management of other river-floodplain systems, especially for rivers with considerably more floodplain areas.

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FIGURE CAPTIONS

Fig.1. Study location and the elevation of focused area.

Fig.2 The landuse information (a) and finite element mesh (b) of study area.

Fig.3 Results of mesh dependence testing

Fig. 4 Results of time sensitivity study

Fig.5 Scenarios of flood events, of which, case 6 and case 7 are representing the 10-yr and 50-yr flood events, respectively .

Fig. 6 Comparison of calculated discharge and observed discharge

Fig.7 Comparison of calculated water depth and observed water depth

Fig.8 (a)The proportion of total flow that routed through the floodplains (α_{fp}) vs. inflow discharge. The function of the fitted line is $y=5.0e\text{-}5x^{1.5}$ ($R^2=0.984$); (b) The mean value of α_{fp} for McCarran ranch from year 1995 to 2000 based on the applying of the former function in (a).

Fig.9 the transboundary flux ratio (or the absolute transboundary flux) vs. river discharge of (a) 50-yr flood (case#⑦) and (b)10-yr flood (case#⑥).

Fig.10 Inundation maps of 50-yr flood event under different flood stage, of which, (a) and (b) are located on the flood rising stage, and (c) corresponds to peak discharge and (d) is located on the flood recession stage.~~The scatter plots of inundated area vs. discharge (a) and inundated volume vs. discharge (b) of a sample flood event.~~

Fig.11 The scatter plots of inundated area vs. discharge (a) and inundated volume vs. discharge (b) of a sample flood event.

Tables

Table 1. Scenarios of mesh dependence testing

Mesh testing	No. of elements
M1	4911
M2	6307
M3	10306

Table 2. Scenarios of time sensitivity study

Time sensitivity testing	Time step(s)
Δt_1	1
Δt_2	10
Δt_3	30