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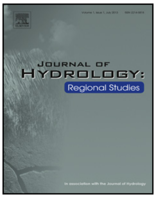

Effects of groundwater pumping on the sustainability of a mountain wetland complex, Yosemite National Park, California

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ABSTRACT

Study Region: We analyzed the effects of groundwater pumping on a mountain wetland complex, Yosemite National Park, California, USA.
Study Focus: Groundwater pumping from mountain meadows is common in many regions of the world. However, few quantitative analyses exist of the hydrologic or ecological effects of pumping.
New Hydrological Insights for the Region: Daily hydraulic head and water table variations at sampling locations within 100 m of the pumping well were strongly correlated with the timing and duration of pumping. The effect of pumping varied by distance from the pumping well, depth of the water table when the pumping started, and that water year's snow water equivalent (SWE). Pumping in years with below average SWE and/or early melting snow pack, resulted in a water table decline to the base of the fen peat body by mid summer. Pumping in years with higher SWE and later melting snowpack, resulted in much less water level drawdown from the same pumping schedule. Predictive modeling scenarios showed that, even in a dry water year like 2004, distinct increases in fen water table elevation can be achieved with reductions in pumping. A high water table during summers following low snowpack water years had a more significant influence on vegetation composition than depth of water table in wet years or peat thickness, highlighting the impact of water level drawdown on vegetation.

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1. Introduction

Mountain meadows are groundwater dependent ecosystems with seasonally or perennially high water tables and highly productive herbaceous vegetation that limits tree invasion (Lowry et al., 2011; Loheide et al., 2009). Meadows provide vital ecosystem services by maintaining the biotic and geochemical integrity of mountain watersheds. They are critical habitat for many plant (Hajkova et al., 2006; Jimenez-Alfaro et al., 2012) and animal (Semlitsch, 2000) species, support regional biodiversity (Stohlgren et al., 1998; Hatfield and LeBuhn, 2007; Flinn et al., 2008; Holmquist et al., 2011), form carbon-rich soils (Chimner and Cooper, 2003), and filter water by storing or transforming mineral sediment and nutrients (Hill, 1996; Knox et al., 2008; Norton et al., 2011). In most mountain regions in the temperate zone meadows cover less than 2% of the landscape, and their persistence is threatened by human activities such as road building and logging that can increase sediment fluxes, overgrazing by domestic livestock that can alter meadow vegetation and cause soil erosion, and dams, diversions, channel incision, ditching and groundwater pumping that alters meadow hydrologic regimes (Patterson and Cooper, 2007; Loheide and Gorelick, 2007; Chimner et al., 2010). The effect of hydrologic alteration on meadows is poorly understood, however hydrologic changes are often identified as the main cause of conifer tree invasion into meadows (Jakubos and Romme, 1993; Vale, 1981).

Several ecological processes maintain mountain meadows in their treeless state, including seasonally or perennially high water tables and highly productive vegetation (Lowry et al., 2011), climate and landform (Jakubos and Romme, 1993; Zald et al., 2012), fire regime (Norman and Taylor, 2005), and herbivory (Manson et al., 2001). In the Sierra Nevada of California many mountain meadows receive sufficient groundwater inflow to maintain areas of surface soil saturation throughout the nearly precipitation-free growing season (Cooper and Wolf, 2006).

Two main types of mountain meadows occur in western North America: wet meadows that have seasonal saturation in the root zone, and fens that are perennially saturated (Cooper et al., 2012). Organic matter production and decomposition are nearly equal in wet meadows, which limits organic matter accumulation in soils. Fens form where the rate of organic matter production exceeds the rate of decomposition due to waterlogging, allowing partially decomposed plant matter to accumulate over millennia, forming organic, or peat soils (Moore and Bellamy, 1974). Fens support a large number of plant, amphibian and aquatic invertebrate species that rely on permanent water availability. They are uncommon in steep mountain landscapes because slopes are excessively well drained (Patterson and Cooper, 2007). However, where hillslope aquifers recharged by snowmelt water support sites of perennial groundwater discharge, fens have formed (Benedict, 1982). Radiometric dating indicates steady peat accumulation in mountain fens in western North America through the Holocene, suggesting long-term hydrologic stability in groundwater-fed fens (Wood, 1975; Bartolome et al., 1990; Chimner and Cooper, 2003).

Seasonal and inter-annual variation of groundwater level and water chemistry influences the floristic composition and productivity of fen vegetation as well as the rate of peat accumulation (Allen-Diaz, 1991; Cooper and Andrus, 1994; Chimner and Cooper, 2003). Even short periods of water table decline allow oxygen to enter soils, increasing organic matter decomposition rates and initiating soil and vegetation changes (Cooper et al., 1998; Chimner and Cooper, 2003). Ditches and water diversions are commonly constructed to lower the water table of fens (Glaser, 1983; Glaser et al., 1990; Wheeler, 1995; Fisher et al., 1996; Chimner and Cooper, 2003), however, groundwater pumping may also influence water levels in fens and other wetlands (Johansen et al., 2011).

Previous studies have addressed the effects of groundwater pumping on riparian ecosystems, coastal wetlands, prairie potholes, and intermittent ponds (Winter, 1988; Bernaldez et al., 1993; van der Kamp and Hayashi, 1998; Alley et al., 1999). Groundwater pumping in riparian areas can result in the death of leaves, twigs and whole trees, such as cottonwoods (Cooper et al., 2003). However, little is known about the long-term effects of groundwater pumping on mountain meadows. Quantitative models developed to analyze pumping in mountain valleys and basins must consider the characteristic steep terrain and bedrock outcrops in these watersheds, as well as the limited volume of aquifer sediments and strong seasonality of precipitation inputs.

More than 3 million people visit Yosemite National Park each year, most during the dry summer months. Providing a reliable public water supply for staff and visitors is a critical issue. The California climate produces abundant winter precipitation and nearly rain-less summers in the Sierra Nevada. Most mountain soils dry excessively (Lowry et al., 2011) and most small streams are intermittent during the summer (Lundquist et al., 2005). Thus, surface water supplies are limited and most water for human use in Yosemite National Park is derived from groundwater sources. Some deep groundwater sources are available, such as along the Merced River in Yosemite Valley, while others are from shallow aquifers. One such shallow aquifer is located at Crane Flat, an important visitor services area that supports a large wet meadow and fen complex important for foraging bears, deer, Great Gray Owls and other wildlife. A single production well was installed in Crane Flat meadow in 1984 and provides water for a campground, gas station, residences, and an environmental campus. The well was drilled 122 m deep, with the intention of drawing water from a deep bedrock aquifer, and the influence of pumping on the meadow ecosystem was assumed to be minimal.

This study was designed to analyze the influence of groundwater pumping on the Crane Flat mountain meadow complex in Yosemite National Park, California. We addressed the following questions: (1) How does groundwater pumping influence the water table in a meadow supported by a shallow aquifer? (2) Can a physically based numerical model be used to predict the effects of pumping on meadow water levels for small and large snow years? (3) What are the long-term effects of pumping on the meadow vegetation composition, (4) Are there pumping regimes that might sustain the hydrologic processes that support the Crane Flat wetland complex?

2. Study area

Crane Flat is a 20 ha meadow complex, located at 37°45′16″ N and 119°48′9″ W, in the west-central portion of Yosemite National Park, California, USA (Fig. 1). Its watershed area is 75.7 ha. Land surface elevations at Crane Flat range from 1870 to 1890 m above mean sea level (m amsl). The underlying watershed bedrock is igneous intrusive Arch Rock Granodiorite and El Capitan Granite, with the metamorphic Pilot Ridge Quartzite outcropping on the northwest side of the study area. A surface layer of peat 10–140 cm thick covers 0.5 ha of the meadow. Most of this area is a fen (Fig. 1) that we define as a groundwater-supported wetland with 20–40 or more cm of organic soil. The peat is underlain by mineral sediments comprised of sand- and gravel-sized particles. This material is a mixture of weathered bedrock, glacial till, and colluvium derived from adjacent slopes. The sand and gravel sediments are over 10 m thick in this area. Other portions of Crane Flat are wet meadows with mineral soil. During mid- to late-summer the organic soils are cracked and uneven with patchy vegetation suggesting oxidation and subsidence (Leifeld et al., 2011). Upland areas support conifer forest dominated by white fir (*Abies concolor*), sugar pine (*Pinus lambertiana*), and lodgepole pine (*Pinus contorta*).

The sand and gravel sediments are the primary near-surface aquifer unit at Crane Flat. High water levels in the fen are produced by convergent groundwater flow paths originating from two areas. Springs that emerge from faults in the metamorphic bedrock from the west arm springs (shown on Fig. 1) provide a source of water that locally recharges the aquifer in the western portion of the study area. Inflow from valley sediments to the north represents the other major source of groundwater inflow to the fen. In addition to these two main inflows, the aquifer is recharged directly by precipitation (primarily snowmelt) throughout the meadow. Intermittent surface water flow does occur during snowmelt. The surface flows are characterized by low velocity, occurring over a rough vegetated surface, and are generally not contained within well-defined channels. During wet years, intermittent surface water is observed between April and late June. However, saturated conditions at the fen are not dependent on surface water inflow.

We considered two reference sites, Drosera Meadow (37°46′0″ N, 119°45′44″ W) and Mono Meadow (37°40′31″ N, 119°34′58″ W), to analyze the hydrologic regime and vegetation of undisturbed fens. Drosera Meadow is 7.03 ha in area located 3.79 km northeast of Crane Flat at 2070 m elevation, and Mono Meadow is 5.69 ha at 2080 m elevation, 21.6 km southeast of Crane Flat (Fig. 1).

The Crane Flat pumping well is located at the edge of the fen (Fig. 1). The well is 122 m deep, with the upper 15 m of borehole sealed with a solid steel casing, while the bottom 107 m is uncased. The casing was built to be a sanitary seal preventing surface water and near surface groundwater from leaking into the well casing. The pump intake is at 98 m depth (Crews and Abbott, 2005) and has a maximum production of 127–137 L/min. Packer testing conducted by Crews and Abbott (2005)

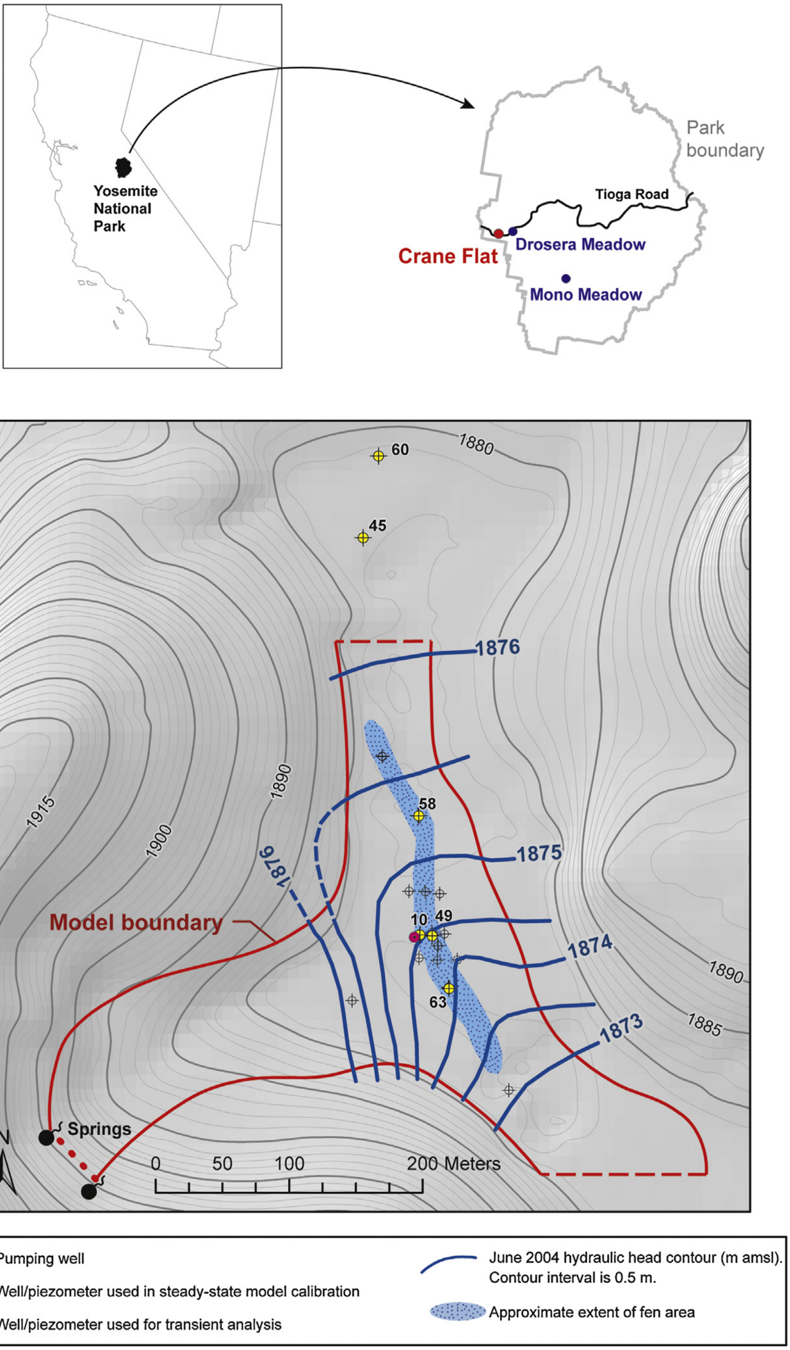

Fig. 1. Overview of the Crane Flat area showing land-surface elevation contours (1-m interval) from a 10-m digital elevation model (USGS National Elevation Dataset). Hydraulic head interpretation is based on piezometers that are open to the sand and gravel. Model boundary segments: dashed line indicates a head-dependent flux boundary; dotted line indicates a constant-head boundary; solid line indicates a no-flow boundary.

Table 1
Date and peak snow water equivalent (SWE) for the water years 2004–2010 for the Gin Flat climate station, located 3.7 km NE of Crane Flat, and 260 m higher in elevation. Also shown are total water year (October 1–September 30) precipitation (Tot Precip.), and the date that snow melted from the station (<1 cm).

Year	Peak date	Peak SWE	Tot Precip.	Melt date
2004	Mar 09	71.9	88.7	May 03
2005	Apr 13	107.5	205.8	Jun 11
2006	Apr 19	75.0	161.9	May 28
2007	Mar 15	39.7	73.6	May 3
2008	Mar 12	79.0	na[a]	May 16
2009	Mar 27	57.2	88.7	May 12
2010	Apr 16	86.8	96.1	Jun 14

[a] Data are not available.

indicated that the vast majority of pumped water comes from the upper portion of the well, above a depth of 27.7 m. Below this depth, the fractured granite has very low permeability and does not contribute significant water volumes during pumping. Therefore, the productive interval of the well is between 15 and 27.7 m below ground surface (bgs). During the summer period of high water demand, pumping occurs for 8–12 h each night, to produce 60,000–100,000 L for storage. On an annual basis the largest volumes of water are needed in July and August, particularly weekends when visitation is highest.

Precipitation and snow-water-equivalent data, recorded at the Gin Flat weather station (37°46′1″ N, 119°46′23″ W), located ~4 km northeast of Crane Flat near Drosera Meadow, was obtained from the California Department of Water Resources (http://cdec.water.ca.gov). During the study period of water years 2004–2010 peak snow water equivalent (SWE) ranged from 39.7 to 107.5 cm, and the timing of peak was as early as 9 March and as late as 19 April (Table 1). A water year as defined by the U.S. Geological Survey is the 12-month period between 1 October and 30 September designated by the calendar year in which it ends.

3. Methods

3.1. Field measurements and hydrologic analysis

We collected and analyzed water table levels and hydraulic heads, as well as soil and vegetation composition data in Crane Flat Meadow, and the two reference sites from 2004 to 2010 (Fig. 1). A total of 57 monitoring wells and piezometers were installed in Crane Flat in June 2004. Nests of two or more instruments (a well and one or more piezometers) were installed in the peat body near the Crane Flat pumping well to determine differences in pumping response at different depths. We do not present the entire 57-well dataset, but use a representative subset of the data from wells with long, high quality records.

Monitoring wells were installed by hand-augering 10 cm diameter bore holes and fitting them with 5 cm inside-diameter fully slotted Schedule 40 PVC pipe, capped on the bottom, backfilled around the pipe with native soil, and bailed to develop the water flow to the well. In fen areas where the peat layer exceeded 20–40 cm in thickness, monitoring wells were installed completely within the peat body. The well depths ranged from 36 to 127 cm bgs.

Piezometers were installed in the fen around the pumping well with screened sections completely below the peat layer in the underlying coarse sand. The total depths (approximate measurement points) ranged from 25 to 315 cm bgs. Each piezometer consisted of a steel drive point with a 38 cm long screened section of 3 cm diameter schedule 80 steel pipe coupled to sections of unslotted steel pipe. The drive point and pipe were hammered to the desired depth using a post-pounder striking a drive cap.

The location and elevation of all monitoring wells and piezometers, and ground surface topography were surveyed using a TOPCON® total station. The survey data were used to calculate water level elevations and to develop a detailed representation of the land surface. The wells and piezometers were instrumented with pressure transducers (Global Water GL-15 and Onset Hobo Level Logger) that recorded water level at fixed time intervals of 5, 30, or 60 min, depending on the season and application. Non-vented loggers were corrected for atmospheric pressure using data from an on-site barometric pressure data logger. See Table 2 for a complete description of the physical properties of the wells and piezometers.

We analyzed vegetation composition in a 1 m radius circular plot around each monitoring well/piezometer nest. In each plot a complete list of vascular plants and bryophytes was made, and the canopy coverage, by species, was estimated. The percent cover of plant species occurring at 17 well locations was analyzed to determine the correlation with hydrologic parameters and peat thickness using Canonical Correspondence Analysis, CCA (McCune and Mefford, 2012). Two hydrologic variables were used, the highest water table elevation during the very dry 2004 growing season (July–September), and the lowest water table during the very wet 2005 growing season. These were selected because; (1) the maintenance of a high water table in a dry year is critical for supporting peat and fen vegetation, and (2) deep water table drawdowns in a wet year would be indicative of an abnormal impact such as pumping drawdown. Distance from each plot to the Crane Flat pumping well is shown on the CCA diagram as unique symbols, but distance was not used in the CCA calculation. The CCA axes were calculated as linear combinations of the hydrologic parameters and peat thickness for each plot. Vegetation data displayed on the ordination include the plot location relative to other plots and plant species centroids, which is the average position of species along the axes based on their abundance at each well. To evaluate the statistical significance of the CCA, we ran a 9998-iteration Monte Carlo test that randomly reassigned the environmental data to different plots. The proportion of Monte Carlo outcomes with an axis-1 eigenvalue greater than the observed eigenvalue is the *p*-value for the CCA.

3.2. Numerical modeling

Groundwater flow in an unconfined aquifer can be described by the following partial differential equation:

$$\nabla \cdot (Kb\nabla h) + W = S_y \frac{\partial h}{\partial t} \tag{1}$$

where h is hydraulic head (L), K is the spatially variable hydraulic conductivity (L/T), S_y is the specific yield (-), b is the aquifer thickness (L), and W is a source/sink term (L/T) that includes the effects of groundwater pumping and distributed areal recharge to the water table. We used the finite difference code MODFLOW-SURFACT (HydroGeoLogic, 2011) to obtain numerical solutions to Eq. (1) for the study area.

The numerical model encompasses an area of 6.77 ha. Boundary segments are shown in Fig. 1. The segments to the north (inflow) and southeast (outflow) were treated using head-dependent flux boundaries (General Head Boundary cells in MODFLOW-SURFACT). For the northern inflow boundary, external heads were specified using data from piezometer 45 (Fig. 1). No wells or piezometers were available to the south of the model domain. Therefore, external heads for the outflow boundary were estimated using the interpreted hydraulic gradient in the southeastern part of the meadow (Fig. 1). During transient simulations the external boundary heads were varied using available time-series data, which allowed for realistic seasonal variations in the simulated boundary flows. Constant-head cells were used along the southwestern boundary to simulate inflow from the west arm springs. The remainder of the model boundary was specified as no-flow, following the bedrock outcrop around the meadow. The total modeled aquifer thickness is 27.7 m, which is the depth of permeable material determined by packer testing at the Crane Flat pumping well (Section 2).

The horizontal grid spacing in most of the model domain is 2 m × 2 m. Near springs in the southwestern part of the meadow we used larger grid cells. This part of the domain is more than 100 m from the main meadow area and detailed simulation of heads and flow directions was not necessary. The model column spacing was increased gradually from 2 to 10 m in this southwestern area. The aquifer thickness was discretized using seven finite-difference layers. Surveyed ground elevations were used to develop a TIN representation of the land surface. This surface provided a starting point

Table 2
Physical characteristics of the water level data collection instruments.

Well #	Pipe diameter (cm)	Instrument type	Depth of lowest opening (cm)	Depth of highest subsurface opening (cm)	Peat thickness (cm)	Distance to pump (m)	Longitude (WGS84)	Latitude (WGS84)	Elevation (m)
10	5.1	Well	−127.0	0.0	132.0	4.53	−119.80185	37.75472	1874.660
45	1.3	Piezometer	−116.5	−116.5	27.0	301.49	−119.80232	37.75740	1876.499
49	3.2	Piezometer	−315.0	−277.0	130.0	13.45	−119.80174	37.75471	1874.542
58	5.1	Piezometer	−129.0	−99.0	103.0	90.95	−119.80185	37.75552	1875.423
60	5.1	Well	−122.3	0.0	0.0	360.00	−119.80213	37.75794	1877.568
63	5.1	Piezometer	−209.0	−179.0	100.0	46.51	−119.80160	37.75436	1874.225
Pump	15.2	Pumping well	−12200.0	−1585.0	0.0	0.00	−119.80189	37.75470	1874.714

to define the model layers. The top model layer has a uniform thickness of 1 m and is used to locally represent the peat body, which has distinct hydraulic properties, in the fen. Layer 2 is 1.5 m thick, and extends from 1.0 to 2.5 m below the ground surface. The layer spacing was systematically increased and the deepest model layer, 7, has a thickness of 8.3 m. There are 101,389 active grid cells in the model. Given the presence of relatively thin layers near the land surface, some model cells are in the unsaturated zone during flow simulations. In certain areas, the water table drops below the base of a model layer during the summer dry season and may subsequently rise into the layer during periods of higher recharge. We adopted the pseudo-constitutive relation approach in MODFLOW-SURFACT to effectively deal with the drying and rewetting of finite-difference cells (Panday and Huyakorn, 2008).

Hydraulic properties were varied using a zonation approach. The peat (Fig. 1) was assigned a hydraulic conductivity of 5.8 m/d, which is the average value estimated from slug tests at three monitoring wells that were located near (<20 m) the Crane Flat pumping well and installed within the peat. The modeled specific yield value was 0.35. These values for K and S_y are within ranges reported for sedge root peat (Boelter, 1965; Schimelpfenig et al., 2013). To reproduce the observed steep head decline between the springs ($h \approx 1900$ m elevation) and the meadow, we used a low-conductivity zone throughout the west arm area. Although no wells have been drilled near the springs, the overall steep hydraulic gradient suggests less weathering of the bedrock in this area. Elsewhere throughout the model, we assumed a constant hydraulic conductivity within each layer.

3.3. *Model calibration*

For the initial steady-state model development and calibration, we utilized hydraulic heads measured in early June 2004 (Fig. 1). Groundwater levels in the meadow tend to be relatively stable in late spring, prior to warm and dry conditions and increased groundwater pumping in the summer. The calibration considered point locations where measured hydraulic heads can be clearly attributed to the peat or underlying sand and gravel material, based on stratigraphic logs from well/piezometer installation. In total, there were seven heads within the peat body and 14 from the sand and gravel used in the calibration. During steady-state model calibration, hydraulic conductivity values were adjusted within reasonable ranges for all zones except the layer 1 peat.

3.4. *Transient simulations*

A 16-month transient simulation was conducted using data collected between June 2004 and September 2005. This period includes the last four months of the 2004 water year and the entire 2005 water year (October–September). The simulation time was discretized using monthly stress periods with daily time steps. Pumping and recharge rates, as well as the external heads for the head-dependent flux boundaries, were varied on a monthly basis using averages from measured data (gauged pumping at the meadow well, measured precipitation, and measured hydraulic heads near the north and southeast boundaries). Well pumping is simulated in layers 6 and 7. This modeled vertical interval corresponds to the aquifer depth where there is significant water production, as determined from the well completion details and packer testing (Crews and Abbott, 2005).

Simulated hydraulic heads from the transient model were compared to observed heads at selected well/piezometer locations where continuously recorded data are available from pressure transducers. During initial transient runs, we further calibrated the model to identify appropriate values of specific yield and groundwater recharge rate. The transient modeling allowed us to investigate the seasonality of the system and evaluate the relative importance of precipitation and pumping in controlling fen area water levels.

Two additional predictive transient simulations were conducted to investigate how water levels within the fen would be affected by reduced groundwater pumping. These simulations focus on the high groundwater use summer months (June–September). The 2004 water year was treated as the base case (i.e., a representative dry year). The first predictive scenario considers a 50% reduction from the actual June–September 2004 pumping. This scenario would reflect a significant reduction in pumping, as suggested by NPS. The second scenario considers no groundwater pumping during this 4-month period.

4. Results

4.1. Water level variations

Winter water use in the Crane Flat area is minor and pumping occurred only 1–2 times per week. During September 2005, after a full summer season of daily pumping, water extraction produced distinct daily water level changes. Water levels in piezometer 49 had a sharp daily decline of up to 40 cm beginning around midnight, followed by a rapid rise in the morning to near the previous day's high (Fig. 2). Water level declines in well 10, which is a water table observation well, completed within the peat body, were up to 10 cm per day. Monitoring well 60, included as a reference well, is 360 m from the Crane Flat pumping well. Daily water table fluctuations at this well were not substantially affected by the pumping at Crane Flat (e.g., measured water levels did not respond to increased or decreased pumping intensity on September 12 and September 14–16, respectively). Rather, the smaller variation at well 60 is associated with evapotranspiration. The magnitude of water level decline was controlled by the duration of pumping, distance to the pumping well, and whether the well/piezometer is open to

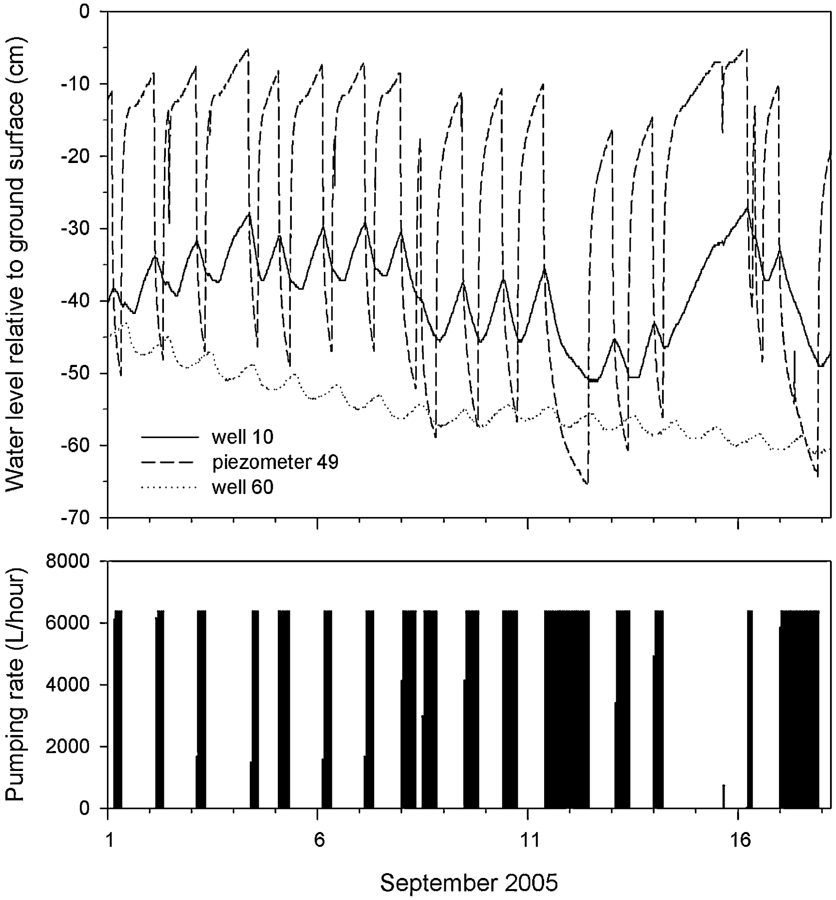

Fig. 2. Hourly pumping (bottom panel) for 1–17 September 2005, and the water level response in wells 10 and 60 and piezometer 49.

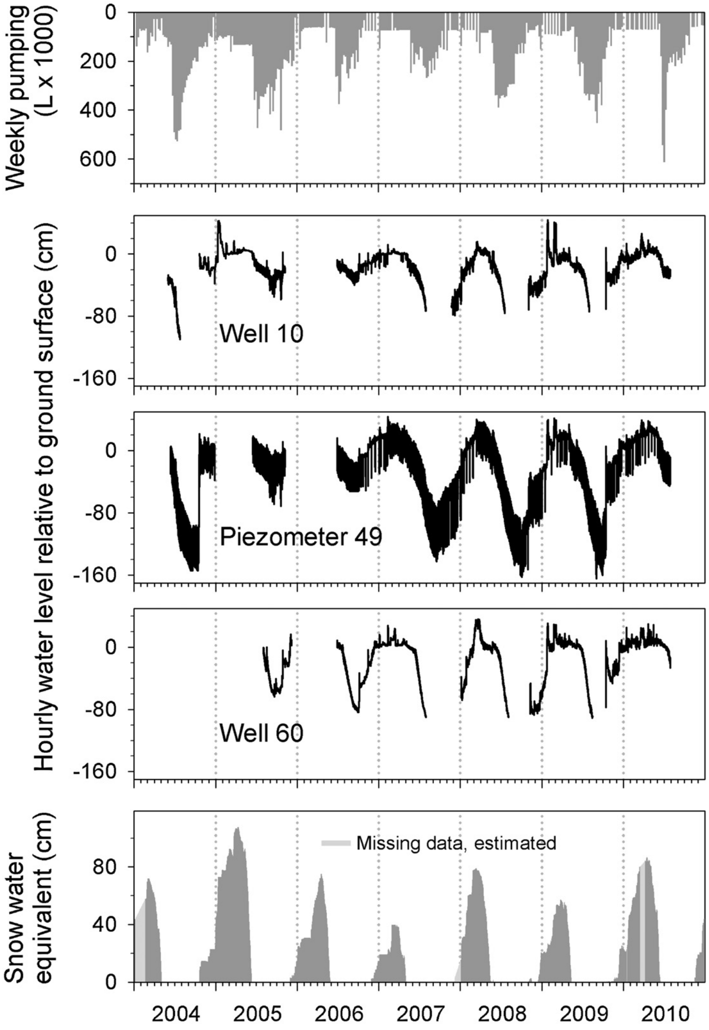

Fig. 3. Weekly pumping schedule and volume, hourly water level in wells 10 and 60 and piezometer 49, and daily snow water equivalent for the years 2004–2010.

the peat body or underlying gravel. Nights with longer duration pumping produced deeper and more sustained water level declines than those with shorter duration pumping. Pumping occurred for an extended period on the weekend of September 11–12 in 2005 and produced a very large drawdown (Fig. 2). Nights with short duration or no pumping resulted in a water level rise, for example on September 14–15, 2005 (Fig. 2).

During the summer of 2004, following a very early melt of the snowpack (Table 1) the water table in Crane Flat declined more than 100 cm from mid-June to late-September (Fig. 3, Well 10). Similar deep declines also occurred in 2007, 2008, and 2009, all years with low or early peaking, and thus early melting, winter snowpack (Fig. 3, Table 1). In water years 2005, 2006 and 2010 larger winter snow packs persisted into April, resulting in water level declines of less than 50 cm under a similar summer pumping regime. In 2004 the water table was below the entire peat body by August, while in 2005 water levels remained within the peat body for the entire summer. Groundwater levels in the reference meadows Drosera and Mono remained within a few cm of the soils surface for the entire

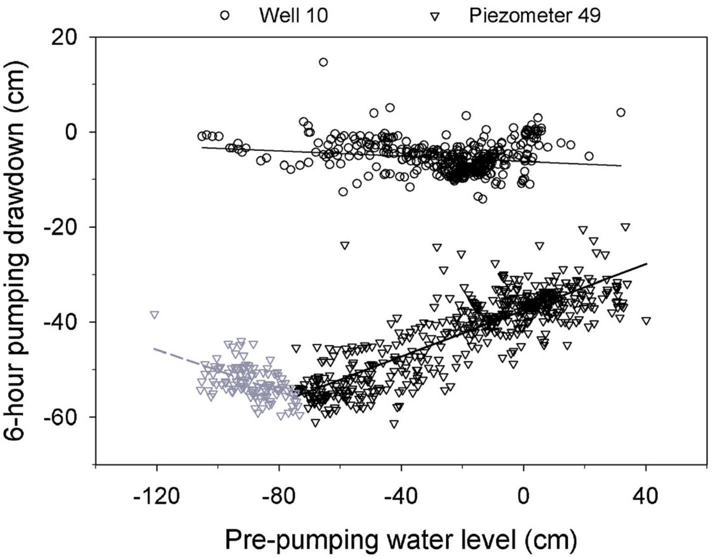

Fig. 4. Water level drawdown in well 10 and piezometer 49 after 6 h of pumping, relative to pre-pumping water level, analyzed for the years 2004–2010. Black triangles show piezometer 49 for water levels (pre-pump + drawdown) above −130 cm (within the surface peat layer), $Y = -37.4975 + 0.2431x$, $R^2_{adj} = 0.7172$, $p \ll 0.0001$, 537 df. Gray triangles show piezometer 49 for water levels below −130 cm (within the sand below the peat), $Y = -72.3662 - 0.2219x$, $R^2_{adj} = 0.2728$, $p \ll 0.0001$, 111 df. Black circles show well 10, $Y = -6.6967 - 0.0608x$, $R^2_{adj} = 0.2561$, $p \ll 0.0001$, 597 df.

summers of 2004 and 2005. Thus, even during large snow years, groundwater levels in Crane Flat would not sustain peat forming conditions as occur at Drosera and Mono Meadows.

The meadow water table responded rapidly to precipitation events. A 3.0 cm precipitation event on June 30, 2004 produced a 10–20 cm water table rise that lasted for more than 6 days. A 10.8 cm precipitation event on October 16, 2004 led to a 100 cm water level rise at all wells.

For all years, 2004–2010, when the hydraulic head in piezometer 49 was within the peat body (above 130 cm bgs), the water level at the start of a 6-h pumping period explained 72% of the variation in how far the water level was drawn down ($P \ll 0.0001$, $R^2_{adj} = 0.7172$, 537 df). A greater 6-h drawdown occurred when the initial water levels were lower (black-outlined triangles, Fig. 4). However, when the head in piezometer 49 dropped below the peat body the relationship reversed and lower initial water levels resulted in less total 6-hr drawdown ($P \ll 0.0001$, $R^2_{adj} = 0.2728$, 111 df; gray-outlined triangles in Fig. 4). Pre-pumping water levels were always within the peat body, but when the initial water level was 70 cm bgs or lower, the 6-h pumping always resulted in heads below the peat body.

The water level drawdown in well 10 was negatively correlated with the initial groundwater level (black-outlined circles, Fig. 4). Deeper initial water levels resulted in smaller drawdowns, although this correlation only accounted for 3% of the variation in drawdown ($P = 0.0002$, $R^2_{adj} = 0.0314$, 411 df).

4.2. Numerical modeling

Calibrated hydraulic conductivities ranged from 10 m/d in the top layer to 0.3 m/d in the bottom layer. These values bracket the hydraulic conductivity (4.4 m/d) that was estimated during an October 2005 aquifer test and are within typical ranges reported for sands and weathered granite (Freeze and Cherry, 1979). The low-conductivity value used in the west arm area was 0.04 m/d. Excluding the peat, the calibrated specific yield was 0.25 in the top layer and 0.1 in all other layers. Transient modeling results were not sensitive to specific storage values.

Using observed hydraulic heads from early June 2004, the mean error and mean absolute error (MAE) for the steady-state model are 0.02 m and 0.12 m, respectively. The observed heads ranged from 1873.05 m to 1875.71 m. The model reasonably reproduces the heads over the entire data range;

the MAE/range is 0.045. Simulated inflow in the steady-state model included spring flow at the southwest boundary (22.6 m^3/d), flow across the northern head-dependent boundary (27.9 m^3/d), and areal recharge derived from precipitation (25.6 m^3/d). The simulated outflow across the southeast boundary was 76.1 m^3/d.

The transient model provided a good match to observed hydraulic heads in the central and southern parts of the meadow (Fig. 5). For well 10, which is screened within the peat (elevation corresponding to model layer 1), and piezometer 63, completed in the underlying coarse sand (layer 2), the model captured the marked decline in heads during summer 2004 and the rapid rise that occurred in October 2004. In the northern part of the meadow (piezometer 58), the simulated heads are lower than the observed heads by 0.1–0.5 m, however the model accurately reproduces the trend behavior.

The 16-month transient model considered variations in recharge and pumping between June 2004 and September 2005. For each stress period, a single recharge rate was applied over the modeled area. Given the scale of the model and the relatively coarse temporal discretization (monthly stress periods), the modeled recharge represents a net inflow. ET is not explicitly simulated. Although this net recharge rate was treated as a calibration parameter, its value was constrained by the measured precipitation at Gin Flat meteorological station. In mid October 2004, a storm delivered 10.8 cm of precipitation, resulting in a rapid water level rise throughout the meadow. The model-calibrated recharge rate was 80% of the measured precipitation for this event. For the remainder of the simulation period, the calibrated recharge varied from 5 to 25% of monthly precipitation.

The hydrograph for well 10 illustrates a key characteristic of the system behavior (Fig. 5a). In the low snow 2004 water year, water levels declined rapidly in response to summer pumping and the lack of precipitation. In the high snow 2005 water year, the meadow water level decline was gradual and the peat remained saturated even though June through September rainfall and pumping totals were nearly identical to 2004. The summer water level response was controlled largely by the volume of shallow groundwater in storage and inflow from the meadow boundaries, which are a function of the previous winter and spring precipitation.

Results of the predictive groundwater use scenarios indicate that reduced groundwater pumping significantly affects fen water levels (Fig. 6). During 2004, the model predicted that if the pumping was reduced by 50%, June–September drawdown near well 10 would be reduced from 1.20 m (Fig. 6a) to 0.75 m (Fig. 6b). With no pumping the predicted summer water table decline is only 0.40 m (Fig. 6c).

Analysis of the fen water storage loss for each predictive scenario indicated that a significant fraction of the pumped water is offset by storage decline within the peat (Fig. 6). The monthly pumping for the base case scenario for June, July, August and September was 1074, 1953, 1203, and 831 m^3. The simulated storage loss within the fen is 348, 559, 396, and 140 m^3 for these months (Fig. 6a). The relatively low September storage loss is due to the already low water table elevation leading into this month during the base case scenario. In this representative dry year, the base case pumping results in almost complete dewatering of the peat body by the end of August; therefore additional storage loss is minimal. With reduced groundwater pumping (Fig. 6b and c), there is less storage loss during June–August and significant saturation of the peat occurs during September.

4.3. Meadow vegetation

The vegetation of undisturbed fens in the region is dominated by plants that occur primarily in sites with perennially high water tables, including *Eleocharis pauciflora*, *Carex scopulorum*, *Drosera rotundifolia*, *Vaccinium uliginosum* and *Sphagnum subsecundum*. These species are common in the two reference meadows, but are uncommon or absent in Crane Flat. Plants that occupy seasonally wet meadows including *Potentilla gracilis*, *Veratrum californicum*, *Poa pratensis*, and *Solidago canadensis* dominate vegetation in the area with peat soils in Crane Flat. Reference meadow sites Drosera well 4 (labeled DR) and Mono Meadow well 70 (labeled MO) occur on the far left side of the CCA ordination space, and are correlated with the smallest summer water table declines (Fig. 7). Crane Flat Meadow plots in areas with thickest peat (plots 1, 10 and 14) appear on the far right side of the ordination space, indicating that their summer water table is deep, and their vegetation, is dominated by wet meadow, not fen plant species. The centroids of fen indicator plant species occur on the left side of the ordination space, in sites with sustained high summer water table, while dry meadow species are

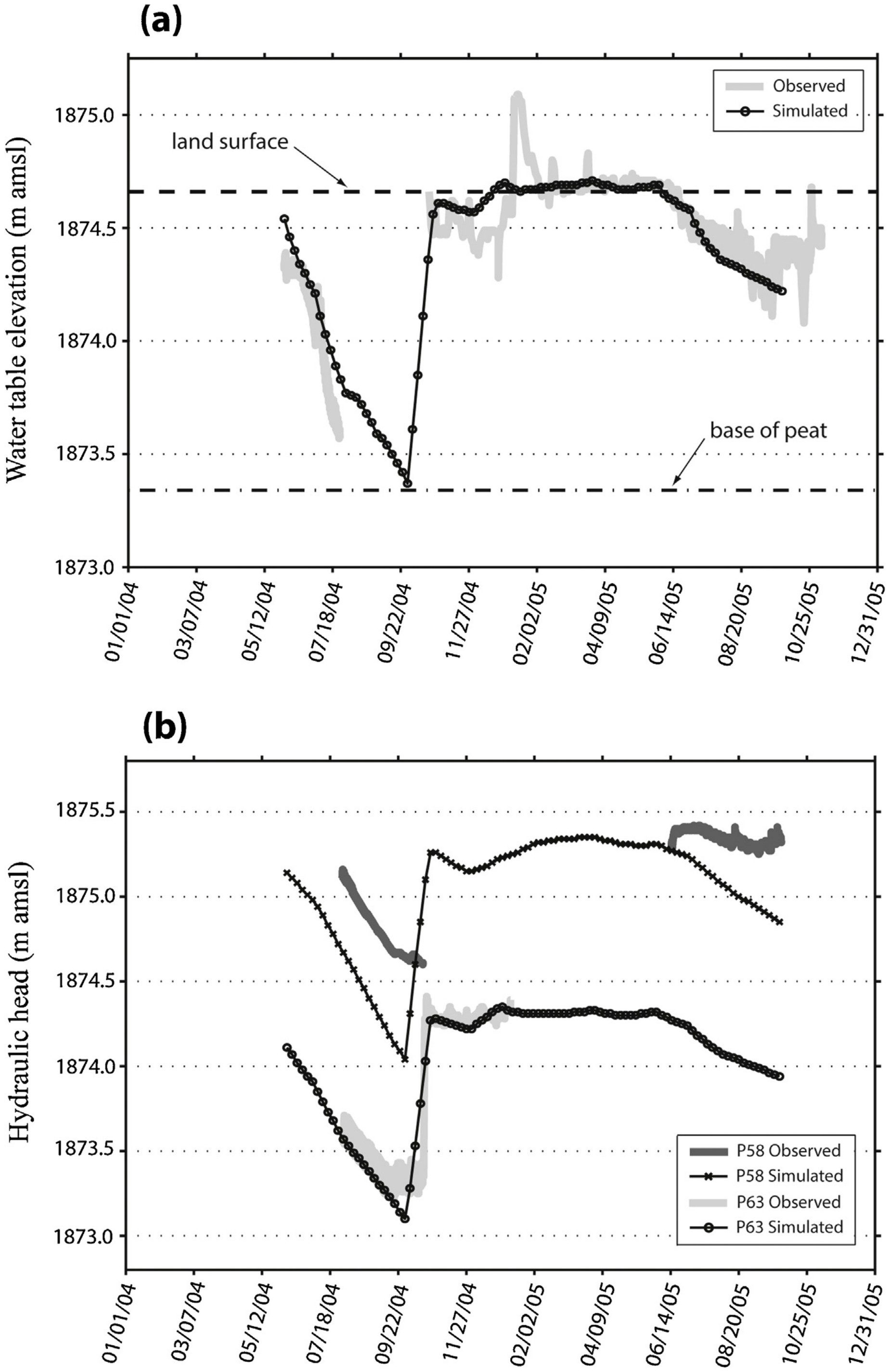

Fig. 5. Transient modeling results for the period June 2004 through Sept 2005. (a) Comparison of simulated and observed water table elevation at well 10, which is screened within the peat. (b) Model comparison at piezometers 58 and 63, which are open to the sand/gravel unit.

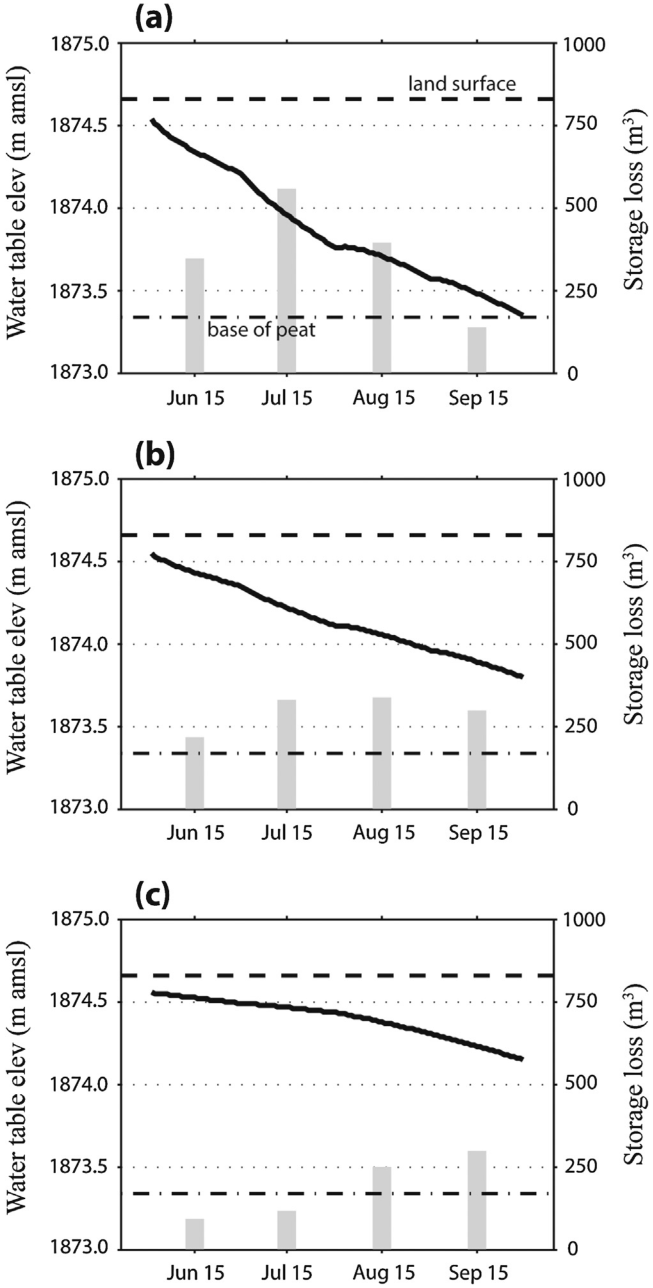

Fig. 6. Predicted water table position and storage loss within the fen for three groundwater use scenarios during a dry year. The simulated water table (solid black line), land surface, and peat bottom elevations are provided for the well 10 location. The storage loss reported for each month (bars) represents the total modeled reduction in water storage within the saturated zone for the fen area polygon shown in Fig. 1. (a) Base case transient model with actual pumping during June–September 2004. (b) and (c) are predictive model results with 50% of actual pumping (b) and no pumping (c).

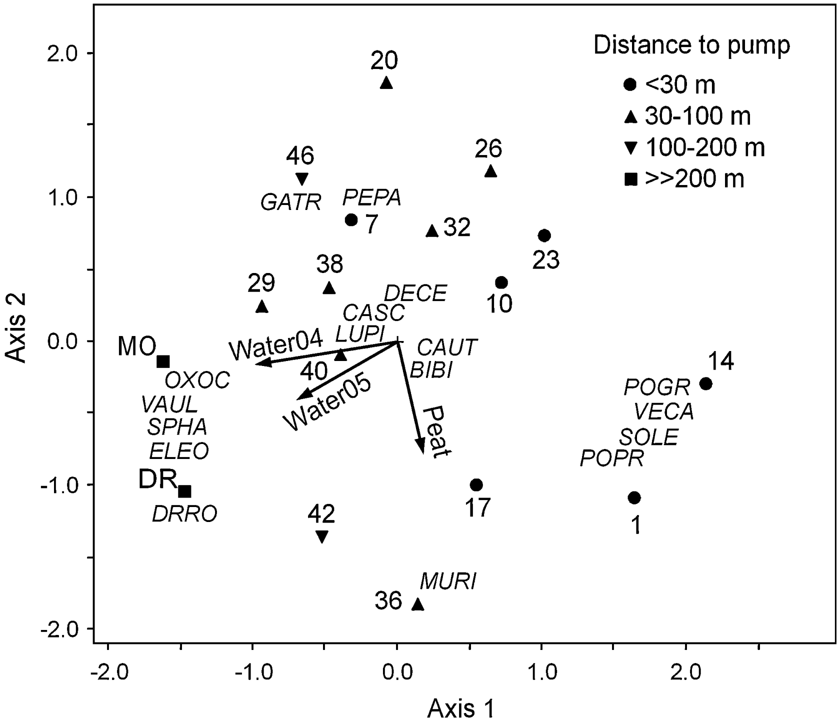

Fig. 7. Canonical correspondence analysis of the vegetation, hydrology, and peat thickness at 17 plots. The reference meadows outside of Crane Flat are plot MO in Mono Meadow and DR in Gin Flat (Drosera) fen. The other 15 plots are all within the Crane Flat wetland. Hydrologic gradients and peat thickness are shown by the vectors Water04 and Water05, which indicate the highest water level in the dry summer of 2004 and lowest water level in the wet summer of 2005 respectively, and Peat. Higher water elevations and thicker peat occur in the direction of the arrow moving away from the intersection, and lower water elevations and thinner peat in the opposite direction. The distance of each plot from the groundwater pumping well is shown, but this variable was not used in the CCA. Plant species are represented by the following codes: DRRO = *Drosera rotundifolia*, VAUL = *Vaccinim uliginosum*, OXOC = *Oxypolis occidentalis*, CASC = *Carex scopulorum*, LUPI = *Lupinus* sp., DECE = *Deschampsia cespitosa*, MURI = *Muhlenbergia rigens*, SPHA = *Sphagnum subsecundum*, ELEO = *Eleocharis pauciflora*, CAUT = *Carex utriculata*, SOLE = *Solidago lepida*, POPR = *Poa pratensis*, BIBI = *Bistort bistortoides*, VECA = *Veratrum californicum*, POGR = *Potentilla gracilis*, PEPA = *Perideridia parishii*, GATR = *Galium trifidum*.

on the right, in plots with deeper summer water tables (Fig. 7). The fen portion of Crane Flat Meadow has peat up to 140 cm thick yet the position of plots in the ordination space opposite the reference fens indicates that the hydrologic regime and vegetation has shifted significantly from its historical natural range of variation.

The total variance (inertia) in the CCA dataset was 2.344, of which 0.420 (17.9%) was explained by axis 1. The Monte Carlo test of axis 1 produced a *P*-value of 0.0491 indicating a statistically significant correlation between axis 1 and the vegetation data at $\alpha = 0.05$. Axis 1 is most strongly correlated (−0.986) with the 2004 maximum growing-season water level data. Axis 2 has an eigenvalue of 0.127 (5.4% of total variance), and is correlated (−0.787) with peat thickness. Minimum growing-season water level in 2005 is the second-ranked correlate with both axis 1 (−0.707) and axis 2 (−0.408). The vectors shown in Fig. 7 indicate the direction of increase in the values of the specified environmental variables. Plots closer to the pumping well generally occur to the right side of the ordination, and those further away are toward the left, in a gradient aligned roughly parallel to axis 1.

5. Discussion and conclusions

Groundwater pumping on summer days produced distinct hydraulic head declines in Crane Flat meadow. The duration of daily pumping controlled the magnitude of decline. Daily head declines were greatest in the coarse sand aquifer beneath the peat, but water level changes also occurred in the peat body. The effect of pumping varied by distance from the pumping well, depth of the water table when the pumping started, and that water year's SWE. The effects were somewhat similar to ditches where the greatest hydrologic effects occur closest to the ditch (Price et al., 2003), but here the effects were closest to the pumping well.

Pumping in 2004, 2007, 2008, and 2009, all years with below average SWE and the snowpack melting in early to middle March, resulted in the water table declining to the base of the peat body by mid summer. The water table decline produced dry soil conditions and peat cracking, which has allowed upland plants such as *Poa pratensis* to invade the peatland. The rapid daily water table decline each day due to pumping was only partially matched by the water table rise after pumping ceased. This suggests that by mid- to late- growing season during dry years, such as 2004, insufficient groundwater inflow occurred to offset the amount of water removed by pumping and to maintain the meadow water table near the soil surface. This was in contrast to reference fens during the same time periods where the water table remained within 20–40 cm of the soil surface.

Pumping in 2005, 2006, and 2010, all years with higher SWE and later melting snowpack, resulted in little water level drawdown despite a nearly identical pumping schedule in those years. For example, in the large snowpack year 2005, the season-long effects of pumping were mitigated by higher groundwater recharge that maintained fen water levels near the ground surface.

Nearly all of the produced water from the Crane Flat pumping well is drawn from shallow (<28 m depth) sediments. This extraction produces an almost immediate hydraulic head decline in the conductive sands that underlie the peat body. The amount of drawdown is dependent on the pre-pumping head level. When the hydraulic head is above 70 cm bgs, increased drawdown is observed for lower initial head levels. We interpret this as a signal of increasing peat density with depth, and a resultant decrease in pore size and free-draining water content (specific yield). For initial head levels lower than 70 cm bgs, total drawdown is less sensitive to the initial hydraulic head, although the negative correlation between initial head and drawdown magnitude may indicate greater porosities within the sand and gravel compared to the deep peat.

Fens in the Sierra Nevada, such as Crane Flat, have formed over thousands of years, due to the accumulation of partially decomposed plant litter (Bartolome et al., 1990). This has occurred where inflowing groundwater maintains the water table near the soil surface even on average to dry water years (Chimner and Cooper, 2003). Water table declines produced by ditching (Cooper et al., 1998), or water extraction such as groundwater pumping, can lead to rapid peat oxidation, erosion and subsidence (Schumann and Joosten, 2008; Schimelpfenig et al., 2013).

Hydrologic changes have allowed the invasion of small mammals into Crane Flat, including pocket gophers and voles. These mammals are absent from intact fens because they cannot survive in perennially saturated or inundated soils, however they are naturally present in seasonally saturated wet meadows. Mammal digging and disturbance exposes peat to rapid oxidation and erosion and creates habitat for plants exotic to the meadow, such as Kentucky bluegrass (Patterson and Cooper, 2007). Small mammal activity has exacerbated the rate of peat degradation, erosion and subsidence in Crane Flat. Peat losses occur at a much faster rate than peat accumulation (Schimelpfenig et al., 2013), and cumulative impacts from hydrologic changes produce drying (Cooper et al., 1998), reduced plant production (Chimner and Cooper, 2003), and physical disturbance by small mammals (Patterson and Cooper, 2007) all of which can lead to rapid meadow degradation.

The numerical model developed for this study provides a quantitative description of groundwater movement and seasonal water level dynamics throughout Crane Flat meadow. The modeling confirmed that the high water table within the fen is a consequence of convergent groundwater flow paths from two distinct inflow sources. Also captured by the model is the strong dependence of summer water table position on the amount of precipitation that occurs during the preceding winter and spring. The short memory of the system reflects the relatively small volume of permeable aquifer sediments, as well as the direct hydraulic connection between the recharge areas and the fen.

In addition to providing insights into the hydrologic dynamics of the meadow, the groundwater model offered an important tool for evaluating the effects of different pumping regimes. Predictive scenarios showed that, even in a dry water year like 2004, distinct increases in the fen water table elevation could be achieved with reductions in pumping. In years with above average SWE, such as 2005, groundwater inflow nearly maintains water levels in the peat even under full pumping scenarios.

Fens are relatively uncommon ecosystems in Yosemite National Park, and only 10 of 31 meadows along the Tioga Pass road had peat soil (Cooper and Wolf, 2006). Fens occupy <1% of the Yosemite landscape, yet they are the only perennially wet terrestrial environments and provide important habitat for many species of plants, amphibians, and birds, including the Great Gray Owl, a regionally endangered species. Fen formation and persistence relies on the perennial flow of groundwater into meadows, the maintenance of saturated soils through the summer, and the support of clonal plant biomass that forms the peat body (Chimner et al., 2002; Chimner and Cooper, 2003).

The CCA indicated that a high water table during summers following low snowpack water years has a more significant influence on vegetation composition than depth of water table in wet years or peat thickness. This highlights the significant impact that water level drawdown due to pumping has on wetland vegetation. In addition, plots closest to the Crane Flat pumping well have the deepest summer water tables, and plots further from the well generally had higher water tables in 2004 and 2005. The water levels and vegetation composition at the two reference sites are distinctly different from the plots in Crane Flat.

5.1. Management implications

Groundwater pumping has apparently shifted the Crane Flat fen from a peat-accumulating to a peat-losing ecosystem. In the long-term, peat that has accumulated over thousands of years will be lost through oxidation and erosion and the system could be changed to a seasonally wet meadow, as has been documented with drained peatlands throughout the world (Waddington et al., 2002; Coulson et al., 1990; Leifeld et al., 2011). This change has functionally already occurred as indicated by the summer water table depth and vegetation composition. Further decomposition and loss of peat could facilitate the invasion of trees such as lodgepole pine into the meadow, and the switch from meadow to forest habitat. Maintaining a high water table will reduce the chances of invasive plants altering the meadow composition (Timmermann et al., 2006). An additional danger is the potential of wildfire to burn the dry peat body during the summer, resulting in the loss of organic matter and alterations of the soil physical properties (Dikici and Yilmaz, 2006). Changes in the thickness or decomposition state of the peat body could also reduce its water storage capacity, further altering the hydrologic function of the meadow (Loheide et al., 2009; Lowry et al., 2011). However, the decomposed peat likely has increased capillary rise producing higher volumetric water content higher above the water table than pristine peat (Macrae et al., 2013).

This research provides guidance for the development of water management strategies to maintain or restore the hydrologic processes that formed the Crane Flat fen, and this information is critical to fen and wet meadow management any place in the world where hydrologic alterations occur. For Crane Flat, two options that are supported by the data analysis and modeling performed in this study include: (1) reduce or eliminate pumping during July and August in water years with below average SWE, and (2) allow normal pumping in summers following winters with above average SWE. Other beneficial strategies may involve adjusting the timing and duration of pumping to maintain soil saturation in the plant root zone, which will sustain the peat body and limit the invasion of small mammals and dry land plants. The installation of larger water tanks to store winter snowmelt for summer use is another alternative. However, tanks are expensive and may hold insufficient water to meet the demands of human users. Since the initial investigation, Yosemite National Park has replaced the water distribution system at Crane Flat, which had been leaking up to 75% of pumped water. However the water leaking did not return to the Crane Flat watershed. However, the new pipes may have resulted in a reduction in groundwater extraction impacts to the fen. Replacing the existing well remains an objective, though two new boreholes drilled since 2004 have failed to yield a viable alternative water source.

The methods and results presented here are applicable to fens in many mountain regions of the world particularly in regions where the peat is underlain by coarse textured mineral sediment. Fens support high biodiversity and are a top conservation priority in many regions (Lunt et al., 2010; Schumann and Joosten, 2008). Reinitiating peat-forming processes to disturbed fens and bogs is a goal for restoration programs in many countries (Rochefort et al., 2003). A key to these restoration efforts is avoiding large water table declines that allow aerobic conditions to develop and persist for extended periods of time during the summer (Deppe et al., 2010). Therefore, understanding how well connected fen peat bodies are with the underlying sediments is critical for water and ecological management, and modeling the potential effects of water extraction programs.

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