Journal of Hydrology 432–433 (2012) 98–111

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Improving riparian wetland conditions based on infiltration and drainage behavior during and after controlled flooding

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ARTICLE INFO

Article history:
Received 3 June 2011
Received in revised form 13 December 2011
Accepted 9 February 2012
Available online 20 February 2012
This manuscript was handled by Philippe Baveye, Editor-in-Chief, with the assistance of Peter Wolfgang Swarzenski, Associate Editor

Keywords:
Wetland hydrology
Controlled flood
Restoration
VS2DH

SUMMARY

We present results of an observational and modeling study of the hydrologic response of a riparian wetland to controlled flooding. The study site is located in Poopenaut Valley, Yosemite National Park (USA), adjacent to the Tuolumne River. This area is flooded periodically by releases from the Hetch Hetchy Reservoir, and was monitored during one flood sequence to assess the relative importance of inundation versus groundwater rise in establishing and maintaining riparian wetland conditions, defined on the basis of a minimum depth and duration of soil saturation, and to determine how restoration benefits might be achieved while reducing total flood discharge. Soil moisture data show how shallow soils were wetted by both inundation and a rising water table as the river hydrograph rose repeatedly during the controlled flood. The shallow groundwater aquifer under wetland areas responded quickly to conditions in the adjacent river, demonstrating a good connection between surface and subsurface regimes. The observed soil drainage response helped to calibrate a numerical model that was used to test scenarios for controlled flood releases. Modeling of this groundwater–wetland system suggests that inundation of surface soils is the most effective mechanism for developing wetland conditions, although an elevated water table helps to extend the duration of soil saturation. Achievement of wetland conditions can be achieved with a smaller total flood release, provided that repeated cycling of higher and lower river elevations is timed to benefit from the characteristic drainage behavior of wetland soils. These results are robust to modest variations in the initial water table elevation, as might result from wetter or dryer conditions prior to a flood. However, larger changes to initial water table elevation, as could be associated with long term climate change or drought conditions, would have a significant influence on wetland development. An ongoing controlled flooding program in Poopenaut Valley should help to distribute fine grained overbank deposits in wetland areas, extending the period of soil water retention in riparian soils.

1. Introduction

Wetlands provide essential environmental functions such as water quality improvement, carbon sequestration, nutrient cycling and biodiversity support (Brinson et al., 1981; Turner, 1991; Whiting and Chanton, 2001). More than 50% of the world's wetlands have been damaged or destroyed as a result of urbanization, agricultural development, reconfiguration of water ways, and other manipulation of the natural landscape (Barbier, 1993). California has lost 90% of its wetlands in the last 200 years, more than any of the other United States (Dahl, 1990), comprising a massive reduction in aquatic habitat area, a driving force for soil transformation (Ballantine and Schneider, 2009), and a significant release of nutrients into the environment (Orr et al., 2007). Because wetlands have high ecosystem, economic and hazard mitigation value (Costanza et al., 1997), restoration projects are increasingly common. Riparian wetlands (located adjacent to rivers and streams) are particularly vulnerable to modification by human activities because these wetlands are readily influenced by subtle changes in event and seasonal hydrographs related to channel modification, changes in land use and climate, and the construction of dams and other structures that regulate flow.

Different approaches have been applied to achieve wetland restoration goals, depending on the physical, biological and hydrologic setting, characteristics of available water, extent of landscape manipulation needed, and other factors. Some wetland restoration projects have focused on benefiting a small number of endangered or other species (Mahoney and Rood, 1998; Bovee and Scott, 2002), whereas other projects have assessed wetland conditions on the basis of broader ecological metrics such as species diversity or total species cover (Bendix, 1997; Brock and Rogers, 1998; Johansson and Nilsson, 2002; Capon, 2003; Siebentritt et al., 2004). Another approach is to attempt restoration

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doi:10.1016/j.jhydrol.2012.02.022

of natural hydrologic dynamics, with the idea that native biomes that are adapted to pre-development conditions will be able to make rapid progress towards recovery once hydrologic restoration is achieved (Bayley, 1995; Schiemer et al., 1999; Ward et al., 2001). This approach can be challenging because it requires that restoration projects be designed around a process-based understanding of wetland function, including complex links between hydrologic, biological, and soil conditions and function. In cases where the loss of wetlands has taken place over many years, there may be a lack of baseline information regarding fundamental system properties such as fluid flow pathways, residence times, and typical duration of inundation.

We present results of a study conducted as part of a long-term riparian wetland restoration project associated with controlled flooding downstream from a water supply dam and reservoir. This project, a riparian wetland on a dammed river, is particularly challenging because of the need to simultaneously satisfy environmental and municipal needs. The site is in an area that is highly sensitive to ongoing and projected future climate change, and is difficult to access to set up instrumentation and collect data and samples prior to controlled flood events. All wetland restoration efforts are unique, but many of the characteristics present in the work site described in this study are also found in other wetlands undergoing restoration, as discussed below.

Dams influence discharge on 77% of the rivers in the northern third of the world (Dynesius and Nilsson, 1994), and there is similarly extensive river regulation in Latin America, Africa and South-East Asia (Revenga et al., 2000). In general, dams are designed specifically to regulate downstream flow, often resulting in reductions in the number, timing, and magnitude of high flow events, and reducing the variability of channel discharge in general (Graf, 1999). Dams also change the sediment capacity and load of downstream rivers; modify patterns of sediment supply, erosion, and channel morphology; and impact river temperature and nutrient and carbon contents (Kondolf, 1997; Brandt, 2000; Nilsson and Berggren, 2000). All of these modifications have ecosystem impacts, but riparian wetlands are especially vulnerable because their presence may depend on all of the factors listed above. Thus the restoration of riparian wetlands downstream from dams is a particularly important and vexing challenge.

Riparian wetlands and floodplain habitats are sensitive to the timing and extent of inundation. In some cases, groundwater can provide a significant fraction of the water that maintains shallow soil saturation in these systems (Brunke, 2002), but the relative influence of surface inundation versus groundwater inflow has rarely been quantified. The connectivity between shallow groundwater and wetland soils depends on sediment characteristics and understory growth, and may be correlated to physical river features such as backflow channels and oxbow lakes (Cabezas et al., 2008). Given uncertainties in the relative importance of surface water and groundwater in natural riparian wetland systems, it is not surprising that setting hydrologic goals for restoration can be difficult.

As an added complication in this study, the field site is located on the western side of the central Sierra Nevada mountains, western United States, in an area undergoing significant hydrologic transformation as a result of regional and global climate change. Recent climate modeling predictions suggest that much of the snow pack that accumulates annually in the Sierra Nevada mountains will fall as rain rather than snow by the year 2100 (Snyder and Sloan, 2005; IPCC, 2007). This will change the timing and magnitude of wet-season runoff events, in both unregulated basins and basins where discharge is controlled by dams. Changes in the distribution of the annual runoff hydrograph in many basins will impact the availability of environmental flows and water supplies for municipal, agricultural and industrial purposes, and it is essential to learn how controlled flood releases can be used efficiently for the benefit of ecosystems and stakeholder communities so as to achieve the most benefit from limited resources.

Two primary questions are addressed through this study: (1) What are the relative roles of groundwater and surface water in developing and maintaining riparian wetland conditions during and after a controlled flood, and how might these roles change under varying antecedent groundwater conditions? (2) How can riparian wetland conditions be improved while simultaneously limiting the total amount of water released during controlled floods? These questions are addressed through a study comprising three main components: (a) quantitative observations of riparian wetland response to a controlled flood, (b) use of these data to calibrate a variably-saturated model of wetland soil and groundwater dynamics, and (c) application of the calibrated model to scenarios of controlled flooding that could achieve a similar wetland benefit as part of a smaller total reservoir release. For the purposes of this study, we follow an established riparian wetland definition that includes riverine wetlands and palustrine wetlands (emergent, scrub-shrub and forested) (Cowardin, 1978). We use the US Army Corps of Engineers (USACEs) wetland delineation definition, requiring saturation within 30 cm of the surface for 14 consecutive days, five out of every ten years (US Army Corps of Engineers, 2008). This metric is somewhat arbitrary, but it is widely applied, provides a clear test of observed and modeled wetland response, and is useful for comparative purposes. The emphasis of this study is on the physical hydrology of controlled flooding and wetland soil response, but results of this work have implications for related topics such as valley geomorphology, biome development and support, and riparian nutrient cycling. The present study is based on field observations from a particular location, but a similar combination of field techniques and modeling can be used in other locations.

2. Site and hydrologic description

The study site is located in Poopenaut Valley, adjacent to the Tuolumne River on the western side of Yosemite National Park (YNP), USA (Fig. 1). Poopenaut Valley covers an area of 25 hectares, trending northeast to southwest. The valley was carved from granitic rocks of the Sierra Nevada batholith primarily by glacial processes, the most recent of which, the Tioga glaciations, ended approximately 18 kya (Huber, 1990). Subsequent alluvial and fluvial processes have formed a broad valley with a gentle slope towards the southwest. Alluvial sedimentary fill extends across the valley floor, ending at the steep northwestern and southeastern valley walls, and abutting granitic massifs at upstream and downstream ends of the valley.

The O'Shaughnessy Dam is located at the northeastern end of Poopenaut Valley, forming the lower limit of the Hetch Hechy Reservoir. The dam was constructed to an initial height of 69 m in 1923, and subsequently raised to 95 m in 1938; the current storage capacity of the reservoir is 0.444 km^3. The drainage basin that supplies water to Hetch Hechy Reservoir has an area of 1180 km^2, and extends from an elevation of 1170 m to >3700 m on the northern slopes of Mt. Lyell. About 1/3 of the water collected behind the O'Shaughnessy Dam is conveyed to the San Francisco Bay Area using a pipeline and aquaduct, providing >85% of the water used by 2.5 million people across five counties in northern California (San Francisco Public Utilities Commission: Water Enterprise, 2009). Additional benefit is provided through power generation and environmental flows, including those used for controlled flooding in the Poopenaut Valley, which is the focus of this paper.

Precipitation averages 89 cm annually at the Hetch Hetchy weather station, with 75% of precipitation occurring between

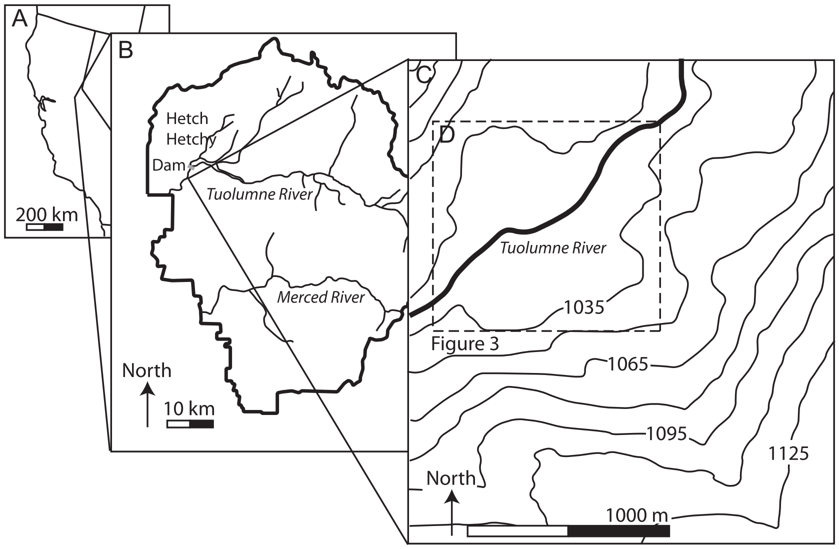

Fig. 1. Site maps. (A) Index map showing location of field area in the Sierra Nevada range of California. (B) Field area is located approximately three kilometers downstream of the Hetch Hetchy Reservoir in Yosemite National Park, CA. (C) Riparian wetlands are located adjacent to the Tuolumne River, as the southwestern end of the Poopenaut Valley. Area labeled 'D' is shown in Fig. 3 with instrument locations.

November and March. The US Geological Survey (USGS) has collected stage and discharge data on the Tuolumne River 3 km upstream of Poopenaut Valley since 1910 (Tuolumne River near Hetch Hetchy CA, Gage number 11276500). More than half of the runoff from the Tuolumne River results from snow melt, with pre-dam peaks in discharge occurring mainly between May and July when melting is most intense (Fig. 2). Dam construction and operations subsequently reduced annual peak discharges by 35%, the duration of high flow periods by 40%, and average monthly discharge by 65%. In additon, much of Poopenaut Valley and the adjacent Hetch Hetchy Valley to the northeast were grazed by sheep and cattle in the 1800s and early 1900s, leading to biological and geomorphologic modification of stream and riparian systems (Greene, 1987).

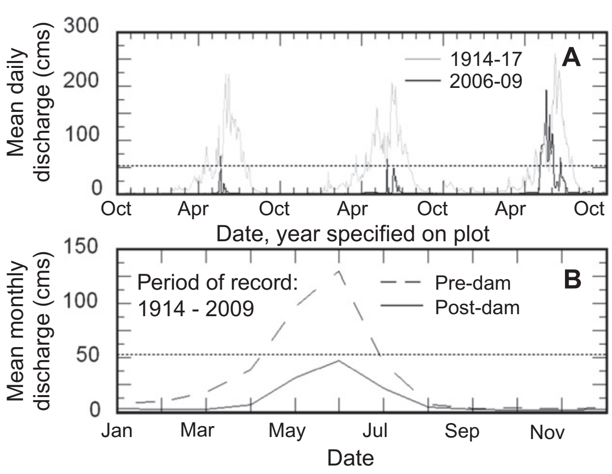

Fig. 2. (A) Three years of average daily discharge on the Tuolumne River from pre-dam construction (1914–1917) and post-dam construction (2006–2009). This paper focuses on wetland soil response during and after the 2009 controlled flood release. (B) Average monthly discharge rates from pre-dam construction (1910–1923) and post-dam construction (1980–2010) periods. Data from USGS gaging station #11276500, downstream of the O'Shaughnessy Dam. The horizontal dotted line on each plot indicates the discharge required in inundate 50% of the wetland area within the valley.

Ten hectares of Poopenaut Valley adjacent to the Tuolumne River have been delineated as 12 distinct wetlands based mainly on vegetation and soil surveys (Fig. 3) (Stock et al., 2009). Cross sections perpendicular to the river that cross these wetland areas illustrate characteristic valley geometry: an asymmetric channel bounded by a levy to the southeast, an irregular flood plain on either side of the channel, and an abrupt break in slope where the valley floor meets the valley walls. Riparian wetlands are strongly influenced by patterns of runoff, so it is not surprising that Poopenaut Valley wetlands have been impacted by a reduction in the number and duration of regular inundation periods following construction of the O'Shaughnessy Dam, in addition to historical grazing and other human activity. Staff of the US National Park Service and the San Francisco Public Utility Commission are evaluating the potential for adapting a program of controlled flooding, using increased releases from the Hetch Hechy Reservoir, as a means to provide recreational (rafting, kayaking) flows and increasing variability in an effort to restore hydrologic function along the Tuolumne River. Controlled floods have been completed along other river systems having a range of sizes and flow durations, in an effort to improve environmental conditions (Junk et al., 1989; Middleton, 1999; Tockner et al., 2000; Patten et al., 2001; Middleton, 2002; Robinson et al., 2004; Henson et al., 2007), but as in the present study, there are often challenges in balancing water supply, power generation, flood control, and a variety of environmental, social, and economic needs (Stanford et al., 1996; Poff et al., 1997; Michener and Haeuber, 1998; Sparks et al., 1998).

3. Materials and methods

There are three main components to the observational part of this study: characterization of shallow soils, quantifying infiltration and drainage response to controlled flooding, and measuring groundwater dynamics in response to vertical and horizontal flows from the Tuolumne River. Most of the sampling and monitoring reported herein was completed in conjunction with a Spring 2009 controlled flood. Access to the Poopenaut Valley field site is limited, and all tools, supplies, and equipment had to be carried in and out on foot using steep trails. There is no power or telecommunication capability at the site, so all instrumentation was designed

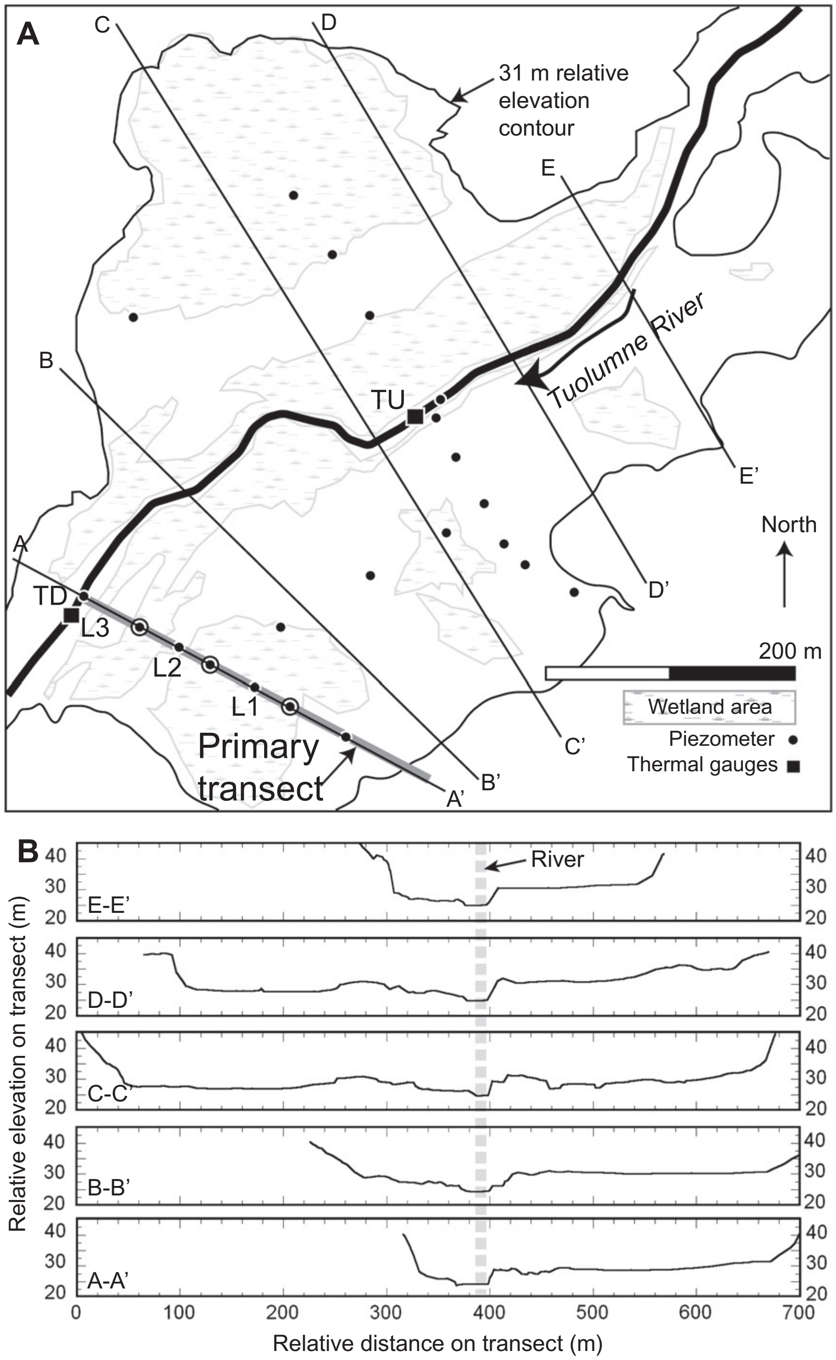

Fig. 3. (A) The study area showing instrument and field test locations. The modeling study simulates conditions along the primary transect. (B) Five elevation transects perpindicular to the river.

to work autonomously before, during, and after flooding. In addition, the 2009 project was initiated with only a few weeks notice and on a limited budget, so the field and associated modeling program was designed to take maximum advantage of existing information, focusing on one wetland area where there was the best opportunity to link surface water and groundwater processes and address key questions.

A series of shallow wells had been installed in Poopenaut Valley in 2007 along three transects, running perpendicular and parallel to the Tuolumne River, and additional wells with pressure gauges were added in 2009 (Fig. 3). We focused instrumentation and modeling on a single cross-valley profile located at the southwestern end of the valley (referred to as the "primary transect"), for several reasons. Capturing the full three-dimensional variability of soil inundation, saturation, and drainage would be impractical, given limitations of time and instrumentation, so we selected a transect of sampling and measurements that (a) had a significant fraction of delineated wetland, (b) was already instrumented with piezometers, (c) had a topographic profile consistent with other parts of the valley (Fig. 3B), (d) included a pre-installed stream gauge at the river, and (e) was located where the dominant flow direction would be to and from the river (rather than down-valley parallel to the river). The latter was assured by the nearby pinch out of alluvial fill against granitic bedrock (Fig. 3). A study of one wetland area such as this cannot be extrapolated across the entire valley with confidence, but provides critical information about one area and is useful for assessing the practicality, cost, effort, and potential benefit of a more extensive sampling and monitoring program prior to future flood events.

Soil properties were evaluated to gain insight into infiltration and drainage characteristics. Soil samples were collected at 10 cm intervals from the ground to a depth of 180 cm at locations L1, L2 and L3 along the primary transect (Fig. 3). A subset of soil samples was analyzed for grain size distribution and organic carbon content. Grain size distribution was measured using a laser diffraction particle size analyzer, after digestion in hydrogen peroxide to remove organics, freeze drying, and deflocculation in a liquid suspension with sodium metaphosphate. Grain size fraction was determined within 162 bins between 0.1 μm and 2 mm, then bins were combined along standard divisions of clay, silt and sand (4 μm and 63 μm). Soil organic carbon was measured on separate (undigested) sample splits using an elemental analyzer coupled to an isotope ratio mass spectrometer.

Volumetric soil moisture content sensors were installed in nests at locations L2 and L3, 55 m and 130 m from the Tuolumne River, respectively (Fig. 3). Sensors were placed at depths of 40 and 70 cm below ground surface (cm-bgs) at L3, and at 40, 70, and 100 cm-bgs at L2. The soil moisture sensors use digital time domain transmissivity (TDT) to measure volumetric water content. The TDT sensors determine the soil moisture content within a spherical region having a diameter of 15 cm. Data collected with these TDT sensors has been compared to results based on time domain reflectometry, impedance probes, capacitance probes and other methods, and the TDT probes have proven accurate across a variety of soil types, environments, and temperatures (Blonquist et al., 2005). Soil moisture sensors were wired to a nearby control system and data logger, and were powered by a sealed lead-acid battery that was trickle-charged using a solar panel.

Autonomous pressure gauges were deployed in 19 shallow (water table) wells, arranged along three transects, and screened to depths of 1.6–4.9 m below ground surface (m-bgs) (Fig. 3). Half of the wells were installed in April 2007, and the remainder in April 2009, prior to the controlled flood discussed in this paper. Wells installed in 2007 were constructed with 5.1 cm (2 in.) diameter machine-slotted PVC, whereas the wells installed in 2009 used 3.2 cm (1.25 in.) diameter galvanized steel pipe with a 45.7 cm (18 in.) long screened drive-tip. Pressure gauges in the wells were programmed to record water levels at 15-min intervals. Absolute pressure readings were corrected for barometric response, based on a separate pressure logger deployed in air at the site. Corrected pressures were converted to water levels based on field measurements of absolute sensor depths below ground, and water levels were referenced to a common elevation datum (also used for measuring stream stage).

Instantaneous discharge values for the Tuolumne River used in this study were determined at US Geological Survey at Gage number 11276500 located at the outlet from the O'Shaughnessy Dam, with data recorded every 15 min. Local measurements of river stage were also made at 15-min intervals at temporary stations located upstream and downstream from the ends of the primary wetland area discussed in this paper (locations TU and TD, respectively, Fig. 3), using pressure gauges deployed in stilling wells and referenced to staff plates. Precipitation data were collected by the California Department of Water Resources from the Hetch Hetchy Dam (Fig. 1) station (HTH), operated by Hetch Hetchy Water and Power.

Subsurface temperature data were collected to quantify vertical seepage directions and rates in shallow soils in the wetland and adjacent streambed, using analytical methods described in the next section. Autonomous temperature loggers were installed in the shallow streambed of the Tuolumne River in sealed PVC tubes at locations TU and TD (Fig. 3). Each thermal tube contained two loggers suspended 20 cm apart below the base of the stream, and the tubes were backfilled with water to ensure a good thermal contact with the surrounding soil. Thermal data were also collected at multiple depths by the soil moisture content sensors deployed at L2 and L3.

4. Analytical methods

4.1. Interpretation of seepage from thermal data

The magnitude and direction of vertical seepage were determined using heat as a tracer (e.g. Constantz and Thomas, 1996) based on time-series analysis of subsurface temperature data, summarized briefly herein (Hatch et al., 2006). Calculations were made only when conditions adjacent to subsurface temperature loggers (both in shallow wetland soils and below the Tuolumne River) were fully saturated. The method is based on the observation that daily variations in subsurface temperatures propagate as a thermal wave, being reduced in amplitude and shifted in phase with time and depth. Data are interpreted based on the analytical solution to a one-dimensional (vertical) conduction–advection–dispersion equation, and changes in the amplitude and phase of thermal oscillations between a pair of subsurface sensors separated by a known distance. Temperature data from each sensor are filtered to isolate diurnal signals, and pairs of records are analyzed to determine the amplitude ratio (A_r) and phase shift ($\Delta\phi$) of propagating thermal waves. Thermal front velocities are calculated as:

$$v_{Ar} = \frac{2\kappa_e}{\Delta z}\ln A_r + \sqrt{\frac{\alpha + v^2}{2}} \quad (1)$$

$$v_{\Delta\phi} = \sqrt{\alpha - 2\left(\frac{\Delta\phi 4\pi\kappa_e}{P\Delta z}\right)^2} \quad (2)$$

where v_{Ar} and $v_{\Delta\phi}$ are the thermal front velocities (m d^{-1}) calculated using the amplitude ratio and phase shift, respectively. κ_e is the effective thermal diffusivity of saturated soil between thermal sensors (m^2 d^{-1}), Δz is the vertical distance between sensors (m), P is period of temperature variations (d), and α is a function of fluid velocity, thermal diffusivity, and signal period. The apparent fluid velocity is calculated once per day as: $v_f = v\gamma$, where v_f is the velocity of the fluid front and γ is the ratio of heat capacity of the saturated soil to fluid. Because this analytical method depends on temperature sensor spacing, rather than absolute depth, it is relatively insensitive to sedimentation and scour (common processes associated with flood events). The method is described in greater detail elsewhere (Hatch et al., 2006), and has been applied in streambeds and shallow soils undergoing managed aquifer recharge (Hatch et al., 2010; Racz et al., 2011).

4.2. Infiltration, drainage, and groundwater modeling

Modeling is a useful approach for understanding wetland hydrologic processes (Bradley and Gilvear, 2000; Bradley, 2002; Joris and Feyen, 2003; Boswell and Olyphant, 2007; Dimitrov et al., 2010; Shafroth et al., 2010), correlating flow regimes to hydroperiods, geomorphological and ecological changes (Bendix, 1997; Mertes, 1997; Cabezas et al., 2008; Shafroth et al., 2010), and evaluating flood response and restoration options (Springer et al., 1999; Rains et al., 2004; Acreman et al., 2007). In the present study, we focus on representing physical hydrologic processes to elucidate some of the mechanisms responsible for wetland formation and maintenance. This approach should help to make the results broadly applicable, although the detailed characteristics of individual model and restoration sites is expected to vary location by location (Schiemer et al., 1999). We have chosen to take a "soil water–groundwater" approach to wetland modeling because we wished to determine explicitly the connections between surface and subsurface water regimes, to understand which is most important for maintaining riparian wetland conditions, as has been assessed in other settings (Bradley and Gilvear, 2000; Boswell and Olyphant, 2007; Staes et al., 2009; Dimitrov et al., 2010).

Our approach was to use moisture content data to quantify soil water retention and drainage characteristics, under a range of groundwater and flood scenarios, to assess the importance of competing processes. The movement and storage of soil water and groundwater were simulated using VS2DH, a variable saturation, transient, two-dimensional, porous medium model (Lapalla et al., 1987; Healy, 1990). VS2DH conserves water mass using the Richards equation for variably saturated flow (for which saturated groundwater flow is a special case):

$$\frac{\partial}{\partial x}\left[K(\psi)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial z}\left[K(\psi)\frac{\partial h}{\partial z}\right]=C(\psi)\frac{\partial \psi}{\partial t} \tag{3}$$

where x and z are spatial dimensions, K is hydraulic conductivity (m s^{-1}), ψ is pressure head (m), h is the total head (m), C is specific moisture capacity (m^{-1}), and t is time (s). The specific moisture capacity (C) is the slope of the moisture characteristic curve, $d\theta/d\psi$. The modeling domain was defined based on observations along the primary study transect, oriented perpendicular to the Tuolumne River near the downstream end of Poopenaut Valley riparian wetlands (Fig. 3). The model domain extended from the middle of the river channel to the southeastern valley wall, 400 m away, and represented the upper 30 m of saturated aquifer and unsaturated soils above valley bedrock. The model contained 9295 grid cells with dimensions ranging from 0.1×1.5 m (height $\times$ width) near the ground surface in wetland areas, to 3×10 m at depth near the far field boundary. No-flow boundaries were assigned to the vertical side of the model domain in the middle of the river (based on symmetry) and the horizontal base of the domain. The far-field boundary opposite the river was set as a Dirichlet (constant head) boundary such that there was a pre-flood gradient resulting in groundwater flow to the river, consistent with pre-flood data from shallow wells. Initial conditions were determined from stream, groundwater, and soil water measurements made prior to flooding. A time-varying total head boundary was imposed on the ground surface of inundated areas during the flood, with the water level at the ground surface forced to follow the flood hydrograph. Water was allowed to "pond" on the ground surface, and the upper surface of the domain was made a potential seepage face throughout the simulations. The total head boundary representing the flood hydrograph had periods ranging from 1 to 7 days, and model time steps were 1 to 5×10^3 s, several orders of magnitude shorter than the periods used to model the flood hydrograph. The time steps were 1 s at the start of each boundary condition period, with a time step multiplier of 1.5 to allow a smooth system response, up to a maximum time step of 5000 s.

Unsaturated soil characteristics were modeled using the Brooks–Corey equations (Brooks and Corey, 1964), which relate soil moisture content, fluid pressure, and variably saturated hydraulic conductivity:

$$S=\frac{\theta-\theta_r}{\theta_s-\theta_r}=\left(\frac{\psi}{\psi_e}\right)^{-\lambda} \tag{4}$$

$$\frac{K}{K_s}=S^{\eta} \tag{5}$$

where S is effective saturation (0–1), θ is volumetric water content, θ_r is residual volumetric water content, θ_s is saturated volumetric water content, ψ is pressure head (m), ψ_e is air entry pressure head (m), K is variably saturated hydraulic conductivity (m s^{-1}), and K_s is saturated hydraulic conductivity (m s^{-1}). λ and η are fitted parameters (determined for the present application by matching modeled and observed soil water contents) where λ is an index of pore size distribution and η is a function of λ. θ_r was inferred to be equal to the pre-flood soil moisture content (based on field observations, as described later), and porosity was determined from the maximum observed saturated soil moisture content. Calibrated hydraulic conductivities of saturated soils were also compared to standard relations based on grain size distributions (Carman, 1956; Bear, 1972; Shepherd, 1989; Fetter, 2001; Hazen, 1911).

The quality of the model fit to data was quantified as the root mean square error (RMSE) of 3000 soil moisture observations (n) from the shallowest water content sensor at L2 during the period of drainage following passage of the flood wave, where:

$$\mathrm{RMSE}=\sqrt{\frac{\Sigma(x_{obs}-x_{calc})^2}{n}} \tag{6}$$

The ability of the model to replicate the behavior of shallow groundwater, as measured with pressure transducers in wells along the primary transect, was also used to adjust simulation parameters, but it was determined that soil drainage characteristics were of greater importance for calibrating the model, particularly because these parameters had the greatest influence on the length of time during which shallow wetland conditions were maintained after passage of a flood wave. We explored fitting modeled to observed soil moisture values based on the Van Genuchten equation (Van Genuchten, 1980), but found that this resulted in drainage behavior that was less consistent with observed soil drainage behavior than did the Brooks–Corey equation.

5. Results

5.1. Controlled flood and extent of inundation

The Spring 2009 controlled flood in Poopenaut Valley began on 4 May (Flood Day 1, FD-1) and ended on 7 July (FD-65), with a total water release of 3.5×10^8 m^3. Prior to the flood, discharge in the Tuolumne River was 15 cubic meters per second (cms). There was a brief, intense precipitation event several days just prior to the start of the flood, and another brief precipitation event on FD-28 (Fig. 5A), but these had little influence on channel discharge, particularly in comparison to the magnitude of the controlled flood. A rating curve for location TU, near the center of the Poopenaut Valley wetlands (Fig. 3), was developed using stage data from this location and discharge data from USGS Gage number 11276500 (Fig. 4A).

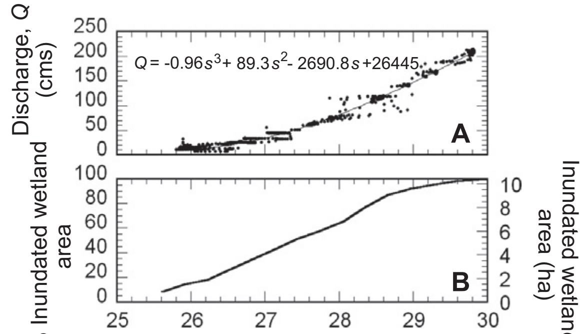

Fig. 4. (A) Rating curve developed using river stage data from Poopenaut Valley and discharge measured at the USGS gaging station #11276500, (B) River stage and inundated wetland area, shown as percent of total wetland area and in hectares.

This rating curve was used with the DEM to calculate the extent of inundation of Poopenaut Valley wetlands as a function of stage (Fig. 4B). The discharge hydrograph (Fig. 5B) during the controlled flood was irregular in form, having three distinct peaks within a high-flow period lasting from 8 May to 8 June (FD-5 to FD-36). The peak of the flood occurred during 18–21 May (FD-15 to FD-18) with discharge reaching 220 cms, at which time the stage was >4 m above pre-flood conditions, and 90% of the riparian wetland area in Poopenaut Valley was inundated (Fig. 4B).

5.2. Soil characteristics

Grain size analyses from soil samples collected along the primary transect are generally indicative of sandy loam, with texture varying with depth (Fig. 6A–C). Shallower soils are more uniform (with a mean grain size of 56 μm), but there is a bimodal distribution of grain sizes between 100 and 180 cm-bgs, with modes of 78 and 140 μm. The organic carbon content of shallow soils vary between 0.7% and 7.1% by weight, with the highest values found near the ground surface at L1 and L2 (Fig. 6D). Carbon concentrations are lower at depth at these two locations, but the pattern is reversed at location L3, with the highest values measured for the deepest samples. Measured organic carbon values are comparable to those seen in similar high-elevation wetlands that experience seasonal periodic inundation and variations in shallow water table elevation (Moorhead et al., 2000; Thompson et al., 2007). It was also apparent from visual inspection of soil samples that there were variations with depth in soil texture and water content (finer grains retaining more moisture), consistent with expectations for layered flood-plain deposits.

Soil hydraulic conductivities were estimated using empirical relations based on grain size distribution (Hazen, 1911; Carman, 1956; Bear, 1972; Shepherd, 1989; Fetter, 2001), yielding values on the order of 10^{-7}–10^{-5} m s^{-1}. But as shown and discussed later in this paper, higher conductivity values were required for successful calibration of a numerical model of soil drainage response following passage of a flood wave.

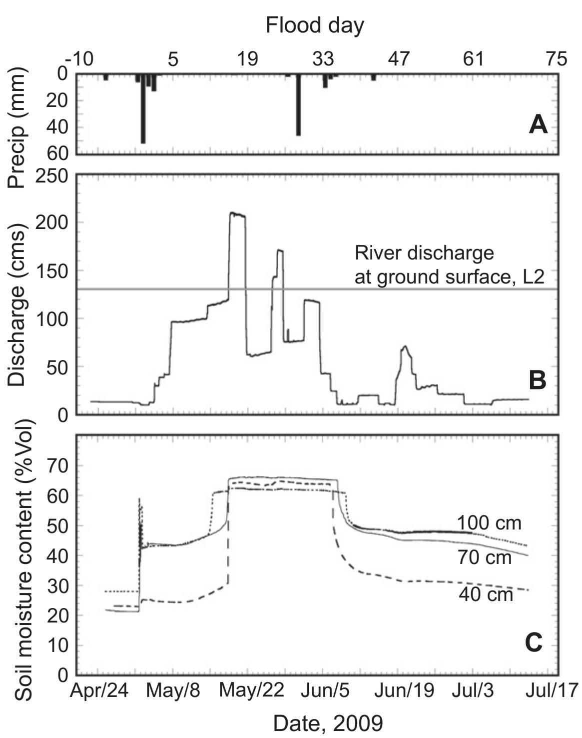

Fig. 5. (A) Precipitation record, (B) discharge measured on the Tuolumne River at USGS gaging station #11276500. The discharge level where location L2 is inundated with flood water is shown at 130 cms, (C) volumetric soil moisture content observations from L2, measured at three depths: 40 cm, 70 cm and 100 cm below ground surface, as indicated.

5.3. Soil moisture content and water table dynamics

The soil moisture content at location L2 prior to the flood varied from 21% to 27% at depths of 40 to 100 cm-bgs, with higher values at greater depth (Fig. 4C). There was a brief increase in soil moisture content associated with the precipitation event that preceded the flood, and a sustained increase in soil moisture once the flood began. Soil moisture rose abruptly to persistent values of 62–66%, interpreted to represent fully saturated conditions, as the leading edge of the flood wave passed. The soil sensor at 100 cm-bgs at L2 showed the earliest increase to saturated values, on 15 May (FD-12), 6 days before the ground surface became inundated. The soil sensor at 70 cm-bgs was next to approach saturated conditions on 17 May (FD-14), and finally the soil sensor at 40 cm-bgs indicated saturated conditions on 18 May (FD-15), coincident with ground inundation. This pattern illustrates the rising water table at 100 and 70 cm-bgs adjacent to the flooding river, and is consistent with water level data from an adjacent shallow well. In contrast to the deeper sensors, the sensor at 40 cm-bgs became saturated immediately after the ground was inundated; it is not clear if saturation would have been achieved at this depth and location without inundation. Collectively, the data from these sensors illustrate two distinct mechanisms for saturating shallow soils below this riparian wetland: rising groundwater from below, and infiltrating floodwater from above. The relative importance of these two mechanisms for achieving and maintaining saturation is evaluated in modeling shown later.

Groundwater hydrographs and river stage data elucidate the patterns of surface water–groundwater interaction before, during, and after passage of the flood (Fig. 7). Prior to the flood, groundwater gradients indicate flow across the southeastern riparian corridor from the valley wall towards the river, consistent with recharge occurring where the valley wall meets the valley bottom. There was also a subtle groundwater gradient oriented from northeast to southwest, consistent with downstream flow along the Tuolumne River. However, the groundwater gradient is virtually perpendicular to the river near the southwestern end of the valley, where the valley alluvium abuts granitic bedrock and the wetland area and underlying shallow aquifer end.

Eight days after the start of the flood, the highest groundwater heads were found in the northeastern end of the aquifer (Fig. 7B), and water flowed from the river into the aquifer throughout the field area, in a direction opposite to that before the flood. In addition, the water table gradient in the downstream direction of the river was significantly larger, indicating a greater rate of groundwater flow through the shallow aquifer during the flood. On 28 May (FD-25), several days after the passage of the first flood peak (Fig. 5), the water table gradient parallel to the river had decreased substantially, although river water continued to move into the aquifer. By 8 June (FD-36), after the main flood wave had passed, the primary groundwater gradient reversed again, and once more indicated flow from the aquifer to the river along the riparian corridor (Fig. 7D). However, water levels in the aquifer were elevated relative to pre-flood levels, indicating that the aquifer was still "charged" with flood water. This is consistent with flow through the aquifer being restricted laterally by bedrock along the valley walls and at the upstream and downstream valley ends. Groundwater levels remained highest at the southwestern end of the aquifer following passage of the flood wave, illustrating that the primary means for groundwater to leave the aquifer after being charged by the flood is subsurface discharge to the river.

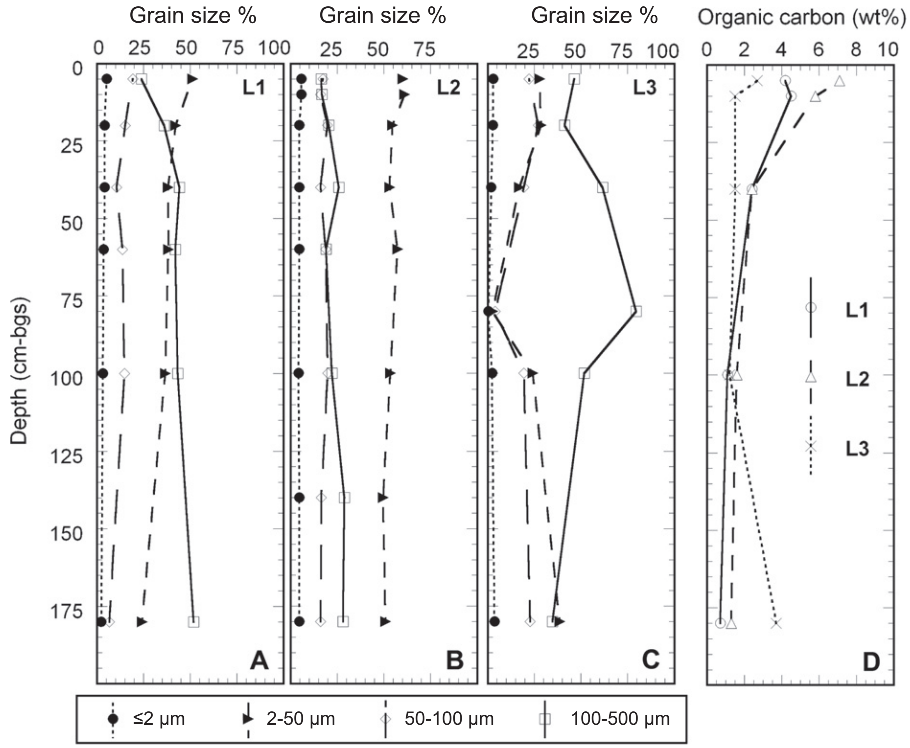

Fig. 6. Soil properties. (A) Grain size at L1. (B) Grain size at L2. (C) Grain size at L3. Grain size data were analyzed at much higher resolution, but binned within the ranges shown. (D) Organic carbon content at L1, L2, and L3.

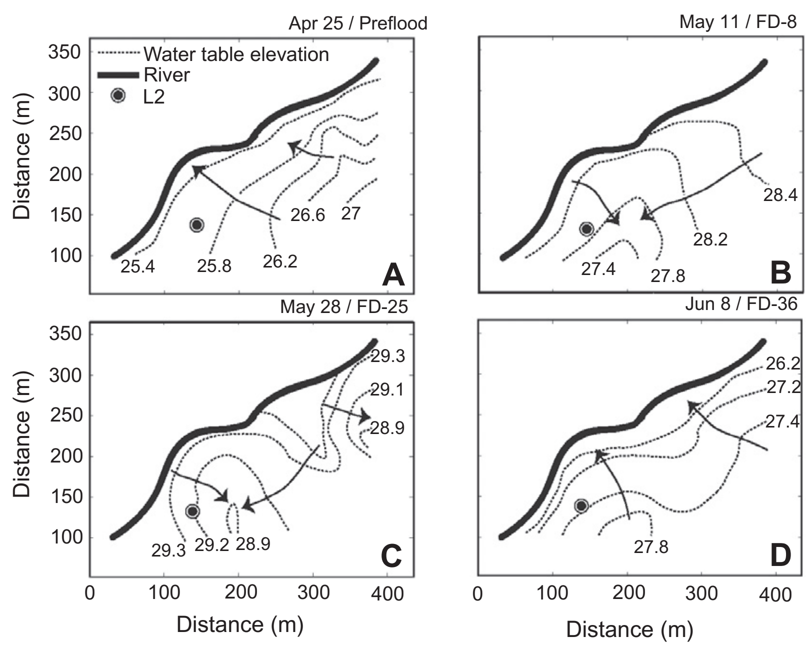

Fig. 7. Contours of groundwater potential (meters relative elevation) south of the Tuolumne River, contoured by hand based on water level records collected in 19 water table wells (profiles indicated with dashed lines, locations shown in Fig. 3). Location of monitoring and sampling site L2 shown with circle. Arrows indicate general trend of groundwater gradients. (A) April 25 (preflood). (B) May 12 (FD-8). (C) May 28 (FD-25). (D) June 8 (FD-36).

5.4. Vertical seepage rates

Thermal data collected in the bottom of the Tuolumne River illustrate the dynamics of surface water – groundwater interactions in Poopenaut Valley (Fig. 8). Prior to the flood, on 3 May, water seeped down into the streambed at the upstream end of the wetland study area, and up and into the river at the downstream end, consistent with the distribution of shallow groundwater heads. As river discharge increased during the flood, water was driven into the streambed at both thermal monitoring locations at rates up to $-0.5\ \mathrm{m\ d^{-1}}$ (negative = downward flow). By the time the thermal instruments were recovered in early July, streambed

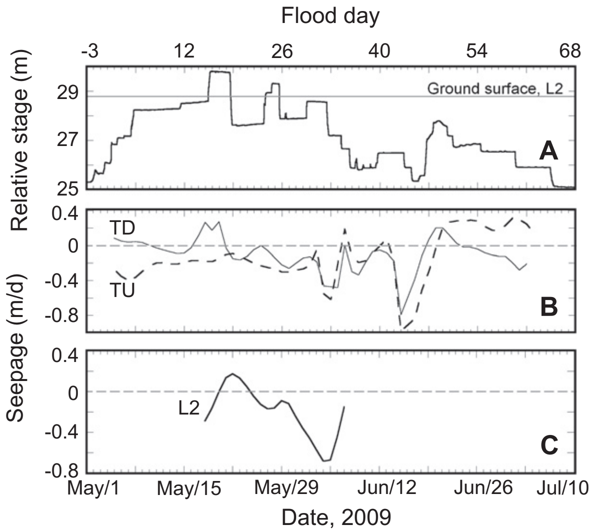

Fig. 8. (A) Stage hydrograph of the Tuolumne River. Horizontal line indicates ground level at location L2. (B) Seepage calculated from thermal data collected at locations TU and TD in the streambed (shown on Fig. 3). (C) Seepage calculated from thermal data during period of saturations at location L2. Positive values indicate upward flow, negative values indicate downward flow.

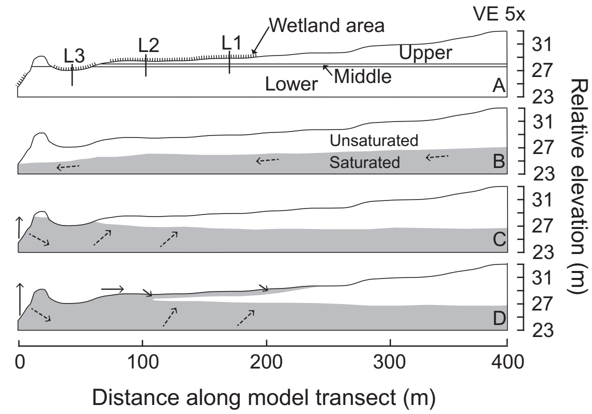

Fig. 9. (A) The upper 10 m simulated by the model geometry showing three soil layers used to simulate TranSection 1. L1, L2 and L3 are labeled and wetland locations are shown. The model extends for an additional 22 m below what is shown. (B–D) Model results showing the dynamics of the saturated–unsaturated zone interface at FD-0, FD-10, and FD-15, respectively. Dashed arrows indicate direction of groundwater flow, and solid arrows indicate direction of surface water flow.

Table 1
Model parameters.

Layer	K_s (m/s)	θ_r	θ_s	η	λ
Shallow	8.0×10^{-4}	0.22	0.62	−0.15	0.8
Middle	2.5×10^{-4}	0.22	0.64	−0.05	0.25
Deep	1.0×10^{-4}	0.22	0.6	−0.01	0.12

K_s is saturated hydraulic conductivity.
θ_r is residual moisture content.
θ_s is saturated moisture content.
η and λ are Brooks–Corey parameters.
Soil saturation and conductivity parameters for three soil layers used in VS2DH to model surface water–groundwater flow on the primary transect of Poopenaut Valley.

seepage was heading back towards pre-flood conditions. Streambed seepage patterns in the middle of the flood, when water levels in the river repeatedly moved rapidly up and down, are more difficult to interpret. The thermal time-series method is subject to greater errors when there are abrupt changes in flow rate and direction (Hatch et al., 2006), as was likely during the flood because of the complex nature of the hydrograph.

The thermal method was also applied to estimate infiltration rates using temperature data collected by the soil moisture sensors at location L2 (Fig. 8C). Only a short segment of the thermal data collected in this location was analyzed to assess seepage rates because the time-series method, as currently developed, is applicable only under saturated conditions. Infiltration rates calculated at location L2 suggest that inundation caused an initial increase in downward flow (approaching −0.8 m/day), which subsequently reversed to upward flow once the flood wave passed, concurrent with the rise groundwater levels in the underlying aquifer.

5.5. Groundwater model calibration and behavior

Soil moisture data from location L2 were used to calibrate the transient, variably saturated soil and groundwater model from the time of the first inundation event at location L2 through the soil drainage following the passage of the flood wave, during 18 May to 19 June (FD-15 to -47). The complex flood hydrograph was approximated using 21 short periods of constant stage, with the total head surface boundary condition corresponding to flood inundation levels as a function of local topography. The duration of each period depended on the period of time represented in the hydrograph. Residual and saturated soil water contents were fixed based on observations of pre-flood and mid-flood conditions (Fig. 5C), and the remaining Brooks–Corey parameters (η, λ, and K_s) were adjusted to achieve a fit between observed and modeled soil moisture values (Fig. 9; Table 1). The residual and saturation soil moisture values used for the model may seem high based on consideration of soil texture alone, but these values are similar to those found in shallow wetland soils in other settings (e.g. Sumner, 2007). We experimented with using lower residual moisture values but found a much poorer fit to field observations. We ran the model initially using homogeneous soil properties, and but added layered heterogeneity in order to achieve a satisfactory fit between observed and simulated soil water contents during the drainage period.

We found that replicating observed soil drainage behavior (Fig. 10) at location L2 required a model with three soil layers (Fig. 9A), with η, λ, and K_s having the highest absolute values in the shallowest soil layer (Table 1). Calibrated Brooks–Corey model parameters are consistent with soils comprising mainly fine sand

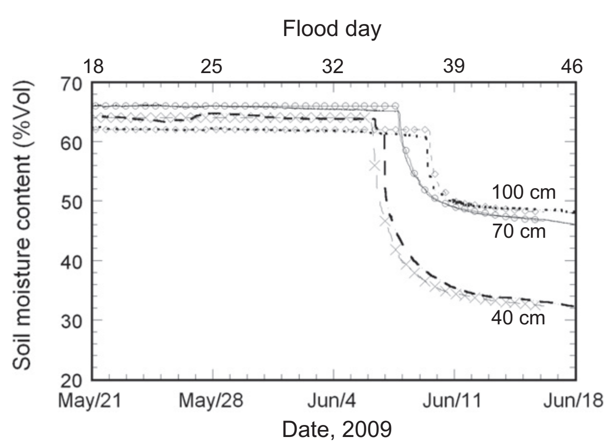

Fig. 10. Calculated soil moisture content values are plotted with the observed values at L2. Calculated values are shown with marker symbols; diamonds for 100, circles for 70 and Xs for 40 cm-bgs.

Table 2
Model parameter sensitivity analysis results.

Variation	K_s	η	λ
10% Increase	1.1	1.1	1.2
10% Decrease	2.9	1.7	3.8

The RMSE between water content values measured during the drainage period and those calculated by the model, varying the Brooks–Corey parameters and saturated hydraulic conductivity by ±10%. The RMSE for the original model parameters is 1.0% volumetric moisture content.

and silt, as observed at the field site. Both K_s and λ (the pore size distribution index) appear to decrease with depth, consistent with the unimodal grain size distributions of surface soil samples, and bimodal distributions of samples at 100 cm and 180 cm depth. We do not suggest that this model stratigraphy is unique in replicating observed soil drainage behavior, or that this layering must apply throughout the wetland area. Our preferred set of Brooks–Corey parameters generated a RMSE of 1.0% volumetric moisture content, based on comparison of 3000 model results and soil moisture data collected with the sensor at 40 cm-bgs. A sensitivity analysis of the Brooks–Corey parameters shows that λ and K have the greatest impact on model results (Table 2). Changes in these parameters by ±10% increased the RMSE value by up to 370%.

Having calibrated for soil properties, we ran a series of simulations that included the entire controlled flood hydrograph to examine the importance of surface inundation versus groundwater rise in maintaining wetland conditions. Prior to the start of the flood, modeled groundwater flow was from the far field boundary towards the river, as observed (Fig. 9B). The net flow from the aquifer to the river was 9.6×10^{-3} m^3 s^{-1} m^{-1} of river reach. If extrapolated along the reach of the Tuolumne River that flows through Poopenaut Valley, this would comprise a net gain to river discharge of 4.8×10^{-3} m^3 s^{-1}, a value too small to be resolved with confidence using standard stream gauging techniques, which have typical uncertainties that are the greater of 5–10% of gauged discharge or 0.04 m^3 s^{-1} (Schmadel et al., 2010). As the first part of the flood wave passes and river stage rises, but before the area adjacent to the river is inundated, water flows from the river into the adjacent aquifer, and the water table rises, causing a reversal in the lateral groundwater gradient (Fig. 9C). As the river continues to rise and riparian wetlands are inundated, there is a zone of unsaturated soils that becomes temporarily trapped between infiltration from above and the rising water table from below (Fig. 9D). Eventually the simulated groundwater gradient reverses again after the flood wave passes, and groundwater flow is restored to the pre-flood direction, towards the river.

5.6. Modeling alternative flood scenarios

We explored alternative flood scenarios to evaluate options to benefit riparian wetlands while releasing less total water from the Hetch Hetchy Reservoir. The minimum acceptable wetland benefit was defined, following the USACE definition, as saturation for 14 consecutive days at 30 cm below ground surface. In the case of Hetch Hetchy flood releases, additional considerations include retaining sufficient water in the reservoir to meet anticipated municipal demand, and supplying downstream recreational benefits. In addition, there are limitations on the rate of change of reservoir releases from Hetch Hetchy (how abruptly a flood wave can be initiated and ended) specified in the US Department of the Interior 1985 flow stipulation, and because of the mechanical operations needed to open and close valves in the O'Shaunessey Dam. At other sites where water is released from reservoirs, additional considerations could include power generation needs and restoring capacity for flood control by lowering reservoir levels.

Because there are so many considerations involved in designing a controlled flood release, we focus for illustrative purposes on three scenarios that emphasize surface water inundation of the wetland at location L2 (Fig. 11). The extent to which any flood scenario will achieve wetland conditions will depend on soil properties, local elevation and topography, and other factors, but we use location L2 for this analysis because achieving wetland conditions at this location by inundation should result in inundation of 90% of Poopenaut Valley riparian wetlands (Fig. 4B). The characteristics of each flood scenario hydrograph, including stage, and duration of both inundating and non-inundating periods, have been adjusted specifically to reduce the total water requirement while meeting wetland conditions in the calibrated model.

The first scenario is a sustained release lasting 12 days, which results in 14 days of saturation at 30 cm-bgs. This is a reference case, with the water level set high enough to inundate the area of interest. The second scenario includes two days of higher stage, to inundate a larger initial area, followed by a somewhat lower stage for the remainder of a 12-day flood. Scenario 2 was intended to test whether it might be possible to delay drainage following the initially high flood stage, using a combination of inundation and raising the underlying water table, without discharging as much water as needed to maintain the higher stage throughout the flood. Scenario 3 comprises multiple cycles of higher and lower stage within a flood of the same 12 day duration, a "flood pulsing" approach that has proven useful in other restoration projects (Middleton, 1999; Tockner et al., 2000; Middleton, 2002). Flooding during short periods, rather than constant discharge for long periods (Springer et al., 1999; Rains et al., 2004), allows for more efficient water releases that account for soil retention and drainage characteristics. In all scenarios presented, peak stages and durations were adjusted incrementally so as to achieve the minimal saturation (wetland) objective at modeled location L2, releasing as little water as possible. Once this goal was achieved, we converted the individual stage hydrographs to discharge hydrographs based on a rating curve developed from data collected during the 2009 controlled flood (Fig. 4). Integrating under these idealized discharge hydrographs allowed calculation of how much water would need to be released from the reservoir to achieve the desired result. Numerous alternative flood scenarios could also achieve the minimal hydrologic objective (14 days of continuous saturation down to 30 cm depth), but these three show a range of options and illustrate key issues that should be considered in designing a flood release plan.

All three flood scenarios were capable of meeting minimum wetland conditions at location L2, as did the 2009 controlled flood (Table 3). However, the modeled scenarios used only 28–40% of the total 2009 flood release, in part because the scenarios minimized the period of the flood that put river stage below the ground elevation at location L2 (before 19 May, after 7 June). The third flood scenario, based on cycling between higher and lower flood stage, was ideally timed to take advantage of the delayed drainage behavior of Poopenaut Valley soils, and so required the least river discharge to achieve minimal wetland goals.

We also attempted to achieve wetland conditions at location L2 with shallow saturation supported mainly by rising groundwater, but it proved to be impractical to extend wetland conditions far enough from the river in this way. In scenarios that achieved wetland conditions by shallow groundwater alone, the river discharge requirements associated with maintaining an elevated water table were far greater than those of the other idealized flood scenarios, and were also greater than the observed total discharge during the 2009 controlled flood.

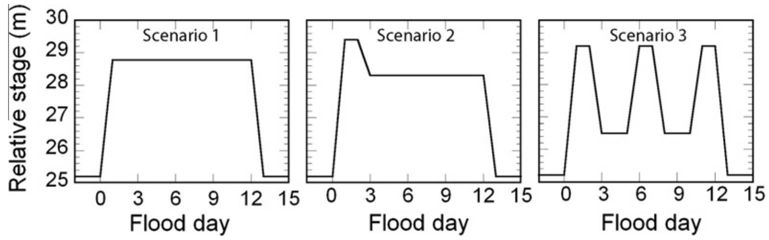

Fig. 11. Three alternative flood scenarios tested with the model. All three scenarios will maintain saturation at 30 cm-bgs for 14 consecutive days, meeting wetland conditions specified by the USACE. Scenario 1: Constant stage reaching the ground at L2. Scenario 2: Brief period of inundation at L2, followed by a constant lower flood stage. Scenario 3: Multiple cycles of high and low stage.

Table 3
Flood scenario results.

Flood scenario	Q (m^3)	% of 2009 release
#1	1.4×10^8	40
#2	1.2×10^8	34
#3	9.7×10^7	28

Total water released and percent of water released in the 2009 controlled flood release for three scenarios. All scenarios meet the US Army Corps of Engineers wetland requirements.

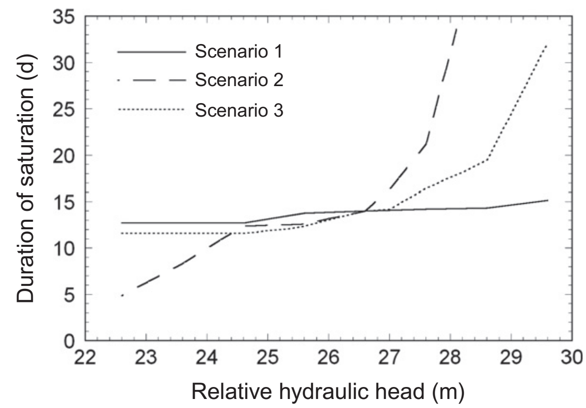

Fig. 12. Days of saturation at 30 cm-bgs for three flood scenarios with varying antecedent water table depths.

5.7. Alternative pre-flood groundwater conditions

Several climate studies have predicted large changes in annual precipitation and snowpack in the Sierra Nevada mountains over the next 50–100 years (Snyder and Sloan, 2005; IPCC, 2007). These changes would impact both the timing and quantity of water flowing into the Hetch Hechy reservoir, and the flow of water into Poopenaut Valley along the valley walls. The latter will have a significant influence on regional groundwater storage and flow conditions. One of the primary considerations for riparian wetland restoration in Poopenaut Valley is the limited supply of water that can be released from Hetch Hetchy reservoir. As shown in the previous section, varying the flood duration and magnitude can be effective for meeting wetland restoration requirements while reducing the total amount of water released from the reservoir. But these scenarios were evaluated based on groundwater conditions observed in Spring 2009.

Additional simulations were run to assess how future hydrologic changes might impact saturation of wetland soils in response to flooding. We did not change the soil moisture retention parameters that were calibrated based on field observations, because these should be relatively insensitive to antecedent moisture, but focused instead on boundary and initial aquifer conditions consistent with wetter and dryer climate scenarios. If there were a larger fraction of precipitation in the Tuolmne River Basin falling as rain rather than snow, this could result in a greater flow of water from higher elevations into Poopenaut Valley along the northwestern and southeastern valley walls earlier in the year, when much of the winter precipitation is currently stored at higher elevations as snow pack. This was represented in the model by raising the elevation of the water table at the far field boundary, bringing the water table closer to the surface below wetland areas and increasing the horizontal head gradient towards the river. Conversely, if there were less precipitation overall, or more of the current annual amount falling during a shorter winter rainy season, there could be less groundwater flowing into Poopenaut Valley, which would result in a lower water table and shallower gradient towards the river.

In all of the climate change simulations, the initial soil moisture content was the same as that measured prior to the controlled flood in 2009, 20–30%. This is based on the assumption that future controlled floods would continue to occur during the late Spring, when Poopenaut Valley is relatively warm and dry. We also assumed that the background stage (discharge) of the Tuolumne River would remain unchanged, being controlled mainly by releases from the reservoir prior to the flood.

Changes in the elevation of the water table at the far field boundary on the order of ±1 m had little influence on the duration of maintenance of wetland conditions, in comparison to results from the calibrated 2009 flood simulations (Fig. 12). When the far field water table was lowered more than 1 m (dryer initial conditions), the constant flood and pulsed flood simulations (Scenarios 1 and 3) provided the longest periods of wetland conditions. Even when the initial far field water table boundary was lowed by 3 m, wetland conditions were little changed in these scenarios, illustrating the importance of soil water retention relative to upflow of groundwater. Similarly, when the far field water table was elevated by >1 m (wetter initial conditions), the constant flood scenario showed no significant increase in wetland conditions. In contrast, the higher initial flood and pulsed flood simulations (Scenarios 2 and 3) showed much greater periods of saturation and wetland conditions. In these simulations, upflow of groundwater could play a much more important role in wetland hydrology. In fact, even a small increase in water table elevation would have a significant influence on the duration of soil saturation conditions in this setting.

6. Discussion

6.1. Hydrologic restoration of Poopenaut Valley wetlands

The first objective of this project was to evaluate the relative importance of inundation versus rising groundwater in establishing and maintaining riparian wetland conditions during and after controlled flooding. Observations and modeling suggest that, in the areas investigated, inundation is more efficient for this purpose than raising the water table, although a shallow water table can help to maintain soil saturation after a flood wave passes. The shallow aquifer in Poopenaut Valley is well connected to the Tuolumne River, and this means that flooding has strong short-term influence on groundwater conditions below riparian wetlands. But most of the time, the river serves as a sink for groundwater that flows laterally from the edges of the valley. It may be that wetlands in this area were better supported by groundwater prior to installation of the O'Shaughnessy Dam, because the seasonal flood hydrograph was higher and longer (Fig. 2), and this should have helped to develop a shallow water table earlier in the season and to maintain this condition longer following the end of major rain and meltwater events.

The second objective of this study was to evaluate what kind of hydrograph might be most beneficial from a wetland restoration perspective, while simultaneously limiting the magnitude of total flood releases. A surface water–groundwater model was developed and calibrated using water content data from shallow wetland soils. Three soil layers were required to calibrate the model to the observed data. The properties of each layer agree with field observations of soil type and grain size distribution, but were optimized based on the hydrologic behavior rather than attempting to define soil properties solely based on cores. Model results indicate that "flood pulsing" is relatively efficient for improving the duration and area of wetland conditions. This approach depends on linking the timing of flood pulses to the timescale of soil drainage. The flood scenario that is most successful in achieving a particular wetland restoration goal will also depend on initial groundwater and soil water conditions, and this will change year by year and with location in these heterogeneous systems. Modeling suggests that the flood pulsing scenario should be relatively robust for the monitored wetland even if groundwater levels are initially lower (dryer conditions) than seen at present, and could result in a longer period of wetland saturation if groundwater levels are initially higher (wetter conditions) (Fig. 12). Wetter conditions would likely be accompanied by an increase of water availability from the Hetch Hetchy Reservoir, so there would be less need to conserve water during controlled flooding, and this could provide opportunities for inundating a larger area or maintaining saturation for a longer period of time.

Grain size and carbon analyses of shallow samples collected as part of the present study, along the primary transect, indicate significant variations in properties horizontally and with depth. Soils underlying adjacent wetland areas, identified initially on the basis of vegetation, are likely to have dissimilar wetting and drainage characteristics (Bradley et al., 2010). This suggests that there will be considerable spatial variability in wetland response to controlled flooding, making local soil characterization and monitoring important for both wetland delineation and flood management. Our results also suggest that soil textural analysis may have limited use in characterizing hydrologic properties in the absence of in situ drainage measurements. We suspect that the hydraulic conductivity values estimated using in situ soil moisture data and model calibration (Table 1) are higher than values estimated based on grain size distribution because of preferential flow paths resulting from biological activity (burrowing, root tubules, etc.). This interpretation is consistent with soil moisture data indicating effective soil porosity >60%, considerably higher than would be expected from a simple mixture of fine sand and silt, and is further supported by field observations of drainage into burrows during inundation.

The benefits of inundation to maintaining wetland conditions in Poopenaut Valley are likely to vary spatially along the Tuolumne River, independent of heterogeneity in soil and wetland types. At the southwestern end of the valley, where the river passes from alluvium to bedrock, groundwater that flows parallel to the river is forced to move upward and towards the river. Seepage rates calculated from temperature data collected with the soil moisture sensors at L2 show that water tends to seep upward through the wetland soils within a few days after the passage of a flood wave. This helps to extend the beneficial influence of seasonal and controlled flooding in this area; a similar benefit may not be achieved higher (upriver) in the valley.

Riparian wetlands in Poopenaut Valley are likely to be undergoing a period of transition, after decades of grazing on the valley floor, followed by installation of a large dam and associated modifications to the seasonal hydrograph of the Tuolumne River. Repeated flood events will help to establish wetland conditions for the short term, and should have longer term impacts by helping to deliver sediment to wetland areas. As wetland conditions develop and improve, leading to more obligate plants and hydric soils, wetland areas will slow the movement of floodwater, leading to the deposition and trapping of fine sediment, which should improve soil moisture retention in riparian areas. In addition to benefiting wetland conditions, controlled flooding can also contribute to improved nutrient cycling and creation of more complex riverine habitats.

6.2. Study applicability and limitations

Results of this study show that a modest field instrumentation and sampling program can provide insights regarding surface water - groundwater interactions and the establishment of riparian wetland conditions. The simultaneous collection of shallow groundwater level and soil moisture data helped to quantifying the relative importance of rising groundwater versus inundation during flooding, and was essential for calibration of a numerical model. Additional field tests and sampling, including more extensive soil sampling and slug testing, would have provided additional benefit during model calibration. Time, budget, and access limitations required that this study be focused on a relatively small area, but results can be used to guide future field and numerical work if justified on the basis of restoration and water management goals. A much more extensive field and modeling effort would be required to account for the heterogeneity of shallow soils and the three-dimensional nature of surface and subsurface fluid flow pathways throughout Poopenaut Valley wetlands.

There are numerous metrics for evaluating the success of wetland restoration. The USACE definition used in this study was observationally and computationally convenient, but satisfying this constraint should not be viewed as a de facto indication of wetland health. There would also be benefit in biological and biogeohemical sampling and monitoring in order to quantify the success of wetland restoration efforts over time, ideally done simultaneously with hydrologic studies to link processes and conditions with confidence. When considering wetland restoration and health over even longer time periods, it could also be useful to incorporate larger floods at five or ten year intervals (Capon, 2003; Hughes and Rood, 2003), if water availability permits.

A saturated–unsaturated numerical model proved useful for interpreting field observations and testing a variety of flood scenarios. The model domain was cast in two dimensions, following careful selection of a focused field transect where this flow regime was expected (and subsequently confirmed). The representation of soil properties was layered, as needed to replicate observed drainage behavior, but was otherwise highly idealized. The code used for this analysis, VS2DH, represents transport of a single (liquid) phase, and as such does not simulate air that would be trapped in shallow soils between the rising water table and a wetting front extending downward following rapid flood inundation (Heliotis and DeWitt, 1987). This relatively simple model worked well to achieve the stated goals of this project, but a multiphase flow model might be helpful for resolving fine-scale flow paths of both water and air in the shallow soil. The model also neglected evapotranspiration, although VS2DH can represent this process, mainly because we were interested in a relatively short time period associated with flooding and drainage response. Modeling evapotranspiration is likely to be more important in studies that extend across several seasons or multiple years, particularly in arid climates (Gerla, 1992), and would require collection of additional field data for calibration purposes.

The direct application of these results to restoration projects in other riparian wetlands and floodplains impacted by upstream flow regulation will depend on specific hydrologic conditions. But the overall approach taken in this study should be broadly useful. Simultaneous monitoring of shallow groundwater, soil moisture, stream discharge and stage, and streambed seepage throughout a controlled flood event provides information that is essential for resolving the relative importance of surface and subsurface hydrologic processes in saturation of wetland soils. A calibrated model is useful for evaluation of hypothetical controlled flooding and climate change scenarios, particularly where there are limitations to the water available for flood releases. Model results could be tested and extended through additional monitoring and analyses, including an evaluation of the importance of flood duration, rate of change of discharge during flooding, and the depth to a shallow water table (Nicol and Ganf, 2000; Sprenger et al., 2002; Siebentritt et al., 2004; Stromberg et al., 2007). Additional studies should be completed in riparian settings to help determine the typical importance of surface versus subsurface water in developing wetlands, and to assist in resource management for the benefit of environmental, agricultural, municipal, and recreational needs.

7. Conclusions

We completed a study of riparian wetland response to a controlled flood, combining soil sampling, analyses and in situ data collection; a two-dimensional saturated–unsaturated numerical model of flood response; and evaluation of flood scenarios capable of achieving a desired metric of wetland function based on soil saturation and drainage characteristics. Observations of soil moisture and groundwater levels were used for model calibration. The model was subsequently applied using several controlled flooding scenarios, with the goal of establishing wetland conditions (saturated soils at 30 cm depth for 14 consecutive days) while limiting total water released during the flood. Several model scenarios were capable of achieving the wetland metric while discharging considerably less water than was released during the 2009 controlled flood.

The ability of riparian soils to maintain wetland conditions in this setting depends mainly on: the height and duration of the flood wave (which determine the spatial and temporal extent of inundation), and soil drainage characteristics and the depth to the underlying water table (which determine the length of time following passage of a flood wave during which saturation is maintained). In the riparian wetland monitored as part of the present study, inundation was found to be more important than a rising water table in establishing wetland conditions during a controlled flood, but this result depends, in part on the antecedent water table elevation. Model scenarios that included a higher initial water table achieved wetland conditions for a longer time based on the sample flood hydrograph. In contrast, a lower initial water table resulted in a somewhat shorter period of shallow soil saturation, but in this case, soil drainage behavior was more important in determining the extent of wetland development.

Soil drainage characteristics during restoration will depend, in turn, on repeated short-term development of wetland conditions by controlled flooding, as this helps to move sediment out of the primary channel and into riparian areas, and contributes to an increase of organic carbon in shallow soils. Thus the benefits of controlled flooding to riparian wetlands should increase with time. Optimizing for multiple benefits from controlled flooding is likely to become increasingly important in future years, as hydrologic conditions become more variable and demand increases for limited fresh water resources. Future studies such as this one can help with developing a mechanistic understanding of links between river and wetland hydrology and associated ecosystem function.

Acknowledgements

This research was supported by the Committee on Research (University of California, Santa Cruz), the US National Science Foundation Graduate Fellowship Program, and the US National Park Service (Award J8CO790007). Critical lab and field support was provided by Dan Sampson, Lucas Beem, Kerri Johnson, Ted Baker, Brianne Davidson, Aaron Rinehart, Josh Baccei, and Roger Putnam. This manuscript benefited from thoughtful reviews by G. Stock and M. Buhler, and two anonymous reviewers.

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