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ORIGINAL PAPER

Hydrogeology of a groundwater sustained montane peatland: Grass Lake, California

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Abstract Persistently wet conditions are essential to prevent the decomposition of organic material that forms peatlands. Wetlands in areas with a snow-melt dominated precipitation regime and little or no summer precipitation often rely on groundwater to meet late-season water requirements. Past and predicted changes in climate for the Sierra Nevada show a trend towards more winter precipitation falling as rain rather than snow. This is expected to result in reduced late-season water availability and the subsequent degradation of peatlands. Measurements of groundwater levels, stream flow, specific conductance, and peat water retention characteristics are used to quantify aspects of the hydrologic system that supports Grass Lake, south of Lake Tahoe California, the largest peatland in the Sierra Nevada. Water budget calculations using periodic measurements collected throughout the growing season show that groundwater discharge is a significant component of the water balance in the late-summer and fall. Late-season evapotranspiration needs were approximately balanced by groundwater inflow for 2010 (average water year). Groundwater discharge to the peatland dominated the late-season water budget in 2011 (above average water year) and persisted into October. Water retention experiments and field data suggest desaturation of the peatland accounts for approximately 0.5 mm day^{-1}, or roughly 10 % of the estimated evapotranspiration rate.

Keywords Peatland · Groundwater · Fen · Montane

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Introduction

Grass Lake is the largest peatland in the Sierra Nevada, located on Luther Pass, south of Lake Tahoe, California (Fig. 1). Peatlands are wetlands with thick organic soils that have formed in place. The formation of these organic soils requires perennial saturation to prevent decomposition of the organic material. Peatlands provide unique habitats, covering 3 % of the Earth's surface and making up only 0.1 % of the mountain landscape (Cooper and Wolf 2006b; Matthews and Fung 1987). In many areas of the Sierra Nevada, peatlands are the only source of perennial moisture and support ecosystems with high biodiversity.

Current climate trends and predictions for the Sierra Nevada suggest warmer winter temperatures, resulting in a more rain-dominated precipitation regime and/or earlier snow melt (Cayan et al. 2008). This is expected to decrease late-season groundwater availability and result in a lowering of the water table, leading to accelerated aerobic decomposition of organic matter (Arnold et al.

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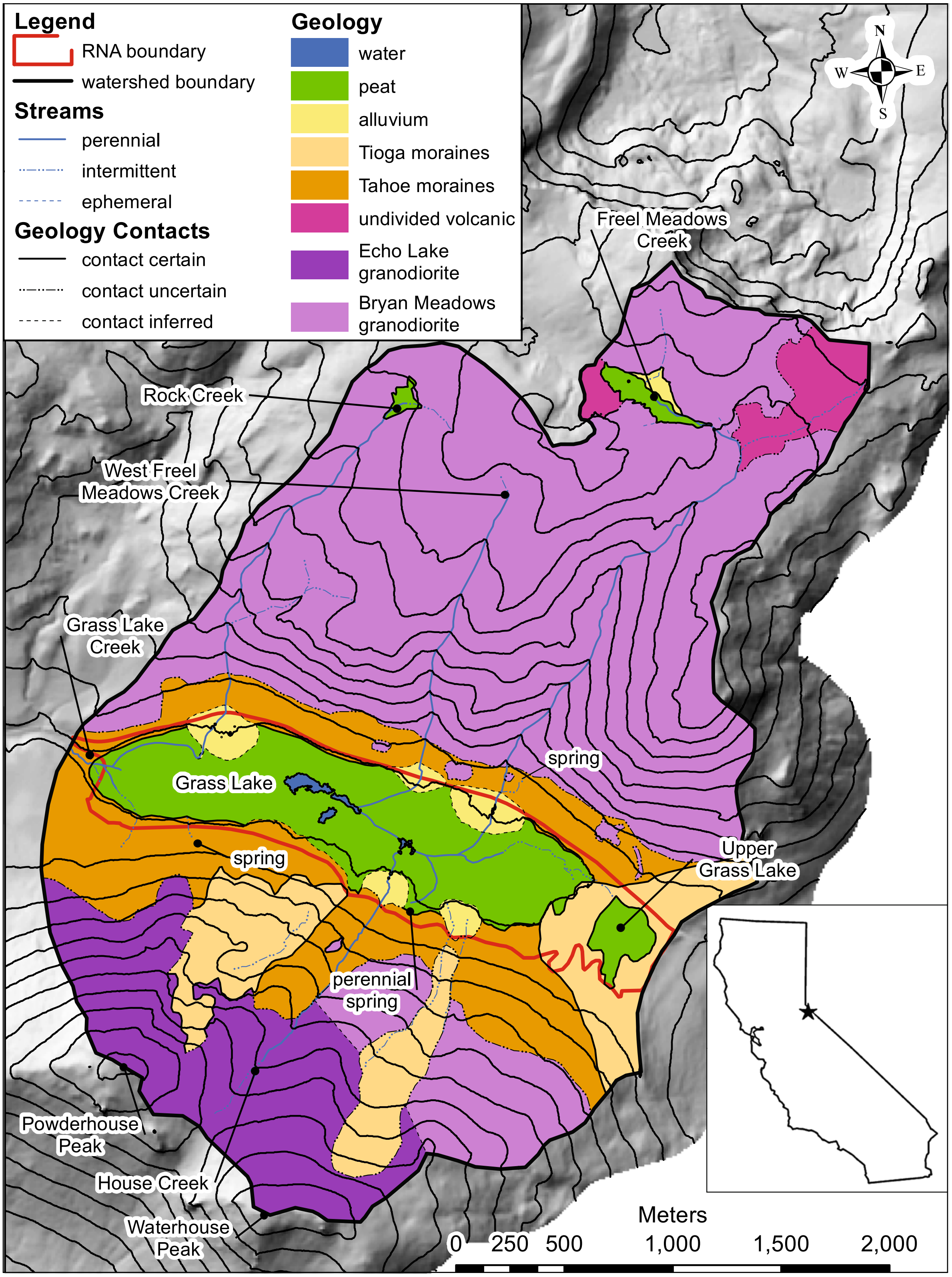
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RNA boundary
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Streams
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intermittent
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Tioga moraines
Tahoe moraines
undivided volcanic
Echo Lake granodiorite
Bryan Meadows granodiorite
N
W
E
S
Freel Meadows Creek
Rock Creek
West Freel Meadows Creek
Grass Lake Creek
spring
Grass Lake
spring
Upper Grass Lake
perennial spring
Powderhouse Peak
House Creek
Waterhouse Peak
Meters
0 250 500 1,000 1,500 2,000

◀ **Fig. 1** Geologic map of the Grass Lake Watershed, California showing the location of major hydrologic features and piezometers installed for this study. Geologic units were identified using imagery from lidar data and field mapping. Piezometers along the northern edge are denoted with the prefix *N*, while those along the south side are denoted with the prefix *S*. Contour interval is 50 m

2014). Characterizing the hydrogeology of montane peatlands provides insight into how these systems might respond to changes in the precipitation regime.

The Grass Lake Research Natural Area (GLRNA) was established in 1988 "to preserve a representative area of the sphagnum bog type in the Northern Sierra Nevada physiographic province" (USDA 1988). Bogs are defined as peatlands that receive the majority of their water from precipitation, while fens are defined as peatlands that receive the majority of their water from runoff and/or groundwater (Cooper and Wolf 2006a; Mitsch and Gosselink 1993). The GLRNA boundary is defined by Highway 89 to the north, the Alpine County line to the east, the 7720 ft contour to the south, and Forest Road 12N13Y to the west. The current GLRNA covers approximately 146 ha and is limited to within a couple hundred meters of the peatland, reflecting the interpretation that Grass Lake is a bog. However, this study quantifies the hydrologic budget of Grass Lake and clearly shows groundwater is important component of the hydrologic system supporting Grass Lake. It is recommended that the GLRNA boundary be extended to include the surrounding watershed in order to help protect the health and function of the peatland.

Methods

Site description

Grass Lake is located at Luther Pass on highway 89 just south of South Lake Tahoe, California (38° 47.5′, 119° 57.5′; WGS84). Watershed elevations range from 2347 m (7700 ft) above sea level in the peatland to 2920 m (9580 ft) along an unnamed ridge north of Freel Meadows (Fig. 1). The total watershed area is approximately 926 ha (2290 ac). The southern slopes of the watershed are dominated by red fir (*Abies magnifica*) and the northern slopes are dominated by Jeffrey pine (*Pinus jeffreyi*). Aspens (*Populus tremuloides*) are found on alluvial fans, along streams, and along the slopes of the Tioga glacial deposits below Powderhouse Peak. Lodgepole pine (*Pinus contorta*) occurs along the forest-meadow ecotone and in small (<100 m^2) stands within the meadow. A more complete description of the vegetation communities can be found in Burke (1987) and Berg (1991).

Airborne lidar data provided by Tahoe Regional Planning Agency and field observations were used to map the surface geology of GLRNA at a scale of 1:5000 (Fig. 1). The high spatial resolution of the lidar dataset (3.5 cm RMSE, TRPA 2012) facilitated the identification of geomorphic features previously obscured by trees and the complex topography.

Luther Pass was formed by a spur from a Tahoe age (145 ka; Rood et al. 2011) glacier that originated near Carson Pass. This glacier left behind a moraine that impounds Grass Lake to the west and forms the hillsides adjacent to Grass Lake. Tioga age (19 ka; Rood et al. 2011) glacial deposits impound the east end of Grass Lake and form a smaller peatland ("Upper Grass Lake", Fig. 1) to the east of Grass Lake proper. Deposits from two Tioga age cirque glaciers occur along the south side of Grass Lake and overlie portions of the older Tahoe moraine.

The bedrock in the GLRNA is dominated by Cretaceous granodiorite (Fig. 1). The northern and the southeastern corner of the watershed are dominated by the Bryan Meadows granodiorite (Armin et al. 1983). The younger Echo Lake granodiorite underlies the south side of the watershed and forms both Waterhouse Peak and Powderhouse Peak. Tertiary volcanic deposits unconformably overlie the granodiorite and are exposed near Freel Meadows. Deeply weathered, unglaciated granodiorite dominates the north side of the watershed at elevations above approximately 2600 m (8530 ft). Where larger streams have eroded into the unglaciated material, the bottom of the drainage consists almost entirely of large (up to 4 m) rounded corestones (Twidale and Vidal Romani 2005).

Small alluvial fans composed of coarse sand and gravel with some interbedded peat occur at the mouths of four perennial streams and one intermittent stream that enter Grass Lake. The Rock Creek and Freel Meadows Creek fans are incised up to 0.6 m (2 ft). The House Creek fan is incised up to 2 m (6 ft). Fresh deposits of sand overlying peat were found at the mouths of Rock Creek and Freel Meadows Creek after the 2011 peak flows. West Freel Meadows Creek disperses into a broad riparian area with several poorly defined anastomosing streams after exiting the culvert, suggesting a predominantly depositional regime.

Four peat bodies occur within the GLRNA covering approximately 100 ha (247 ac). The largest is Grass Lake, with an area of approximately 88 ha (217 ac). The next largest peatland (7 ha; 17 ac) is located approximately 100 m east of Grass Lake. The third largest peatland is Freel Meadows (4 ha; 10 ac), located northeast of Grass Lake at an elevation of 2815 m (9236 ft). The smallest peat body (2 ha; 5 ac) documented in this study is located at the headwaters of Rock Creek at an elevation of 2740 m (8989 ft). Grass Lake proper is dominated by slightly humified to unhumified peat consisting of organic material from both bryophytes (e.g. *Sphagnum* spp., *Meesia triquetra*) and herbaceous plants (e.g. *Carex* spp., *Deschampsia cespitosa*, *Drosera rotundifolia*) (Stanek and Silc 1977).

The edge of Grass Lake was mapped using the Soil Survey Staff (1999) general description of an organic soil (Histosol: more than 40 cm of organic material in the upper 80 cm of soil). An extendible tile probe was used to determine the depth of peat within 2 m (6 ft) of each piezometer as well as 10 additional locations between piezometers. Resistant layers and/or probe instability limited soil probe data to less than 1 m (3 ft) below ground surface on alluvial fans and 5 m (15 ft) in the peatland. The peat boundary was interpolated between probe locations.

Coarse sand and gravel deposits ranging from 0.1 to over 0.5 m (0.3–1.6 ft) thick were encountered below the peat. The horizontal extent of the coarse layers parallel to the hillslope is variable, while perpendicular to the hillslope there is a trend of decreasing sand content and increasing peat depth at a rate of approximately 10 % (0.1 m/m) for the first 10–30 m in most locations. Peat thickness was more variable on the edges of the alluvial fans, with interbedded layers of coarse sediment and peat on the order of 1.0 and 0.1 m (3 and 0.3 ft), respectively. The location of the edge of the peatland is expected to be accurate to within 5 m near each piezometer and within 10 m between piezometers.

Estimates of annual precipitation at Grass Lake for the 2010 and 2011 water years were 1.0 m (39 in.) and 1.7 m (67 in.), respectively (PRISM 2013). These values represent 100 and 158 % of the 1900–2011 estimated average annual precipitation, respectively. Approximately 90 % (2010) and 88 % (2011) fell between October 1 and May 1, presumably as snow.

Evidence of surface water flow in the GLRNA is limited to the peatlands, streams, impervious rock surfaces, and adjacent to rapidly melting snow. There are three perennial streams along the north side of the lake (Fig. 1): Rock Creek, West Freel Meadows Creek, and Freel Meadows Creek. House Creek is the only perennial stream along the south side. Grass Lake Creek is the only surface water flowing out of the watershed. The sources of all perennial streams are located in the unglaciated upper watershed. Rock Creek and Freel Meadows Creek originate in peatlands. West Freel Meadows Creek originates from a spring 700 m southwest of Freel Meadows and 29 m (95 ft) lower in elevation. This spring is assumed to be groundwater seepage from Freel Meadows based relative elevation, proximity, and sustained late-season discharge. The source of House Creek is not well defined and has been observed as high as the pass between Waterhouse Peak and Powderhouse Peak (2740 m, 8990 ft) in 2010 and as low as 2650 m (8690 ft) in 2009.

One spring surfaces within the Tahoe age lateral moraines on each side of Grass Lake. The largest spring surfaces approximately 100 m uphill of the Freel Meadows Creek alluvial fan and 100 m east of Freel Meadows Creek. By late fall flow was not measurable ($<0.003\ m^3\ s^{-1}$) and the stream disappeared before reaching Freel Meadows Creek. The spring on the south side surfaces approximately 100 m uphill of the peatland. In 2011, two seeps flowed from road cuts in the Tahoe moraine approximately 70 m east and 50 m west of Rock Creek until late-June.

A perennial groundwater spring is associated with a small peat mound approximately 1 m above grade just east of the House Creek fan. This spring often melts out during the winter despite partial shade from the hillslope and large conifers. This suggests a perennial source of deeper groundwater with enough thermal energy to melt the accumulating snow. Groundwater flows from natural seeps in the peatland at over 20 locations along the southwest edge of Grass Lake. Shallow soil probes suggest some of these seeps are associated with large woody debris buried in the peat, providing preferential flow paths for the groundwater.

Specific conductance

Specific conductance (SC) measures the ability of a fluid to conduct electricity and is related to the concentration of dissolved ions in solution. Measurements of SC were made using an Oakton multi-parameter PCTestr 35 at each piezometer during field visits. The instrument was calibrated at the beginning, middle, and end of each field season using an 84 μS cm^{-1} solution. The reported accuracy of the instrument is ±2.0 μS cm^{-1} and calibration readings were within ±3.0 μS cm^{-1} at each calibration. A 6-ft (1.8 m) hose was used to siphon water from the piezometer. The hose, instrument and sampling vessel were rinsed three times or until the SC reading stabilized before a final reading was recorded. The SC of adjacent surface water was measured when present.

A two-component mixing model can be used to estimate the contribution of groundwater and surface water to the total flow, assuming SC is conservative with a known and constant value for each component (Hill 1990). The SC of stream water during peak flow (SC_T) is assumed to be the result of two components mixing: surface runoff from snowmelt (SC_s) mixing with groundwater (SC_g). The fraction of groundwater contributing to baseflow is given by:

$$f_g = \frac{SC_T - SC_s}{SC_g - SC_s} \quad (1)$$

The relatively constant SC values recorded for a perennial spring near Freel Meadows, assumed to represent the equilibrium SC value for groundwater, are used to estimate the minimum contribution of groundwater to peak flow. The SC values of the streams during baseflow provide a reasonable estimate of minimum SC for groundwater and are used to estimate the maximum contribution of groundwater to peak flow. The average value of SC for melted snow is used for SC_s.

Surface hydrology

Measurements of stream flow and SC were made approximately biweekly for perennial streams entering and leaving Grass Lake (Fig. 1). Stream flow measurements were complicated by the dynamic nature of the stream channels (Rock Creek, West Freel Meadows Creek, and House Creek), irregular culverts (Freel Meadows), heavy vegetation (Grass Lake Creek), limited length of suitable reaches, and the need to compare measurements made using various methods. Stream flow measurements are assumed to be accurate to within ±30 %.

Stream flow measurements were made using a combination of methods depending on channel conditions. Due to the steep, rocky nature of the channels, sections with greater than 1.5 m (5 ft) of relatively uniform flow, adequate depth (>6 cm, 0.2 ft), and fairly consistent channel profile were considered marginally adequate for cross-sectional discharge measurements using a current meter (Fetter 2001). The float method was used in shallow streams where current meter measurements were not feasible (Kondolf and Piegay 2002). The float velocity was measured over a distance of 1.0–3.0 m in relatively straight sections of natural streams and culverts during low flow, and distances up to 18 m (60 ft) in culverts during high flow. Velocity measurements were repeated until a minimum of 5 were within10 % of the mean. The depth-averaged velocity was estimated to be 60 % (±20 %, n = 6) of the surface velocity using independent measurements of flow (Christensen 2013).

Discharge measurements can be estimated using width and depth measurements if the Manning coefficient and slope of the culvert are known. Freel Meadows Creek and West Freel Meadows Creek both had culverts that were conducive to estimating the Manning's coefficient. The average velocity (V) of water flowing over a uniform surface is given by:

$$V = \frac{k}{n} R_h^{2/3} S^{1/2} \quad (2)$$

where n is the Manning coefficient, R_h is the hydraulic radius defined as the ratio of cross-sectional (A) area to wetted perimeter (P), S is the slope of the water surface (assumed equal to the culvert slope), and k is a conversion factor. Equation (2) can be rearranged using the relationship $Q = V{*}A$, where Q is the volumetric discharge, V is the average velocity, and A is the cross-sectional area. The Manning coefficient was calculated with the following equation using independent values of discharge (Q) measured by one or more of the above mentioned methods:

$$n = \frac{k}{Q} \frac{A^{5/3}}{P} S^{1/2} \quad (3)$$

The Manning coefficients for the Freel Meadows Creek culvert were calculated to be 0.023 (σ = 0.003, n = 8) for the east culvert and 0.016 (σ = 0.002, n = 4) for the west culvert using Eq. (3). These values are consistent with common values for the surface materials: corrugated metal and asphalt, respectively. The Manning coefficient for the West Freel Meadows Creek culvert was calculated to be 0.023 ($\sigma = 0.003$, $n = 11$) using independent measurements of discharge during the 2010 field season. Peak flows in 2011 caused West Freel Meadows Creek to avulse, bypassing the only section suitable for cross sectional discharge measurements. All 2011 discharge measurements for West Freel Meadows Creek are based on measurements of the width and depth using Eq. (2).

Stream flow records for 2010 cover the period from May 1 to September 20. Stream flow records for 2011 cover the period from May 13 to October 23. The average seasonal stream flow was estimated as:

$$\bar{Q} = \frac{\sum_{i=1}^{N} (Q_i + Q_{i-1})(t_i - t_{i-1})}{2t_T} \quad (4)$$

where N is the total number of stream flow measurements made for the stream in question, Q_i is the i^{th} stream flow measurement made at time t_i, and t_T is the total time period. Minimum estimates of annual seasonal stream flow were made assuming there was no flow prior to the first measurement. Maximum estimates of the annual seasonal stream flow were made by extrapolating from the first measured values to zero flow to mark the start of the season. The seasonal surface water yield for each watershed was calculated as the ratio of total stream flow to contributing area (Table 1).

Groundwater

Measurements of piezometric head and SC were made approximately biweekly during the 2010 and 2011 field seasons for 32 piezometers located along the margins of Grass Lake (Fig. 1). Piezometers were constructed of 1¼-inch nominal schedule 40 stainless steel pipe (4.22 cm outer diameter). The piezometers were installed where peat thickness was approximately 1–3 m (3–10 ft) thick. The 15 cm (6 in.) screened interval of each piezometer was placed at a depth of 1.3–2.8 m (4.3–9.2 ft) below ground surface and located in the sand/gravel layers that underlie the peat. Piezometers on the alluvial fans were installed such that the screened intervals were in sand layers below significant (>0.25 m) peat deposits. The elevation of the rim of each piezometer was determined using a total station. The standard deviation for all surveys is better than 15 cm (6 in., $n \geq 6$) based on repeated measurements of points of known elevation established along Highway 89 by the California Department of Transportation.

The upslope geology, vegetation type, and the proximity to other piezometers were used to determine the locations of the piezometers. Eighteen piezometers were placed down slope of the interface of the Tahoe age lateral moraines and the peat. Seven of these 18 were also located down slope of the large terminal moraine associated with the Tioga age cirques along the south side of Grass Lake. Nine piezometers were placed near the interface of the alluvial material and the peat. Four piezometers were placed near the Tioga age terminal moraines that forms the east side of the Grass Lake watershed, including two in Upper Grass Lake (Fig. 1).

Measurements of the depth from the rim to the water surface inside and outside (when present) of each piezometer were recorded with a precision of

Table 1 Seasonal surface water yield (volume of water per contributing area) and percent of annual precipitation for the GLRNA in 2010 and 2011

Watershed	Contrib. area (ha)	2010				2011			
		Seasonal surface water yield (m^3/m^2)		% annual precipitation (1.04 m)		Seasonal surface water yield (m^3/m^2)		% of annual precipitation (1.66 m)	
		Min	Max	Min (%)	Max (%)	Min	Max	Min (%)	Max (%)
Rock Creek	108	0.07	0.23	6	22	0.21	0.51	13	31
W. Freel Meadows Ck	65	0.08	0.15	8	14	0.24	0.45	15	27
Freel Meadows Ck	210	0.13	0.24	13	23	0.39	0.72	23	43
House Creek	66	0.04	0.13	3	13	0.17	0.39	10	23
Grass Lake Creek	926	0.10	0.17	10	16	0.24	0.44	14	27

1 mm (1/16th in). The high precision of these measurements allowed accurate calculations of the vertical hydraulic gradients (VHG) between the bottom of the peat and the surface water. The lack of surface water prevented accurate calculation of VHG for many of the northern piezometers in 2010. Positive values of VHG indicate groundwater flowing upward through the peat.

Manual measurements of depth to groundwater from the rim of each piezometer were used to construct contour maps of groundwater head for the fall of 2010 and the spring of 2011, representing the driest and wettest conditions during the study, respectively. The elevations of streams were used to approximate the elevation of the piezometric surface in the upper portions of the alluvial fans.

Peat water retention and material properties

Four peat samples were collected from Grass Lake to measure the water retention characteristics for water levels ranging from 0 to −1.79 m (0–17.5 kPa of suction). Samples were taken from the low lying hollows to avoid complications associated with defining the transition between the low density living peat (acrotelm) and the higher density non-living peat. The locations of these samples (PC1, PC2, PC3 and PC4) are shown on Fig. 1.

The peat samples were placed in 9.5 cm diameter Pyrex Buchner funnels with a reported pore size of 4.5–5 µm. The saturated volume of each sample was calculated once the sample and hanging column apparatus was fully saturated. The water level was lowered by approximately 10 cm increments and the amount of water released was recorded to the nearest milliliter. The samples were weighed after reaching equilibrium under a suction pressure of 1.79 m (W_f). The samples were spread and dried at 103 °C for 15 h and reweighed (W_d). The final volumetric water content (θ_f) was calculated as:

$$\theta_f = \frac{W_f - W_d}{\rho_w V_T} = \frac{V_f}{V_T} \quad (5)$$

where ρ_w is the density of water (1000.0 kg m^{-3}), V_f is the volume of water remaining in the sample, and V_T is the total volume of the sample at saturation.

The volume of water at saturation (V_s) was calculated by adding the final water content (V_f) to the water released from the sample during the experiment (V_r):

$$V_r = \sum_{i=1}^{N} V_i \quad (6)$$

$$V_s = V_f + V_r \quad (7)$$

where V_i is the volume of water released during suction step i and N is the total number of suction steps. The volume of water contained in the sample for a given value of suction ($V_{\psi n}$) is calculated by subtracting the volume of water released in all subsequent suction steps (V_n) from the volume of water at saturation (V_s), where (V_n) is given by:

$$V_n = \sum_{i=1}^{n} V_i \quad (8)$$

and n is the suction step of interest. The volumetric water content at suction step n is given by:

$$\theta_\psi = \frac{V_f + V_r - V_n}{V_T} = \frac{V_{\psi n}}{V_T} \quad (9)$$

The saturated volumetric water content (θ_s) is the ratio of (V_s) to total volume (V_T). The degree of saturation (S_w) is the ratio of ($\theta_{\psi n}$)/(θ_s), and equal to 1 when n = *0* and the sample is at full saturation. The pressure intervals and resulting degree of saturation define the pressure–saturation relationships for water storage in unsaturated peat.

Water budget

The water budget for the peatland was calculated using periodic measurements of stream flow and estimates of storage changes. The contribution of groundwater to the peatland was estimated using a simple water budget give by:

$$G_{in} = S_{out} + ET - S_{in} - S_{direct} + \Delta S \quad (10)$$

where G is the net volume (or flux) of groundwater entering Grass Lake, S_{in} is the volume (or flux) of surface water inflow, S_{out} is the volume (or flux) of surface water outflow, S_{direct} is the volume (or flux) of water resulting from direct snow melt, ET is the volume (or flux) of water leaving due to evapotranspiration, and ΔS is the change in water storage. The minimum groundwater contribution is estimated using the minimum values for S_{out} and ET along with the maximum values for S_{in}.

The evapotranspiration rate at Pope Marsh, located approximately 10 miles (16 km) north-northwest of Grass Lake, was estimated to be 4.2 mm day^{-1} (Green 1998). Evapotranspiration rates ranging from 5.0 to 6.5 mm day^{-1} have been estimated for riparian meadow sites in the Sierra (Loheide and Gorelick 2005). Comer et al. (2000) reported values of latent heat flux from seven peatlands in Canada and the northern United States ranging from 69 to 142 W m^{-2} for fens and 105–199 W m^{-2} for bogs. These values of latent heat flux are equivalent to evapotranspiration rates of 2.6–5.4 mm day^{-1} for fens and 4.0–7.6 mm day^{-1} for bogs. We assumed an evapotranspiration rate of 5.0 mm day^{-1} ($\pm$2.5 mm day^{-1}) for all water budget calculations based on the above studies.

All of the winter precipitation accumulated on the peat surface is assumed to contribute to streamflow from the peatland. Four rainstorms contributed approximately 22 mm of direct precipitation to the peat surface during the summer of 2010. However, the storm flow and peak flow data suggest precipitation and snow melt on the surface of Grass Lake moves through the system quickly (2–3 days). As such, precipitation and snow melt on the peat surface are only included in the periodic water budget calculations if they occurred within 3 days prior to the date of interest.

The change in water storage for a lake can be estimated as the change in water level multiplied by the average area of the lake. For a porous media the change in storage is calculated as:

$$\Delta S = \Delta h \times A \times S_y \tag{11}$$

where Δh is the change in water level, A is the area covered by the porous media, and S_y is the specific yield or drainable porosity. The areas of peat, floating peat, and open water were not accurately measured during this study. As such, the contributions from the change in storage for each component cannot be accurately calculated. However, and upper limit for storage changes in the entire peatland can be estimated using a maximum value of specific yield (1.0) and the average rate of decline of water levels measured in the peatland (2.4 mm/day). The rate of water derived from storage in the peatland is estimated to be 0.02 m^3 s^{-1}.

Results

Specific conductance

Specific conductance values for Grass Lake Creek dropped from a high of 235 to a low of 28 µS cm^{-1} between late-March and mid-June 2010 and then increased to 40.0 µS cm^{-1} by mid-September. In 2011 values dropped from approximately 125 to a low of 23 µS cm^{-1} between late-April and early-July before increasing to 49 µS cm^{-1} by late-October. House Creek had the lowest SC in both 2010 and 2011, with values consistently less than 17.0 µS cm^{-1}. West Freel Meadows Creek, Freel Meadows Creek, and Rock Creek had similar values of SC, dropping from approximately 34 ($\sigma = 4$, n = 12) to 20 ($\sigma = 2$, n = 9) µS cm^{-1} between late-April and mid-June in 2010 and dropping from approximately 33 ($\sigma = 6$, n = 8) to 18 ($\sigma = 1$, n = 11) µS cm^{-1} between mid-May and mid-July 2011. The SC of snow samples was 5.2 µS cm^{-1} ($\sigma = 2$, n = 9). The SC values for these three streams increased from approximately 20–33 ($\sigma = 2$, n = 14) µS cm^{-1} between mid-June and mid-September of both years. The declining trend in SC during the spring and early summer can be explained by snow melt (low SC) mixing with subsurface flow (high SC) in the streams.

The SC values of the springs and seeps originating in the Tahoe age moraines along the north side of Grass Lake were higher than the SC values recorded for the streams. The average SC value of the spring east of Freel Meadows Creek was 78 ($\sigma = 2$, n = 11) µS cm^{-1} in 2010 and 69 ($\sigma = 1.5$, n = 5) µS cm^{-1} by July, 2011. In 2011 two seeps manifested in road cuts located near Rock Creek along highway 89. Water from these seeps collected within 0.5 m of the O horizon was 52 ($\sigma = 6$, n = 19) µS cm^{-1} between late April and late June, after which they dried up. Melting snow banks with SC values of 8.5 µS cm^{-1} were identified approximately 20 m upslope of each seep. This rate of increase in SC (2.18 µS cm^{-1} m^{-1}) may be higher than expected due to the influence of salt from the adjacent road.

The two component mixing model in Eq. (1) was used to estimate the contributions of subsurface flow to peak stream flow for streams on the north side of GLRNA. The value of SC during peak stream flow (20 $\pm$ 2 µS cm^{-1}) is used for SC_T in Eq. (1). The

Table 2 Average seasonal stream flow (ASSF) and peak stream flow values in cubic meters per second ($m^3\ s^{-1}$) for the GLRNA in 2010 and 2011

Source	2010				2011			
	ASSF ($m^3\ s^{-1}$)		Peak ($m^3\ s^{-1}$)		ASSF ($m^3\ s^{-1}$)		Peak $m^3\ s^{-1}$)	
	Min	Max	Flow	Date	Min	Max	Flow	Date
Rock Creek	0.006	0.020	0.133[a]	7-Jun[a]	0.017	0.040	0.323	26-Jun
W. Freel Meadows Ck	0.003	0.008	0.093	7-Jun	0.011	0.020	0.136	26-Jun
Freel Meadows Ck	0.023	0.042	0.419[a]	8-Jun	0.057	0.108	0.937	26-Jun
House Creek	0.003	0.006	0.034[a]	17-Jun[a]	0.008	0.017	0.113[a]	7-Jul[a]
Grass Lake Creek	0.071	0.133	0.651[a]	20-May[a]	0.156	0.289	1.999	29-Jun

An assumed measurement error of ±30 % has been included in the minimum and maximum estimates of average seasonal stream flow

[a] Best estimate and date of peak stream flow due to missing data

value of SC for melted snow (5 ± 2 μS cm^{-1}) was used for SC_s. The lowest estimate of SC for baseflow (27 μS cm^{-1}) and the highest estimate of SC for the perennial spring (80 μS cm^{-1}) were used as the minimum and maximum value of SC for the groundwater contribution (SC_g), respectively. The contribution of groundwater to peak stream flow was estimated to be between 15–70 %.

Specific conductance measurements in and around the piezometers indicate a distinct difference between groundwater along the north side of Grass Lake (near Highway 89) and the south side of Grass Lake (undeveloped) during both years. The higher values of SC on the north side may be attributed to salts used for highway deicing or by increased weathering rates associated with southern exposure. Values of SC were lower on both sides in 2011 than they were in 2010, likely due to the larger snow pack in 2011. The decrease in SC during spring is attributed to low SC snowmelt (5.2 μS cm^{-1}) and stream water, while the increase in fall may be explained by a greater proportion of high SC groundwater and/or ion enrichment associated with increased ET.

Surface hydrology

The surface water yield ranged from 6 to 23 % of the annual precipitation in 2010 and 10–43 % of the annual precipitation in 2011 (Table 1). The annual seasonal stream flow values for 2011 are 1.9 (Rock Creek) to 2.7 times (West Freel Meadows Creek, Freel Meadows Creek, House Creek) higher than the 2010 values (Table 2). The annual seasonal stream flow out of Grass Lake in 2011 was 2.2 times higher than the 2010 value. Stream flow for the four streams entering Grass Lake proper fell below 0.028 $m^3\ s^{-1}$ (1.0 $ft^3\ s^{-1}$) between late-June (House Creek) and late-July (Freel Meadows Creek) in 2010 (Fig. 2), and between late-July (West Freel Meadows Creek and House Creek) and mid-August (Freel Meadows Creek) in 2011 (Fig. 3). Flow out of Grass Lake dropped to 0.017 $m^3\ s^{-1}$ (0.60 $ft^3\ s^{-1}$)by September 2010 yet maintained flows as high as 0.23 $m^3\ s^{-1}$ (0.81 $ft^3\ s^{-1}$) into October in 2011.

Manual measurements and daily field observations suggest peak flows out of Grass Lake occurred in mid-May 2010 and were around 0.65 $m^3\ s^{-1}$ (23 $ft^3\ s^{-1}$). Peak flows for streams entering Grass Lake occurred in early-June 2010, with flow from Freel Meadows Creek (0.53 $m^3\ s^{-1}$; 19 $ft^3\ s^{-1}$), contributing the majority of flow to the peatland (Fig. 2). Peak flows for streams entering Grass Lake occurred on June 26, 2011 and peak flow out of Grass Lake was measured as 2.0 $m^3\ s^{-1}$ (71 $ft^3\ s^{-1}$) 3 days later (Fig. 3). The highest value of discharge for House Creek (0.11 $m^3\ s^{-1}$; 4.0 $ft^3\ s^{-1}$) was recorded on July 7, 2011. The apparent delay in peak stream flow for House Creek is likely due the northern aspect of the House Creek. The actual peak discharge in Grass Lake Creek, Rock Creek, and House Creek were not captured in 2010 due to complications with the field equipment.

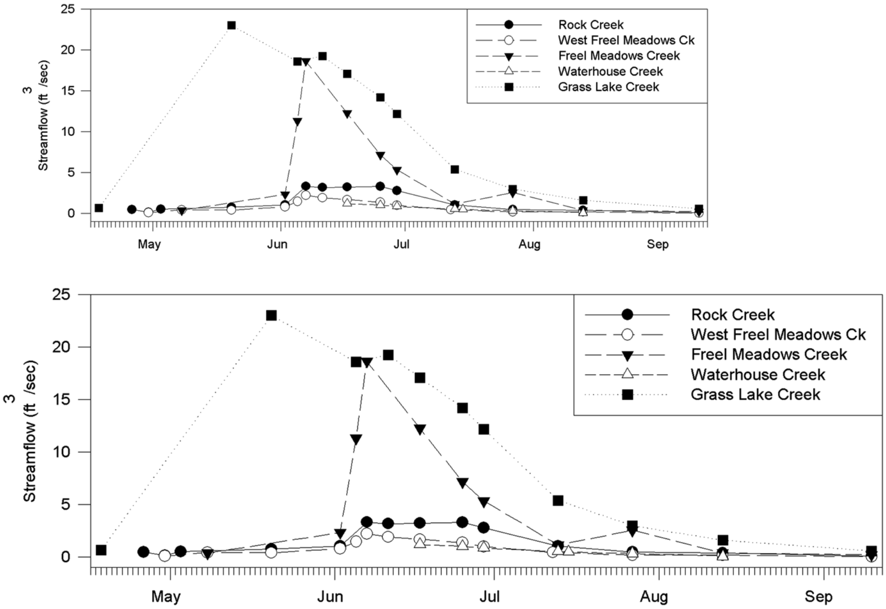


Fig. 2 (Small and large): 2010 manual stream flow measurements into and out of Grass Lake proper

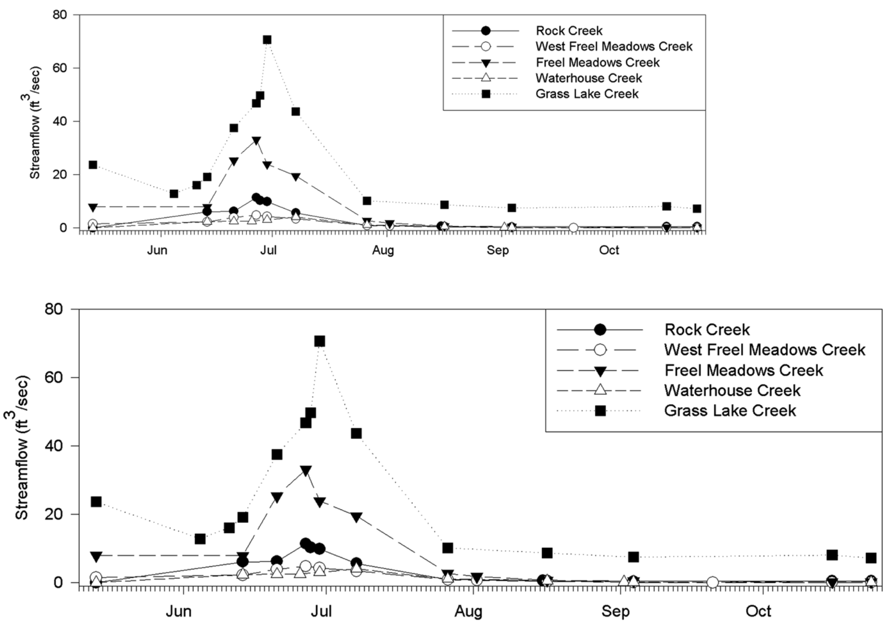


Fig. 3 (Small and large): 2011 manual stream flow measurements into and out of Grass Lake proper

Groundwater measurements

Piezometric head measurements show groundwater elevations were on average 0.32 m ($\sigma = 0.21$ m) higher in the spring of 2011 than the fall of 2010 (Figs. 4, 5). The largest recorded groundwater level difference occurred in piezometer N7 (0.86 m increase), indicating increased flow from Upper Grass Lake. The head data and contour maps of piezometric head (Figs. 4, 5) show areas of divergent flow where streams enter Grass Lake and convergent flow where bedrock outcrops are located immediately above the piezometers. The divergent flow is more pronounced along the north side of Grass Lake where the larger streams enter the peatland. The divergent flow associated with House Creek appears to be offset slightly to the east, suggesting preferential flow towards S5. This is consistent with observations of persistent

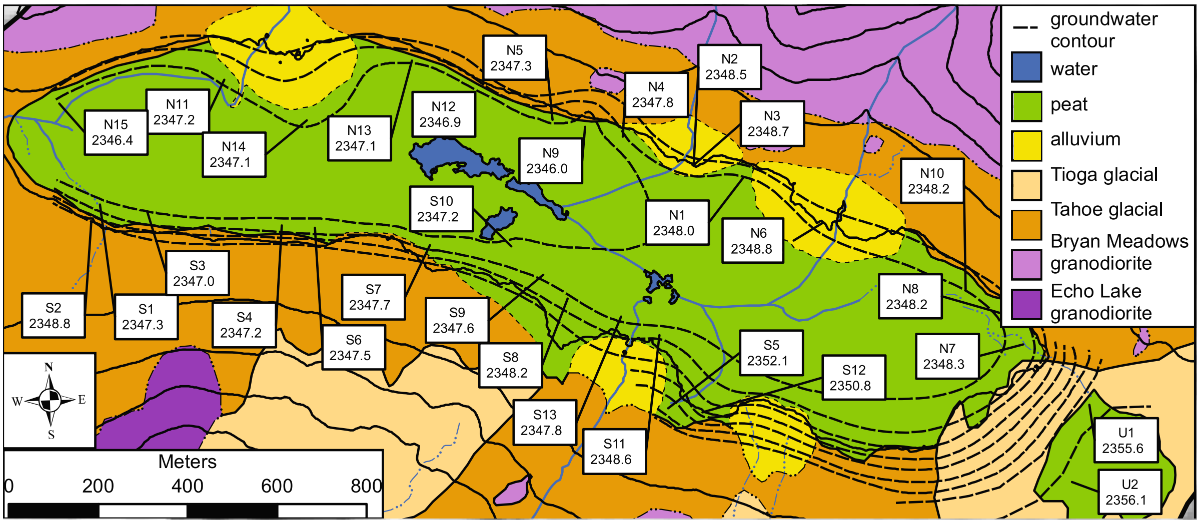


Fig. 4 Groundwater head contours in the Grass Lake peatland, fall 2010. Contours interval is 1 m

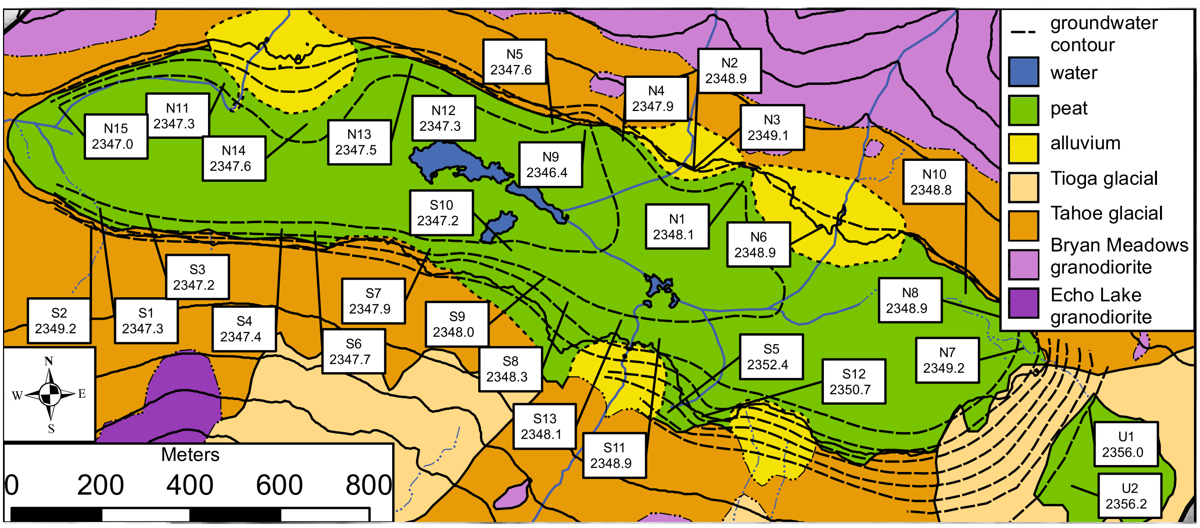


Fig. 5 Groundwater head contours in the Grass Lake peatland, spring 2011. Contours interval is 1 m

saturation along the east side of the House Creek fan and drier conditions to the west. Piezometric head contours below bedrock outcrops on the hillslopes near the margin of Grass Lake indicating convergent flow (piezometers N1 and N9). This may be explained by hillslope groundwater being diverted around the edges of the impermeable bedrock, creating a low pressure zone below the outcrop. The highest horizontal hydraulic gradients (HHGs) indicated on the head contour maps occur at the margins of the peatland, with the largest values on the order of 5 % near piezometers S1, S2, and S3. The HHG along the length of Grass Lake (from east to west) is on the order of 0.25 %.

Vertical hydraulic gradients (VHGs) were higher along the southern edge of Grass Lake than the northern edge and higher in 2011 than in 2010 (Figs. 5, 6). Positive VHGs indicate upward flow of groundwater through the peat (groundwater discharge), whereas negative VHGs indicate flow of surface water into the subsurface (groundwater recharge). The highest VHGs recorded in 2010 were approximately 20 % for piezometers S5 and S9 (e.g. the groundwater level in a 2.0 m deep piezometer was 0.4 m higher than the

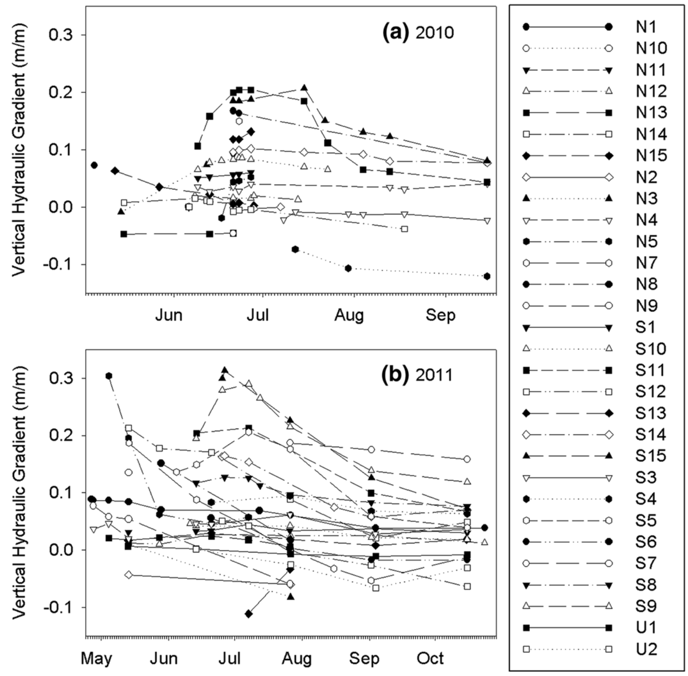
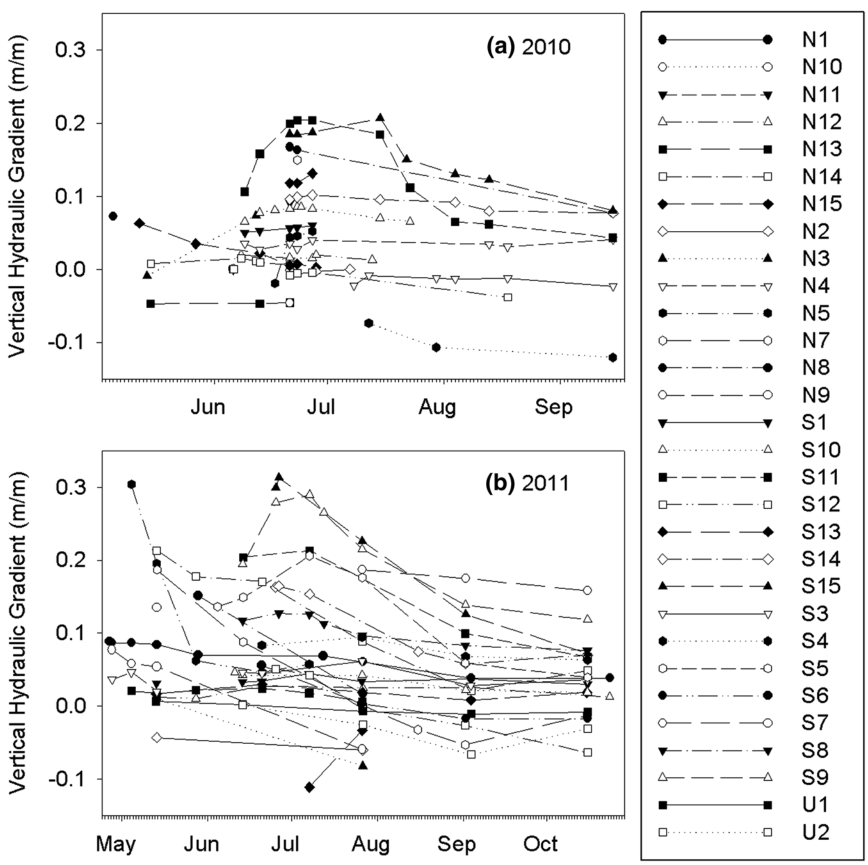


Fig. 6 (Small and large): Vertical hydraulic gradients calculated from 2010 field data **a** and 2011 field data **b** for the north (N) and south (S) sides of Grass Lake



elevation of the adjacent surface water). The highest VHGs recorded in 2011 were approximately 30 % in S9, S15, and N5. Piezometers S5, S7, S11, N7, and N14 also had high positive VHGs (20 %) in the spring of 2011. Positive VHGs were maintained until late-September 2010 in piezometers S1, S5, S8, S9, and S12, indicating late-season groundwater discharge near these piezometers. Piezometer S6 had negative VHGs (downward flow) throughout 2010, indicating groundwater recharge at that location. The VHG in piezometers N9, S6 and S12 went from positive to negative near the end of July 2011, indicating a change from groundwater discharge to groundwater recharge in these locations. The convex shape of the broad hillslope (Tioga age moraine) on the south side of Grass Lake is expected to cause divergent flow, resulting in an area of groundwater recharge near S6. All other piezometers along the southern edge had positive VHGs until mid-October 2011 or later. These persistently high VHGs indicate substantial pressure available to drive late-season groundwater flow up through the peat. Most of the northern piezometers had no surface water present and/or maintained a nearly neutral VHG during the 2010 field season.

The West Freel Meadows Creek alluvial fan is a site dominated by deeper (>2.4 m) groundwater recharge but complicated by seasonal discharge of shallow (<1.4 m) groundwater. Vertical hydraulic gradients measured between the surface water and ground water in piezometer N2 (2.4 m bgs) had a fairly constant value of −4.7 % until late-June 2010, after which surface water was no longer present. The VHG in the adjacent, shallower piezometer N3 (1.4 m bgs) remained positive (0.8–1.5 %) until late-June, 2010. The VHG of piezometer N3 went from positive (1.0 %) in mid-May to negative (−8.2 %) by late-July of 2011. This indicates a switch from shallow groundwater discharge during the spring and early summer to groundwater recharge by midsummer. The VHG between the screened interval of N2 and N3 dropped from −18.8 % on June 21 to −30.4 % on August 21, 2010. In 2011, the VHG between these piezometers dropped from −8.1 % on July 26 to −23.6 % on September 3, 2011.

In the absence of surface water, water level measurements relative to the adjacent peat surface can provide insight into the potential for aerobic decomposition due to unsaturated conditions. The average groundwater level was 0.085 m below the surface of the adjacent peat (bgs) by mid-September 2010, suggesting a general dewatering of the peat. The earliest unsaturated conditions were observed in piezometer N9 and N5, which dropped below the level of the peat in early May and early July, 2010, respectively. The groundwater level in 14 piezometers dropped below the peat surface between mid-July and mid-August in 2010. The water level in the other piezometers did not fall below the level of the peat in 2010, suggesting persistently saturated or nearly saturated conditions. The average groundwater level recorded in the piezometers remained 0.043 m above the adjacent peat surface (ags) through mid-October 2011. The average late-season groundwater levels were 0.19 m ags on the south side and level with the peat on the north side (0 m ags). The lowest levels recorded in 2011 along the north side were in N13 (−0.30 m bgs) and N9 (−0.18 m bgs), while the lowest level recorded along the south side were in S13 (−0.23 m bgs) and S11 (−0.20 m bgs).

For the piezometers with groundwater levels below the peat surface, the average rate of decrease in groundwater level was 2.9 mm day^{-1} ($\sigma = 2.3$, $n = 14$) in 2010 and 2.4 mm day^{-1} ($\sigma = 1.3$, $n = 13$) in 2011. The water level in the center of Grass Lake dropped 0.130 m between July 7 and September 20, 2010, a rate of 1.7 mm day^{-1}. Late-season groundwater levels were lower along the north side than the south side for both years (Table 3). The lowest levels along the north side were recorded in piezometers N7 (−0.64 m bgs) and N15 (−0.55 m

Table 3 Depth of the water table relative to the peat surface along the north and south sides of Grass Lake

	2010					2011				
	Max (m)	Piez	Min (m)	Piez	Ave Sept (m)	Max (m)	Piez	Min (m)	Piez	Ave Sept (m)
North	0.27	U1	−0.64	N7	−0.21	0.6	N13	−0.3	N7	0
South	0.57	S5	−0.28	S13	0.03	0.7	S5	−0.23	S13	0.19

bgs), the furthest east and west piezometers, respectively, in Grass Lake proper. The lowest levels along the south side were recorded in piezometers S13 (−0.28 m bgs) and S6 (−0.11 m bgs).

Peat water retention

The peat samples were dominated by moss and vascular plants with various levels of decomposition and sediment. Sample PC1 contained notable sand and gravel (~10 % volume), but was dominated by slightly decomposed to undecomposed vascular plant material. Sample PC2 contained moderately decomposed moss with some slightly decomposed vascular plant material near the top of the sample (<5 % volume). Sample PC3 contained roughly equal parts vascular plant material and moss, both slightly decomposed. Sample PC4 contained undecomposed to slightly decomposed moss with minor amounts of undecomposed vascular plant material (<5 %).

Samples PC1, PC2, and PC3 had similar saturated water content and water retention characteristics (Fig. 7). Sample PC3 showed slightly less water retention than PC1 and PC2, but the difference is not discernible when measurement errors are taken into account. Sample PC4 showed significantly less water retention than the other samples at suctions above approximately 0.17 m (Fig. 7). Samples PC3 and PC4 had lower bulk densities (0.16 and 0.12 g cm^{-3}, respectively) than PC1 and PC2 (0.25 and 0.21 g cm^{-3}, respectively). Sample PC4 had significantly lower saturated volumetric water content (76 %) than the other samples (83 %). The average saturated volumetric water content for all four samples

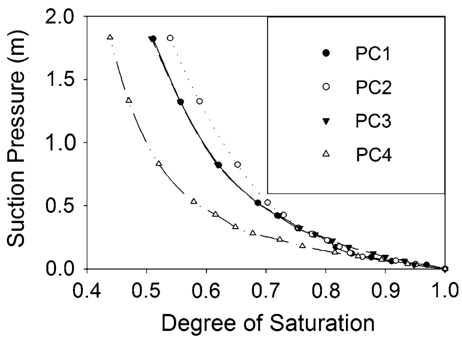


Fig. 7 Results from water retention experiments conducted on four peat samples from the GLRNA

was 81.5 %. These results are consistent with previous work (Boelter 1964; Dasberg and Neuman 1977; Silins and Rothwell 1998; Weiss et al. 1998).

The average depth to groundwater recorded in mid-September was 0.123 m. The water retention experiments (n = 4) suggest this water level would result in a final volumetric water content of approximately 68 %, 13 % below fully saturated conditions. A drop in the water table of 0.17 m resulted in a significant difference in the degree of saturation between samples PC4 (42 %) and the other samples (54 %). The lower water retention of sample PC4 suggests that peat dominated by undecomposed moss may have lower water content than peat dominated by decomposed moss when the water table is more than 0.17 m bgs. The lower water content of the undecomposed moss may lead to accelerated decomposition by aerobic processes, while peat dominated by decomposed moss may be less prone to further decomposition. This may result in a positive feedback system that helps account for the persistence of peatlands in relatively arid climates. Considerations of vital processes that may help protect the undecomposed moss against aerobic decomposition were beyond the scope of this investigation.

Water budget

The contribution of flow from the accumulation of winter precipitation on Grass Lake (90 ha, 222 ac) and Upper Grass Lake (7 ha, 17 ac) was approximately 9.1×10^5 m^3 (3.2×10^7 ft^3) in 2010 and 1.4×10^6 m^3 (5.0×10^7 ft^3) in 2011. Field observations suggest that snow melt on the surface of Grass Lake began in mid-April both years. The peat was snow-free by June 7, 2010 and June 21, 2011. The maximum contribution of snowmelt from the surface of Grass Lake to the outflow at Grass Lake Creek assuming even melting over this period was 0.21 m^3 s^{-1} in 2010 and 0.25 m^3 s^{-1} in 2011.

A seasonally based surface water budget shows no measurable difference between the total seasonal stream flow into and out of Grass Lake in 2010 or 2011. This is attributed to the large errors (30 %) associated with measuring stream flow in these steep, dynamic mountain streams, the uncertainty in the range of evapotranspiration flux, and uncertainty in the contribution of direct snowmelt on the peat surface. However, water budget calculations based on periodic stream flow measurements taken throughout the season

Table 4 Periodic water budget calculations for Grass Lake in 2010 and 2011

Date	S_{out} (m^3 s^{-1})	S_{in} (m^3 s^{-1})	S_{direct} (m^3 s^{-1})	G_{max} (m^3 s^{-1})	G_{min} (m^3 s^{-1})	G_{ave} (m^3 s^{-1})
6/17/2010	0.48	0.52	0.00	0.34	−0.35	0.00
6/25/2010	0.40	0.36	0.00	0.34	−0.20	0.07
6/29/2010	0.35	0.28	0.00	0.32	−0.13	0.10
7/27/2010	0.08	0.10	0.00	0.11	−0.08	0.02
8/13/2010	0.05	0.03	0.00	0.11	−0.01	0.05
9/10/2010	0.02	0.01	0.00	0.09	−0.01	0.04
6/13/2011	0.54	0.53	0.24	0.41	−0.31	0.05
6/20/2011	1.06	1.07	0.24	0.70	−0.66	0.02
6/26/2011	1.33	1.47	0.00	0.77	−0.99	−0.11
6/29/2011	2.00	1.16	0.00	1.86	−0.12	0.87
7/7/2011	1.24	0.92	0.00	1.04	−0.34	0.35
7/26/2011	0.29	0.16	0.00	0.34	−0.01	0.16
8/16/2011	0.25	0.06	0.00	0.35	0.09	0.22
9/3/2011	0.21	0.03	0.00	0.33	0.10	0.21
10/15/2011	0.23	0.02	0.00	0.35	0.12	0.24
10/23/2011	0.20	0.02	0.00	0.32	0.11	0.21

Calculations were conducted using stream flow measurements made periodically in 2010 and 2011. Estimates of evapotranspiration (0.06 m^3 s^{-1}) and contributions due to changes in storage (0.03 m^3 s^{-1}) are assumed constant. Calculations of G_{max} and G_{min} include consideration of ±30 % error in stream flow measurements, ±50 % error in storage, and ±50 % uncertainty in the estimate of evapotranspiration

suggest groundwater contributions (0.05 m^3 s^{-1}) exceeded stream inflow (0.03 m^3 s^{-1}) by August 13, 2010 (Table 4). Similarly, the groundwater contribution began to exceed stream inflow by approximately July 26, 2011. Groundwater contributions were over 0.2 m^3 s^{-1} through late-October.

Discussion

Grass Lake has been described as transitional between a sphagnum bog and a fen (Burke 1987). This study shows that runoff is the major component of the water budget in the spring while groundwater dominates the late-season water budget. Direct precipitation on the peat surface is a relatively minor component of the overall water budget. As such, Grass Lake is more accurately described as a fen than a bog. Periodic water budget calculations conducted between April and October show surface water flow out of the peatland exceeds surface water flow into the peatland by mid-August in 2010 and by late-July in 2011. Persistently positive VHGs in many of the piezometers indicate groundwater discharge from the coarse sediment beneath the peat for much of the growing season. Estimates of late-season groundwater flow into Grass Lake during the 2010 field season are similar to the estimated evapotranspiration requirements of approximately 5 mm day^{-1} based on other studies in the region (Green 1998; Loheide and Gorelick 2005).

Local upslope geology and drainage appears to influence the hydrologic conditions within the peatland. Piezometers located in the alluvial fans associated with perennial streams have higher groundwater head than nearby piezometers, indicating divergent flow and groundwater recharge from the streams. A similar pattern of groundwater divergence is suggested by the piezometers located below the Tioga age cirque on the south side of Grass Lake. The earliest unsaturated conditions were observed in piezometer N9 and N5, suggesting that the area surrounding these piezometers (west of West Freel Meadows Creek) may be more susceptible to peat decomposition in dry years. This area appears to be influenced by a "groundwater shadow" created by the bedrock outcrop located upslope of piezometer N9 (Figs. 4, 5). The importance of stream and groundwater input for maintaining peat saturation suggests the health and function of the peatland depends on the health and function of the surrounding watershed. Therefore, the GLRNA should be expanded to include the surrounding watershed in order to meet the original objectives of the RNA designation (USDA 1988).

The groundwater system in this glaciated mountain valley is expected to be shallow. This suggests groundwater flow is unlikely to be sustained for a significant period of time (greater than 1 year) following precipitation and/or snowmelt. Groundwater flow into the peatland continued for at least 6 months following peak snowmelt in both years of this study, meeting (2010) or exceeded (2011) the approximate evapotranspiration rate inferred from other studies. Climate change predictions for the Sierra Nevada Mountains suggest warmer temperatures resulting in more precipitation as rain rather than snow, more extreme precipitation events, and little change in average annual precipitation (Cayan et al. 2008; Dettinger et al. 2004). In such a scenario, water from winter storms would be routed through the watershed without delay, rather than being stored in the snowpack and released shortly in advance of the growing season. This is expected to result in drier conditions in late-summer and fall and may result in insufficient water to meet the evapotranspiration needs of the peatland. The hydrologic conditions in the peatland and health of the ecosystem would depend on the timing and magnitude of storms relative to the growing season. As such, a well calibrated groundwater model would be needed to fully explore the hydrologic response of the peatland to various precipitation scenarios.

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References

Armin RA, John DA, Dohrenwend JC (1983) Geologic map of the Freel Peak 15-minute quadrangle. United States Geological Survey, California

Arnold C, Ghezzehei T, Berhe A (2014) Early spring, severe frost events, and drought induce rapid carbon loss in high elevation meadows. PLoS One 9(9):e106058. doi:10.1371/journal.pone.0106058

Berg KS (1991) Establishment record for Grass Lake Research Natural Area within Eldorado National Forest, managed in Lake Tahoe Basin Management Unit, in El Dorado County, California. Pacific Southwest Research Station, Albany, California, Unpublished report on file

Boelter DH (1964) Water storage characteristics of several peats in situ. Soil Sci Soc Am J 28:433–435. doi:10.2136/sssaj1964.03615995002800030039x

Burke MT (1987) Biological survey of Grass Lake candidate Research Natural Area. University Arboretum, University of California, Davis, California

Cayan D, Maurer E, Dettinger M, Tyree M, Hayhoe K (2008) Climate change scenarios for the California region. Clim Change 87:21–42. doi:10.1007/s10584-007-9377-6

Christensen W (2013) Hydrologic characterization and modeling of a Montane peatland, Lake Tahoe Basin, California. University of California, Davis

Comer NT, Lafleur PM, Roulet NT, Letts MG, Skarupa M, Verseghy DL (2000) A test of the Canadian land surface scheme (class) for a variety of wetland types. Atmos Ocean 38:161–179

Cooper DJ, Wolf EC (2006a) Fens of the Sierra Nevada, California. Department of Forest, Rangeland and Watershed Stewardship, Colorado State University, Fort Collins, Colorado

Cooper DJ, Wolf EC (2006b) The influence of groundwater pumping on wetlands in Crane Flat, Yosemite National Park, California

Dasberg S, Neuman SP (1977) Peat hydrology in the Hula Basin, Israel: i. properties of peat. J Hydrol 32:219–239

Dettinger MD, Cayan DR, Meyer MK, Jeton AE (2004) Simulated hydrologic response to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900–2099. Clim Change 62:283–317

Fetter CW (2001) Applied hydrogeology, 4th edn. Prentice-Hall Inc, Upper Saddle River

Green CT (1998) Integrated studies of hydrogeology and ecology of Pope Marsh, Lake Tahoe. University of California, Davis

Hill BR (1990) Groundwater discharge to a headwater valley, northwestern Nevada, U.S.A. J Hydrol 113:265–283

Kondolf MG, Piegay H (2002) Tools in fluvial geomorphology. Wiley, West Sussex

Loheide SPI, Gorelick SM (2005) A local-scale, high-resolution evapotranspiration mapping algorithm (ETMA) with hydroecological applications at riparian meadow restoration sites. Remote Sens Environ 98:182–200

Matthews E, Fung I (1987) Methane emission from natural wetlands: global distribution, area, and environmental charactersists of sources. Glob Biogeochem Cycles 1:61–68

Mitsch WJ, Gosselink JG (1993) Wetlands, 2nd edn. Van Nostrand Reinhold, New York

PRISM (2013) PRISM climate group. Oregon State University. http://www.prism.oregonstate.edu. Accessed 20 Jan 2013

Rood DH, Burbank DW, Finkel RC (2011) Chronology of glaciations in the Sierra Nevada, California, from 10 Be surface exposure dating. Quatern Sci Rev 30:646–661

Silins U, Rothwell RL (1998) Forest peatland drainage and subsidence affect soil water retention and transport properties in an Alberta peatland. Soil Sci Soc Am J 62:1048–1056

Soil Survey Staff (1999) Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys, 2nd edn. Natural Resources Conservation Service, U.S. Department of Agriculture Handbook 436

Stanek W, Silc T (1977) Comparison of four methods for determination of degree of peat humification (decomposition) with emphasis on the von Post method. Can J Soil Sci 57:109–117

TRPA (2012) Lake Tahoe Basin LiDAR. OpenTopography. http://www.opentopography.org/index.php/blog/detail/tahoe_lidar_imagery_in_google_earth. Accessed 15 Aug 2012

Twidale CR, Vidal Romani JR (2005) Landforms and geology of granite terrains. Taylor & Francis Group, London

USDA (1988) Establishment Record for Grass Lake Research Natural Area. U.S. Government Printing Office, El Dorado National Forest

USDA (1999) Soil Taxonomy: a basic system of soil classification for making and interpreting soil surveys, Second, 2nd edn. U.S. Government Printing Office, Washington, DC

Weiss R, Alm J, Laiho R, Laine J (1998) Modeling moisture retention in peat soils. Soil Sci Soc Am J 62:305–313