

Stream incision and sagebrush expansion on the Kern Plateau, California:
A Hydrologic Perspective

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Abstract

Within the last hundred years, landscapes across the western United States have experienced stream incision and vegetation change. In wet meadows in the southern Sierra Nevada Mountains, the streams are incising and sagebrush (*Artemisia rothrockii*) has displaced meadow vegetation, dramatically changing a unique alpine habitat. This study examines the relationship between vegetation and water table depth and the impacts of stream incision on the meadow hydrology in order to determine whether the hydrologic changes associated with stream incision are responsible for sagebrush encroachment. To document these relationships, Bullfrog Meadow on the Kern Plateau, Sierra Nevada Mountains was surveyed and 34 groundwater-monitoring wells were installed. Water table measurements and hydraulic conductivity data were collected during the summer of 2003. Data on stream discharge, sediment type, and vegetation distribution were also gathered. As observed in other studies, there is a strong correlation between vegetation type and water table depth. The water table is on average 50 cm below meadow vegetation within the study area, 120 cm below sage meadow vegetation, and on average 200 cm below sagebrush vegetation. In the incised region of the meadow, stream incision lowered the water table adjacent to the stream by up to 150 cm and approximately 50 cm further from the incised stream. The groundwater flow direction, water table gradient and stream discharge have also been altered by the incision. These results indicate that the hydrologic effects of stream incision may have significant impacts on vegetation change and should be considered in meadow restoration studies.

Keywords

alpine, ecosystems, hydrology, water table, groundwater, Sierra Nevada

Introduction

In the arid and semiarid western United States, soil moisture determines the distribution between woody plants and herbaceous meadow plants. In the last century, shrubs including creosotebush (*Larrea tridentata*) and sagebrush (*Artemisia sp.*) have invaded grasslands because of changes in soil moisture. A combination of biotic and abiotic controls are responsible for these changes (Martin and Chambers, 2001).

Biotic controls of soil moisture include animal grazing and differences in plant morphology and physiology (Gifford and Hawkins, 1978; Berlow et al., 2003; Bhark and Small, 2003). Intensive grazing decreases herbaceous plant density, which leads to reduced infiltration rates and exposed soil and causes losses in soil moisture (McCalla et al., 1984; Trimble and Mendel, 1995; Martin and Chambers, 2002). Soil compaction from livestock grazing also reduces soil moisture by increasing runoff and decreasing infiltration (Gifford and Hawkins, 1978; McCalla et al., 1984; Trimble and Mendel, 1995). Plant-related infiltration and evapotranspiration differ for woody species and for herbaceous species. This causes plant-induced water gradients (Bhark and Small, 2003). In arid and semiarid regions, biotic factors often act as positive feedbacks on soil moisture gradients introduced by the groundwater (Martin and Chambers, 2001).

Studies have shown that depth to the water table is the most important abiotic control on soil moisture in semiarid and arid regions (Allen-Diaz, 1991; Stromberg et al., 1996; Castelli et al., 2000). When groundwater elevations are lowered, the reduction in available soil moisture can drive out wet meadow vegetation and allow plants with a tolerance for lower water tables to invade (Scott et al., 1999; Castelli et al., 2000). For example, in the Sierra Nevada Mountains, meadow vegetation is associated with water

table depths of 20-50 cm of the land surface (Allen-Diaz, 1991). In central Nevada, meadow vegetation has water table depths within 50 cm of the land surface while sagebrush has water table depths 200 cm below the land surface (Castelli et al., 2000). In either study, a drop in water table elevation below 50 cm from natural hydrologic changes or human groundwater use would cause a change in vegetation (Or and Groeneveld, 1994; Elmore et al., 2003; Wurster et al., 2003)

In the last hundred years, it is well documented that incision has increased in many streams in the western United States. The impacts on groundwater hydrology of this incision have been studied as one possible cause of vegetation change (Scott et al., 2000; Wurster et al., 2003). The sediment/water balance is widely accepted as the principal control on stream morphology and evolution. Changes in the amount of sediment or runoff reaching the stream channel can cause aggradation or incision (Kondolf et al., 2002). Sediment starvation and/or increased stream flow could be responsible for the widespread stream incision in the southwestern United States in the context of geology, climate, and land use. Miller (2001) studied the evolution of the streams in central Nevada basins. Between 2500 and 1300 years ago, a dry, warm climate initiated hillslope erosion, alluvial fan growth, and main valley deposition. The hillslopes in the study area have been depleted in fines since this period of high erosion; so today incision of valley streams is being driven by high magnitude, sediment-deficient spring snowmelt (Miller et al., 2001).

Within the last century, montane meadows in the southern Sierra Nevada Mountains along the Kern River have experienced expansion of native sagebrush (*Artemisia rothrockii*), stream incision and aridification (Wood, 1979; Berlow et al.,

2002; Berlow et al., 2003) (Figure 1). Sagebrush historically populated the edges of the meadows on the dry hillslopes and upper terraces between the meadows and lodgepole pines (Wood, 1979). The stream has incised in many of the meadows along the South Fork of the Kern, creating abandoned terraces (Wood, 1979; Collins, 1995). This study hypothesizes that stream incision changed the depth to the water table near the stream thus lowering the soil moisture available to plants on the surfaces of the new terraces. The lower soil moisture makes these areas less viable for meadow vegetation, which allows sagebrush expansion (Figure 2).

This study examines the relationship between depth to water table and vegetation type in one meadow on the Kern Plateau and assesses how altered meadow hydrology might be responsible for the change in the ecosystem. Specifically it: 1) examines the relationship between vegetation and shallow groundwater hydrology; 2) quantifies the impact of stream incision on the subsurface hydrology; and 3) considers how changes in hydrology may have contributed to sagebrush expansion.

Study Area

Bullfrog Meadow (UTM Zone 11, 391200 m, 4029400 m) is a 0.38 km² alpine meadow in the southern Sierra Nevada Mountains, California (Figure 1). The meadow elevation ranges between 2850 and 2900 meters. Bullfrog Meadow was unglaciated during the Pleistocene and alluvial valley fill overlies granitic bedrock. The semiarid alpine climate receives approximately 50 cm annual precipitation from a varying winter snow pack and about 7 cm from summer thunderstorms (Berlow et al., 2003). The

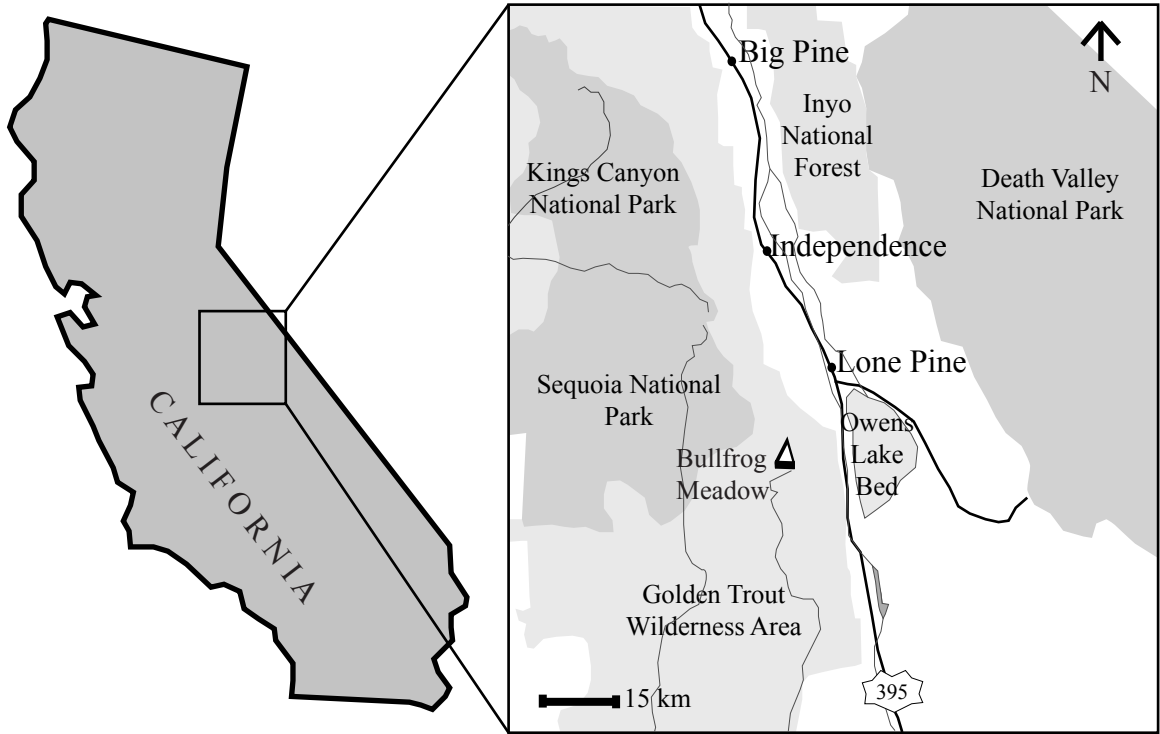


Figure 1. Location Map of Study Area. Bullfrog Meadow is marked by the triangle. The Kern Plateau is south of the Sequoia National Park.

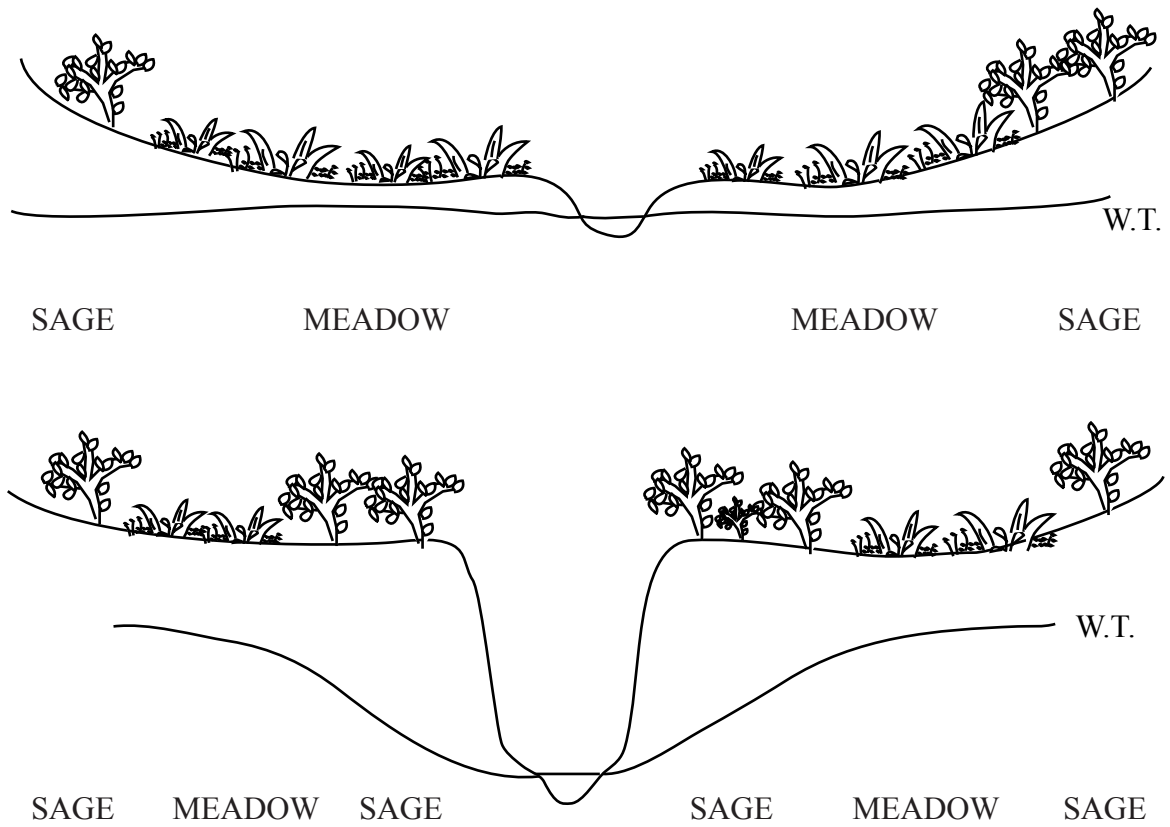


Figure 2. Schematic diagram of vegetation pattern before and after stream incision on the Kern Plateau. Before stream incision, meadow vegetation (MEADOW) is adjacent to the stream and sagebrush (SAGE) is on the hillslopes. After incision, the water table (W.T.) lowers to intersect the new stream elevation. The lowered water table reduces soil moisture allowing sagebrush to populate the incised stream banks (Modified from Trimble and Mendel, 1995).

meadow is principally drained by one stream fed by snowmelt, rainfall and perennial springs. The groundwater system in the meadow is shallow with water table depths between 0 and 200 cm below land surface. The plant community is comprised of herbaceous plants including *Carex* spp., *Eleocharis* spp., *Juncus* spp., *Deschampsia* spp., *Poa* spp., and *Potentilla gracilis*, and the woody plant sagebrush (*Artemisia rothrockii*).

Like most meadows along the South Fork of the Kern River, Bullfrog Meadow is undergoing stream incision and sagebrush encroachment. In the last century, stream incision has worked halfway up the meadow, creating a knickpoint. Watershed crews from the Inyo Forest Service stabilized the knickpoint with boulders and logs, slowing its migration rate. In the unincised region of Bullfrog Meadow upstream of the knickpoint, sagebrush has historically been—and still is—limited to hillslopes and alluvial fans. Downstream of the knickpoint, sagebrush has spread to the areas adjacent to the incised stream and continues to spread away from the stream. These new growth sites are a shift from historical sagebrush habitat (Figure 3).

Methods

Bullfrog Meadow was selected for this study because the current patterns in vegetation distribution and stream incision can be used in a space-for-time substitution, where spatial variation is equated to change through time. In this study, the region upstream of the knickpoint represents the initial state before stream incision and sagebrush expansion. The region downstream of the knickpoint represents the final state because the stream is incised and sagebrush has invaded. Differences between the groundwater system above and below the knickpoint can be related to vegetation

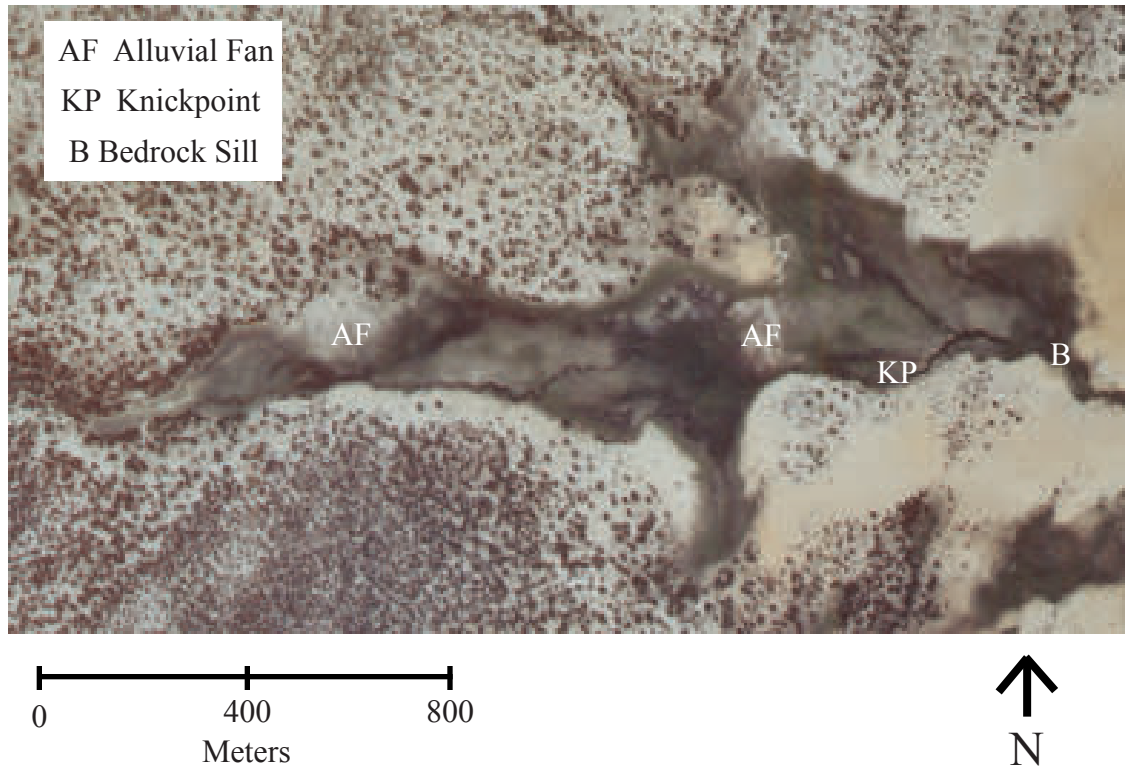


Figure 3. 2001 aerial photograph of Bullfrog Meadow. The darker areas are meadow, which are often found behind an alluvial fan or bedrock sill. The lighter colored sagebrush is found on the hillslopes, alluvial fans and below the knickpoint.

distribution, stream incision and time. To determine the conditions before and after stream incision, five transects above and below the knickpoint were sampled for topography, vegetation, sediment, depth to water table, hydraulic conductivity, and stream discharge in the summer of 2003. The transects run perpendicular to the principal stream with two located above the knickpoint, one directly below the knickpoint and two further downstream (Figure 4).

Transect Sampling

The five cross-valley profiles and a longitudinal profile of the stream were surveyed to define relative elevations of well locations, stream gradient, and basin topography. Surveys were completed using an automatic level and rod and were adjusted to a benchmark from a differentially corrected GPS unit.

Groundcover along each transect was assigned to one of three classifications: meadow, sage meadow, or sage. Meadow is composed solely of herbaceous grasses, sedges, rushes and forbs within one square meter of the survey, sage meadow is a mixture of herbaceous plants and sagebrush and sage is sagebrush within one square meter of the survey.

For each of the five transects, the sediments were cataloged based on texture, Munsell soil color, and reduction/oxidation (redoximorphic) features in approximately 1.5 m-long cores (8-12 cores per transect). Redoximorphic features included any of the following; iron and manganese concentrations, mottling, or gleying.

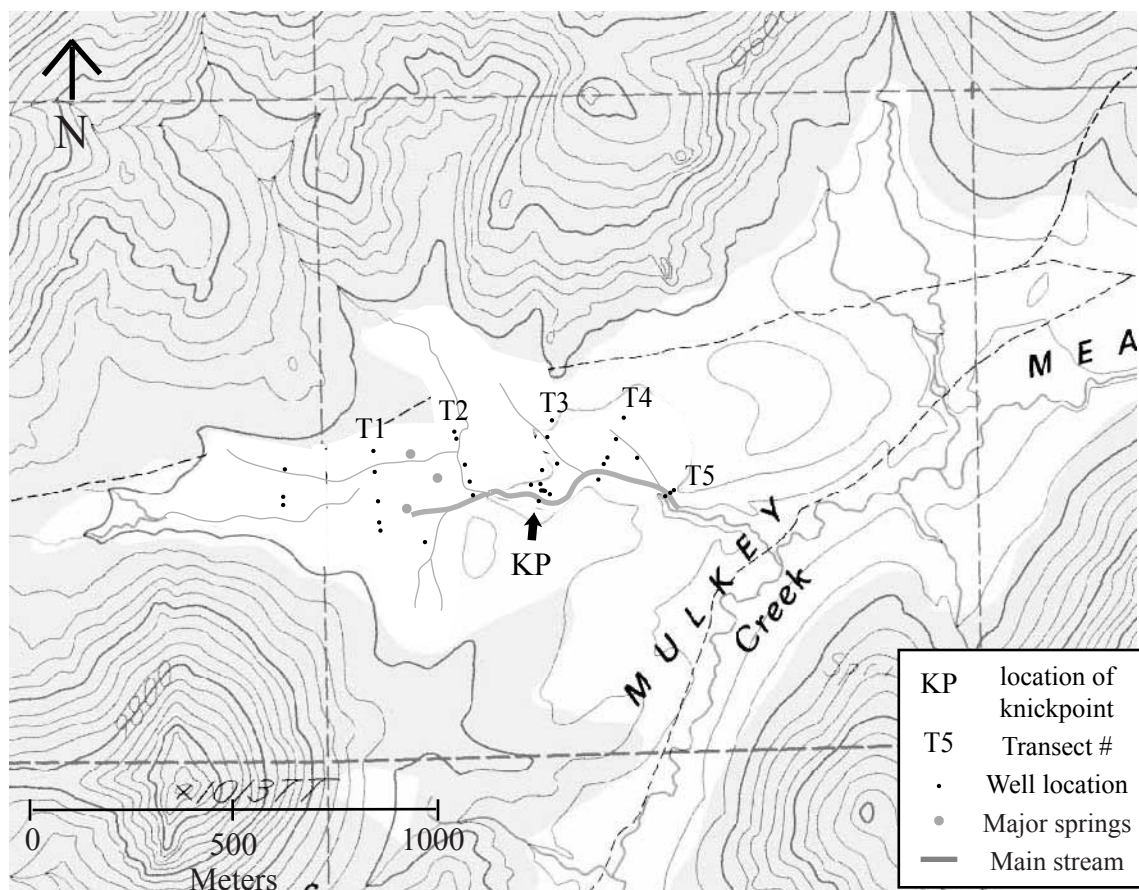


Figure 4. Transect and well location map of Bullfrog Meadow. Transects are labeled T1, T2, T3, T4, T5. All five transects were sampled for topography, vegetation, sediment, depth to water table, hydraulic conductivity, and stream discharge in the summer of 2003. Discharge was also measured for the major springs shown. There are 15 wells above the knickpoint and 19 wells below it. The topographic contour interval is 40 ft.

Hydrology

In the fall of 2002, 24 shallow groundwater-monitoring wells were installed on the five transects across Bullfrog valley, with an additional ten wells above and adjacent to the knickpoint. Fifteen wells were installed above the knickpoint and nineteen were installed below it (Figure 4). The wells were constructed out of PVC pipe with an inner diameter of 3.45 cm. The PVC wells were screened with horizontal slits for 50 cm and installed using an 8 cm diameter soil auger. Gravel was used to fill around the screened portion of the wells and the rest of the hole was backfilled with excavated sediments. Installation was conducted in the early fall at annual low water table so that the screened section would be below the annual average water table. After installation, the wells were developed with a plunger rod to purge sediment from the well slits and decrease the skin effect associated with installation (McElwee, 2002).

The depth to water table was measured for the 2003 summer season using an electrical resistivity meter. For each well, water table data was taken twice a week between June 15 and July 20 and once a week until August 15.

Hydraulic conductivity (K) was estimated for the sediment around the screened section using duplicated slug tests on 19 of the wells. A two-gallon slug of water was quickly added to each well and a pressure transducer measured the drop in pressure over time as the well re-equilibrated. Two different calculations were used to estimate hydraulic conductivity, the Bouwer and Rice slug test method (Bouwer and Rice, 1976) and the Hvorslev time-lag method (Hvorslev, 1951). (Information on the two methods used to calculate K is presented in Appendix 1.)

Stream velocity was measured at each transect and at the major springs using a flow meter once in June and twice in July (Figure 4). Velocity measurements were taken at 0.2, 0.6, and 0.8 of flow depth every 10 cm across the stream. The 0.2 and 0.8 velocities were averaged. This value was then averaged with the 0.6 velocities for each segment following the techniques of Fetter (2001). The area and velocity of each stream segment were multiplied together. All the stream segments were added together for the discharge of each transect and spring. The discharges for Transect 1 and the major springs in Upper Bullfrog were combined into the Upper Bullfrog discharge.

Spatial Analysis

Swartz, Berlow and D'Antonio studied vegetation change in Bullfrog Meadow using ArcGIS to compare aerial photographs (Swartz et al., in prep.). The polygons prepared by Swartz et al. (in prep.) from the 1974, 1994, and 2001 aerial photographs of Bullfrog Meadow were used in this study to correlate hydrology with vegetation change. They divided vegetation into meadow and sagebrush, where sage meadow was considered part of the sagebrush polygon.

ArcView version 3.2 Spatial Analyst was then used to examine the spatial relationship between topography, groundwater elevation, hydraulic conductivity and vegetation type. Topographic data was obtained from a 10m Digital Elevation Model (DEM). Field data from the summer of 2003 was used for average water table depth, stream elevation and hydraulic conductivities. The mean and standard deviation of the elevation and hydraulic conductivity was found for the sage and meadow vegetation

types. The mean hydraulic conductivity was determined for 0-50, 50-100, 100-150 m distance from the stream.

Results

This section presents results for data gathered on vegetation and stream incision in relation to hydrology measurements from Bullfrog Meadow. The data used to examine vegetation include vegetation distribution, water table elevations, topography, and hydraulic conductivity. The data used to examine stream incision include the longitudinal profile of the stream, the water table relative to the distance and elevation of the stream, discharge measurements from the five transects, and redoximorphic features. Finally, vegetation and stream incision variables are correlated above and below the knickpoint.

Vegetation and Hydrology

The vegetation distribution and area of meadow and sagebrush vegetation can be compared between 1974, 1994 and 2001 (Figure 5). The 1974 aerial photograph includes the lower half of Bullfrog Meadow, and within that area sagebrush represents 31% of the vegetation. For both 1994 and 2001, sagebrush represents 43% of the vegetation, and meadow vegetation represents 57%. Sagebrush vegetation has always been found on the edges of Bullfrog and is often located on alluvial fans. It is more prevalent in Lower Bullfrog than in Upper Bullfrog in 1994 and 2001.

Summer measurements from 34 wells demonstrate the depth to water table varies with respect to vegetative cover. The average water table depth in the meadow areas

ranges from 20 cm to 60 cm. The sage meadow areas have water table depths ranging from 90 cm to 122 cm. The sage areas have water table depths between 124 cm and 144 cm. Water table records show little deviation over the summer season, but the most responsive water table is in meadow areas. The water table in meadow areas dropped in early June by 20 cm and rose in response to a group of August thunderstorms by 10 cm (Figure 6).

In 1974, meadow vegetation in Lower Bullfrog had a mean elevation 1-2 m higher than sagebrush. The trend of the data indicates a topographic relationship between sagebrush and herbaceous meadow from 1994 to 2001. In all of Bullfrog Meadow in 1994 and 2001, the mean elevation of sagebrush is higher than meadow vegetation by 3 m (Figure 7).

The two methods used to calculate hydraulic conductivity (K) produced different results for identical wells. The Hvorslev time lag method yielded minimum and maximum hydraulic conductivities of 1.72×10^{-5} cm/s and 2.9×10^{-3} cm/s (Hvorslev, 1951). The Bouwer and Rice slug-test method yielded values between 5.07×10^{-7} cm/s and 8.97×10^{-4} cm/s (Bouwer and Rice, 1976). The Hvorslev equation estimated hydraulic conductivity values approximately 100 times higher for every well (Table 1).

The measured hydraulic conductivities correspond to the theoretical K values for clayey and silty sand (10^{-5} to 10^{-3} cm/s) (Fetter, 2001), but average conductivities for each transect have a poor correlation with the observed grain size around the screened portion of the wells. Transect 1, in Upper Bullfrog, is mostly clay and peat at the well screen but has a high K . Other transects are mostly sand and gravel at the well screen but have low K values (Appendix 2). After excluding outliers, Hvorslev hydraulic

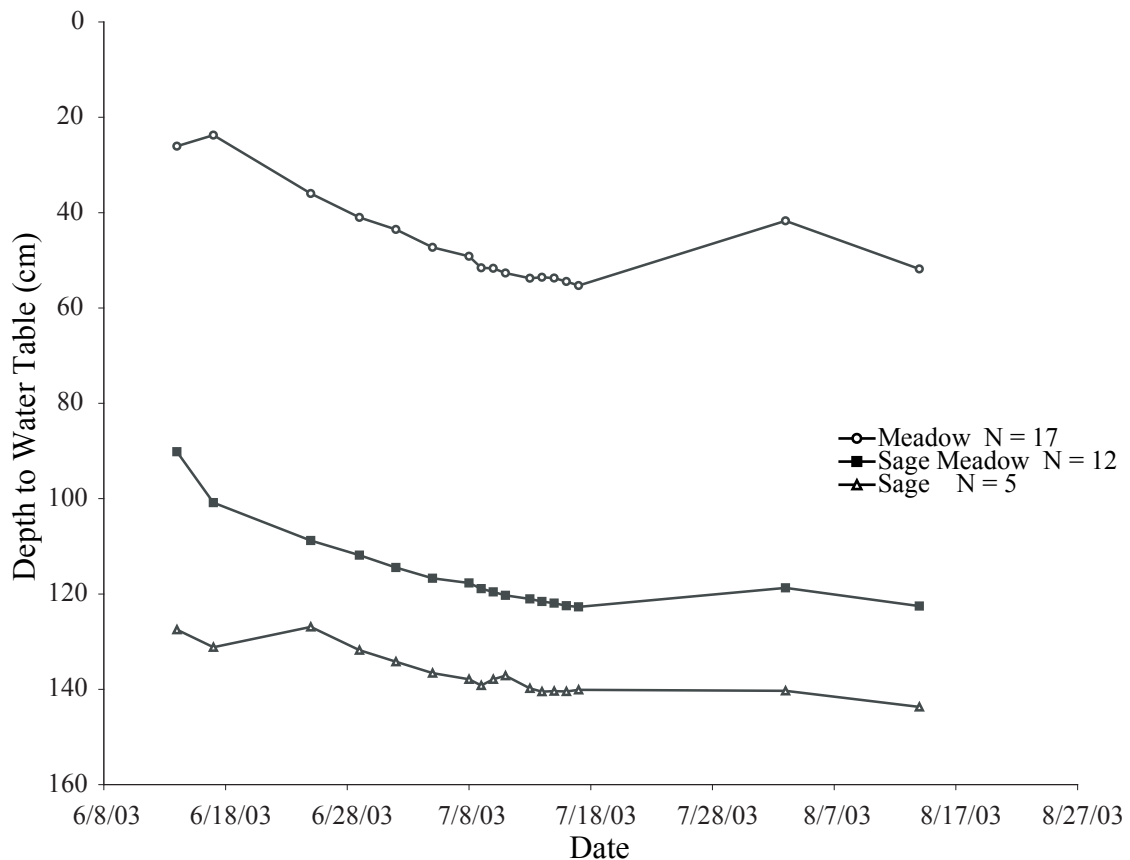


Figure 6. Graph of average water table depth (cm) from June 15 to August 15 for three vegetation types. Meadow vegetation has a much higher water table than either sage meadow or sage. The water table in meadow also fluctuates the most, dropping in early June and rising in response to August thunderstorms.

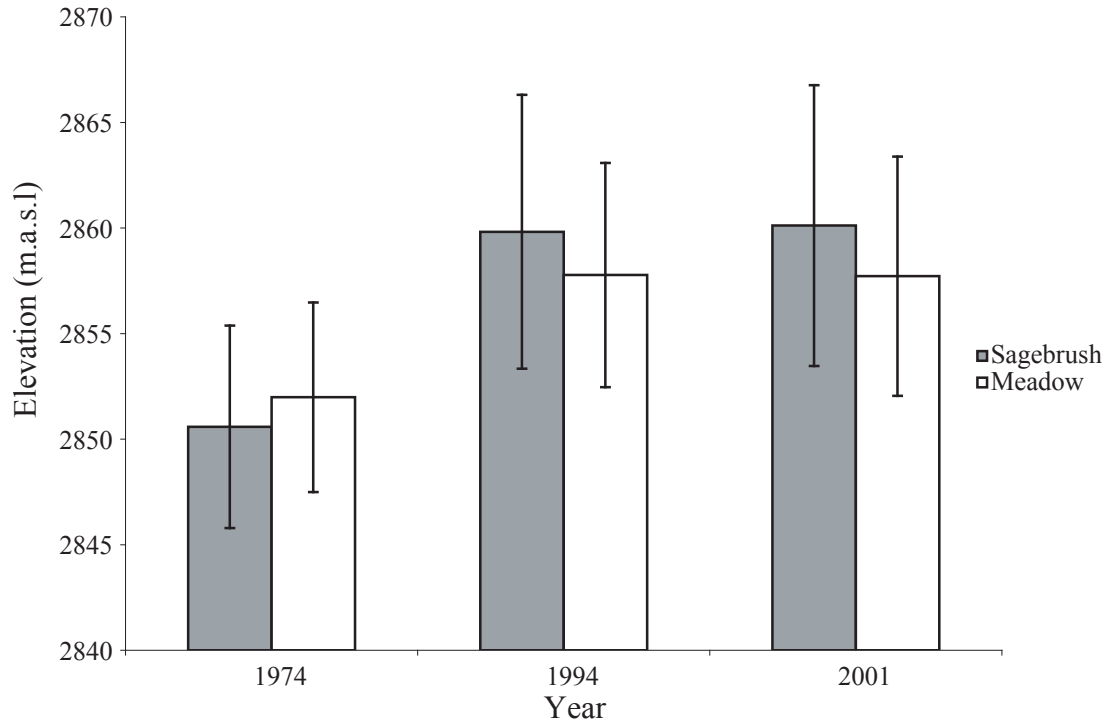


Figure 7. Average elevation of sagebrush and meadow vegetation types in the study area. The 1974 elevation data is only for lower Bullfrog Meadow while 1994 and 2001 data is for all of the meadow. The elevation of sagebrush is higher than meadow in 1994 and 2001 indicating the importance of topography in distribution. Error bars show one standard deviation.

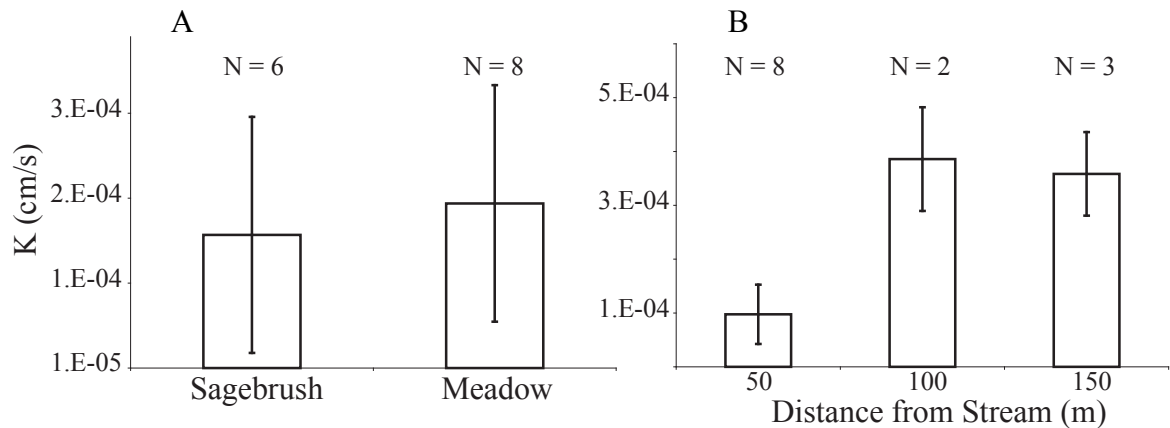


Figure 8. (A) Average hydraulic conductivity values compared to vegetation type. (B) Hydraulic conductivities based on distance from principal stream. There is no statistical difference between K for vegetation types. However, there is a strong correlation for hydraulic conductivity and distance from stream. K values are much lower closer to the stream. Error bars show one standard deviation.

Transect	Well	Vegetation	Hvorslev (cm/s)	Bouwer (cm/s)
1	Well 03	MEADOW	4.82E-04	5.59E-05
1	Well 04	MEADOW	1.31E-03	3.20E-04
2	Well 06	MEADOW	3.72E-05	6.45E-06
2	Well 07	SAGEMDW	9.57E-04	2.04E-04
2	Well 09	MEADOW	4.67E-04	3.55E-04
3	Well 11	MEADOW	1.42E-04	3.88E-05
3	Well 12	SAGEMDW	6.47E-05	9.60E-06
3	Well 14	SAGEMDW	2.90E-04	1.21E-05
3	Well 15	MEADOW	3.17E-04	4.16E-05
3	Well 29	SAGE	7.48E-05	7.99E-06
4	Well 17	SAGE	2.98E-03	2.51E-04
4	Well 18	SAGEMDW	1.45E-04	3.68E-06
4	Well 19	SAGEMDW	1.12E-04	1.03E-05
4	Well 21	MEADOW	2.91E-04	8.97E-04
5	Well 22	SAGEMDW	1.88E-04	2.56E-05
5	Well 24	MEADOW	1.72E-05	5.07E-07
none	Well 26	SAGEMDW	1.40E-04	1.59E-05
none	Well 27	SAGEMDW	9.95E-05	1.60E-05
none	Well 28	MEADOW	7.21E-05	1.32E-05

Table 1. Hydraulic conductivity values for 19 of the wells. K values were calculated using Hvorslev (1951) and Bouwer and Rice (1976) slug test methods. Hydraulic conductivity correlated best with distance from stream (see Figure 8).

conductivities averaged by transect yielded K values of 4.8×10^{-4} cm/s for Transect 1 and 2 and values of 1.5×10^{-4} cm/s for Transects 3, 4 and 5.

There is little difference between the hydraulic conductivity in meadow and sagebrush vegetation for 2001 (Figure 8A). However, comparing hydraulic conductivity to distance from the stream reveals a spatial pattern. The average hydraulic conductivity of wells within 50 m of the stream is 1×10^{-4} cm/s. Wells that are further from the principal stream (100 m and 150 m) have average hydraulic conductivities of 4×10^{-4} cm/s (Figure 8B).

Stream Incision and Hydrology

The longitudinal stream profile shows the primary knickpoint of the stream incision. The difference between bank height and stream elevation is less than 0.5 m upstream of the knickpoint (excluding the alluvial fan on Transect 2) and the stream gradient is 0.006 m/m. Downstream of the knickpoint, the bank height is 1 to 2 m above the stream elevation and the stream gradient is 0.013 m/m (Figure 9).

Above the knickpoint, the water table and the stream have similar elevations. The water table elevation changes little with distance from the stream. The average slope of the water table from the edge of Bullfrog Meadow towards the stream is 0.01 m/m for Transects 1 and 2. Below the knickpoint however, the water table dips steeply toward the stream within 25 m of the stream. Further from the stream, the water table elevation changes more dramatically than above the knickpoint. On Transect 3, the water table has a similar slope to Upper Bullfrog, but Transects 4 and 5 have slopes of 0.02 m/m and 0.013 m/m respectively (Figure 10).

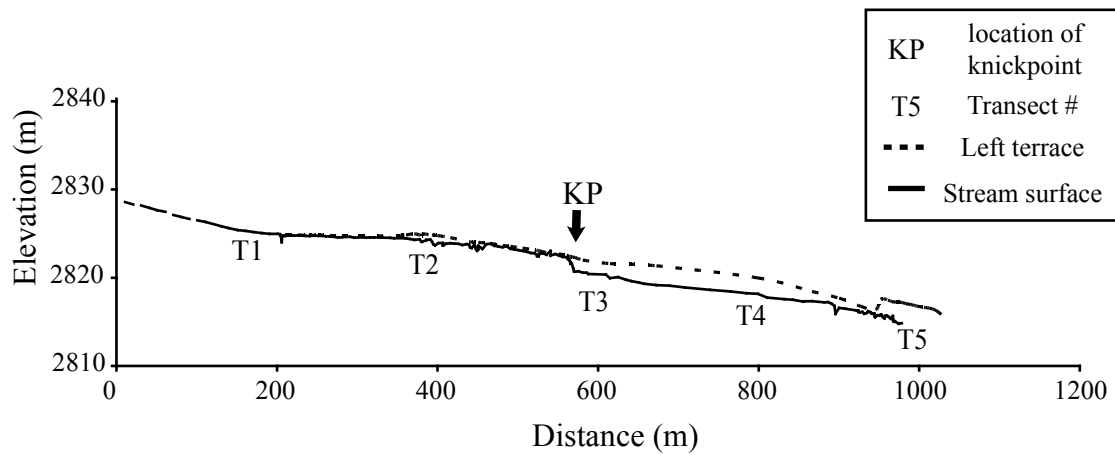


Figure 9. Longitudinal stream profile of Bullfrog Meadow. The gradient above the knickpoint is 0.006 m/m and below the knickpoint is 0.013 m/m.

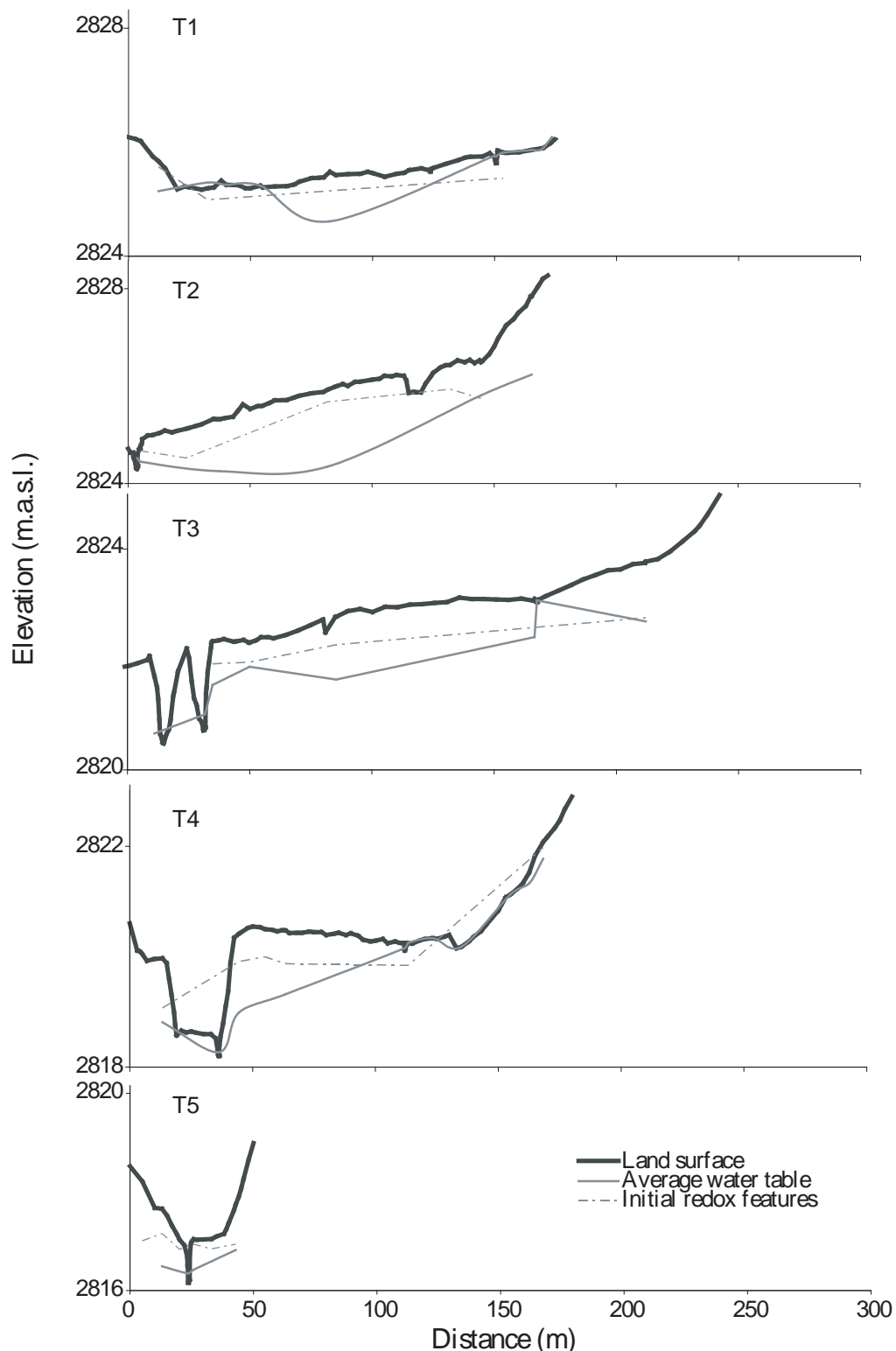


Figure 10. Profiles of the five transects. Average water table and the inferred historic water table line from initial redoximorphic features are included. Above the knickpoint on Transect 1, the water table is high and similar to historic water table depths. Below the knickpoint, the current water table is low next to the stream and is very different from historic water table elevation. 30 times vertical exaggeration.

The elevation of the water table changes in relation to surface topography. Above the knickpoint, the water table is within 1.0 m of the land surface on Transect 1 and 1.7 m below the land surface on Transect 2 (alluvial fan). Below the knickpoint, on average the water table is ~1.0 m below land surface, but is about 2.0 m where topography is changing more dramatically (Figure 10).

Stream discharge varies above and below the knickpoint. Upstream of the knickpoint, discharges dropped between the upper meadow and Transect 2 by about 26 cm³/day and dropped between Transect 2 and Transect 3 by about 30 cm³/day. This indicates a loss of 60 cm³/day upstream and immediately downstream of the knick point (upstream of Transect 3). Below the knickpoint, stream discharge increases between each transect for a total discharge at Transect 5 of approximately 183 cm³/day (Table 2).

The water table contour map of average summer water table elevations indicates changing gradients and flow directions. Upstream of the knickpoint, the water table dips gently away from the stream channel, while at the knickpoint the water table dips steeply away from the stream. In the incised region downstream of the knickpoint, the water table dips steeply toward the channel (Figure 11). The flow arrows, perpendicular to the equipotential lines, indicate a change in flow direction down Bullfrog Meadow. Flow is parallel to the stream channel above the knickpoint and towards the stream channel below the knickpoint.

Initial redoximorphic conditions in the soil cores occur consistently higher than the current water table. Above the knickpoint, initial redoximorphic conditions have similar elevations and geometry to the current water table depth but are about 0.3 m

Average Discharge (cm ³ /d)	
Upper Bullfrog	116.91
T2	91.15
T3	62.31
T4	91.62
T5	182.55

Table 2. Average discharge from flow meter measurements. Measurements from Transect 1 are combined with spring discharges for the Upper Bullfrog values. The knickpoint is directly above Transect 3. The stream is losing before Transect 3 and gaining after Transect 3.

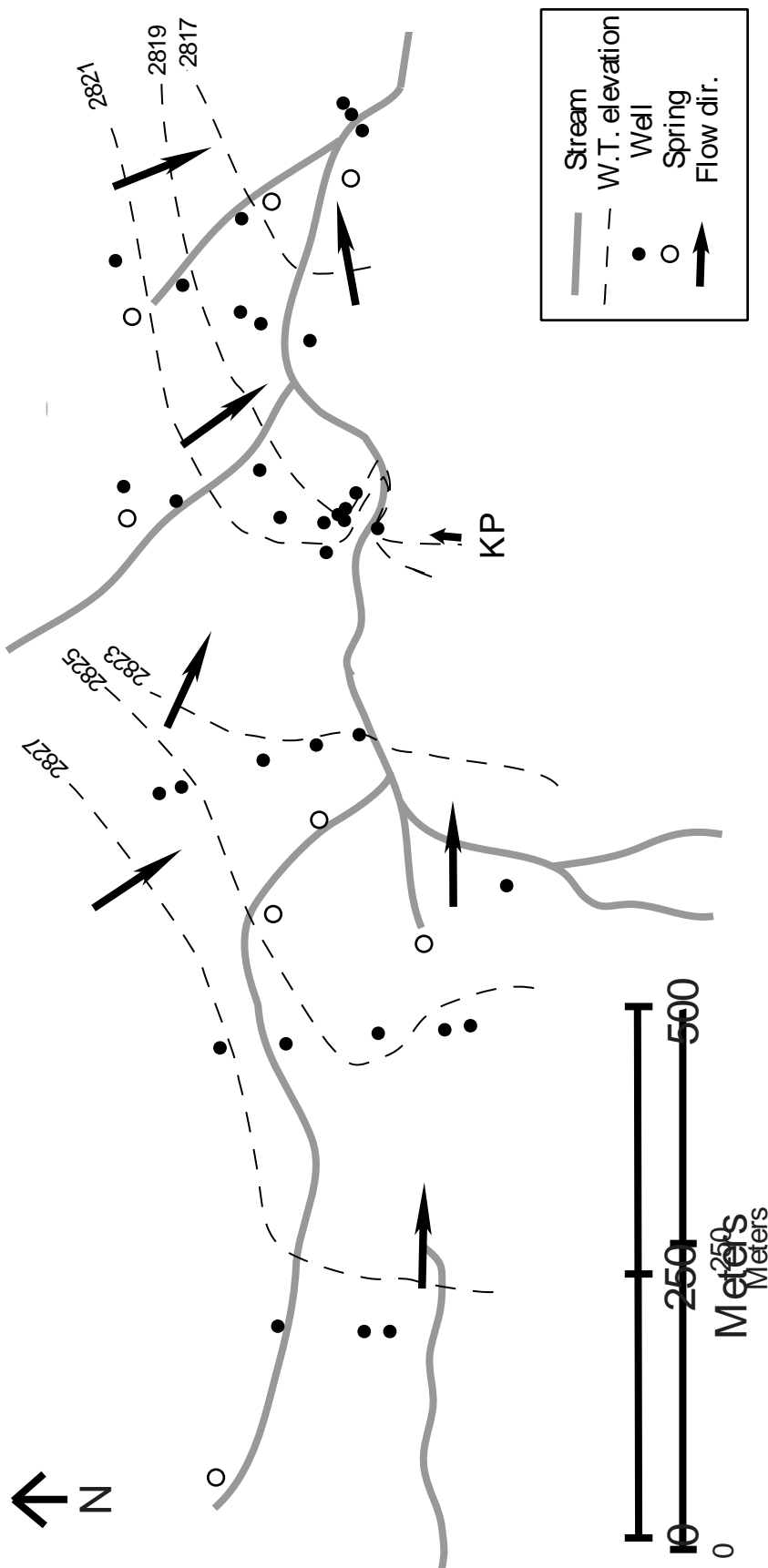


Figure 11. Water table elevation map. Flow direction is indicated by arrows perpendicular to equipotential lines. A losing stream has equipotential lines pointing upstream and a gaining stream has equipotential lines pointing downstream. Above and at the knickpoint (KP), the stream is losing water to the groundwater and flow is down the meadow. Below the knickpoint, the stream is gaining water from the groundwater and flow is toward the stream. Topographic contour interval 40 ft. and water table contour interval is 2 m.

below the land surface. Below the knickpoint, redoximorphic conditions begin at comparable elevations to those above the knickpoint but are very different from the current water table patterns. On Transects 3 and 4, redoximorphic conditions begin about 0.5 m below the land surface (Figure 10).

Vegetation and Stream Incision

Above the knickpoint, meadow and sagebrush vegetation occupy very different sites. Meadow vegetation can be any distance from the stream and have water table elevations at approximately the same elevation as the stream. The water table elevation is usually within ± 0.5 m of the stream elevation. The sagebrush and sage meadow sites are located on the hillslopes and alluvial fans (Transect 2) and have higher water table elevations in relation to the stream, usually at least 1 m higher (Figure 12A).

Below the knickpoint, sagebrush and sage meadow vegetation are both located within 50 m of the stream and have water table elevations within 1 m of stream elevation. The meadow vegetation is located at least 70 m from the stream and the water table is more than 1.5 m above stream elevation (Figure 12B).

Discussion

This section examines the groundwater hydrology of Bullfrog Meadow in terms of current vegetation patterns and stream incision to determine two things: one, if the hydrologic system is an important control of vegetation, that can clarify some of the complexities of sagebrush expansion; and two, if the variation in groundwater above and below the knickpoint can be related to stream incision. Then, the hydrologic changes

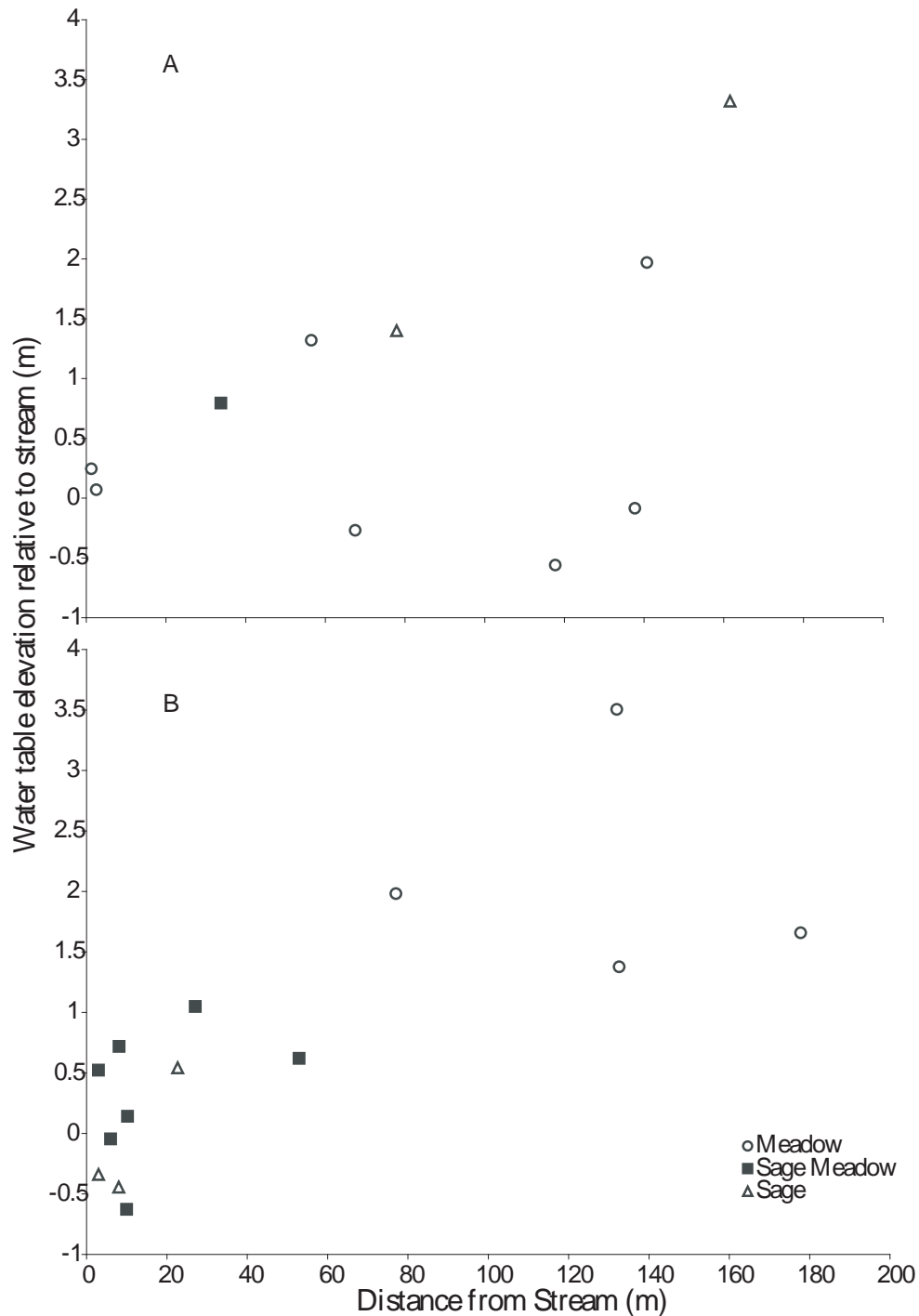


Figure 12. Water table elevation in relation to the stream elevation (m) versus distance from stream (m) for wells above the knickpoint (A) and wells below the knickpoint (B). Above the knickpoint, the water table elevation is close to the elevation of the stream for most of the meadow vegetation even further away. The sage meadow and sage vegetation with water table elevations above the stream are located on an alluvial fan (Transect 2). Below the knickpoint, sage and sage meadow vegetation are located close to the stream and have similar water table elevations to it. The meadow vegetation is further from the stream with higher relative water table elevations.

associated with stream incision will be considered with the vegetation patterns using a space-for-time substitution.

Vegetation and Hydrology

There was vegetation change from meadow to sagebrush and from sagebrush to meadow during the seven years from 1994 to 2001, but it did not result in any net change in the total amounts of these vegetation types (Swartz et al., in prep.). The distribution of vegetation is currently changing in Bullfrog Meadow, and in the last thirty years more dramatic vegetation changes (up to 20% conversion from meadow to sagebrush) occurred in other meadows on the Kern Plateau like Monache Meadow (Swartz et al., in prep.)(Figure 5). In Monache Meadow, downstream of Bullfrog Meadow, Dull (1999) examined meadow and sagebrush pollen in soil cores and found that sagebrush pollen concentrations have increased in the last 100 years.

Multiple studies have used depth to water table to characterize herbaceous species type (Allen-Diaz, 1991; Stromberg et al., 1996; Castelli et al., 2000). The current vegetation patterns in Bullfrog Meadow have a strong correlation to water table elevation (Figure 6). In agreement with previous studies, meadow cover is most dense in areas with high water tables and sagebrush currently occupies areas with lower water tables.

The rooting depth and lateral root spread of herbaceous and woody plants are different. Sagebrush roots grow to great depths but do not extend laterally. Most herbaceous species have fibrous root mats that exploit lateral shallow soil moisture (Welch and Jacobson, 1988; Abbott et al., 1991). Studies have shown that the differences between root type dictate what soil moisture conditions these plants can grow in

(Linnerooth and Chambers, 1997; Castelli et al., 2000). The ability of plant roots to reach the water table in late summer becomes a primary factor in the establishment of a plant population (Linnerooth and Chambers, 1997).

Castelli (2000) states that in addition to depth to water table, plant species relate to environmental variables. These variables include the number of days the water table was below a specific depth, the number of days with low oxygen content, and the range in water table over the growing season. The seasonal fluctuation of the water table was minimal in sage and sage meadow vegetation, while the water table underwent greater and more frequent fluctuation for meadow vegetation (Figure 6). Measured June water table levels were lower than expected even though the snow pack for the season was above average. Large volumes of snowmelt raises the water table at the beginning of the summer season and as summer evapotranspiration begins, the water table should drop (de Vries, 1995). However, this pattern was not strongly observed.

Topography has a strong spatial control on vegetation distribution and the height of the water table. Thus sagebrush has more recently populated the alluvial fans and stream terraces (Figure 7) (Swartz et al., in prep.). The basin morphology of Bullfrog Meadow is dominated by the presence of streams, alluvial fans and bedrock sills (Figure 3). Miller et al. (2001) and Richardson et. al. (1999) have noted alluvial fans and bedrock topography in the basins of central Nevada elicit a groundwater response. The alluvial fans and bedrock create upstream groundwater mounds with higher water tables. Similar groundwater mounds, behind the alluvial fan and bedrock sill in Bullfrog Meadow can be seen in Figure 3 where the wettest meadows are directly behind these topographic features. Sagebrush grows on relatively high areas where the water table tends to be

further from the surface, and meadows prefer regions where the topography has created a very shallow water table.

Hydraulic conductivity was measured to estimate the porosity and permeability of the sediment below the water table. Low values of K were expected to correspond to areas with dense meadow coverage, and high values of K would correspond to sagebrush. However, hydraulic conductivities seemed inversely proportional to the vegetation and sediment types logged. It was found that higher values of K occur on transects with clayey sediment around the well screen and lower values of K on transects with sand and gravel around the well screen (Appendix 2). Hydraulic conductivity values could be divided into low and high values based on distance from the main stream with lower values closest to the stream (Figure 8B). Unexpectedly, sagebrush is most invasive in areas of low hydraulic conductivity (further discussion on hydraulic conductivity results is presented in Appendix 1).

The depth to water table is more influential than hydraulic conductivity in determining where sagebrush expansion will occur. Plant rooting depth varies by species and plant type, causing water table controlled plant establishment (Abbott et al., 1991). The hydraulic conductivity of the surface strata could be more closely related to plant occurrence than groundwater hydraulic conductivity.

Stream Incision and Hydrology

Data from Bullfrog Meadow clearly indicate that the incision of the stream has affected the groundwater hydrology. The vertical profile of the stream shows a dramatic knickpoint and a change in stream channel gradient associated with the incision. The

water table profiles of the five transects indicate that the incision has pulled down the water table adjacent to the incised reaches of the stream (Figure 9, 10). Beyond affirming that stream incision lowers the water table next to the stream (Cooke, 1976; Trimble and Mendel, 1995; Scott et al., 2000; Wurster et al., 2003), little work has been done to quantify other impacts of stream incision on groundwater hydrology.

Discharge measurements from the stream and the water table contour map also indicate influences of the incision on the water table. Above the knickpoint, the water table slopes away from the stream channel, and discharge decreases downstream. Therefore above the knickpoint, the stream is losing water to the groundwater. The water table equipotential lines indicate that most of the water is being lost at the knickpoint. Conversely, below the knickpoint, the water table slopes steeply towards the channel and discharge increases downstream. Thus, the stream is gaining flow from the groundwater. The flow paths based on water table equipotential lines indicate that groundwater is flowing directly into the stream below the knickpoint. This is exactly what one would expect to see in a situation where a stream incises below the water table (Figure 11, Table 2).

The large amount of surface water recharging the groundwater at the knickpoint is puzzling. The stabilization of the knickpoint with boulders and logs and construction of check dams by the Inyo National Forest Service could be responsible. These additions may influence the water table like a bedrock sill or alluvial fan by creating a groundwater mound. The actions taken to reinforce the knickpoint could be backing up the groundwater directly behind it, causing local recharge of the water table.

The differences between the losing and gaining reaches of the stream in Bullfrog Meadow are dramatic. The water table is much higher in the losing reach of the stream and the meadow vegetation reflects it. However, when Harner and Stanford (2003) examined cottonwood growth patterns on losing and gaining reaches of a river, the results were very different. The gaining reach had higher water tables and upwelling nutrients aiding cottonwood growth, while the cottonwoods were stunted in the losing reach. The results from Bullfrog Meadow reflect the sensitivity of losing reaches. The shallow water table depth in a losing reach is dependant on quantity of water whereas the vegetation in a gaining reach can be supported by inflow of groundwater (Kondolf et al., 1987).

The sediment cores of Bullfrog indicate widespread red-orange, high chroma redoximorphic features and manganese concretions that usually begin within 50 cm of land surface. The formation of oxidized iron and manganese in sediment can occur from two processes: the weathering of primary iron and manganese-rich minerals or the translocation to a precipitation zone (Birkeland, 1999). The weathering of primary minerals in place is an unlikely cause of iron and manganese concentrations because the climate is semiarid and soil formation is low. Groundwater can transport soluble Fe^{2+} and Mn^{2+} while oxidized states are insoluble. Near the water table, oxygenation of the groundwater causes the iron and manganese to precipitate out, forming redoximorphic features. When the water table drops (either seasonally or permanently), these oxidation features can remain until the groundwater returns and reduces them (Birkeland, 1999). In this study, the iron and manganese concentrations and mottling features are most likely indicators of groundwater saturation, and the oxidation of reduced species. Thus, initial redoximorphic features can be considered historic high water table markers (Scott et al.,

2000; Wurster et al., 2003). Comparing this historic high water table line with the current water table indicates little change above the knickpoint. In the incised region, historic high water tables indicate that the water table was flatter and shallower before incision, where the current water table is much lower overall and dips steeply close to the stream. The geometry of the historic water table is very similar to the geometry of the water table on Transect 1, located in the unincised meadow. These historic water table markers indicate that the water table in the incised region dropped both next to (about 150 cm) and further away from the incision (about 50 cm) and it was historically similar across Bullfrog Meadow. In unincised Upper Bullfrog, the historic water table is most likely recording years with unusually high precipitation (Figure 10).

By causing a dramatic drop in the water table elevation next to the stream, the incision has changed the way water flows throughout Lower Bullfrog. Below the knickpoint, the lowered water table, groundwater gradient, flow direction, and gaining stream are likely outcomes of the stream incision. In Lower Bullfrog, these changes are causing groundwater to funnel directly into the stream. Long-term implications of this new hydrologic pattern around the incision include less groundwater storage, which is how long groundwater remains in the system, and increased stream flow.

Vegetation and Stream Incision

In Bullfrog Meadow, the regions upstream and downstream of the knickpoint can be used as a space-for-time substitution. The area above the knickpoint represents the initial state with unchanged vegetation patterns, stream geomorphology and meadow hydrology. Early records of the Kern Plateau, from the 1800s and early 1900s, describe

wet herbaceous meadows with sagebrush and lodgepole pines on the hillslopes and unincised streams (Wood, 1979; Collins, 1995; Dull, 1999). The incising stream, invading sagebrush, and changing hydrologic regime in Lower Bullfrog is the final state. Recent work has documented these changes in Bullfrog Meadow and across the Kern Plateau (Collins, 1995; Berlow et al., 2002; Berlow et al., 2003; Swartz et al., in prep.).

The data collected are consistent with the hypothesis that stream incision can cause vegetation change. Water table depth is dependent on distance from the stream below the knickpoint but not above. When vegetation types are considered with these trends a strong pattern emerges. Above the incision, the majority of the vegetation is meadow, which can be found at any distance from the stream because of the constant water table elevation. Below the knickpoint, the depressed water table near the incised stream allows sagebrush to grow very close to the stream, and the only remaining meadow is distant from the stream where the draw down is not affecting the water table (Figure 10, 12).

The other meadows on the Kern Plateau are undergoing similar incision and vegetation change on different time scales, so it is likely that local meadow conditions are mediating the changes (Collins, 1995; Swartz et al., in prep.). The connectivity between the groundwater and surface water, the degree and extent of incision, the scale of the lowered the water table in the surrounding groundwater system, and the texture of the sediments all amplify or dampen the effects of an incising stream on vegetation (Scott et al., 2000).

Hupp (1992) studied stream evolution after anthropogenic straightening and channeling of streams in West Tennessee and found plant communities were so closely

related to cycles of stream deposition and erosion that the stream geomorphology and evolution could be predicted based on species occurrence. The current changes on the Kern Plateau could be modified by this relationship between riparian vegetation and stream geomorphology. Sagebrush decreases stream bank stability, leading to collapsed banks and stream channel aggradation. This can change the incised stream morphology to low banked, meandering stream morphology (Micheli and Kirchner, 2002b, a).

Whether groundwater decline is caused by stream incision or groundwater exploitation, the effects on riparian vegetation are similar. Studies examining vegetation in relation to water table declines have always found changes in vegetation density, distribution, composition and diversity (Kondolf et al., 1987; Or and Groeneveld, 1994; Stromberg et al., 1996; Scott et al., 1999; Scott et al., 2000; Elmore et al., 2003; Wurster et al., 2003). Because the current incision in Bullfrog is stalled by relief efforts, when the stream incision continues up the meadow—based on the space-for-time substitution—it is likely the vegetation will change with it. The water table in Upper Bullfrog will drop and more meadow vegetation will be lost.

Stream incision has dramatically influenced the vegetation distribution in Bullfrog Meadow by changing alluvial water table elevations and decreasing groundwater storage across Lower Bullfrog. Upper Bullfrog will most likely be invaded by sagebrush when stream incision migrates upstream. However, the stream in Lower Bullfrog could begin a period of aggradation because sagebrush decreases bank stability. Further research could examine whether the hydrologic system will respond to aggrading stream morphology and meadow vegetation can colonize sites currently occupied by sagebrush.

Conclusions

This study of Bullfrog Meadow in the Sierra Nevada Mountains analyses the potential effects of stream incision on vegetation distribution. Several variables were used to perform this assessment. First, the relationship between vegetation distribution and hydrologic indicators such as water table elevation and sediment hydraulic conductivity were analyzed. Vegetation distribution correlates well with hydrologic variables such as water table depth and topography but appears to be independent of hydraulic conductivity. Meadow vegetation prefers sites with a shallow water table, which are often lower with groundwater mounding, and sagebrush grows in areas with deeper water tables, which are often topographically higher.

Second, the effects of stream incision on hydrology were examined using a spatial comparison of the hydrology in the incised lower region of Bullfrog Meadow to the hydrology of the unincised upper region. The basin hydrology is very different upstream and downstream of the knickpoint. Below the knickpoint, the water table next to the stream has adjusted to the new, lower channel elevation causing the gradients in Lower Bullfrog to funnel water into the stream.

Using these two relationships, conclusions can be drawn regarding the effects of stream incision on vegetation. Examining the stream incision and vegetation change through time indicates that stream incision removes groundwater from the basin creating a lower water table both close to and further from the stream. This process allows sagebrush to invade the drier areas associated with the incision. The hydrologic and vegetation changes seen in Lower Bullfrog meadow will spread to Upper Bullfrog when the incision migrates upstream.

Streams have incised across the southern Sierra Nevada Mountains in the last century. In view of the widespread effects that incision has on both vegetation and hydrology, meadow hydrology should be incorporated in meadow restoration and management plans. Further studies should examine whether management practices and/or natural stream evolution can reverse the effects of stream incision on groundwater hydrology and vegetation diversity and distribution.

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Appendix 1

Two methods were used to determine hydraulic conductivity (K), the Hvorslev time lag method and the Bouwer and Rice slug test method. The Hvorslev time lag method was used to calculate hydraulic conductivities using the equation for ($L_e/R > 8$):

$$K = \frac{r^2 \ln(L_e / R)}{2L_e t_{37}}$$

Where K is hydraulic conductivity (cm/s), r is the radius of the well casing (cm), R is the radius of the well screen (cm), L_e is the length of the well screen (cm), and t_{37} (s) is the time it takes for the water to fall 37% of the initial change (Hvorslev, 1951). For comparative K values, the Bouwer and Rice slug-test method was also used:

$$K = \frac{r_c^2 \ln(R_e / R)}{2L_e} \frac{1}{t} \frac{\ln(H_0)}{H_t}$$

Where K is hydraulic conductivity (cm/s), r_c is the radius of the well casing (cm), R is the radius of the gravel backfill (cm), R_e is the effective radial distance over which the head is dissipated (cm), L_e is the length of the well screen (cm), H_0 is the drawdown at time $t = 0$ (cm), H_t is the drawdown at time $t = t$ (cm), t is the time since $H = H_0$ (s). If L_w , the distance from the water table to the bottom of the well screen, is less than h , the saturated thickness of the aquifer, then $\ln(R_e/R)$ is:

$$\ln(R_e / R) = \left[\frac{1.1}{\ln(L_w / R)} + \frac{A + B \times \ln[(h - L_w) / R]}{L_e / R} \right]^{-1}$$

from (Bouwer and Rice, 1976) (Figure A1).

There are four different ways to interpret the results of the hydraulic conductivity calculations. One possibility is the results could be accurate showing an interesting spatial distribution where the lowest conductivities correspond to areas where sagebrush is invading.

Another option is the two calculations used to determine K are poorly calibrated for a study of this design. Both equations have inherent assumptions and expect a linear equilibration, which was not evident in the results. The hydraulic conductivity estimation using the Hvorslev method (1951) considered the entire response time and thus does a better job of smoothing out changing response rates. The middle section of each slug test was used for the Bouwer and Rice (1976) calculation so it was worse at accounting for variation in the response rate.

The third possibility is well installation and construction could be responsible for this result. The fill around the screen is coarse gravel and sand from the hillslopes with excavated sediment capping the gravel. Water added during the slug test could move quickly into the gravel and then slowly into the aquifer or even up the backfill around the well.

Finally, the result could be achieved because values are reflecting the amount of water in the system, where the two-gallon slug of water will have a smaller impact where the water gradient is stronger. The water gradient close to the stream would cause a slower response rate decreasing the hydraulic conductivity measurement.

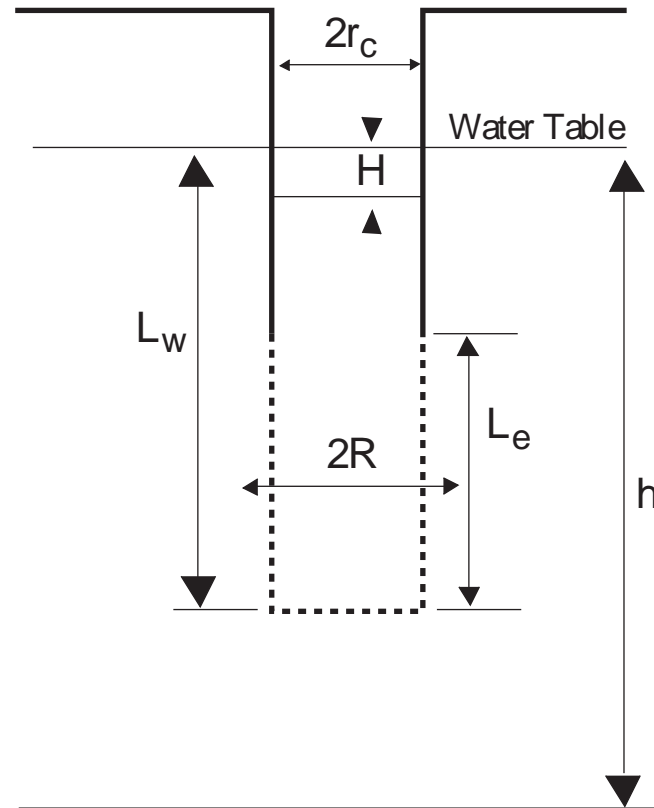


Figure A1. Geometry and symbols for a slug test on a partially penetrating screened well in an unconfined aquifer. r_c is the radius of the well casing (cm), R is the radius of the gravel backfill (cm), R_e is the effective radial distance over which the head is dissipated (cm), L_e is the length of the well screen (cm), H_0 is the drawdown at time $t = 0$ (cm), H_t is the drawdown at time $t = t$ (cm), t is the time since $H = H_0$ (s) (modified from Bouwer and Rice, 1976).

Appendix 2

For each of the five transects, the sediments were cataloged based on texture, Munsell soil color, and redoximorphic features. The grain size—clay or peat, fine to coarse sand, and gravel—is presented by transect. The grain size in the lowest 50 cm of each core, which corresponds to the location of the well screen, can be compared to hydraulic conductivity values. Average hydraulic conductivities for each transect are listed in the figure captions to compare measured results and grain size. Hydraulic conductivity does not correlate well with grain size because the highest hydraulic conductivities were measured for Transect 1 and Transect 2. High hydraulic conductivities are reasonable for Transect 2 because it is a dry alluvial fan with coarser sediments (Figure B1, B2, B3, B4, B5).

The initial redoximorphic conditions for most cores are also indicated because they correspond to historic high water table. All the transects have very similar depths for initial redoximorphic conditions. This indicates that the groundwater regime was historically similar throughout Bullfrog Meadow.

