RIVER RESEARCH AND APPLICATIONS
River. Res. Applic. **24**: 735–753 (2008)
Published online 16 April 2008 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/rra.1077

QUANTIFYING THE HYDROLOGICAL EFFECTS OF STREAM RESTORATION IN A MONTANE MEADOW, NORTHERN CALIFORNIA, USA

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ABSTRACT

Stream restoration efforts, particularly within meadow systems, increasingly rely on 'pond and plug' type methods in which (a) alluvial materials are excavated from the floodplain, forming ponds; (b) excavated alluvial materials are used to plug incised channels and (c) smaller dimension channels are restored to the floodplain surface. A commonly stated objective of these efforts is to restore ecologically significant hydrological processes to degraded riparian systems. However, little research has been conducted to evaluate and quantify the restoration of these hydrological processes. Direct comparisons of pre- and post-restoration hydrological observations are often misleading due to an inter-annual climatic variability. To overcome this issue and accurately quantify the hydrological effects of restoration, we developed, calibrated and validated a hydrological model of a 230 ha mountain meadow along a 3.6 km restored reach of Bear Creek in the northeastern California. We then applied the model to simulate the pre- and post-restoration scenarios by altering the floodplain topography and stream channel networks. Our results document three general hydrological responses to the meadow restoration effort: (1) increased groundwater levels and volume of subsurface storage; (2) increased frequency/duration of floodplain inundation and decreased magnitude of flood peaks and (3) decreased annual runoff and duration of baseflow. This study supports and quantifies the hypothesis that 'pond and plug' type stream restoration projects have the capacity to re-establish hydrological processes necessary to sustain riparian systems. In addition, the results of this study can be used to improve quantitative objectives for 'pond and plug' type stream restoration activities in similar settings. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: stream restoration; hydrological model; surface–groundwater interaction; water table; flood peak attenuation; channel modification; pond and plug; MIKE SHE

Received 16 July 2007; Revised 27 September 2007; Accepted 2 October 2007

INTRODUCTION

An increased appreciation of the multitude of environmental services that healthy stream systems provide has prompted large investments in restoring degraded watercourses in the United States (U.S. Environmental Protection Agency and U.S. Department of Agriculture, 1998) and throughout the world (Moser *et al*., 1997). An exponential increase in river restoration projects over the last decade (Bernhardt *et al*., 2005), has made stream restoration one of the most visible elements of hydrological sciences (Malakoff, 2004) and placed river restoration at the forefront of applied hydrological sciences (Wohl *et al*., 2005). An increasingly popular stream restoration strategy is the 'pond and plug' method, in which (a) alluvial materials are excavated from the floodplain, forming ponds; (b) excavated alluvial materials are used to plug incised channels and (c) smaller dimension channels are restored to the floodplain surface. Objectives of 'pond and plug' projects typically include: improved aesthetics, improved land productivity, improved aquatic and terrestrial habitats, decreased streambank erosion and downstream sediment delivery, increased water table elevations and enhanced baseflow conditions (Benoit and Wilcox, 1997; Rosgen, 1997). Despite the popularity of this approach, only a small number of projects receive

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sufficient monitoring and assessment to evaluate their effectiveness and to inform future restoration efforts (Bernhardt *et al*., 2005), seriously limiting advancement in design and implementation.

The purpose of this study is to quantify the hydrological effects of a 'pond and plug' type stream restoration. We hypothesize that topographic modification of channels and floodplains, typical of 'pond and plug' restoration projects, will result in measurable changes to all surface and subsurface hydrological processes. Hydrological processes of particular interest are the spatial and temporal changes to groundwater (e.g. water table elevation, range of water table elevations and subsurface storage), surface water (e.g. floodplain inundation frequency, area and duration, flood peak attenuation, baseflow duration and total annual runoff) and atmospheric exchange (e.g. evapotranspiration). Direct comparisons of pre- and post-restoration hydrological observation data can be instructive, yet also can be misleading due to the inter-annual climatic variability, which affects many surface and subsurface hydrological processes. In order to quantify the effects specific to stream restoration, two linked surface water-groundwater numerical models were developed with the MIKE SHE hydrological modelling system using a well-documented 'pond and plug' stream restoration project as an example. The two models (incised vs. restored) differ only in the size, shape and alignment of the channels and the presence/absence of ponds on the floodplain surface. Identical boundary conditions are used to simulate the hydrological effects and allow for a direct comparison of the stream restoration's effects on the surface and subsurface hydrological processes. The results of this work offer new insight into the impact of this restoration technique on meadow hydrology. In addition, the methods used can guide future efforts to monitor and assess stream restoration efforts.

STUDY AREA

Geology and hydrology

Bear Creek Meadow (meadow) is a low-gradient alluvial floodplain ~100 km northeast of Redding in the northern California, USA (Figure 1). The meadow is located at an elevation of ~1010 m, and is situated at the bottom of the ~218 km^2 Bear Creek watershed, immediately upstream of the confluence of Bear Creek with the Fall River, the largest spring-fed river system in California (Grose, 1996), and among the largest spring-fed river systems in the United States (Meinzer, 1927; Rose *et al*., 1996).

The meadow is approximately 3 km long, 1 km wide, 230 ha in size and is situated at the northwestern margin of the Fall River Valley. The meadow is bounded on the south and west by the steep slopes of Soldier Mountain, to the north and east by the low-relief basaltic flows of the Medicine Lake Highlands, and to the southeast by the Fall River Valley. The head of the meadow lies at the base of a relatively steep, heavily-forested bedrock reach. The Fall River Valley is underlain by lacustrine deposits consisting of clay, silt and sand. In the meadow, the lacustrine deposits are overlain by 0.5 to 2 m of deltaic sands and gravels, and 1 to 3 m of floodplain silty loam soils (Grose, 1996). The meadow vegetation is dominated by grasses, sedges and rushes, in addition to stands of Oregon ash lining inactive stream channels.

The climate of the Fall River Valley is semi-arid, receiving an annual average of 508 mm of precipitation (California Irrigation Management System data for McArthur for water years 1984–2006). Most of the precipitation in the Fall River Valley occurs as rainfall in the late fall-early spring. Higher elevation areas of the Bear Creek watershed, located to the north and west of the meadow, receive considerably more precipitation, which occurs as snow and rain in the late fall-early spring.

The hydrological system of the study area is complex, consisting of seasonal or intermittent surface-water inflow from the Bear Creek and Dana Creek and perennial spring discharge from the Fall River spring system (Figure 1). The latter system is fed by meteoric water, which falls on the Medicine Lake Highlands, perches on low-permeability lacustrine deposits, flows south through fractured basalt and discharges at the downstream end of the meadow (Rose *et al*., 1996). These springs form the headwaters of the Fall River and several short tributaries (i.e. Mallard Creek and Lower Dana Creek). The local groundwater system is unconfined and down-valley fluxes occur primarily through the deltaic silts, sands and gravels of the shallow subsurface.

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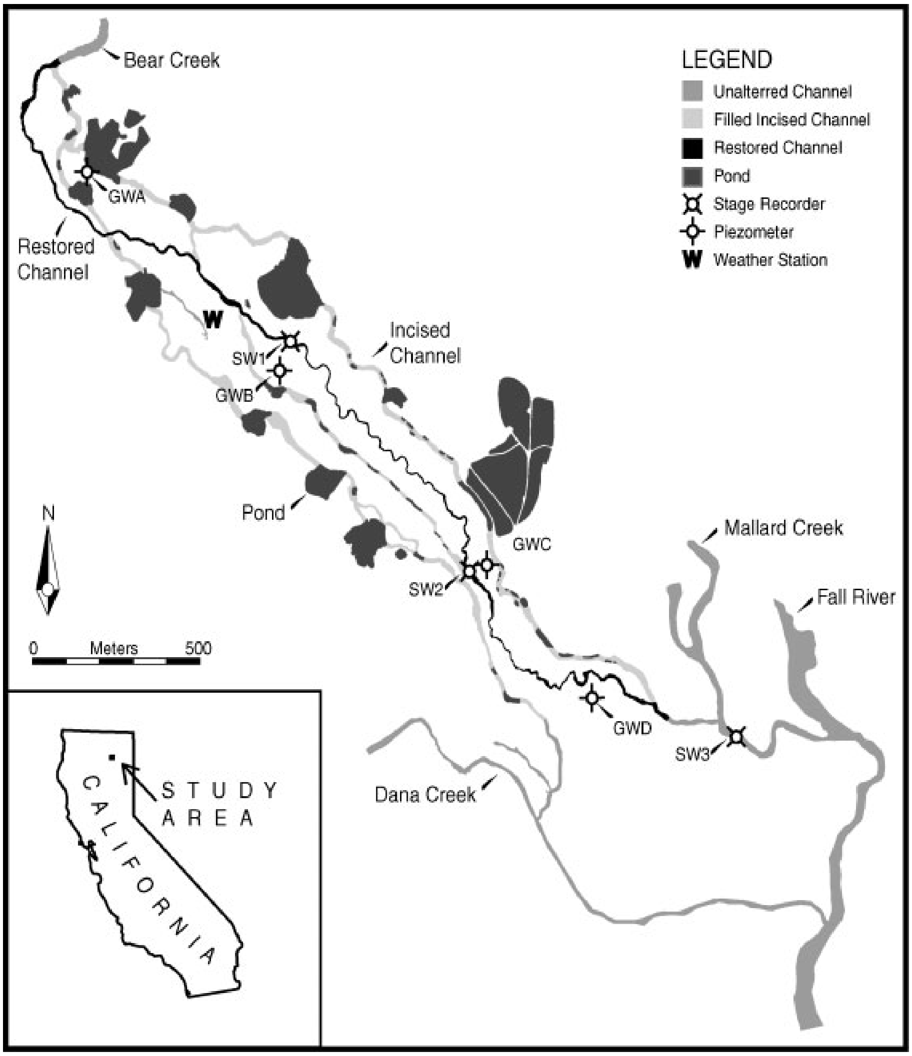

Figure 1. Bear Creek Meadow study area. Portions of the incised channels were filled with alluvium excavated from ponds throughout the meadow. A 3.6 km single thread restored channel reach was created from remnant channel segments and excavated where necessary. Flow direction is from upper left to lower right. Surface and groundwater comparison locations are also shown

Surface-water input to the meadow is supplied primarily by the intermittent Bear Creek and secondarily by the intermittent Dana Creek, which bounds the southwestern edge of the lower meadow (Figure 1). Stream discharge results from spring snowmelt, and fall, winter and spring rain events including episodic rain-on-snow events. In 7 years following the restoration in 1999 that is described below, the peak discharge in Bear Creek measured at the head of the meadow ranged from 3.11 to 20.73 $m^3 s^{-1}$ (Figure 2). Based upon a flow frequency analysis of 15 discontinuous years of annual peak discharge data available, the 2-, 5- and 10-year recurrence interval discharges are 12.7, 29.6 and 48.2 $m^3 s^{-1}$, respectively.

Anthropogenic disturbance, incision, widening and restoration

Prior to restoration, the meadow was channelized and overgrazed (Poore, 2003), resulting in degradation of both aquatic and terrestrial ecosystems of the meadow and the Fall River immediately downstream (Spencer and Ksander, 2002). After several years of pre-restoration data collection and consultation, the meadow's incised

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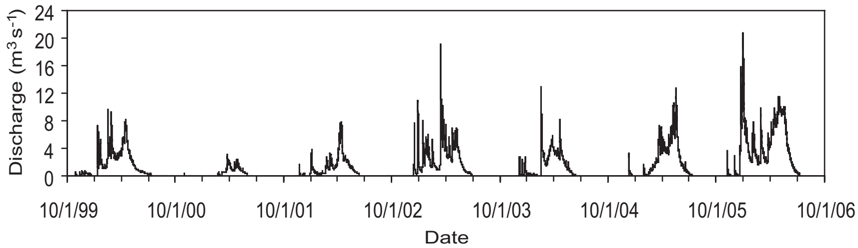

Figure 2. Bear Creek discharge at the upstream extent of the restored reach for the water years from 2000 to 2006. Annual peak discharge ranged from 3.11 to 20.73 $m^3 s^{-1}$. Stream discharge is intermittent with flood peaks resulting from rainfall, rain on snow, and spring snowmelt

channels were restored in 1999 as a joint venture between California Department of Fish and Game and the private landowner. The restoration design followed the 'Natural Channel Design Using a Geomorphic Approach' method developed by David Rosgen (Rosgen, 1996; Malakoff, 2004). A 'priority 1' approach (Rosgen, 1997), more commonly referred to as a 'pond and plug' strategy was utilized.

Following the usual 'pond and plug' method, the incised stream channels were intermittently filled with plugs of locally derived alluvial material. The remaining unfilled incised channel segments were left as ponds, and many were enlarged to provide the fill material necessary to plug portions of the incised channels. While configuring the restored channel, the existing remnant channel segments were used when possible, connected by sections of an excavated new channel. The restored channel was constructed with reduced width, depth and cross-sectional area (Figures 3 and 4, Poore, 2003). The restored channel was classified as C4 and E4 types of the Rosgen classification system (Rosgen, 1996; Poore, 2003). Upon completion, a 3.6 km single thread sinuous channel connected the bedrock controlled upstream reach to the unaltered downstream reach (Figure 1). In addition, 17 ha of new ponds (remnant gully segments and fill sources) exist throughout the meadow.

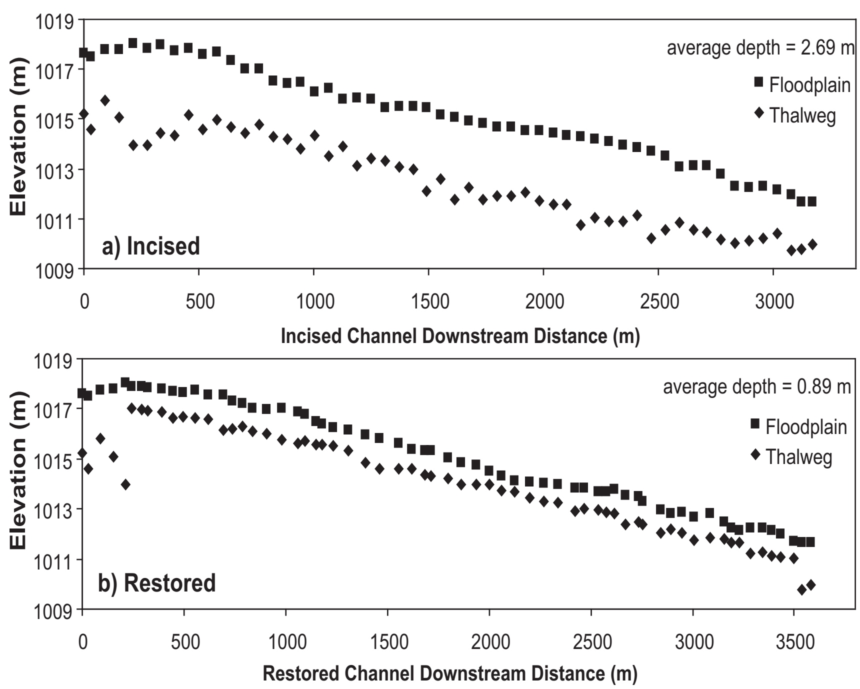

Figure 3. Long profiles of riffle crest thalweg and adjacent floodplain elevations for (a) incised and (b) restored channel geometries. The restored reach begins at restored channel station 800 m and ends at restored channel station 3535 m corresponding to incised channel station 800 and 3124 m, respectively. The first five and last two points in each of the surveys represent identical locations

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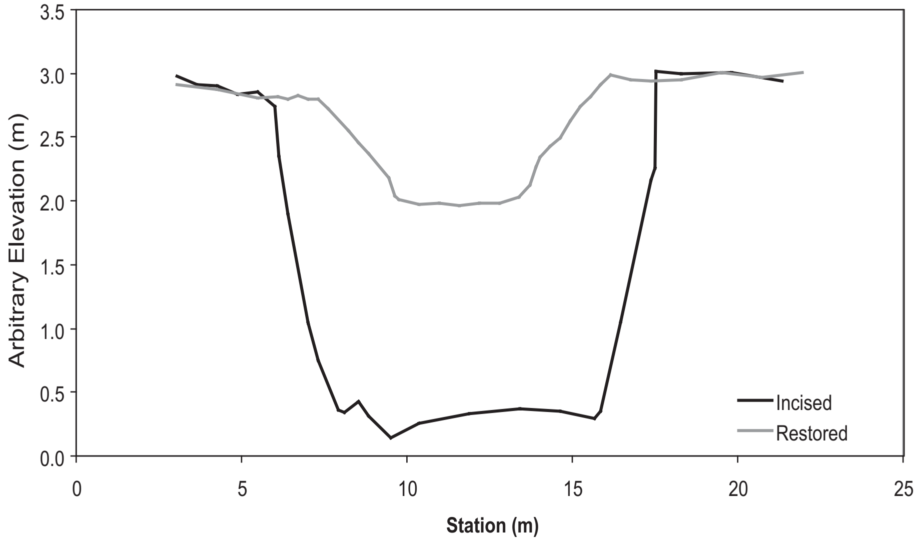

Figure 4. Representative restored and incised cross sections of the Bear Creek channel

METHODS

Model development

A numerical hydrological model was developed using the MIKE SHE modelling system (Refsgaard and Storm, 1995), which is based upon the Systeme Hydrologique Europeen (SHE) model (Abbott *et al*., 1986a, 1986b). MIKE SHE is a commercially available, deterministic, fully distributed and physically based modelling system that has been applied to a wide variety of problems where surface water and groundwater are closely linked (for examples see Jayatilaka *et al*., 1998; Thompson, 2004; Sahoo *et al*., 2006). Using a finite difference methodology, MIKE SHE solves partial differential equations describing the processes of saturated subsurface flow (three-dimensional Boussinesq equation), unsaturated subsurface flow (one-dimensional Richards' equation), channel flow (one-dimensional St. Venant equations) and overland flow (diffusion wave approximation of the two-dimensional St. Venant equations). Channel hydraulics are simulated with the one-dimensional MIKE 11 hydraulic modelling system which is dynamically coupled to the MIKE SHE modelling system. The processes of interception and evapotranspiration are handled with analytical solutions.

Separate MIKE SHE/MIKE 11 models were developed for the pre-project (i.e. incised) and post-project (i.e. restored) scenarios. Initially, a base model of the restored scenario was developed, calibrated and validated. Subsequently, the surface topography, channel size and alignments were altered to reflect the incised pre-restoration scenario. The altered surface topography and channel configuration were the only differences between the two models. All other components remained unchanged between the two models. The models were comprized of 2898 $30\,\mathrm{m} \times 30\,\mathrm{m}$ grid squares, representing a total area of 261 ha.

Grose (1996) and three well logs from within the model domain provided the conceptual model of the hydrostratigraphy. The vertical and horizontal extent of the various hydrostratigraphic units were further defined by excavating shallow boreholes with hand augers, excavating test pits with a backhoe, and conducting a three-dimensional survey of the contact of the upper two layers as observed in the restored channel and ponds. Based upon the refined conceptual model, the subsurface component of the model was composed of three layers with the lower layer a sandy clay, the middle layer a high-permeability alluvial sand and gravel mixture and the upper layer an alluvial silty–clayey loam.

Slug tests were conducted at three piezometers and analysed using the Bouwer and Rice (1976) method. The arithmetic mean for six slug tests performed in the upper silty–clayey loam was $9.3 \times 10^{-7}\,\mathrm{m\,s^{-1}}$ with values ranging from 6.3×10^{-6} to $1.5 \times 10^{-8}\,\mathrm{m\,s^{-1}}$. The arithmetic mean for five slug tests performed in the sand and

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gravel layer was 4.5×10^{-2} m s^{-1} with values ranging from 1.5×10^{-2} to 9.0×10^{-2} m s^{-1}. These values all lie within values found in the literature for units with similar textural descriptions (Masch and Denny, 1966; Adams and Gelhar, 1992; Martin and Frind, 1998; Woesner *et al.*, 2001; Loheide and Gorelick, 2007). No slug tests were conducted in the lower sandy clay unit, instead a value of 1.0×10^{-9} m s^{-1} was taken from the literature (Freeze and Cherry, 1979; Martin and Frind, 1998). These values for saturated hydraulic conductivity were used as a starting point in the model development, and were subsequently varied during model calibration.

Surface topography was obtained from previous surveys of pre- and post-restoration scenarios. Two digital elevation models (DEMs) were developed, one representing the incised scenario and one representing the restored scenario. The one representing the restored scenario was updated in 2004 with an additional topographic survey. The DEMs were sampled on a 30 m grid to provide surface elevations to the model. Two MIKE 11 models were developed to reflect the altered channel configuration due to restoration. Channel alignments and cross sections were extracted for each MIKE 11 model from the pre- and post-restoration DEMs (Figure 5).

Vegetation inputs included the spatial extent of various vegetation types, in addition to leaf area index (LAI) and root depth (RD) of each prescribed vegetation type. Three vegetation types were employed in the model: ash forest, pine forest and grassland (Figure 6). The distribution of each vegetation type was determined through a combination of field reconnaissance and aerial photo interpretation. The ash forest was assigned a variable LAI with a maximum of 5 and a constant RD of 1.83 m. The pine forest was assigned a constant LAI of 5 and RD of 3.05 m (Misson *et al.*, 2005). The grassland was assigned a variable LAI with a maximum value of 2.5 (Xu and Baldocchi, 2004) and a variable RD with a maximum of 0.45 m (Wu, 1985; Weixelman *et al.*, 1996). Unsaturated soil conductivity and moisture retention properties were adopted from Loheide and Gorelick (2007). Meteorological data were collected at 15 min intervals from a data logging weather station (HOBO weather station, Onset Computer Corporation) deployed within the meadow (Figure 1). Reference evapotranspiration was computed using these meteorological data and the FAO Penman–Montieth combination equation (Allen *et al.*, 1998).

Additional input parameters included the leakage coefficient, which governs river-aquifer exchange, and channel and overland flow roughness coefficients (i.e. Manning's *n*). River-aquifer exchange was simulated using the reduced contact (b) method with an initial value of 1.0×10^{-5} s^{-1} adopted from the literature (Thompson *et al.*, 2004). Manning's *n* for channel flow was estimated to be 0.033 s m$^{-1/3}$ based upon values found in the literature for similar channel conditions (Chow, 1959; Barnes, 1967; Coon, 1998). An initial floodplain Manning's roughness value of 0.5 s m$^{-1/3}$ was adopted from the literature (Thompson *et al.*, 2004). Each of these values was subsequently altered during model calibration.

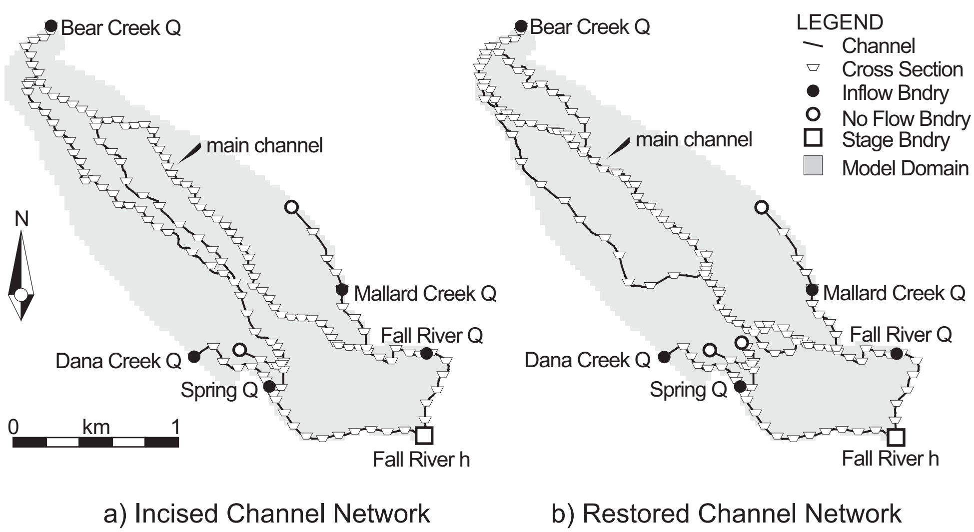

Figure 5. Channel alignment, cross section locations, and surface water boundary condition type and locations for the (a) incised and (b) restored channel flow components of the two models

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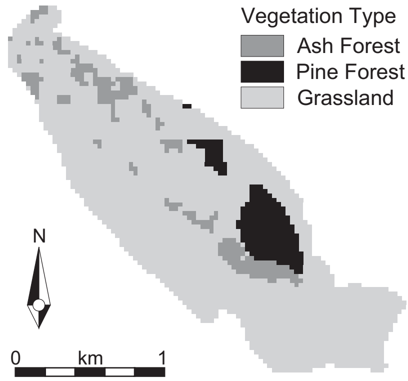

Figure 6. Spatial distribution of the three vegetation types employed in the model

Boundary conditions

The subsurface domain boundaries consisted of a combination of no-flow and specified-flux subsurface external boundary conditions and one internal specified-head boundary condition (Figure 7). Pre- and post-restoration observation data from 28 piezometers arranged along four transects were used to define the subsurface external boundary conditions. No-flow boundaries were on the upper portion of the meadow and along the southwestern border of the meadow. A short specified-flow boundary was along the northeastern border where subsurface irrigation runoff from an irrigated pasture discharges to the meadow. A flux of $2 \times 10^{-2}\,m^3\,s^{-1}$ was applied during the June–September irrigation season with zero flow applied to the remaining portion of the year. The spring-fed, perennial streams Mallard Creek, Lower Dana Creek and Fall River bound the downstream portion of the model domain (Figures 1 and 5). While no-flow boundaries were used in the subsurface, these surface channels were linked to the subsurface, essentially acting as specified-head boundaries. The advantage to this approach was that while a constant inflow to these surface channels was specified, stream stages were calculated by the model and differed between the incised and restored scenario runs. The specified head internal boundary was used for an area that received subsurface spring discharge. Water levels in this area were not affected by the stream restoration, and a geochemical analysis of groundwater in this area indicated that the groundwater is similar to nearby springs and dissimilar to Bear Creek surface water (Hammersmark, unpublished data). The low-permeability lacustrine clay underlying the meadow justified the use of a no-flow boundary along the bottom of the model domain.

The surface domain boundaries for each MIKE 11 model were developed from flow records from Bear Creek inflow, Mallard Creek inflow, Fall River inflow, Dana Creek inflow, Dana spring inflow to Lower Dana Creek and Fall River stage at the downstream extent of the model domain (Figure 5). Data logging pressure transducers

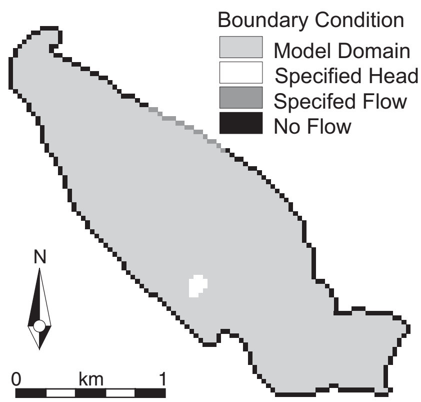

Figure 7. Domain and subsurface boundary conditions for the hydrological model. Subsurface boundary types include no flow, specified flow and specified head

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(Solinst LT 3001 Leveloggers) were installed in spring 2004 to provide stage hydrographs at each location. At the five inflow locations, over a wide range of flow levels, discharge was measured using standard velocity-area methods (Harrelson *et al*., 1994), with water velocity measurements collected with a flowmeter (Marsh-McBirney Flo-Mate). Flow measurements and corresponding stage levels were used to create rating curves/tables for each inflow location to allow the conversion of the stage hydrographs to discharge hydrographs. Several additional no-flow boundaries were employed at minor channels' heads, which did not experience surface inflow but nevertheless played important roles in regulating the elevation of the water table.

Model calibration and validation

Model calibration parameters included hydraulic conductivity, the leakage coefficient, and channel and overland roughness coefficients. Uniform values for each of the parameters were used. The calibration consisted of individual parameter manipulation and subsequent model performance evaluation. Only the post-restoration model was calibrated and validated because water table and stream flow data of sufficient temporal resolution were not available for the pre-restoration period.

The 2005 water year (i.e. 1 October 2004 to 30 September 2005) was used for model calibration. Values of saturated hydraulic conductivity, the leakage coefficient and channel roughness were varied during the calibration process, but the best fit was achieved with the initial value estimates, which all fall within reasonable ranges of values found in relevant literature. The value of overland roughness was decreased from 0.5 to 0.1 s $m^{-1/3}$. This final value resulted in improved channel stage agreement and more closely resembles values for floodplains found in the literature (Chow, 1959).

The 2006 water year (i.e. 1 October 2005 to 30 September 2006) was used for model validation. Model performance evaluation during both calibration and validation was based upon a combination of graphical assessment and statistical methods. The Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe, 1970; McCuen *et al*., 2006) was employed to statistically judge the performance of the model simulation as compared to observed data. The Nash-Sutcliffe efficiency coefficient is widely used when evaluating the statistical goodness-of-fit of model simulations, however time-offset bias and bias in magnitude have been observed (McCuen *et al*., 2006). In addition to the Nash-Sutcliffe efficiency coefficient, the correlation coefficient and the mean error for each comparison location were calculated and evaluated. Modelled and observed hydraulic heads were compared at 28 shallow piezometers, and modelled and observed stages were compared at two locations on Bear Creek within the meadow and one location on Bear Creek below the meadow.

Model application

Once model development, calibration and validation were completed, the two models were used to simulate an identical 2-year time period (i.e. 1 October 2004 to 30 September 2006). The only differences between the two models were the altered channel configuration (alignment and size), the topography of the meadow surface (ponds vs. no ponds) and the initial water table elevation. Starting both model simulations with the same potentiometric surface was unrealistic because the incised scenario could not possibly support the same elevated water table elevations that occur in the restored scenario at the beginning of the water year. To address this issue, both models were first run with initial hydraulic heads determined by interpolating hydraulic head data collected in early October 2004. Each scenario model was then run for the 2005 water year. Water table elevations from the end of this run were then utilized as initial conditions for the comparison model simulations described below.

RESULTS

Model calibration and validation

The hydrological model of the restored scenario successfully simulates observed conditions (Figures 8 and 9). Nash-Sutcliffe efficiency coefficients are all greater than 0.90, correlation coefficients are all greater than 0.95 and mean error values are all less than ± 0.05 m (Table I).

The agreement between modelled and observed hydraulic heads was particularly strong during the winter, spring and summer, when Bear Creek was flowing. The agreement between modelled and observed hydraulic heads was

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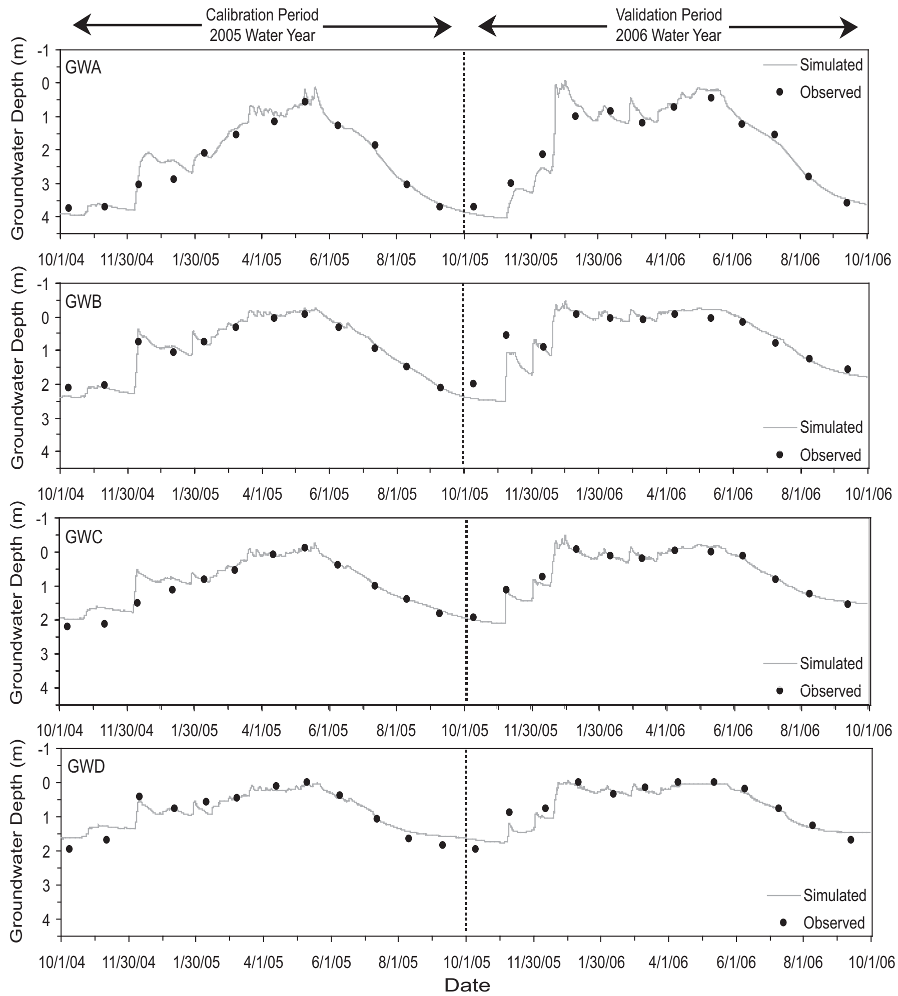

Figure 8. Comparison of simulated and observed groundwater depth at four piezometer locations within the meadow. The 2005 water year (left side) was used for model calibration and the 2006 water year (right side) was used for model validation. Negative groundwater depths indicate surface inundation that is common in the restored meadow. Piezometer locations are shown on Figure 1

less strong during late fall, prior to the initiation of flow in Bear Creek, and as initial surface flow began to recharge the subsurface.

The agreement between modelled and observed stage was strong throughout the simulation. However, modelled values were variously higher or lower than observed values during many overbank flow events when flows are largely controlled by floodplain topographic features that are below the resolution of the 30 m grid DEM. Furthermore, modelled stage values were lower than observed values during baseflow conditions downstream of the meadow when Bear Creek ceased to flow in the meadow but continued to flow below the meadow due to discharge from spring-fed Mallard Creek.

Model application—incised and restored scenario comparison

Groundwater. Groundwater levels were higher in the restored scenario (Figures 10 and 11). Restoration had the smallest hydrological effect during the summer and fall when Bear Creek ceased to flow and groundwater levels were lowest, and the largest effect during the winter and spring when Bear Creek was flowing and groundwater levels were highest. Winter and spring meadow average groundwater levels were increased by 0.72 and 1.20 m,

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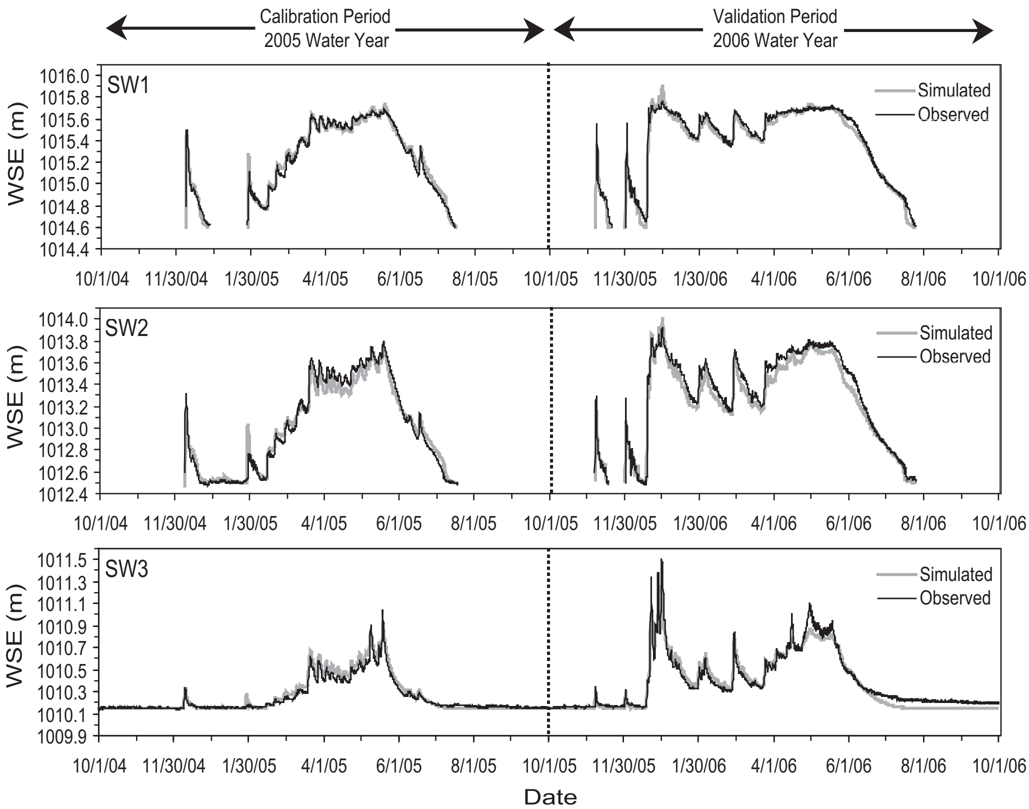

Figure 9. Comparison of simulated and observed water surface elevations (WSE) at three locations along Bear Creek. The 2005 water year (left side) was used for model calibration and the 2006 water year (right side) was used for model validation. At the upper two locations (SW1 and SW2) Bear Creek is intermittent, however at the third location (SW3) Bear Creek is perennial due to its confluence with Mallard Creek, a perennial spring channel. Locations of SW1, SW2 and SW3 are shown on Figure 1

respectively, above incised levels. Smaller seasonal differences occurred in summer and fall when restored average groundwater levels for the entire meadow were 0.34 and 0.06 m higher, respectively. Restoration had the smallest effect in the lower meadow, where inflows from springs maintained relatively stable groundwater levels throughout the year, and the largest effect in the upper and middle meadow where inflows from the springs were absent and groundwater levels were therefore more related to intermittent stream flows. Restoration increased the range of

Table I. Nash-Sutcliffe efficiency coefficient, correlation coefficient and mean error statistics for the 2-year model simulations at four subsurface and three surface comparison locations

Location	Nash-Sutcliffe	Correlation coefficient	Mean error (m)
Groundwater comparisons			
GWA	0.95	0.98	−0.01
GWB	0.93	0.98	0.02
GWC	0.90	0.95	−0.05
GWD	0.91	0.97	0.04
Surface water comparisons			
SW1	0.98	0.99	0.01
SW2	0.97	0.99	0.03
SW3	0.93	0.97	0.02

Subsurface locations compare simulated and observed groundwater depths as shown in Figure 8. Surface locations compare simulated and observed water surface elevations as shown in Figure 9.

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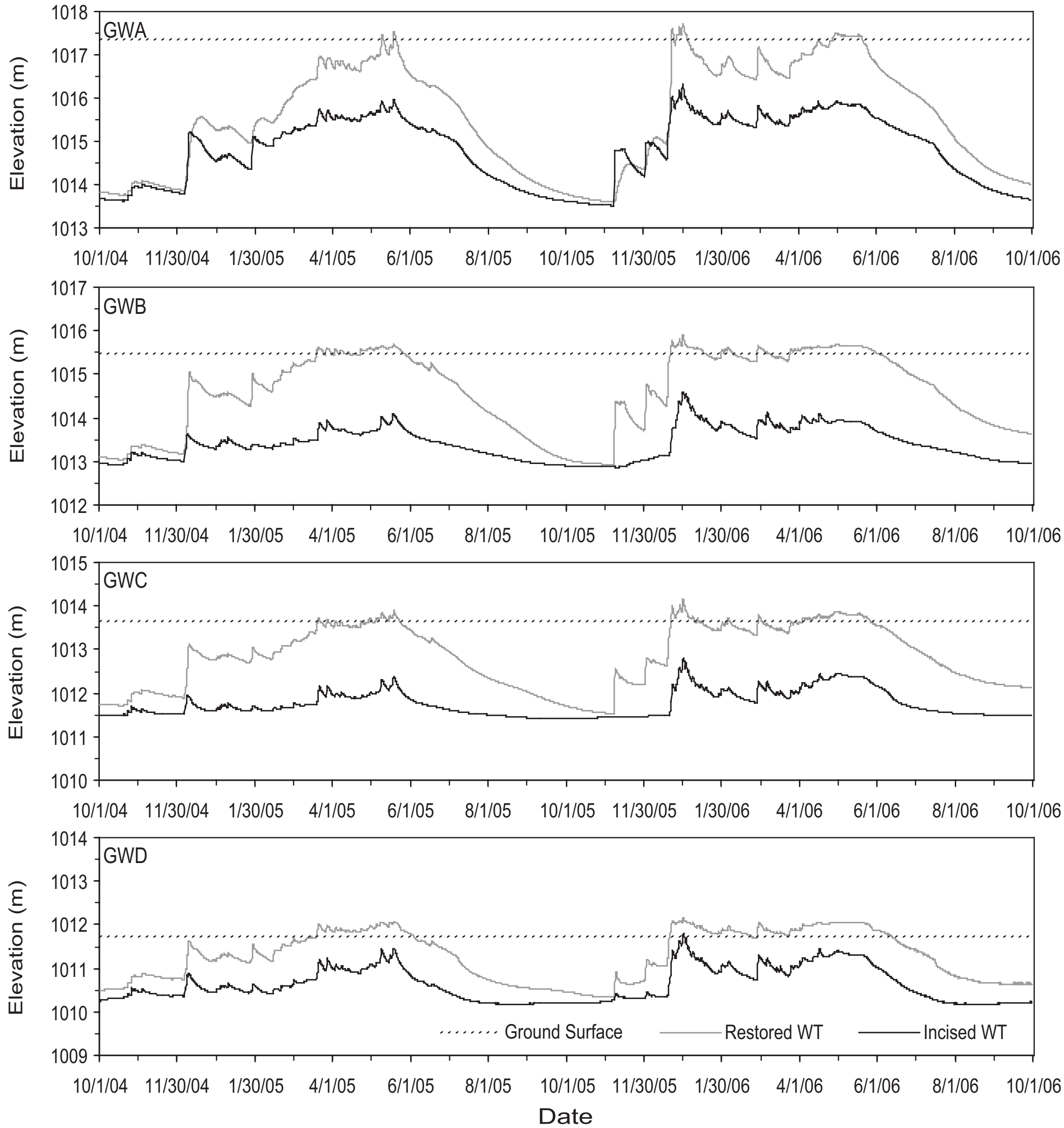

Figure 10. Comparison of water table elevations for the restored and incised scenarios at four locations within the meadow. The largest water table elevation differences are seen in the winter and spring, corresponding to surface flow in Bear Creek. In the restored condition, the elevation of the water table is above the ground surface for extended periods at each location. Comparison locations coincide with the locations of piezometers shown on Figure 1

water table fluctuations throughout the meadow. Groundwater levels were at or above the ground surface at least once during the simulation at 3.8 and 76.7% of the model grid squares in the incised and restored scenarios, respectively.

Maximum groundwater storage and residual groundwater storage was greater in the restored scenario (Figure 12). Maximum groundwater storage was 10.11×10^5 and $12.11 \times 10^5\,m^3$ for the incised and restored scenarios, respectively. Residual groundwater storage (i.e. the groundwater storage that remained at the end of the 2006 water year) was 5.83×10^3 and $3.48 \times 10^5\,m^3$ for the incised and restored scenarios, respectively. Groundwater residence time was greater in the restored scenario. In the incised scenario, the centre of mass of

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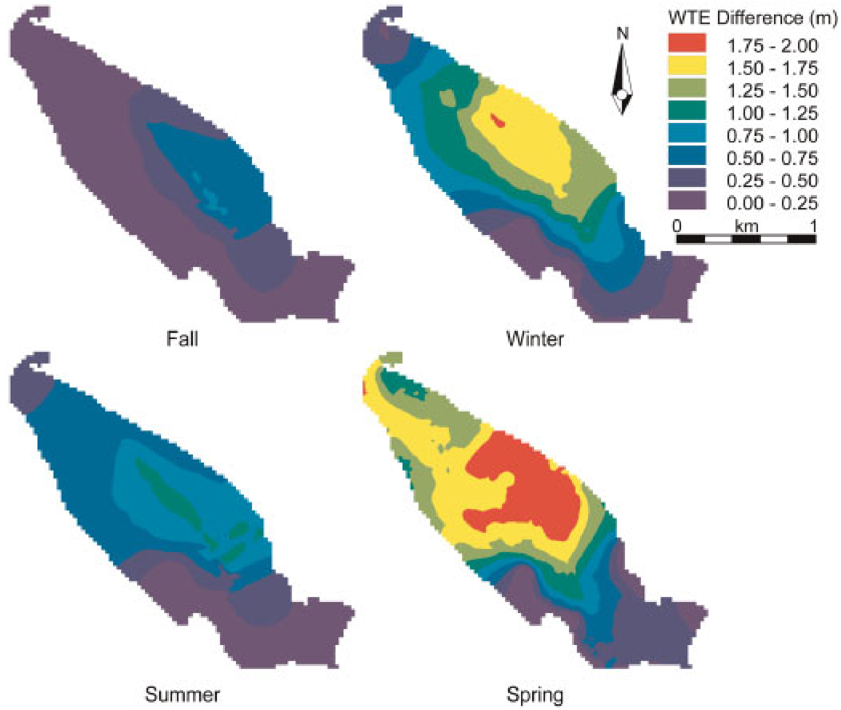

Figure 11. Seasonal water table elevation (WTE) differences between the 2005 water year incised and restored simulations. Clockwise from top left: mid-fall (15 October 2004), mid-winter (14 February 2005), mid-spring (16 May 2005) and mid-summer (15 August 2005). Positive difference indicates the restored water table is higher than the incised water table. Spatial patterns in water table elevation differences are complex due to differing channel alignments, pond locations, subsurface and surface water inputs. This figure is available in colour online at www.interscience.wiley.com/journal/rra

the annual groundwater storage occurred on 14 March 2006, while in the restored scenario, the centre of mass of the annual groundwater storage occurred 16 days later on 30 March 2006.

Surface water. Overbank flows were more frequent in the restored scenario (Figure 13). The average channel capacity was 61.7 and 5.35 $m^3 s^{-1}$ in the incised and restored scenarios, respectively. While average channel capacity values are useful for communication purposes, minimum channel capacity values exert a larger influence upon the frequency and duration of flooding. The capacity of the restored channel varied between 1.2 and 9.7 $m^3 s^{-1}$. In the restored scenario, local floodplain inundation occurred when stream discharge exceeded the minimum channel capacity, and widespread floodplain inundation occurred when discharge surpassed the average channel capacity. The minimum capacity of the incised channel was 28.0 $m^3 s^{-1}$, thus floodplain inundation due to overbank flooding did not occur in the incised scenario. Floodplain inundation also occurred when groundwater levels rose above the ground surface. Annual surface water storage on the floodplain increased in the restored scenario (Figure 12). Maximum surface water storage on the floodplain was 0.27×10^5 and 6.47×10^5 m^3 for the incised and restored scenarios, respectively.

Floodplain storage was positively correlated with surface water inflow to the meadow in the restored scenario (Figure 14). Due to this floodplain storage, flood peak discharges were attenuated in the restored scenario (Figure 15). Within the restored reach, flood peak stages were increased, but downstream of the reach flood peak stages were reduced. Instantaneous inflow and outflow were essentially equal in the incised scenario, indicating that floodwaters remained within the channel in the incised scenario. Conversely, instantaneous inflow exceeded instantaneous outflow in the restored scenario, indicating that floodwaters flowed overbank onto the floodplain in the restored scenario. The effects of restoration were most apparent when discharge exceeded the 5.35 $m^3 s^{-1}$ average channel capacity. Subsequent flood peak reductions ranged from 12.6 to 25.0% of the upstream peak value with the largest reductions of 23.3, 25.0 and 24.4% for largest magnitude flood peaks of 15.71, 17.25 and

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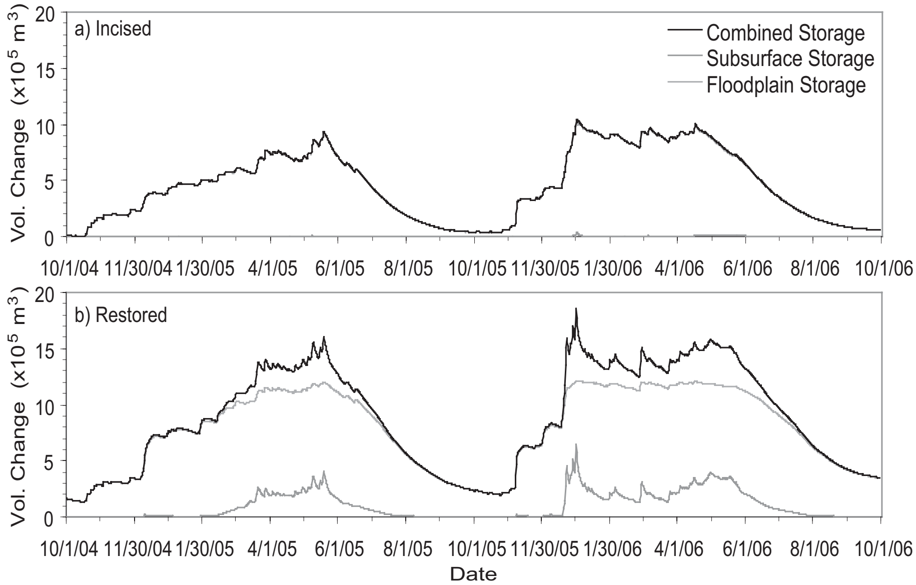

Figure 12. Storage volume change for subsurface storage, floodplain storage and combined (subsurface & floodplain) storage for (a) incised and (b) restored scenarios. The restored scenario stores a larger volume in each of the three categories with a maximum combined storage of 10.45×10^5 and $18.52 \times 10^5\,m^3$ for the incised and restored scenarios, respectively. Due to negligible amounts of water stored on the surface in the incised scenario, the combined storage time series plots nearly on top of the subsurface storage time series. For ease of comparison, stored volume is set equal to $0\,m^3$ for the beginning of the 2005 water year (i.e. 1 October 2004) in the incised scenario

$20.67\,m^3\,s^{-1}$, respectively. Most of the overbank water was stored temporarily and returned to the channel at downstream locations, while some of the overbank water infiltrated and/or evapotranspired.

Within the restored reach, baseflow duration was shorter in the restored scenario (Figure 13). When compared at the longitudinal midpoint of the meadow, baseflow ceased 16 days earlier in the restored scenario in each of the years simulated. Increased baseflow levels occurred downstream of the restored reach.

Total annual runoff was higher in the incised scenario. During the 2005 water year, total annual runoff was 4.11×10^7 and $4.05 \times 10^7\,m^3$ for the incised and restored scenarios, respectively. Therefore, total annual runoff was $6.60 \times 10^5\,m^3$ (i.e. 1.6%) higher in the incised scenario. During the 2006 water year, total annual runoff was 9.09×10^7 and $8.99 \times 10^7\,m^3$ for the incised and restored scenarios, respectively. Therefore, total annual runoff was 9.38×10^5 (i.e. 1.0%) higher in the incised scenario.

Evapotranspiration. ET was higher in the restored scenario (Figure 16). Daily ET rates were very similar in both scenarios until mid-April. After this point, daily ET rates declined in the incised scenario, but continued to increase in the restored scenario. During the 2005 water year, the peak daily ET rate of $6.5\,mm\,d^{-1}$ occurred on 22 May 2005 in the incised scenario, while the peak daily ET rate of $7.0\,mm\,d^{-1}$ occurred 41 days later on 2 July 2005 in the restored scenario. During the 2006 water year, the peak daily ET rate of $5.5\,mm\,d^{-1}$ occurred on 2 May 2006 in the incised scenario, while the peak daily ET rate of $6.9\,mm\,d^{-1}$ occurred 56 days later on 27 June 2006 in the restored scenario. The maximum difference of $3.6\,mm\,d^{-1}$ occurred on 11 July 2006. During the 2005 water year, total annual ET was 1.22×10^6 and $1.52 \times 10^6\,m^3$ for the incised and restored scenarios, respectively. During the 2006 water year, total annual ET was 9.63×10^5 and $1.44 \times 10^6\,m^3$ for the incised and restored scenarios, respectively. Therefore, total annual ET was 25 and 50% greater in the restored scenario for the 2005 and 2006 water years, respectively.

SUMMARY AND DISCUSSION

This analysis of the Bear Creek Meadow restoration project indicates that plugging of the incised channels and construction of a shallow, sinuous, single-thread channel initiated at least three significant hydrological responses that are likely to have important ecological effects (Table II). These include: (1) increased groundwater levels and

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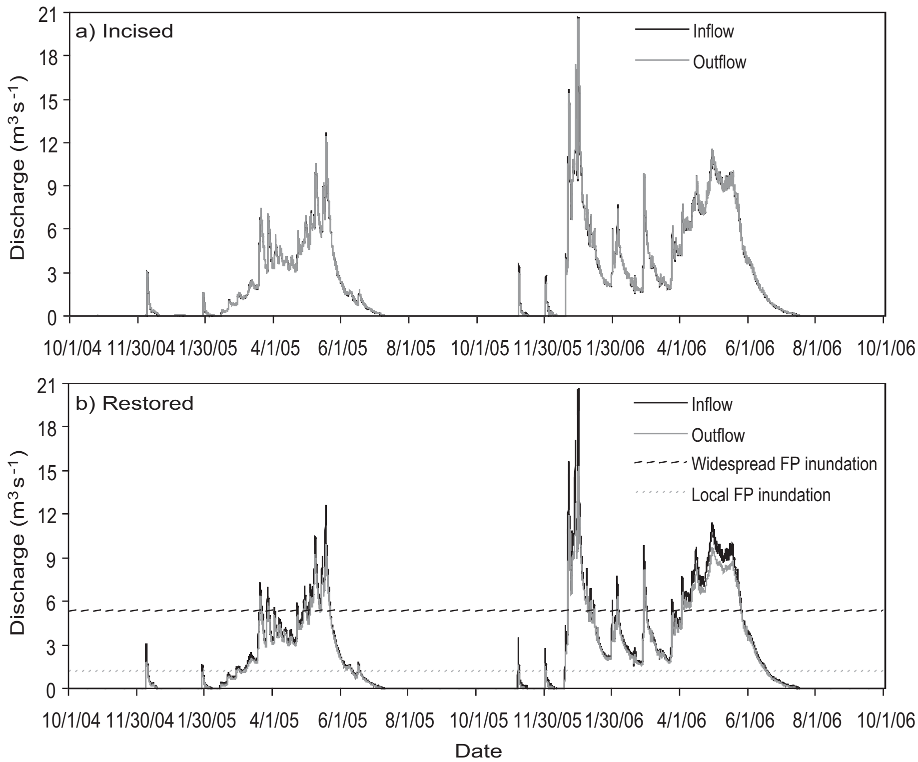

Figure 13. Time series of surface inflow and outflow for the (a) incised and (b) restored scenarios. Channel-floodplain exchange did not occur in the incised scenario, but occurred frequently and for extended periods in the restored scenario. Incised outflow was nearly identical to inflow, however restored outflow was lower than inflow. For the restored scenario, two floodplain inundation thresholds are shown. The dotted line corresponds to the minimum restored channel capacity (1.2 m^3 s^{-1}), above which local floodplain inundation occurred. The dashed line corresponds to the average capacity of the restored channel (5.35 m^3 s^{-1}) above which widespread floodplain inundation occurred. Minimum bankfull capacity of the incised channel was 28.0 m^3 s^{-1}, therefore floodplain inundation did not occur in the incised scenario

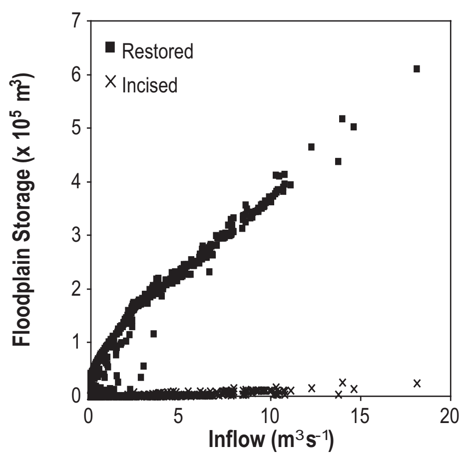

Figure 14. Average daily inflow versus average daily floodplain storage for the incised and restored scenarios. As inflow increased the volume of water stored on the floodplain increased. A much larger volume of water is stored on the restored floodplain, due to enhanced channel floodplain connectivity resulting from the lower capacity restored channel

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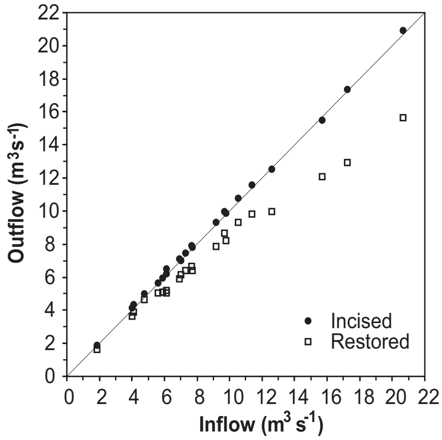

Figure 15. Comparison of flood peak inflow/outflow values for incised and restored conditions. Little change is observed between inflow and outflow values for the incised condition. Flows below ~4 $m^3 s^{-1}$ are mostly contained within the restored channel, and only minor reductions are observed due to subsurface recharge. However, for the largest peaks (i.e. >15 $m^3 s^{-1}$) a 25% reduction of the inflow peak is observed

volume of subsurface storage; (2) increased frequency of floodplain inundation and decreased magnitude of flood peaks and (3) decreased baseflow and annual runoff.

Increased groundwater levels and volume of subsurface storage

Stream channelization and subsequent incision lower water tables (Choate, 1972; Schilling *et al*., 2004) resulting in altered riparian vegetation patterns and species composition (Jewitt *et al*., 2004; Loheide and Gorelick, 2007). Consequently, a commonly stated objective of many 'pond and plug' type stream restoration projects is to raise groundwater levels in order to improve the health of riparian vegetation (Benoit and Wilcox, 1997; Rosgen, 1997; Doll *et al*., 2003; Poore, 2003). Based upon simulations, we demonstrate significant increases in groundwater levels and subsurface storage, which occurred largely in response to the raised channel bed. In the incised scenario, the channel bed was well below the meadow surface, acting as a deep linear sink that efficiently drained the subsurface of the meadow. In the restored scenario, the channel bed was raised, the deep linear sink was removed (i.e. plugged) and groundwater levels were raised (e.g. average increase during spring of 1.2 m), in some cases up to and above the meadow surface. Consequently, subsurface storage was consistently greater in the restored scenario.

The increased water table elevations simulated in this study are consistent with the one-dimensional groundwater modelling simulations of Schilling *et al*. (2004), and the three-dimensional groundwater modelling simulations of

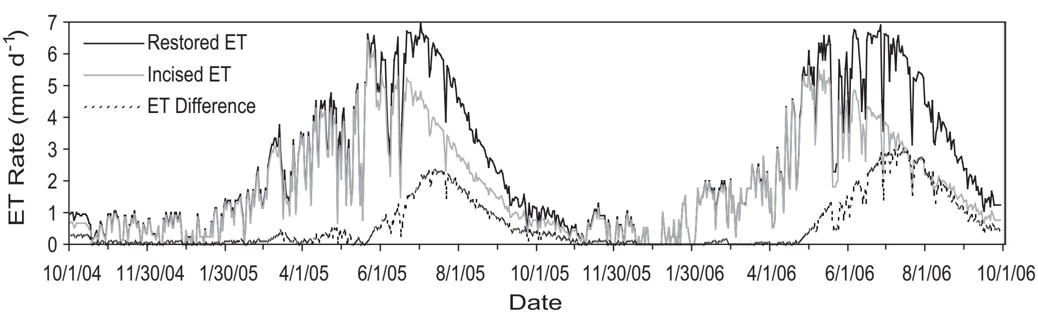

Figure 16. Daily evapotranspiration rates for the restored and incised scenarios. The difference between these two values is also provided. Daily ET rates were similar in both scenarios until mid-April of each year. After this point, daily ET rates declined in the incised scenario, but continued to increase in the restored scenario. Peak daily ET rates occurred 41 days and 56 days later for the restored scenario in the 2005 and 2006 water years, respectively. The maximum difference of 3.6 mm d^{-1} occurred on 11 July 2006

DOI: 10.1002/rra

Table II. Hydrological effects and their causes due to pond and plug stream restoration

Hydrological effect	Cause
(a) Raised groundwater levels	Raised channel bed no longer acted as a deep line sink
(b) Increased subsurface storage	Raised channel bed no longer acted as a deep line sink
(c) Increased frequency of floodplain inundation	Channel capacity reduced, reconnecting channel and floodplain at lower flow levels
(d) Decreased magnitude of flood peaks	Water transferred from channel to floodplain, and temporarily stored
(e) Increased surface storage	Increased channel-floodplain exchange and increased surface storage in ponds
(f) Decreased duration of baseflow	Raised channel bed no longer drains groundwater after surface water inflow terminates
(g) Decreased total annual runoff	Increased subsurface storage and ET
(h) Increased evapotranspiration	Elevated groundwater levels available to root zone and increased evaporation from ponds

Loheide and Gorelick (2007). However, these previous studies focused on groundwater alone (i.e. floodplain flow was not simulated), in hypothetical situations with perennial stream flow. Conversely, this study simulated actual conditions where substantial overland flow and intermittent stream flow occurred, creating a more complex hydrological response. In addition, the results of this study support the findings of Bradley (2002), who showed that spatial and temporal trends in groundwater levels are closely linked to the stages of adjacent river channels.

Increased frequency of floodplain inundation and decreased magnitude of flood peaks

The natural flow regime has been identified as the key determinant in the ecology of river and riparian systems (Poff *et al*., 1997). In addition, multidimensional connectivity (Vannote *et al*., 1980; Junk *et al*., 1986; Ward and Stanford, 1995; Tockner *et al*., 2000) and the resulting variable levels of natural disturbance determine successional patterns and habitat heterogeneity in floodplain river systems. Lateral connectivity, in particular is responsible for the transfer of water, sediment, nutrients and organic matter between river channels and their adjacent floodplains (Tockner *et al*., 1999). In this study, simulations demonstrate a significant increase in the hydrological connectivity of Bear Creek to its floodplain due to stream restoration. The changes in frequency, duration and magnitude of floodplain inundation, along with declines in the magnitude of peak flood flows exiting the meadow appear to be a response to the decreased channel capacity. The average channel capacity of the incised channel was more than 11 times the average capacity of the restored channel (i.e. $61.7\,m^3\,s^{-1}$ vs. $5.35\,m^3\,s^{-1}$). For the 2 years simulated here, overbank flooding did not occur in the incised scenario. Conversely, overbank flooding was frequent and of long duration in the restored scenario, with 13 widespread flooding events (defined as when flows reached sufficient magnitude to exceed the average channel capacity of $5.35\,m^3\,s^{-1}$) for a total duration of 106 days (i.e. 27% of time the stream was flowing) of overbank flooding. This is the most dramatic change in the hydrology of the meadow. These simulation results are consistent with the qualitative observations of local landowners, who recall extremely rare floodplain inundation in the pre-restored condition (i.e. only during 100+ year return interval events), and frequent and long-duration floodplain inundation in the post-restored condition. Increased inundation frequency due to channel restoration is consistent with the findings of Helfield *et al*. (2007).

Floodwater storage on the floodplain acted to attenuate flood peaks at the base of the meadow. The peak discharge values for the largest events simulated, which lie between 2- and 5-year return interval flow values, were reduced by up to 25%. Even greater flood-peak reduction is expected for larger flood pulses than those simulated here. However, the magnitude of flood-peak reductions is capped by floodplain accommodation space. Therefore, flood-peak reductions for very large floods are likely to be less dramatic for lower-frequency, higher-magnitude flood flows. Flood peak attenuation coincident with wetland restoration is consistent with the results of other studies where off-channel areas were hypothetically reconnected to adjacent river channels (Hey and Philippi, 1995; Hammersmark *et al*., 2005).

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Decreases in baseflow and annual runoff

There is a general perception that stream restoration will improve all hydrological components of a river-riparian system, resulting in improved conditions for all native plant and animal communities. In the meadow restoration simulated here, anticipated improvements in aquatic habitat associated with increases in baseflow did not occur. The decline in channel capacity and the raising of the channel bed decreased the total amount of runoff by 1–2% and shortened the duration of baseflow by 2 weeks, extending the period of flow disconnection in the meadow.

The decline in baseflow is largely in response to the raised channel bed and the related changes in evapotranspiration and groundwater flow paths. Increases in ET were responsible for roughly half of the decreases in total annual runoff. In the incised scenario, much of the groundwater flowed laterally across the valley, discharged to the incised channel and flowed out of the meadow as stream flow. In the restored scenario, groundwater flowed down the valley, in some cases discharging to the meadow surface and flowed out of the meadow as either shallow groundwater or overland flow. Therefore, some water that flowed out of the meadow as stream flow in the incised scenario instead left the meadow as evapotranspiration or groundwater discharge in the restored scenario.

The increased ET occurred largely in response to both the raised channel bed and the decreased channel capacity and the related increased groundwater levels, increased the frequency of floodplain inundation and increased surface storage. In the restored scenario, groundwater levels were higher, providing water to the root zone over a greater area and for longer duration. Furthermore, in the restored scenario, surface water—both the overbank flows and floodplain ponds—covered a greater area and for a longer duration. These results are consistent with the findings of Loheide and Gorelick (2005) who measured ET rates in degraded and pond and plug restored meadows in northern California.

CONCLUSION

Hydrology is the primary driver of the establishment and persistence of wetlands (Mitsch and Gosselink, 2000). Natural flow regimes (Poff *et al*., 1997) and multidimensional connectivity (Ward and Stanford, 1995; Stanford *et al*., 1996) have been identified as key determinants in the ecology of river-riparian systems. Moreover, hydrology is so crucial that a National Research Council report on the management of riparian areas states that 'repairing the hydrology of the system is the most important element of riparian restoration' (National Research Council, 2002). The restoration of the meadow channel studied here resulted in the restoration of shallow groundwater levels. The project also resulted in the restoration of the natural flow regime and channel-floodplain connectivity, primarily reflected in the increased frequency and duration of floodplain inundation. These changes to the physical attributes of the system are having and will continue to have profound effects upon the ecology of the meadow (Hammersmark *et al*., in preparation).

While this work focuses on the hydrological effects of a particular 'pond and plug' restoration project, the results should be utilized towards improved goal setting, restoration design and performance monitoring in similar degraded environments. The methods utilized in this study provide an essential tool for monitoring and assessing the performance of restoration efforts. Considerable complexity and uncertainty exist in the emerging multidisciplinary science of river restoration (Wohl *et al*., 2005). This approach to evaluating the hydrological response of a restored meadow provides an improved understanding of the magnitude of change and the causes of those changes, supplying a learning tool to improve the science of river restoration. Lessons learned in this study should be used in support of similar methods in appropriate environments, and towards setting realistic and quantifiable objectives for similar projects (see Reference Klein *et al*., 2007 for example).

ACKNOWLEDGEMENTS

Funding for this research was provided by grants from the University of California—Center for Water Resources (grant number WR995), USDA US Geologic Survey (grant number 06HQGR0074) and the David and Lucile Packard Foundation (grant number 2001–16376). Additional support was provided by the University of California—John Muir Institute of the Environment—Environmental Fellows Program, the Cantara Trust, and the Peter and Nora Stent

DOI: 10.1002/rra

Fund at the Peninsula Community Foundation. DHI Water and Environment provided the MIKE SHE software and technical advice as needed. We thank those who contributed to the extensive field data collection including: Rick Poore, Eric Booth, Evan Buckland, Nathan Gilligan, Shane Gilligan, Jim Gilligan, David Grauer and Lucinda Macy. We also thank two anonymous reviewers for their constructive comments and suggestions, which improved this paper. Lastly, we thank Nora and Peter Stent, whose support and encouragement were invaluable.

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