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Riparian hydroecology: A coupled model of the observed interactions between groundwater flow and meadow vegetation patterning

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[1] Stream incision is altering the hydroecology of riparian areas worldwide. In the Last Chance watershed in the northern Sierra Nevada, California, logging, overgrazing, and road/railroad construction have caused stream incision, which resulted in drainage of riparian meadow sediments and a succession from native wet meadow vegetation to sagebrush and dryland grasses. Restoration efforts have been initiated to reestablish the ecosystem function of these systems. Original field data including stream stage records, water table hydrographs, sediment hydraulic properties, topographic transects, and aerial imagery of vegetation patterning were used to develop a model of an archetype meadow. Hydrologic behavior was simulated with a finite element model of variably saturated groundwater flow. This model was coupled to an empirical, time-dependent, vegetation threshold relationship between vegetation type and depth to the water table. This was a two-way coupling requiring an iterative approach because water table depth is a determinant of vegetation type, yet the vegetation regime influences water table depth through evapotranspiration. The hydrology and vegetation patterns were analyzed under pristine, degraded (incised), and restored conditions. For the case of deep streambed incision, our hydroecological model predicts the observed shift from mesic (wetter) to xeric (drier) vegetation communities and reproduces their imaged longitudinal zonation. This patterning is explained as a response to groundwater drainage to the stream, which creates dry zones with xeric vegetation adjacent to the stream, while preserving sufficient moisture at the margins of the meadow to support holdout populations of mesic vegetation. The model further predicts the reestablishment of meadow vegetation when the incised channel is filled and a new shallow channel is restored. The coupling of a near-surface hydrologic model to a vegetation response model may be used to design stream restoration projects by predicting vegetation patterning.

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1. Introduction

[2] Extraordinary changes in the dominant vegetation communities have been occurring in the meadow systems of the northern Sierra Nevada of California, where streambed incision has led to meadow degradation and subsequent restoration. Not only has there been a succession from native, mesic (wet meadow) vegetation to xeric (dryland) vegetation, but we note a remarkable vegetation pattern of xeric vegetation near the stream and mesic vegetation at the margin of the meadow. Our hypothesis is that vegetation succession and patterning are controlled by changes in the configuration of the water table [*Stromberg et al.*, 1996], and that shifts in vegetation community have important feedback on the hydrologic budget. In particular, *Loheide and Gorelick* [2005] demonstrated that the evapotranspiration (ET) of native wet meadow vegetation is about twice that of sagebrush and dryland grasses that dominate degraded meadows. The purpose of this work is to understand hydroecologic linkages between the groundwater and vegetation systems through analysis of field data and numerical modeling. Such insight might ultimately improve the scientific basis for riparian meadow restoration and provide a better appreciation of the hydrologic consequences of restoration [*Palmer and Bernhardt*, 2006; *Wohl et al.*, 2005].

[3] Many of the world's ecosystems are water controlled in that water availability is the most important driver of vegetation structure and organization [*Rodriguez-Iturbe et. al.*, 2001]. These systems have been the primary focus of the relatively new field of ecohydrology [*Eagleson*, 2002; *Rodríguez-Iturbe and Porporato*, 2005]. A special case of water-controlled ecosystems is the groundwater-dependent ecosystem (GDE), where species composition and natural ecological processes are primarily controlled by groundwater [*ARMCANZ and ANZECC*, 1996; *Boulton*, 2005], and groundwater is required to maintain the current composition and functioning [*Murray et al.*, 2003].

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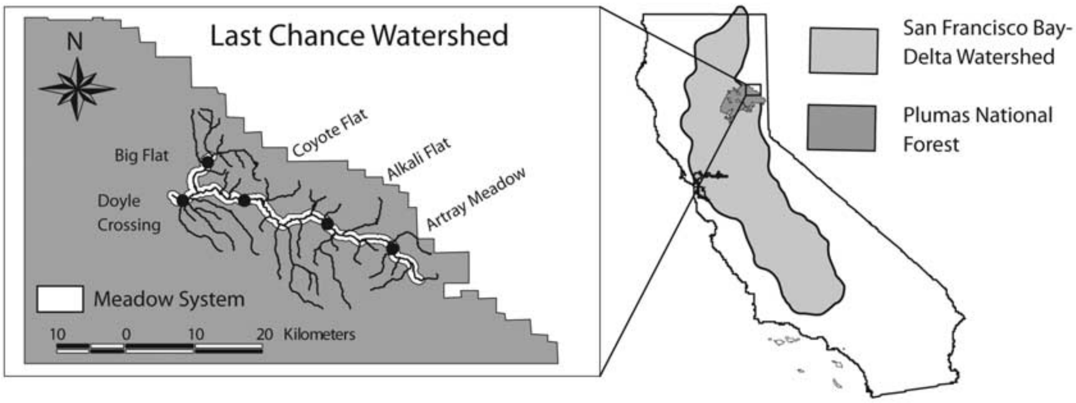

Figure 1. Site map of the location of Plumas National Forest and the stream network in the Last Chance watershed showing the location of five meadows mentioned in the text.

[4] Riparian meadow systems in arid and semiarid environments are GDEs that have recently received attention in the literature because of their sensitivity to changes in water table position, need for management, and potential for restoration [e.g., *Chambers and Miller*, 2004; *Baker et al.*, 2004; *McKinstry et al.*, 2004]. They are particularly important because they physically, hydrologically, chemically and biologically link the terrestrial and aquatic environments, playing a critical role in hydrologic buffering of streamflow, purification/filtration of water, habitat preservation and chemical/nutrient cycling. *Dwire et al.* [2006] demonstrate through a detailed statistical analysis of field data from two montane meadows in northeastern Oregon that zonation and composition of plant communities in riparian meadows are strongly related to the water table depth and redox potential. *Elmore et al.* [2003] present vegetation community–groundwater relationships and show long-term shifts in the vegetation community that have resulted from groundwater declines in the Owens Valley, California. *Castelli et al.* [2000] investigated the spatial and temporal relationships among hydraulic gradients, vegetation, and soil type and identified correlations between riparian meadow vegetation type and water availability using discriminant analysis and canonical correspondence analysis; their work indicates that it is particularly useful to consider integrative variables that incorporate temporal variability (i.e., number of days water table depth is less than 30 or 70 cm). Advanced groundwater modeling techniques for estimating vegetative groundwater use on the basis of the ecophysiology of plant functional groups is presented by *Baird et al.* [2005]. Initial efforts at linking groundwater flow and vegetation response models for predicting riparian vegetation patterning are presented by *Rains et al.* [2004] and *Springer et al.* [1999]. Given these recent advances in understanding the relationship between vegetation community and hydrologic conditions, we are now embarking on an era when we can hope to predict vegetation response to alterations in the hydrologic regime resulting from factors such as reservoir operations, stream incision, groundwater pumping, climate change, and restoration initiatives.

[5] The first objective of this work is to synthesize our understanding of meadow function in the northern Sierra Nevada, California, on the basis of field data collected in the Last Chance watershed. The second objective is to link models of groundwater flow and vegetation response so that vegetation patterning may be predicted under equilibrium/maintenance conditions. The work focuses on developing a conceptual understanding of the hydroecologic changes that occur when a pristine meadow is subjected to various degrees of stream incision as well as restoration and comparing these changes to general conditions suggested by field data from several monitored meadows.

2. Field Data and Observations

2.1. Site Description and Hydrology

[6] Our analysis is motivated by recent restoration activities in the Last Chance watershed (Figure 1). It is located in the headwaters of the Feather River Basin and the runoff drains to Lake Oroville. Not only is the region critically important to California's water supply, providing drinking water for 23 million people and irrigation for 755,000 acres (Department of Water Resources, California, 2006, http://www.water.ca.gov/nav.cfm?topic=State_Water_Project), but it is typical of snowmelt dominated systems throughout the Cordilleran and Rocky Mountain regions of North America.

[7] The Last Chance watershed is $\sim$250 km^2 in size at an elevation of 1680–2350 m and has been designated as a demonstration watershed for testing the effectiveness of landscape-scale restoration. Land use practices such as overgrazing [*Clary and Webster*, 1990; *Trimble and Mendel*, 1995], logging, and railroad and road construction [*Ffolliott et al.*, 2004] have resulted in deeply incised streams, a loss of meadow hydrologic and ecologic function, and general stream quality deterioration in this watershed (D. S. Lindquist and J. Wilcox, New concepts for meadow restoration in the northern Sierra Nevada, 2000, Feather River Coordinated Resource Management Group, Quincy, Calif. (Available at http://www.feather-river-crm.org/pdf/ieca.pdf)) and throughout other areas of the country [*Chambers and Miller*, 2004; *Ffolliott et al.*, 2004; *NRC*, 2002; *Federal Interagency Stream Restoration Working Group*, 2001]. Natural stream incision may also occur over geologic time periods and at geologic rates as has been reported for rivers in the Sierra Nevada through the Cenozoic [*Wakabayashi and Sawyer*, 2001]. Regardless of the cause, stream incision results in a lowering of the water table and aridification of the meadow soils. As

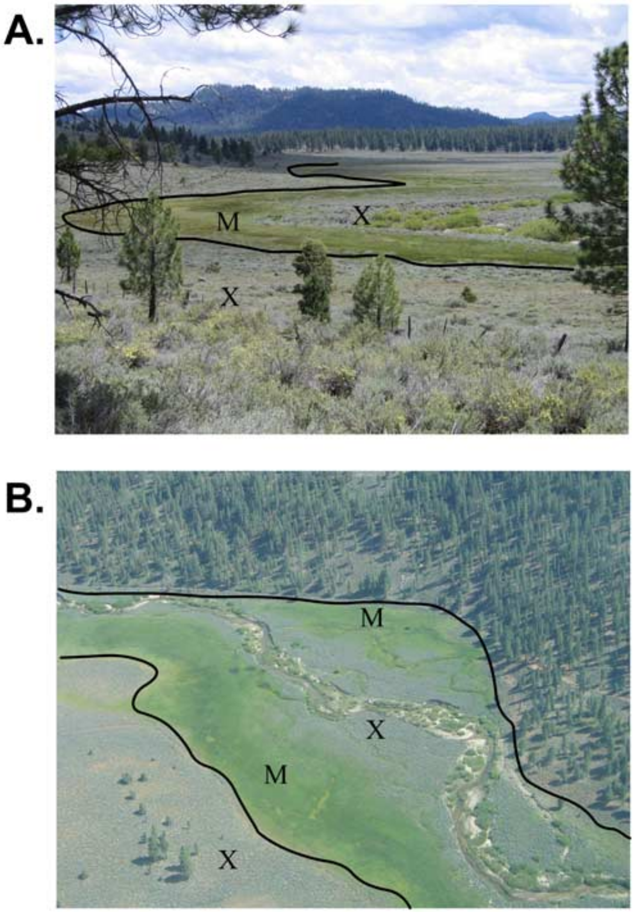

Figure 2. (a) Photograph of the meadow system along Last Chance Creek. The incised channel can be seen on the right side of the photograph. Xeric (X) sagebrush scrub (light green) can be seen on the hillslope and adjacent to the incised channel. Mesic (M) meadow vegetation (dark green) appears in a zone between the near-stream xeric vegetation and the edge of the meadow. (b) Areal photograph of an unnamed meadow along a reach of Last Chance Creek showing the same vegetation patterning as described above. While the vegetation types are evident in these photos, in the field the distinction between the vegetation communities is obvious, and statistical analysis is not necessary to differentiate the vegetation communities. In both images the meadow boundary is marked by a line and is identifiable in the field as a topographic break and a boundary between vegetation and soil types.

discussed by *Wilcox* [2005] and *Loheide and Gorelick* [2005], this reduction in water availability causes a succession from native wet meadow vegetation to xeric vegetation. As is becoming increasingly common in the United States [*Bernhardt et al.*, 2005], a local nonprofit group, the Feather River Coordinated Resource Management (FRCRM) group has initiated riparian restoration. Specifically, they are pioneering pond-and-plug restoration, in which segments of the deeply incised channel are filled with material obtained by excavating ponds along the channel. Streamflow is then rerouted into either an abandoned (unincised) channel or a newly constructed channel resulting in an increase in water table elevation and a return of wet meadow vegetation. Further discussion of restoration at this site can be found in the works of *Wilcox* [2005], *Loheide and Gorelick* [2005, 2006], and *FRCRM* [2004]. To date, restoration has been completed in about one-third of the meadow system ($\sim$14 km) that could potentially be restored. Stream incision of this nature is ubiquitous around the globe and an improved, physically based understanding of the hydroecology is required to improve the success of restoration initiatives.

[8] The Last Chance watershed is located on the eastern (dry) slope of the Sierra Nevada in a semiarid environment (precipitation $\approx$ 41cm/yr). Nearly all precipitation falls in the winter, and the hydrology is driven by the spring snowmelt. The available climatic and streamflow data are summarized in Text S1.[1] Because of the seasonality of the hydrology, the meadow systems in Last Chance watershed are GDEs. The wet meadow vegetation depends on shallow groundwater stored in the meadow sediments for survival through the annual dry summer period, and almost all streamflow during the summer is derived from baseflow. Recognizing that the meadows are GDEs is critical in establishing the link between the groundwater flow system and the vegetation community. Diurnal water table fluctuations demonstrate this connection and are discussed in detail in Text S1 (section S3).

2.2. Vegetation Communities and Patterning

[9] Natural wet meadows are vegetated with hydric (wet meadow) and mesic species such as sedges (*Carex spp.*), rushes (*Juncus spp.*), and other herbaceous species. Xeric vegetation communities such as the sagebrush scrub (i.e., *Artemisia tridentata*, *Purshia tridentate*: antelope bitterbrush, and *Chrysothamnus nauseosus*: rabbitbrush) and yellow pine/juniper (i.e., *Pinus jeffreyi*, *Pinus ponderosa*, and *Juniperus occidentalis* var. *australis*) dominate on the hillslopes. Encroachment of sagebrush [*Berlow et al.*, 2002; *Wright and Chambers*, 2002; *Darrouzet-Nardi et al.*, 2006] and woody vegetation is a problem that is endemic throughout the western United States. This phenomenon is a direct result of aridification of riparian areas, which could potentially be caused by draining of meadow sediments as a consequence of stream incision, land use changes, climate change, or other factors.

[10] Contrary to the intuitive notion that the range of xeric vegetation and sagebrush expands from the hillslopes onto the margin of the meadow, xeric vegetation borders (incised) channels. The photographs in Figures 2a and 2b show the pattern of the mesic and xeric vegetation communities. In both photos, the mesic vegetation is dark green whereas the xeric vegetation is a lighter, sage green.

[11] Color infrared imagery is useful for mapping vegetation communities because healthy, lush vegetation is very reflective in the near infrared region of the electromagnetic spectrum. The near infrared band is displayed as red in Figure 3, so that mesic vegetation appears red. In Figure 3a, an image of a moderately degraded meadow shows a relatively narrow blueish/gray zone near the channel that represents xeric vegetation. We interpret this to represent an historic succession from the native mesic vegetation community to xeric species near the incised channel, although we note dominantly mesic vegetation remains near the

[1] Auxiliary materials are available in the HTML. doi:10.1029/2006WR005233.

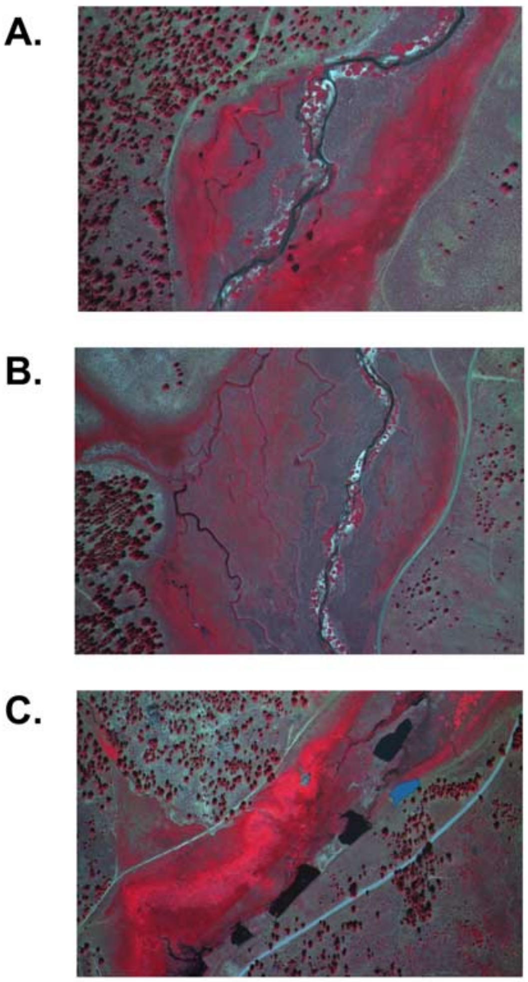

Figure 3. In this helicopter-based color infrared imagery collected 3 June 2005, healthy, lush, mesic vegetation appears red because of its high reflectivity in the near infrared portion of the electromagnetic spectrum. (a) A partially degraded meadow showing xeric vegetation near the incised channel, but mesic vegetation at the margin of the meadow. (b) A nearly completely degraded meadow with xeric vegetation throughout except at the extreme meadow margins and in the less incised tributary meadow entering from the left edge of the image. (c) A restored meadow (Artray: restored during 2002) with healthy mesic vegetation throughout the meadow except on the plugs where vegetation has not fully recovered and near the downstream end of the project area where the stream is rerouted into an incised channel.

margins. Figure 3b shows a more severely degraded meadow (Coyote Flat) where xeric vegetation dominates the system; the extreme margin of the system supports some mesic vegetation mixed with sagebrush and dryland grasses. Here, we believe that deeper stream incision has more completely shifted the vegetation type from mesic to xeric. The tributary meadow entering from the upper left of the image has shallower stream incision and supports mesic vegetation. Figure 3c, shows Artray Meadow, which was restored in 2002 using the pond-and-plug technique. Mesic vegetation dominates Artray Meadow; however, toward the downstream portion of the restoration project (see Figure 3c, top), the stream is rerouted into the incised channel and xeric vegetation is present.

2.3. Groundwater Hydrographs

[12] Annual well hydrographs were recorded in four wells that were centrally located in the Alkali Flat, Big Flat, Coyote Flat, and Doyle Crossing meadows and all are positioned between 20–35 m from the active stream channel. Alkali Flat and Big Flat have both been restored; Coyote Flat is severely degraded; and Doyle Crossing is degraded, but the observation well is located in a nearly pristine tributary meadow. Each well was installed by hand augering to a position near the minimum annual water table elevation and was screened across the water table. Each well was equipped with an Instrumentation Northwest (Kirkland, Washington) P2TX 5PSI pressure transducer that recorded the pressure head every 15–30 min during water years 2004 and 2005 (Figure 4). The well hydrographs show that recharge occurs from October–April. In the restored meadows (Alkali Flat and Big Flat) and the semipristine tributary at Doyle Crossing, the water table is at or near the land surface during April, a time when shallow standing water is common in the restored and pristine meadows. The water table in the degraded system (Coyote Flat), also reaches a maximum during this period; however, it is more than 1 m below the land surface. Water table elevations drop quickly during the summer months as groundwater flows from the meadow and is removed by evapotranspiration. During the growing season, daily evapotranspiration cycles produce diurnal fluctuations of the water table. The magnitude of these fluctuations is up to $\sim$10 cm and a portion of these data can be found in the work of *Butler et al.* [2007]. In Text S1 (section S3), these fluctuations are used to estimate evapotranspirative consumption of groundwater.

[13] In addition, during the 2004 and 2005 growing seasons (May–September) the hydraulic head data in Figure 5 were collected by manually measuring the depth to the water table every 2–4 weeks at 22 wells (5–6 in each of the 4 meadows) screened across the water table. The manual measurements could not be made year-round because the site is only accessible by snowmobile during the winter. We characterized each site as being exclusively wet meadow vegetation, mixed/dominantly wet meadow vegetation, mixed/dominantly dryland vegetation, and exclusively dryland vegetation. Some common species listed in approximate order from wettest to driest include *Carex douglasii*, *Carex nebraskensis*, *Carex angustata*, *Juncus balticus*, *Pyrrocoma hirta var. lanulosa*, *Ranunculus occidentalis*, *Muhlenbergia richardsonis*, *Achillea millefolium*, *Poa secunda ssp. Secunda*, *Carex exarata*, *Ivesia aperta var. aperta*, *Hordeum brachyantherum*, *Artemisia cana ssp. cana*, *Artemisia arbuscula ssp. arbuscula*, *Hordeum jubatum*, *Elymus elymoides ssp. californicus*, *Artemisia tridentate*. The four vegetation groupings used here are comparable to the four ecosystem types used by *Castelli et al.* [2000], which are wet meadow, mesic meadow, dry meadow, and sagebrush meadow. Our data set, consisting of groundwater measurements and vegetative classification,

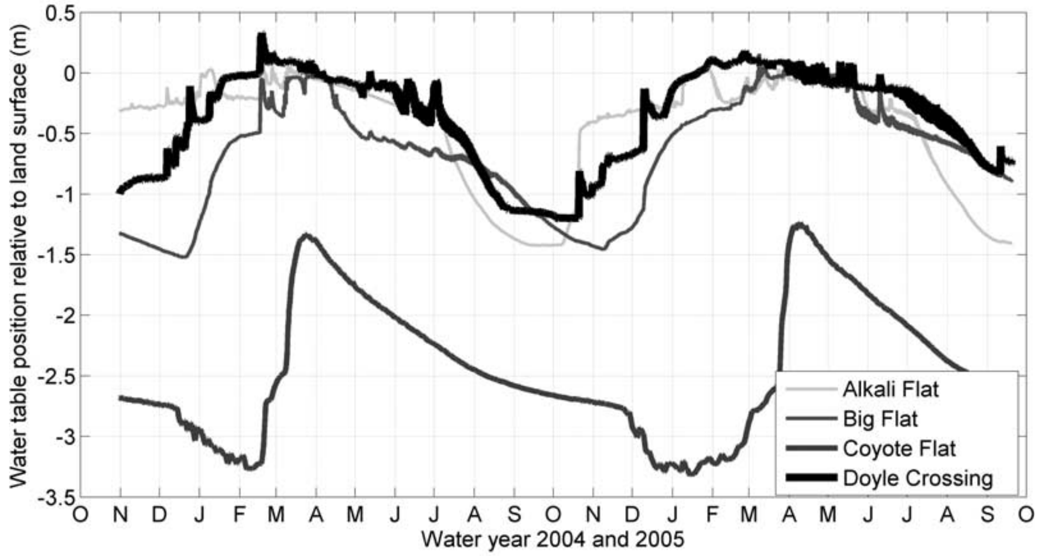

Figure 4. Observed water table hydrographs in Alkali Flat (restored 2003), Big Flat (restored 1995 and riffle treatment in summer 2004), Coyote Flat (~3 m of stream incision), and Doyle Crossing (minimally affected tributary meadow). Recharge begins in the fall of each year, culminating with the spring snowmelt during March and/or April. Meadow drainage and evapotranspiration reduce water table position through the summer months.

will be discussed further in section 3.2, which introduces a model that relates depth to the water table and vegetation community.

3. Coupled Modeling of Groundwater Flow and Vegetation Patterning in a Typical Meadow System

3.1. Definition of an Archetypical Meadow

[14] The approach adopted here is to gain insight into the hydroecologic function of meadow systems in the Last Chance watershed by employing a modeling framework. To this end, we define an archetypical meadow for which we simulate the groundwater flow and vegetation patterning under pristine, incised, and restored conditions. Recognizing that our simulated meadow system is somewhat stylized, our purpose nevertheless is to (1) reproduce the salient hydroecologic features observed in the meadows at our field site and (2) compare directly the hydroecologic response of the simulated meadows under the different meadow conditions.

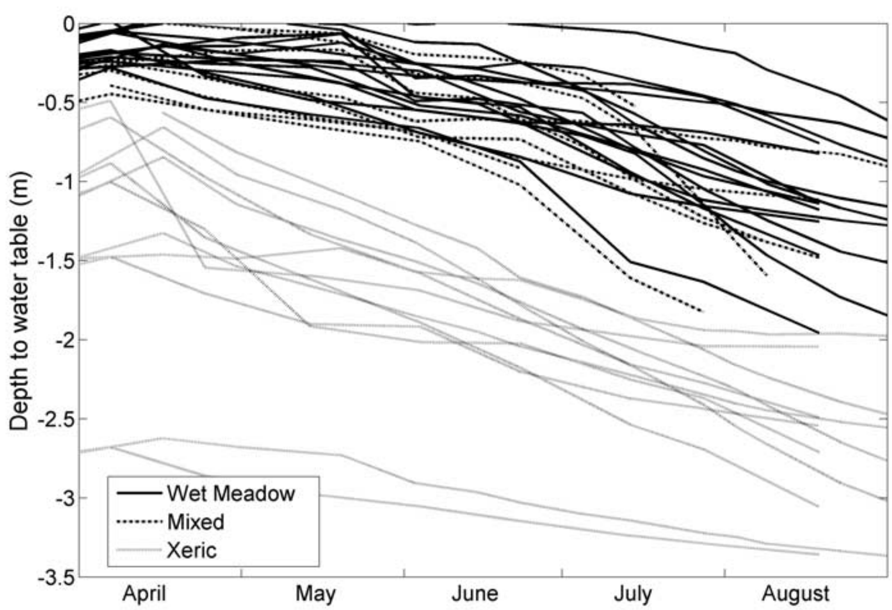

Figure 5. Water table hydrographs collected every 2–4 weeks during the growing season. There is a clear distinction between hydrographs collected at sites dominated by wet meadow/mesic vegetation and those dominated by xeric vegetation such as dryland grasses and sagebrush.

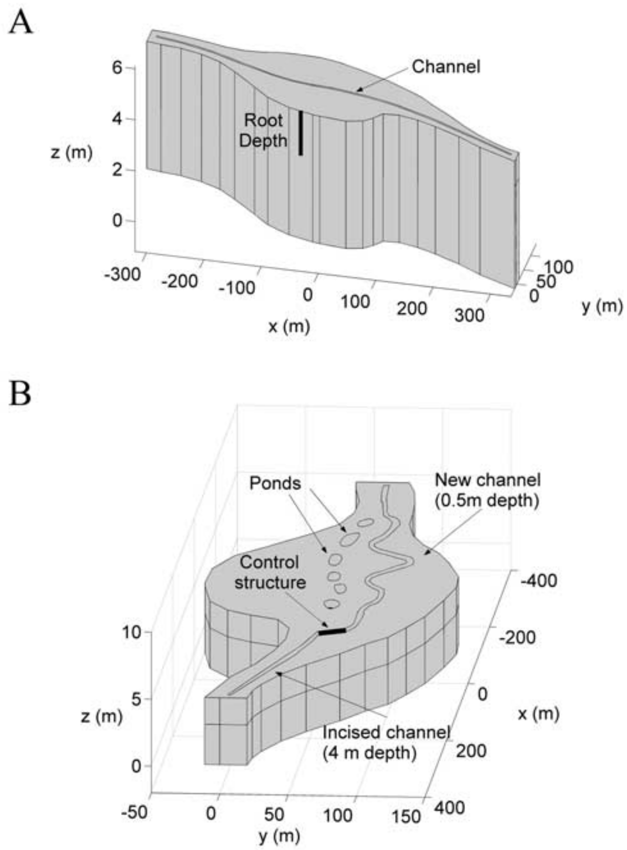

Figure 6. Model domain used for numerical simulations of (a) the pristine and degraded cases and (b) the restored case. Dimensions of both domains are identical.

[15] We have historical accounts that two of the meadows in this study, (Big Flat and Alkali Flat) have experienced pristine, degraded, and restored conditions. Unfortunately we only have data available for the current condition. By making a substitution of space for time, we are able to make general comparisons between how the archetype meadow condition changes through various degradation states (time) with the field observations collected at various locations (space).

[16] Figure 6a displays the simulation domain of the pristine and degraded cases. The simulated meadow is $\sim$180 m wide in the widest portion and narrows to $\sim$30 m in the upstream and downstream regions. On the basis of topographic surveys presented in Text S1 (section S5), the down-valley surface slope is 0.2°, and the meadow sediments have a constant thickness of 5 m. The location of the stream is as shown, also with a bed slope of 0.2°. The depth to the streambed was varied to simulate different states of stream incision. Figure 6b represents the restored case and has exactly the same outer boundary as shown in Figure 6a. In the model of the restored case, the incised channel is replaced with a series of six, 3.5 m-deep ponds and a new 0.5 m-deep channel to represent pond-and-plug restoration. In the model, the new channel is more sinuous than the incised one; as noted by *Benoit and Wilcox* [1997], the incised channels are typically straighter than remnant channels (see active and remnant channels of Figures 3a and 3b). At the downstream end of the restoration project area, the new channel is routed back into the incised channel through an outflow control structure. In the field, each control structure consists of a series of pools created with rip-rap to step the stream down to the position of the incised channel and to prevent channel incision from propagating upstream into the new unincised channel.

3.2. Vegetation Threshold Hydrographs

[17] It has long been recognized that different vegetation communities have various water requirements. Particularly in semiarid meadow environments, depth to groundwater has been identified as a critical parameter determining the type of vegetation that will flourish at a given location [*Allen-Diaz*, 1991; *Ridolfi et al.*, 2006]. However, understanding these water requirements has proven difficult because they are dependent not only on the species present, but also on environmental conditions such as climate, nutrient limitations, and soil type, amongst others. According to *McKinstry* [2004], a critical gap in our knowledge of the ecology of mountain meadows is the water requirements of meadow species.

[18] High groundwater levels are particularly critical for supporting groundwater-dependent ecosystems. Because the meadows are GDEs, we believe depth to the water table is the primary driver of vegetation patterning. We maintain that differing depth-to-water requirements of mesic versus xeric plant types are time variant, and quantitative relationships must be developed that describe this time dependency as it relates to specific communities.

[19] The depth-to-water characteristics that differentiate wet meadow vegetation from sagebrush/dryland grass vegetation communities are in fact related to the phenology of these plants. The phenology of Nebraska Sedge (*Carex nebraskensis*), a species found in wet meadow vegetation communities, was reported by *Ratliff* [1983] in the Sierra National Forest. He found that initiation of new growth occurred between 22 May and 4 June. The reproductive stage was reached by 48% of individuals by 2 July. Full bloom was reached by 30 July, and continued into mid-August. The seed continued to ripen until late September. These important phenologic events help us interpret the observed depth-to-water requirements discussed below.

[20] The required depth-to-water characteristics as a function of plant community type are shown in Figure 7, where a vegetation threshold hydrograph is introduced. Regions on the graph were determined using the water table hydrographs in Figure 5 and the characterization of the vegetation at each site (mesic/wet meadow, mixed, or xeric) on the basis of species composition. On the basis of the data, we define three curves. The upper, middle, and lower vegetation threshold hydrographs define the thresholds between exclusively wet meadow/dominantly wet meadow, dominantly wet meadow/dominantly dryland, and dominantly dryland/exclusively dryland vegetation communities, respectively. The middle vegetation threshold hydrograph differentiates between the two vegetation communities by providing a threshold above which the water table would support wet meadow vegetation and below which the area would be dominated by sagebrush and dryland grasses.

[21] There are two portions of this threshold curve that are particularly important and may be related to phenolog-

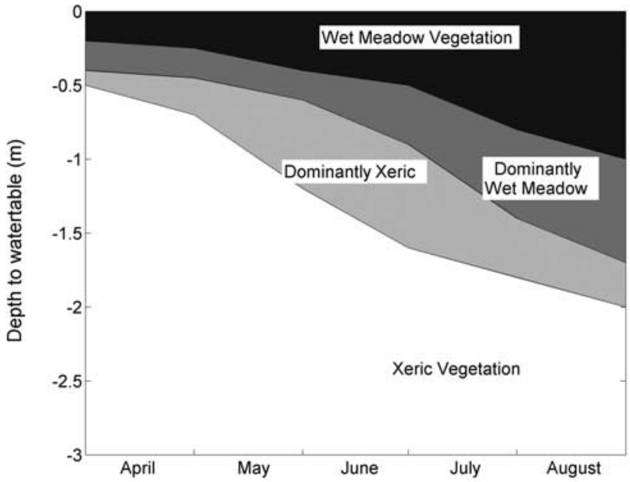

Figure 7. On the basis of the data shown in Figure 5, vegetation threshold hydrographs separating sites of wet meadow vegetation from those with xeric vegetation are shown.

ical patterns during typical growing seasons. First, the most critical feature of the vegetation threshold hydrograph is that water levels are very near, or above, the land surface during April and May. If the water table is within 0.5 m of the surface during this period of growth initiation, the very high moisture content in the root zone will cause waterlogging and mortality of xeric vegetation. Second, it appears as though the water table must remain within ~1 m of the surface through June and July to maintain sufficient soil moisture for the wet meadow species to reach full bloom during the annual dry period. This depth may be related to the rate at which rooting depth can increase through the growing season in an attempt to reach the water table [*Martin and Chambers*, 2002]. Through August (and later), the wet meadow species begin to senesce, water requirements are reduced, and a shallow water table is no longer required to supply water to the vegetation. The upper and lower vegetation hydrographs are included in recognition of the fact that the threshold is not precisely defined and is perhaps better thought of as a transition from wet meadow to dryland vegetation communities.

3.3. Groundwater Flow Modeling Techniques

[22] The effect of stream incision on groundwater flow and vegetation patterning is explored through numerical modeling in the archetypical meadow described in section 3.1. The stream is incised to various degrees in five simulated cases. In the pristine case, the streambed is located 0.5 m below the meadow surface. Increasing severity of meadow degradation is simulated by lowering the streambed elevation to 1 m, 2 m, and 4 m below the meadow surface. A fifth case, that of a restored meadow, is simulated by creating a domain in which a series of ponds and plugs replaces the original channel and a secondary, meandering channel is added with a streambed elevation 0.5 m below the meadow surface. Toward the downstream end of the meadow, the stream course is located in the incised channel (4 m deep) to simulate the transition into an unrestored reach. The conceptual model in all cases includes (1) infiltration at the meadow surface during the winter months, which peaks during the spring snowmelt, (2) a stream that is represented as a time-dependent, specified pressure head boundary (i.e., $\psi(t)$), (3) a basal influx that represents the contribution of water from the regional groundwater flow system, and (4) evapotranspiration from the root zone that is vegetation- and time-dependent during the growing season. The model does not include surface water routing, overland flow, or meadow flooding.

[23] Three-dimensional, variably saturated, transient groundwater flow modeling was performed using Richards' equation as shown below:

$$\left[C(\psi)+\left(\frac{\theta-\theta_R}{\theta_S-\theta_R}\right)\left(\rho_f g\right)\left(x_p(1-\theta_R)+x_f\theta_R\right)\right]\frac{\partial\psi}{\partial t} = \nabla(K(\psi)\nabla(\psi+z))+\mathrm{Q_s} \quad (1)$$

where θ is the water content (−), θ_R is the residual water content (−), θ_S is the water content at saturation (−), ψ is the pressure head (L), $K(\psi)$ is the unsaturated hydraulic conductivity (L/T), $C(\psi) = \partial\theta/\partial\psi$ (1/L), ρ_f is the density of the fluid (M/L^3), g is the gravitational constant (L/T^2), x_f is the compressibility of the fluid (1/P), x_p is the compressibility of the solid (1/P), and Q_s is a source/sink term (1/T). The functional forms of the characteristic curves given by *van Genuchten* [1980] were used and are shown below:

$$\theta=\theta_R+\frac{\theta_S-\theta_R}{\left[1+(\alpha|\psi|)^n\right]^m} \quad (2)$$

$$K(\theta)=K_S\left\{\frac{\theta-\theta_R}{\theta_S-\theta_R}\right\}^{1/2}\left\{1-\left[\left(\frac{\theta-\theta_R}{\theta_S-\theta_R}\right)^{1/m}\right]^m\right\}^2 \quad (3)$$

where K_S is the saturated hydraulic conductivity (L/T), and α (1/L), n (−), and m (−) are empirical coefficients with m = 1 − 1/n. On the basis of measured values reported in Text S1 (section S4), the following hydraulic properties were used in the simulations: $K = 7\times10^{-6}$ m/s, $\alpha = 1.5$ m^{-1}, n = 2, $\theta_s = 0.65$; and $\theta_r = 0.2$. The aquifer compressibility was 1×10^{-6} Pa^{-1}. The ponds are represented as an extension of this domain with $\theta_s = 1$, $\theta_r = 0$, a high hydraulic conductivity (100 times that of the meadow sediments), and a very steep characteristic curve to approximate an open water body. Representing the hydraulic behavior of the ponds as an effective porous media with high hydraulic conductivity and porosity of 100% allows the ponds to act as regions with low resistance to flow and high water storage capability while allowing them to communicate with the nearby sediments. In terms of their hydrologic impact, the ponds were treated as groundwater sinks because of evaporation.

[24] Comsol Multiphysics version 3.2® [*Comsol*, 2005], a finite element software package for solving user-defined partial differential equations, was used to solve equation (1). The time-dependent solver was used in combination with a linear geometric multigrid (GMRES) solver using the LU preconditioner; the results were checked using a much less memory efficient direct solver (UMFPACK) with excellent agreement. The domain was discretized into ~160,000

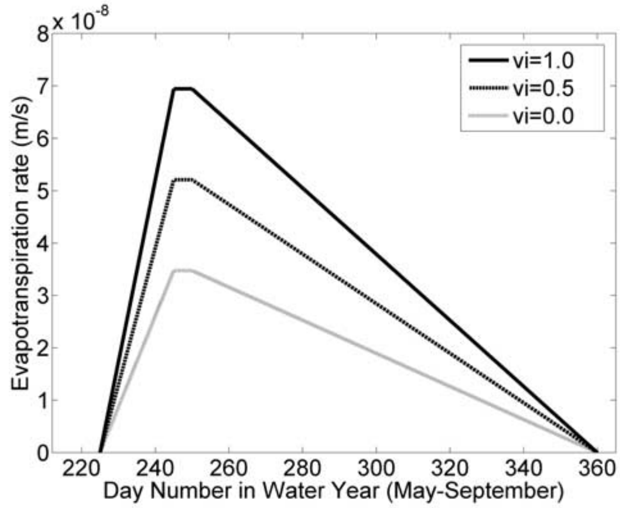

Figure 8. Growing season evapotranspiration rates used in simulations for vegetation indexes (*vi*) of *vi* = 1 (100% mesic), *vi* = 0.5 (50% mesic and 50% xeric), and *vi* = 0.0 (100% xeric).

elements, and ~220,000 nodes. The simulations were run on a Sun v40z with 32 GB of memory. The simulations were each run for a water year (beginning 1 October).

[25] The boundary conditions at the edges of the meadow are all defined as no-flow boundaries and are set by prescribing a zero head gradient ($\nabla(\psi + z) = 0$). An upward flux is specified at the base of the model domain at a rate of 1×10^{-8} m/s to represent a deep groundwater contribution as a constant flux boundary condition; the rationale for selecting this flux rate is presented in Text S1 (section S6). The top of the domain is represented by a time-dependent downward flux describing the infiltration rate. In the model, the infiltration rate is 2×10^{-8} m/s from 1 November to 1 March when winter storms typically occur. The majority of the recharge due to infiltration occurs during the spring snowmelt; this is represented as an infiltration rate of 2×10^{-7} m/s from 1 March to 1 April. The maximum total infiltration is 73 cm/yr, representing more than the annual precipitation because both surface flow from the hillslopes and stream water from meadow flooding infiltrate into the meadow sediments during the spring snowmelt. During the remainder of the year, there is no infiltration in the model. The values of both of the inflow terms (infiltration and deep groundwater) are specified at rates less than their respective maximum rates if the meadow is completely saturated; at all locations, the reduced inflow rates are linearly interpolated between the maximum value and zero by scaling between the pressure head that indicates saturation (in a hydrostatic state) and a pressure head 10 cm higher than saturation. This is to represent the fact that surface waters accumulate on the meadow surfaces, but great depths do not occur. Neither streamflow routing nor surface water storage are included in the model.

[26] To represent ET, water extraction by roots occurs within the top two meters of the meadow, regardless of whether this zone is saturated or unsaturated; there is no bare surface evaporation. The extraction rate is determined as a function of time, vegetation type, and soil water pressure head. From data in Text S1 (section S3), the time dependency of transpiration over the growing season was determined by analysis of diurnal water table fluctuations using the methods of *White* [1932] and *Loheide et al.* [2005]. We introduce a vegetation index (*vi*) in which "1" represents mesic, wet meadow vegetation and "0" represents xeric vegetation, and intermediate values represent mixtures of the two vegetation communities. *Loheide and Gorelick* [2005] determined that near-peak evapotranspiration rates for xeric meadow vegetation and wet meadow vegetation were 1.5–4.0 and 5.0–6.5 mm/day, respectively. The ET rate in the model is determined by linearly scaling between the values of 3 mm/d and 6 mm/d for these end member vegetation types given the temporal pattern determined previously (Figure S2). Figure 8 shows the ET that would be specified for vegetation indices of 1.00, 0.50, and 0.00 under the condition when water is not strongly limiting ET. If soil water tension is less than −10.0 m, ET is further reduced in a linear manner until it is zero at the wilting point (−140.0 m). Evaporation from the ponds is specified using the daily rate function shown in Figure 8 for *vi* = 1.

[27] The stream stage is represented as a time-dependent specified pressure head; using a lookup table with eleven equally spaced time and stage data pairs, the values specified for this boundary condition are interpolated from the function presented in Text S1 (section S2) on the basis of typical annual stream stage (Figure S1). This boundary condition is imposed at the streambed. In the pristine case, the streambed is located 0.50 m below the meadow surface. Under low flow conditions, the surface of the stream is 0.2 m above the streambed and the high flow conditions are 0.5 m above the streambed. Therefore in the pristine case, the stream surface is 0.3 m below the meadow surface under low flow conditions and at the surface during high flow.

[28] The only two differences between the model of the pristine case and that of the degraded cases are that (1) the streambed and the stream boundary condition are lowered to a depth below the meadow surface of 1 m, 2 m, and 4 m in the degraded cases and (2) the ET rates are different because the predicted vegetation maps are different. In the restored case, the streambed is relocated, but the streambed depth is 0.5 m as in the pristine meadow case.

[29] A several year warm-up period was simulated to obtain reasonable initial soil moisture/pressure head conditions needed for the coupled groundwater/vegetation model. Because the same boundary conditions are applied during repeated years, a dynamic equilibrium develops in which the water table (and pressure head) response is the same in successive warm-up years. To start this warm-up period, we assumed hydrostatic conditions and a planar water table with a slope and elevation that are equivalent to that of the stream surface on the first day of the water year (1 October). A one year period was simulated that included infiltration, groundwater flow, and ET. The simulated pressure head values at the final time step of the year were then used as the initial conditions for the next simulation under the same conditions of system stresses and boundary conditions. This process was repeated until a stable (<1 cm difference) annual water table hydrograph was obtained in successive years. For this warm-up period, a constant vegetation type was assumed (i.e., *vi* = 0.0, 0.5, 1.0, 1.0, and 1.0 for the degraded 4 m, degraded 2 m, degraded 1 m,

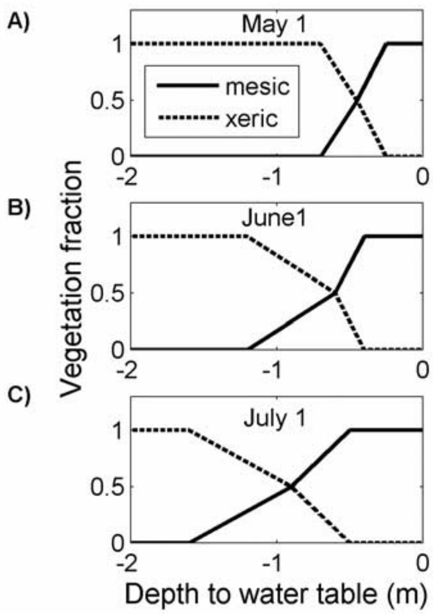

Figure 9. Curves relating depth to the water table to the fraction of mesic and xeric vegetation expected for (a) 1 May, (b) 1 June, and (c) 1 July. These relationships were created by assuming vegetation communities are 100% mesic at sites where the water table depths are above the upper vegetation threshold. Similarly, vegetation communities are assumed 100% xeric at sites where the water table depths are below the lower vegetation threshold. Vegetation communities at sites with water table depths that are exactly at the middle vegetation threshold are 50% mesic and 50% xeric. The relationships are linear between these points.

the pristine, and restored cases, respectively). A constant vegetation type was assumed, as no better estimate was available for the initial simulation and was retained through the warm-up period. The results from the final time step of this warm-up period were used as initial conditions when the groundwater and vegetation models were linked.

3.4. Linking the Groundwater Flow and Vegetation Models

[30] *Springer et al.* [1999] and *Rains et al.* [2004] significantly advanced the ability to predict vegetation patterning through a one-way coupling of a saturated groundwater flow model to a vegetation model. In both studies, groundwater flow and vegetation patterning were influenced by connected surface water bodies with regulated flows and stages. Depth to the water table was used to predict vegetation type under various surface water reservoir operation scenarios; *Rains et al.* [2004] focused on vegetation surrounding a reservoir whereas *Springer et al.* [1999] considered the downstream effects of reservoir releases on riparian vegetation communities. We build on these efforts in several ways by considering (1) a three-dimensional, transient, variably saturated groundwater flow system, (2) a time-dependent vegetation model, and (3) feedback between the vegetation community and the groundwater flow system.

[31] Similar to *Springer et al.* [1999] and *Rains et al.* [2004], we predict vegetation patterning on the basis of depth to the water table. Our predictive vegetation model is based on the vegetation threshold hydrograph (Figures 7 and 9) determined using field data. However, instead of using a mean or steady state depth to the water table, we use the simulated depth to the water table at three critical times in the life cycle of these vegetation communities. The three dates we chose for this analysis are 1 May, 1 June, and 1 July. At the earliest date, if a very high water table is present, the root zone of xeric vegetation will be waterlogged and anaerobic [*Dwire et al.*, 2006], causing the xeric species to die out. Near 1 June, sufficient water must be present for initiation of growth of the mesic communities. By 1 July, the water table must still be accessible by mesic vegetation to ensure reproductive success. Because the reproductive stages have already been reached by early August, it is likely that even very dry conditions will not negatively impact the long-term success of the mesic communities. On each of these dates, a vegetation index (vi) ranging from 0 to 1 is estimated on the basis of the depth to the water table. A vegetation index of 1 indicates 100% mesic/wet meadow vegetation (0% xeric) and a value of 0 indicates 0% mesic/wet meadow vegetation (100% xeric). If the depth to the water table is above the upper vegetation threshold hydrograph, a $vi = 1$ is predicted. If the depth to the water table is equal to the middle vegetation threshold hydrograph, a $vi = 0.5$ is predicted. If the depth to the water table is at or below the lower vegetation threshold hydrograph, a $vi = 0$ is predicted. In this vegetation model, vi values at intermediate water table depths are linearly interpolated as shown in Figures 9a, 9b, and 9c for the 1 May, 1 June, and 1 July, respectively. The overall vi is calculated as the equally weighted mean of these three estimates, and is used as the vegetation map for the next model iteration.

[32] There is a two-way coupling between the water table and the vegetation pattern. Because different vegetation types transpire at different rates, updating the vegetation map in the model affects the groundwater system. When applying the vegetation threshold hydrograph to determine vegetation type, we used the post warm-up simulated depth to the water table to update our initial guess of a constant vegetation type for the warm-up simulations. Then, pressure head values at the final time step are used as initial conditions in the subsequent simulation, and an annual simulation is rerun using the updated vegetation map. Water table depth resulting from this simulation is again used to update the vegetation map using the vegetation threshold hydrograph at the three evaluation dates. The flow model is rerun, with the updated vegetation conditions. This iterative process is repeated until the water table configuration and vegetation patterning reach an equilibrium condition ($\Delta vi < 0.01$).

4. Results

4.1. Model Results: Pressure Head

[33] The groundwater flow model produced 3-D pressure head fields that evolve through time. As an example, a slice of the pressure field for the degraded, 4-m incised channel case on 1 August is shown in Figure 10. The water table is represented by the zero pressure head contour, ($\Psi = 0$). The most striking feature of Figure 10 is the spacing of the contour lines. The contours above the water table and

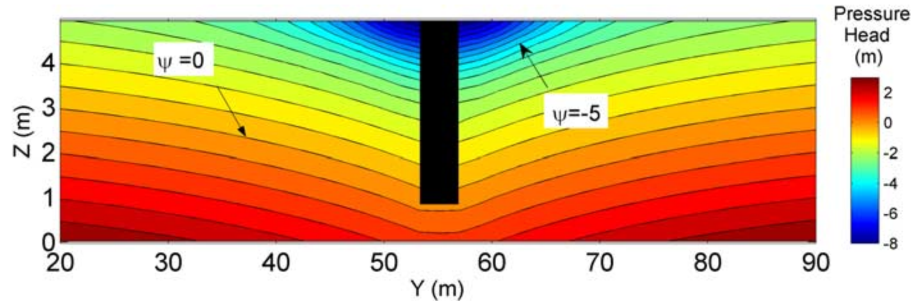

Figure 10. Slice perpendicular to the channel showing contoured pressure head simulated for 1 August for the degraded case with 4 m of stream incision. The surface where the pressure head equals zero represents the water table.

near the channel are more tightly spaced than below. In fact, $\partial\psi/\partial z < -1$, indicating upward flow of water from the water table to supply root uptake. Although the 3-D pressure head fields reflect all of the simulated elements, we can interpret much about the groundwater flow regime by looking only at the configuration of the water table. In Figure 10, the water table ($\Psi = 0$ isocontour) is sloping toward the stream indicating this is the direction of groundwater flow. From the fully 3-D pressure head fields, the 3-D Cartesian coordinates of the $\Psi = 0$ isocontour were used to create contour maps of the water table (section 4.3). The depth to the water table was calculated as the difference between the elevation of the land surface and the elevation of the water table. Similarly, simulated water table hydrographs were created by determining the internodal elevation where $\Psi = 0$ at the observation well location at a 3-day interval.

4.2. Simulated Versus Observed Water Table Hydrographs

[34] The simulated water table hydrographs shown in Figure 11 reproduce many of the salient features of the observed hydrographs in Figure 4 for both degraded and nondegraded meadow systems. For comparison to nondegraded systems, we consider the restored meadows Alkali Flat and Big Flat (water year 2005). In addition, while not pristine, the small tributary meadow within Doyle Crossing, where the observation well was located, is among the most undisturbed subsystems identified in the watershed. We consider the data from Big Flat during water year 2004 to be representative of a slightly degraded meadow as this preceded a second round of restoration at this site. For comparison to a degraded system, we consider the Coyote Flat meadow for which the channel is incised by ~3 m. We will discuss and compare the observed and simulated water table hydrographs starting with the least impaired systems and progressing to the most degraded systems.

4.2.1. Pristine and Restored Cases

[35] For the restored and pristine/near pristine meadows, the most important similarity between the well hydrographs collected at Alkali Flat, Big Flat, and Doyle Crossing (Figure 4) and the simulated pristine and restored simulated cases (Figure 11) is the general pattern of the annual hydrograph. Starting at the beginning of the water year, the water table rises through the fall until meadow saturation occurs. Then during the winter, meadow saturation/flooding occurs when the position of the water table/free water surface is at or above the meadow surface. In all of these cases, the meadows remain saturated until mid-May and maintain a relatively high water table into June. The water table then drops quickly through June, July, and in some cases into August. Two related differences between the simulations and the observations in nondegraded meadows are that (1) the simulated water tables do not continue to drop as fast or fall as far as the observed water table hydrographs and (2) the simulated meadows reach saturation around 1 December, whereas the observed meadows do not typically reach saturation until January. The primary reason the simulated water table elevations do not decrease further during the late summer is that in the model the streams recharge the groundwater system. This would be the case for perennial systems, but our observations are biased toward ephemeral systems, which are more prevalent since stream restoration is proceeding from headwater systems to progressively larger streams. Cottonwood Creek through Big Flat, Last Chance Creek through Alkali Flat, and Squaw Canyon Creek through the Doyle Crossing tributary meadow were not flowing, and therefore not recharging the meadows at our instrumented sites. This lack of focused recharge from the streams at our field sites allowed the water table to continue to drop in late July and August. Because the water table dropped further at the field sites, it also had further to recover to reach saturation; therefore meadow saturation was delayed in the observed cases (compared to simulated cases).

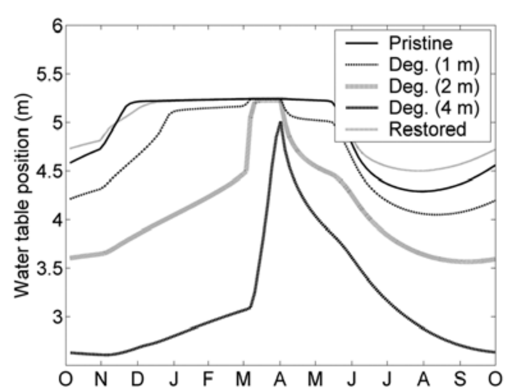

Figure 11. Simulated water table hydrographs for the pristine, degraded (1 m, 2 m, and 4 m), and restored cases at observation location $x = -70$ m and $y = 70$ m.

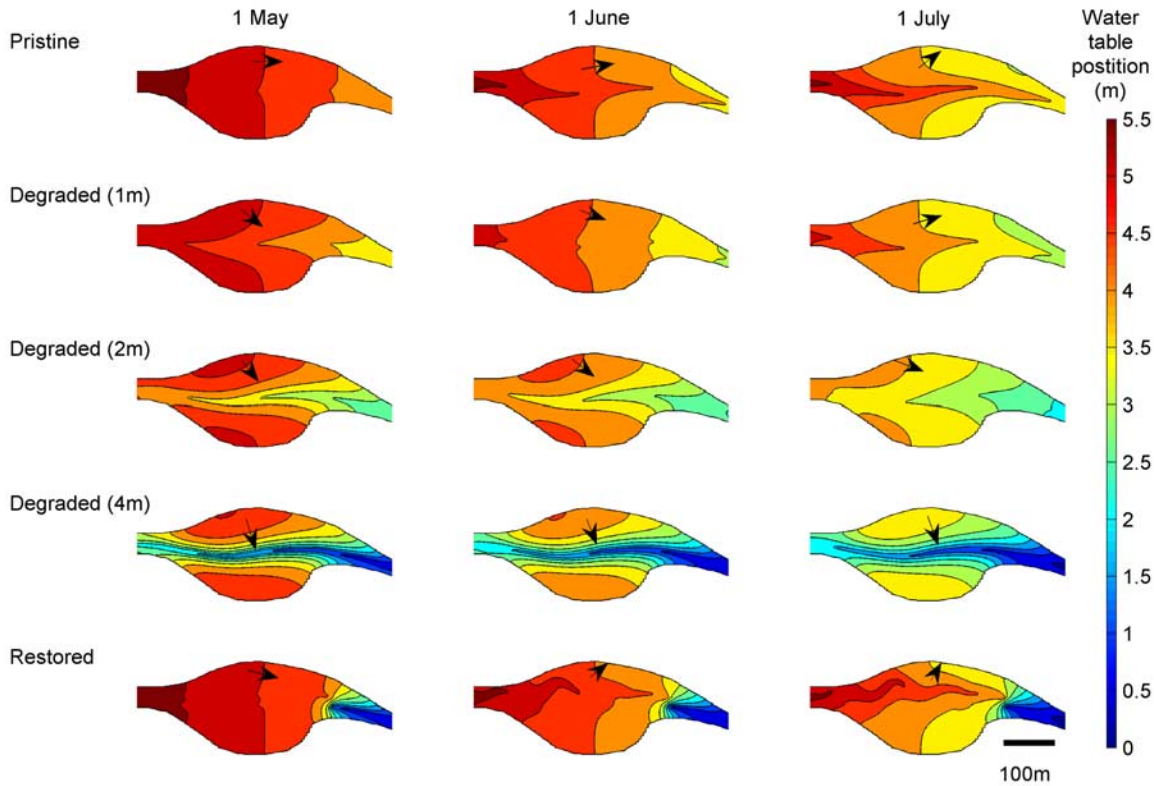

Figure 12. Contour plots of the water table elevation at three times (1 May, 1 June, and 1 July) for all five simulation cases. Arrows indicate approximate groundwater flow direction.

4.2.2. Slightly Degraded Case

[36] Second, we compare the observed hydrograph at Big Flat in 2004 (Figure 4) and the simulated case of slight degradation with 1 m of incision (Figure 11). In both the observed and simulated hydrographs representing the case of slight degradation, the water table is rising in January and February, but the meadows have not yet reached complete saturation. Complete saturation at Big Flat (2004) and in the degraded 1 m case both occur for only a 4–5 week period associated with the spring snowmelt during March. The data and simulations show that after the end of meadow flooding associated with spring snowmelt, the groundwater in the meadow quickly (~2–3 weeks) drains to the level of the semi-incised channel (~1 m). After that time, down-meadow groundwater flow and ET further lower the water table. Similar to the pristine and degraded cases discussed previously, the important difference between slightly degraded cases is that the observed hydrograph in Big Flat (2004) does not begin to rise as early in the fall as the simulated degraded 1-m hydrograph. This early recharge does not occur in the degraded 2-m case.

[37] In order to compare the slightly degraded case to the nondegraded cases considered earlier, we point to a very interesting and telling difference between water year 2004 and water year 2005 in the April through July period at Big Flat. Although Big Flat was originally restored in 1995, an additional pool and riffle treatment was performed on the channel during August 2004 (after stream flow had ceased). The purpose of this treatment was to correct for the oversized channel that was initially constructed. This effectively raised the streambed from approximately 1 m to 0.5 m below the meadow surface, by adding a series of rip-rap riffles with associated backwater effects. At Big Flat in 2004, the brief plateau in the water table hydrograph during March, represents meadow flooding during which the water table/free water surface is at or slightly above the meadow surface. The riffle treatment affected the hydrograph such that meadow flooding was more extensive, and because there was effectively less stream incision, the water table dropped to a lesser extent before slowly declining during the rest of the season. This change is similar to the differences between the simulations for the degraded 1-m case and the pristine case (Figure 11). In the pristine case simulation, meadow saturation extends into mid-May, whereas in the degraded 1-m simulation meadow saturation ends immediately after the snowmelt at the end of March. Similar to the observed hydrographs in Big Flat for 2004 and 2005, respectively, the pristine simulation case remains saturated until ET begins in May, whereas in the degraded 1-m simulation, meadow drainage causes the water table to fall in early April as a result of groundwater drainage to the stream. In these simulated cases, the water table continues to fall through June and July because of evapotranspiration, with shallower water tables supporting higher ET rates.

4.2.3. Degraded Case

[38] Third, we compare the water table hydrographs in simulated and observed severely degraded cases. In the degraded cases both at Coyote Flat (Figure 4) and the 4-m incision simulated case (Figure 11) there was insignificant recharge to the water table during the early season precipitation events because much of the infiltration was absorbed by the thick and very dry vadose zone. In observation and simulation, the major recharge to the degraded system occurs during the short period when snowmelt occurs; immediately

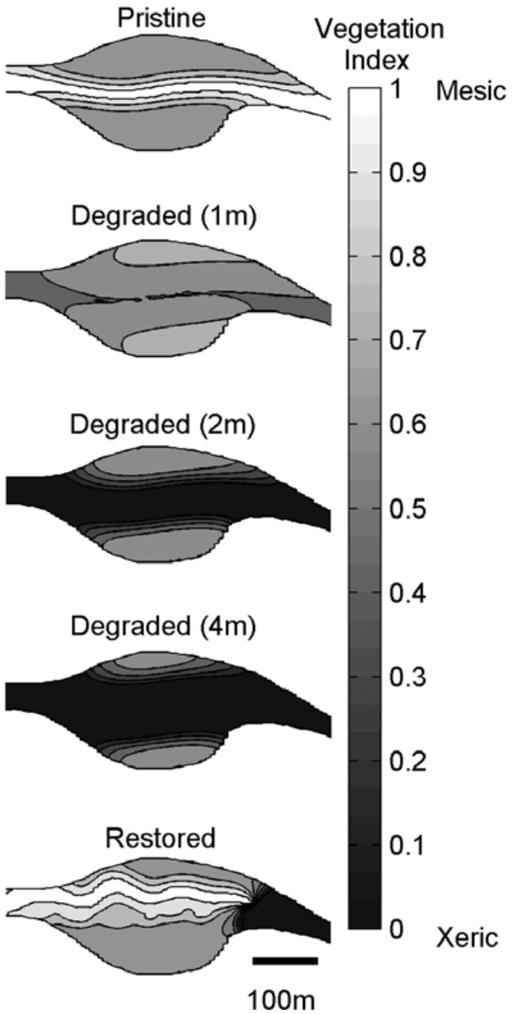

Figure 13. Predicted vegetation patterning based on numerical simulation with a coupled groundwater flow and vegetation model. The model predicts transverse zonation of vegetation communities in all cases. The pristine and restored meadows are populated with dominantly mesic vegetation, however, xeric vegetation becomes increasingly prevalent with increasing stream incision. In the pristine and restored cases, the most mesic vegetation occurs adjacent to the channel; however, this pattern is inverted in the degraded cases. The water table is lowered as a result of stream incision causing an aridification of the soils near the channel and transition to xeric vegetation, particularly near the channel.

following this snowmelt recharge, the position of the water table begins to fall as a result of meadow drainage to the stream. During the growing season, ET also contributes to the observed and simulated drop in the water table. In both the simulated and observed degraded meadow systems, the water table continues to drop even after ET ends in the early fall because groundwater drainage toward the deeply incised channel has a greater effect than the influx of deep groundwater. The only noteworthy difference between the simulations and the observed hydrographs in the severely degraded case is the anomalous portion of the record, which occurs in the observed data at Coyote Flat from December through March. This is probably not reflective of water table changes, but may be due to freezing of water within the well casing, or snow covering the pressure transducer vent tube.

4.3. Pristine Versus Degraded Case Water Table Maps and Groundwater Flow Patterns

[39] The groundwater flow regime exhibits significant differences between pristine and degraded meadow cases. Contoured maps of the water table for all five simulated cases are shown in Figure 12 for 1 May, 1 June, and 1 July. In the pristine case, groundwater flow is dominantly in the downstream direction on the 1st of May, but later in the season, water is flowing from the stream into the meadow sediments. When the meadow is only slightly degraded (1 m of stream incision) groundwater flow is dominantly downstream; the stream is slightly gaining during May, but is a losing stream in the later part of the growing season. With more severe channel incision (2 m and 4 m cases), groundwater flow increases toward the channel. This is because the lower, incised channel drains the meadow sediments more effectively. Not only does stream incision change the direction of groundwater flow, but it also has two additional effects: (1) The lengths of flow paths are shorter and more direct toward the channel and (2) the hydraulic gradients are steeper. Both of these factors decrease the residence time of groundwater in degraded meadows compared to pristine ones. In the restored case, the groundwater flow field resembles that of the pristine case with one marked difference; at the downstream end of the restoration project area, there is a very steep groundwater gradient toward the old, incised channel. In addition, the ponds slightly influence the groundwater flow paths because flow is focused through the ponds as in the case of flow through lakes simulated by *Winter* [1976, 1978]. The generalization that can be drawn from these data is that stream incision exerts control on the groundwater flow system and changes the direction of flow from down-valley to almost exclusively toward the channel, altering the timing and magnitude of baseflow.

4.4. Modeled Hydrologic Fluxes

[40] The absolute and relative magnitude of hydrologic fluxes through the meadow system change in response to stream incision and restoration. For example, the simulated evapotranspirative discharge from the system on 1 June is -3.45×10^{-3}, -3.01×10^{-3}, -2.36×10^{-3}, -2.17×10^{-3} and -3.31×10^{-3} m^3/s, for the pristine, degraded 1 m, 2 m, 4 m, and restored cases, respectively. During this time of year, the groundwater−surface water exchange can be either from or to the meadow aquifer and range from a streambed recharge of 6×10^{-4} m^3/s to a baseflow contribution of 8×10^{-4} m^3/s for these cases. The maximum basal influx of deep groundwater is 5.6×10^{-4} m^3/s for all cases. The peak infiltration into the meadow system is as high as 1.1×10^{-2} m^3/s, during the snowmelt in March. Comparison of these fluxes reveals that while ET and recharge are the dominant processes, deep groundwater inflow and stream-aquifer interactions cannot be neglected.

4.5. Hydrogeologic Determinants of Vegetation Patterns

[41] Here we show the results of simulated vegetation patterns (Figure 13) and compare them to those observed in both nondegraded and degraded meadow systems. Under

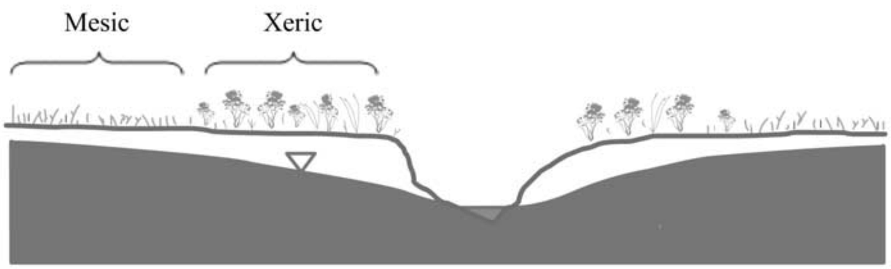

Figure 14. Schematic diagram showing vegetation patterning of a swath of xeric vegetation adjacent to the stream channel. This zonation of vegetation is caused by a water table which slopes toward the incised stream, creating a drier soil zone near the channel.

the pristine conditions, mesic vegetation is dominant throughout the meadow and occurs exclusively in certain portions. The exclusively mesic vegetation occurs near the channel with some mixed vegetation occurring closer to the meadow margins. This is similar to the zonation described by *Dwire et al.* [2006, Figure 3, p.134] for two meadows that were among the least disturbed in their study region in northeast Oregon. None of the meadows in our field area are in pristine condition.

[42] Simulations suggest that the former vegetation pattern becomes inverted as degradation occurs with 1, 2, and 4 m of stream incision. In other words, as observed in the field, the xeric vegetation occurs near the stream. For example, the meadow shown in Figure 3a has ~2 m of stream incision and bears similarity to our simulated 2-m incision case. Both the observed and simulated vegetation pattern suggests a narrow swath of xeric vegetation adjacent to the channel and more mesic vegetation toward the meadow margin. In addition, Coyote Flat, which exhibits incision depths of ~3 m, (Figure S3a) has a vegetation pattern shown in Figure 3b. Coyote Flat contains dominantly xeric vegetation, with small populations of mesic vegetation at the extreme margin of the meadows. The observed pattern closely resembles that predicted in the 4-m incision case (Figure 13) where xeric vegetation becomes increasingly dominant near the channel.

[43] Interestingly, for the cases of 2 and 4 m of incision, exclusively xeric vegetation is found adjacent to the channel. This pattern is counterintuitive to the notion of sagebrush encroachment. Typically, sagebrush encroachment is thought of as the movement of sagebrush from its natural position on the hill slope to the margins of the meadow as a result of soil aridification. However, in the degraded meadows the soil adjacent to the incised channel is the driest because of the severe lowering of the water table in this region as groundwater discharges to the stream. The drying of the near-stream unsaturated zone results in conditions favorable to xeric vegetation as shown in Figure 14. At the margins of the meadow, conditions are suitable for supporting mixed xeric/mesic vegetation. These holdout populations contribute to the resilience of the meadow and are particularly important to the success of restoration.

[44] In the simulated restored case, conditions very similar to the pristine case exist. Exclusively mesic vegetation occurs near the channel and dominantly mesic vegetation occurs near the margin. However, near the lower end of the restored reach, xeric vegetation dominates and occurs in the lower end of the restored reach because of the draining in this portion of the meadow. This vegetation pattern is very similar to that seen at the downstream end of the restoration reach at Artray Meadow (Figure 3c).

5. Discussion

5.1. Related Meadow Systems

[45] Here we discuss some features of degraded versus nondegraded meadows that we do not simulate, but about which some comments are in order. One process not included in this study is the difference in meadow flooding regime in the restored and pristine cases as compared to the degraded meadows. Surface flooding and consequent surface water storage can result in longer periods of inundation and delay the onset of meadow drainage. This process is not only affected by the depth of stream incision, but is strongly influenced by the contributing area, condition of the upstream watershed, and valley slope. A large, pristine watershed upstream of the study meadow would favor extended meadow flooding, delayed surface and subsurface drainage, and mesic vegetation; whereas, the opposite effects are more likely downstream of small, degraded watersheds.

[46] Although the case of an ephemeral stream was not simulated in this study, a brief discussion of how this system may behave differently is worthwhile. Many of the streams which are tributary to Last Chance Creek are ephemeral. Streamflow typically ceases between the months of May and July, but returns in the fall. The onset of flow is either associated with early season precipitation events or the senescence of vegetation that uses groundwater that would otherwise flow to the stream. It is important to note that while there is no surface water flow in these tributary meadows, they do have significant, down-valley groundwater flow that reaches the main stem meadow system where the stream valleys converge. In other words, there is no tributary surface flow, but there is tributary groundwater flow from low-order ephemeral meadow valleys. In these ephemeral systems, once streamflow ceases the channel no longer serves as a boundary condition for the meadow's groundwater flow system. This implies that a groundwater gradient away from the stream in the pristine, degraded (1 m) and restored cases would not likely develop (or would not last as long) if the streamflow is intermittent through a given reach. Instead of a groundwater flow reversal shifting flow from toward the stream to away from the stream, the groundwater flow will transition to a direction subparallel to the valley. These very long groundwater flow paths may provide streamflow reliability late in

the summer season and during droughts. The downstream groundwater discharge would be greatest in the pristine and restored cases because the saturated thickness is greatest in these cases.

[47] In this work, we are predicting equilibrium (steady state) vegetation patterning. We are not considering the rate of change as a succession occurs from one vegetation community to another. We suspect that as stream incision occurs, xeric vegetation may not immediately appear in the zone adjacent to the channel. In fact, the process likely takes many years (or tens of years), and may be dependent on local disturbances of the soil, the proximity of xeric vegetation (often on the hillslopes), and the effectiveness of seed dispersal mechanisms. We have observed that the transition from xeric to mesic vegetation as a result of restoration is quite quick. By the end of the first growing season following pond-and-plug restoration xeric vegetation has often died out and mesic vegetation has reappeared because of the viable seed bank in the meadow soils [*Goodson et al.*, 2001; *Richter and Stromberg*, 2005].

5.2. Methodological Comments

[48] The simulations presented here focus on the effects of stream incision and restoration on vegetation type and pattern; however, the results are also sensitive to a myriad of other parameters in the model. On the basis of preliminary sensitivity analysis, the effects of several parameter value changes are mentioned. (1) An increased basal influx raises the water table and promotes mesic vegetation; the degree of water table rise depends on the consequent rates of discharge as baseflow and ET. (2) A decrease in the porosity or an increase in the residual moisture content decreases the storage capacity of the sediments resulting in a water table that responds more quickly to meadow drainage or ET; this change encourages xeric vegetation except in the case of a strongly losing stream. (3) An increase in hydraulic conductivity increases the rate of meadow drainage, resulting in a lower water table and more xeric vegetation (except in the case of a losing stream).

[49] Sediment heterogeneity may create vegetation anomalies by affecting the local, site specific groundwater flow patterns. For example, high-K stream deposits may result in earlier drainage of nearby sediments favoring xeric vegetation, whereas meadow stratigraphy may result in local perched water tables that would locally favor mesic vegetation. These effects and others resulting from sediment heterogeneity, variability in annual precipitation, climate change, and meadow geometry could be explored through an additional suite of simulations.

[50] Methodologically, we found the iterative procedure used to determine vegetation patterning to be quite efficient. Four to six iterations (each requiring 0.5–3 days of single processor computer run time) were necessary to reach an equilibrium vegetation pattern for each case. We found that successive iterations tend to oscillate around the actual vegetation index but the solution rapidly converges. Consider the case where a particular iterate predicts a vegetation index that is too high (mesic). Under these conditions, the groundwater flow model will extract too much water for evapotranspiration, lowering the water table below the equilibrium conditions. Thus the next iterate would predict a vegetation index that is too low (xeric). These two solutions bracket a range in which the actual solution should reside. Geometric considerations prevent this logic from holding strictly under all conditions (e.g., one region has been overpredicted and another underpredicted), but we found that the solution converged to a value lying within this range in our cases.

[51] In this approach, we have chosen to use the depth to the water table as a predictor of vegetation community. This is likely a good choice for groundwater-dependent ecosystems in semiarid and arid environments. However, compilation of additional data from many sites and for longer time periods would be helpful to better define the vegetation threshold hydrograph and account for (1) different species composition occurring at additional meadows, (2) adaptations of local populations to water table depths, and (3) year-to-year variability in water table depth which often occurs in semiarid ecosystems. In addition, the approach can easily be adopted to condition the vegetation response to other variables. For example, a specific hydroperiod may be required for a specific wetland vegetation community to flourish; in this case, the number of continuous days of inundation/saturation could be used as a predictor of vegetation response. In humid environments, the primary source of water may be rainfall percolating through the vadose zone; under these conditions it may be more appropriate to use soil moisture as a predictor of vegetation community. Similarly, models of nutrient availability, salinity, required soil redox conditions [*Dwire et al.*, 2006], fire response [*Wright and Chambers*, 2002] or soil characteristics could also be included to condition the vegetation response. An advantage of our approach is that many or few criteria can be included to condition the vegetation response. The disadvantage is that neither these criteria nor their relative importance are well known.

[52] The vegetation threshold hydrograph is likely site specific and strongly influenced by soil texture. *McKinstry* [2004, p. 299], identified hydrologic needs of riparian vegetation, specifically in terms of minimum depth to water table requirements, as a critical gap in knowledge for systems similar to the ones considered here. However, many depth to water table requirements are reported in the literature for meadow vegetation communities [e.g., *Allen-Diaz*, 1991; *Dwire et al.*, 2006; *Castelli et al.*, 2000; *Chambers et al.*, 1999; *Martin and Chambers*, 2001; *Steed and DeWald*, 2003; *Blank et al.*, 2003; *Chambers and Miller*, 2004]. The difficulty is that there is not a definitive consensus among the reported values. The reason for these discrepancies is likely twofold: (1) Most studies report a mean depth to the water table, even though the water table varies seasonally and a time-dependent measure of water table depth may be necessary (e.g., the integrated variables of *Castelli et al.* [2000]) and (2) physiologically, soil tension in the root zone may exert a more direct control on vegetation (than depth to the water table) and this parameter is related to depth to water in a nonlinear fashion that depends on soil hydraulic properties. The threshold vegetation hydrograph accounts for (1) by presenting the depth requirements as a function of time, but because of (2), it should be noted that different threshold hydrographs may exist for different soil types.

6. Conclusions

[53] Our coupled hydrologic vegetation patterning simulations suggest that the dramatic hydroecologic changes that

have occurred in the Last Chance watershed were a result of the hydrologic consequences of stream incision. Our hydroecological model reproduces key features including (1) the overall shift in vegetation communities in such meadows resulting from falling water tables discussed by *Elmore et al.* [2003] and (2) the general vegetation patterning in a nearly pristine meadow observed by *Dwire et al.* [2006, Figure 3] and the patterns observed in Figure 3 for the degraded and restored meadow systems (compare to the vegetation patterning in Figure 13).

[54] In the discussion section above, six topics are explicitly mentioned that may prove to be interesting avenues of future research. (1) This work focuses on near surface hydrology, but explicit modeling of meadow flooding and surface hydrology would likely improve predictive capabilities at specific sites. (2) Both field-based and modeling comparison of ephemeral versus perennial meadow systems could help determine the relative importance of groundwater flow to and from the stream and in a downmeadow direction. (3) Here we have predicted the equilibrium distribution of vegetation communities, but future work should also consider how these vegetation communities patterns evolve through time as a result of both sudden and gradual changes to the hydrology. (4) We primarily explored the effect of stream incision and restoration on a meadow; however, a sensitivity analysis to the parameter values used would provide insight into meadow characteristics that identify them as either more susceptible to degradation or good targets for restoration. (5) The vegetation threshold hydrograph is likely site or soil-type specific; further work on this topic would help determine under what conditions or with what modifications the threshold hydrographs can be exported to other sites. (6) At our sites groundwater appears to be the dominant control, but at other sites it may be useful to determine other criteria to which the vegetation response may be conditioned (i.e., soil tension and nutrient availability).

[55] Restoration efforts by the FRCRM in the Last Chance Creek watershed have been very successful at reestablishing native vegetation in degraded meadow systems. The pond-and-plug technique of restoration has developed to the current state through 11 years of restoration experience [*Wilcox*, 2005]. As called for by *Palmer and Bernhardt* [2006] and *Wohl et al.* [2005], our modeling framework contributes a quantitative, hydroecological, and scientific context to riparian river restoration analysis. Our approach can be used to predict the vegetative response to restoration during the design phase of a restoration project to help guide successful restoration efforts. It can also be used to help determine whether or not restoration is feasible at a given site, to target potential restoration sites, or to understand the shortcomings of past restoration projects. While this approach was developed for meadow restoration in the northern Sierra Nevada, we hope that it can serve as a framework for understanding and predicting vegetative response to hydrologic changes in other ecosystems.

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