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Climatic and hydrologic processes leading to wetland losses in Yellowstone National Park, USA

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SUMMARY

Wetlands are vital habitats and can be used as landscape indicators because they integrate catchment-scale processes. Wetland drying during the recent decades in Yellowstone National Park's Northern Range has incited concern among National Park managers and the public at large. Our research was focused on developing an understanding of the processes controlling wetland water levels and the changes contributing to wetland decline in the Northern Range. We integrated analyses of hydrology, climate, soils, and vegetation. In 2009, 24 study wetlands were instrumented each with an average of five shallow groundwater monitoring well and piezometer nests. We mapped hydric soils, analyzed aerial photographs, and identified geomorphic indicators of higher water to quantify historic wetland area. The Trumpeter Lake study site was intensively studied to resolve watershed processes driving water table changes through time, and it was used to identify the timescale on which a regionally critical wetland varies. Climate data indicated that warming and drying occurred during the last century, but that this pattern was within the natural range of variation for the study region over the past 800 years, as determined from tree ring data. Hydrologic data revealed that study sites included locations of groundwater discharge, recharge, and flow-through as well as water perched above the regional water table. Hydrologic regimes were classified using a shape-magnitude framework and seven wetland classes were characterized, and the robustness of this classification is assessed using longer-term datasets. Aerial photographs and hydric soil delineation both confirmed formerly greater wetland abundance. Changes varied by wetland class and the presence or absence of surface water outlets. Wetland plant species inhabited distinct habitats of water table depth and variation, and can be used to infer subsurface hydrologic regime in the absence of extensive monitoring well networks. A subset of long-term monitoring wells has been instrumented with groundwater pressure transducers, enabling further understanding of wetland hydrologic processes, promoting additional assessment of the wetland classification, and aiding in identification of wetlands especially vulnerable to climate change.

1. Introduction

Wetlands are among the most valuable yet vulnerable habitats on Earth (Bates et al., 2008; Poff et al., 2002; Winter, 2000). They are formed and sustained by hydrologic processes driven by climate, geology, and landscape setting (Hunt et al., 1996; Mitsch and Gosselink, 2000). Wetlands typically occur at low points in their watersheds, and the flow paths sustaining them integrate catchment-scale processes and environmental conditions (Bates et al., 2008; Williamson et al., 2008). Close proximity of the water table and land surface makes wetlands susceptible to changing hydrologic, landscape, and climatic conditions (Bates et al., 2008; Brooks, 2009). Each wetland integrates its unique environmental setting, and generalizing about the hydrologic functioning of basin wetlands can result in erroneous assumptions.

Distinguishing the role of surface water and groundwater processes that form wetlands is complex because they interact at multiple spatial and temporal scales (Devito et al., 2005; Schot and Winter, 2006; Winter, 1999). Basin wetlands can be supported by groundwater or surface water alone or their dynamic interaction, and the direction of groundwater flow can change seasonally (Rosenberry and Winter, 1997; Woo and Rowsell, 1993). Playa wetlands in the southern Great Plains of the United States (Osterkamp and Wood, 1987) and vernal pools in California (Zedler, 2003) are typically hydrologically isolated from continuous ground- and stream water contributions, and driven by runoff, snowmelt, precipitation, and evapotranspiration. In contrast, wetland basins in the Nebraska Sandhills (Winter, 1986) and Great Sand Dunes in

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Colorado (Wurster et al., 2003) are supported largely by groundwater flows through highly conductive sediment. The groundwater sustaining a wetland may originate hundreds of kilometers away, such as those supporting desert oases in Argentina (Jobbágy et al., 2011) and springs in Death Valley, California (Belcher et al., 2009). Identifying the source of water is further complicated in glaciated landscapes because drainage networks are often poorly developed. In the Northern Rocky Mountains, some wetlands located in a dead-ice glacial moraine complex are connected by near-surface flow while adjacent wetlands are hydrologically isolated (Cook and Hauer, 2007). Similar appearing wetlands can differ in their seasonal and interannual range of water table variance and response to climate change.

Climate changes result in altered temperature and precipitation patterns that affect wetland physical and ecological processes. Wetland disappearances in Alaska (Klein et al., 2005) and Siberia (Smith et al., 2005) have been correlated with recent climate changes, and the trend is predicted to continue (Bates et al., 2008; Sorenson et al., 1998). Wetlands in the North American prairie pothole region with different hydroperiods are variably susceptible to climate change because of the interacting effects of watershed flow paths and evapotranspiration processes (Johnson et al., 2010). Understanding the effects of a changing climate on wetland biotic and hydrologic processes is challenging due to the spatial and temporal complexity of wetland habitats (Bates et al., 2008; Brooks, 2009). However, land management should be based on an understanding of wetland functional types.

Classification is commonly used to group entities, including wetlands. Ecosystem type and climate are primary considerations in large scale classification systems (e.g., Cowardin et al., 1979; Devito et al., 2005; Junk et al., 2011). At regional scales, bedrock composition, geomorphic history, and soil characteristics more strongly influence wetland processes (Brinson, 1993; Devito et al., 2005; Merkey, 2006). At the scale of kilometers, water table data may be the most effective way to develop a wetland classification since this method isolates water as the key abiotic driver of wetlands (Rains, 2011). A classification based on hydrologic regime should be supported by other environmental variables, and compatibility with the other components can be used to validate the classification.

A pronounced lowering of surface water levels has been reported for many wetlands in Yellowstone National Park (YNP), USA. However, quantitative and process-based information explaining the phenomenon are lacking. Wetland decline negatively affects many native species, including trumpeter swans whose nesting habitat has been lost in recent decades (Proffitt et al., 2010). Regional climate models for YNP forecast an ecological shift unprecedented in the Quaternary, making the future of the park's terrestrial and water-based ecosystems uncertain (Bartlein et al., 1997; Westerling et al., 2011). As the world's first national park and a key conservation area, preserving YNP's ecosystem is a priority for the public and resource managers.

To develop an understanding of YNP wetlands, we created a framework based upon hydrologic regime supported by other environmental factors. Our study objectives were to: (1) develop and test a wetland classification based upon hydrologic regimes, (2) determine the patterns and magnitude of water level changes that occurred during the late 20th and early 21st centuries and assess whether these changes are within the natural range of variation, and (3) investigate a wetland complex that has recently experienced substantial water level changes to develop a more detailed understanding of the physical processes affecting the site. To address these objectives we analyzed wetland and watershed hydrology, climate, soils, and vegetation to create an integrated view of the processes supporting YNP wetlands.

2. Study area

2.1. Site description

The 1400 km^2 Northern Range comprises much of northern YNP in Wyoming and Montana (Fig. 1). Our study sites receive an average of 41 cm of annual precipitation, with over half falling as snow (NCDC, 2013). Most of the study area was covered by Pinedale Era glaciers that melted approximately 15 kya. The modern landscape form was created by glacial scour and till deposition that created a heterogeneous hummocky landscape with abundant depressions that support wetland basins. We define basin as a topographic depression that at least periodically contains surface water. Study sites are located within clay rich mollisols and inceptisols (YCR, 2009).

In 2009, 24 non-riparian wetlands at 1783–2284 m elevation were selected to characterize Northern Range wetland types (Appendix, Table A1). Most wetlands had mineral soils but a few had organic soils. The most common wetland plant species include *Carex atherodes*, *C. utriculata*, *Juncus arcticus*, *Eleocharis palustris* and *Schoenoplectus acutus* (nomenclature follows USDA PLANTS (USDA, 2013)). Study wetlands receive water from direct precipitation, groundwater, and overland flow. Through the 20th and early 21st centuries, some Northern Range wetland water levels remained relatively constant, while others varied greatly (Engstrom et al., 1991). Several wetlands exhibit indicators of former high water levels, including dead relict marsh vegetation, lichen trim lines, and eroded former shorelines. Direct modification to the hydrologic landscape from dams, irrigation, and groundwater pumping does not occur in the study area. Trumpeter Lake was selected for a detailed wetland analysis because large water level declines are thought to have occurred in this former trumpeter swan nesting habitat. The lake is located near the confluence of the Lamar and Yellowstone Rivers in dead-ice moraine. Its watershed has hummocky topography comprised of low-permeability unconsolidated till with a high density of granitic glacial erratics (Pierce, 1979). Upland soils are loam and lake-bottom soil is clay-loam.

2.2. Study period weather

Climate data for the Northern Range have been collected since 1931 at the Mammoth and Tower weather stations (Fig. 1) and were averaged to characterize study area weather (NCDC, 2013). All study wetlands are located within 12 km of one station and 350 m elevation of both stations (Fig. 1). 2009 and 2010 annual temperatures were both within 0.3 °C of the 1931–2012 average. Total precipitation in water year 2009 (1 October 2008–30 September 2009) was 97% and snow 120% of average, while 2010 total precipitation was 83% and snow 53% of average. Additional data were collected in 2011, when total precipitation was 110% and snow 150% of average, and in 2012 when total precipitation was 97% and snow 93% of average.

In summer 2010 a HOBO tipping bucket rain gauge (Onset Computer Corp.) measured precipitation near Trumpeter Lake. We used linear regression to compare 2010 weekly precipitation among the Tower, Mammoth, and HOBO rain gauges to analyze spatial variability within the study area. Regression analysis indicated that sites throughout the study area experienced similar precipitation ($0.84 \leqslant R \leqslant 0.97$). We used regression models between the two stations to estimate missing historical monthly precipitation values (Iglesias et al., 2006).

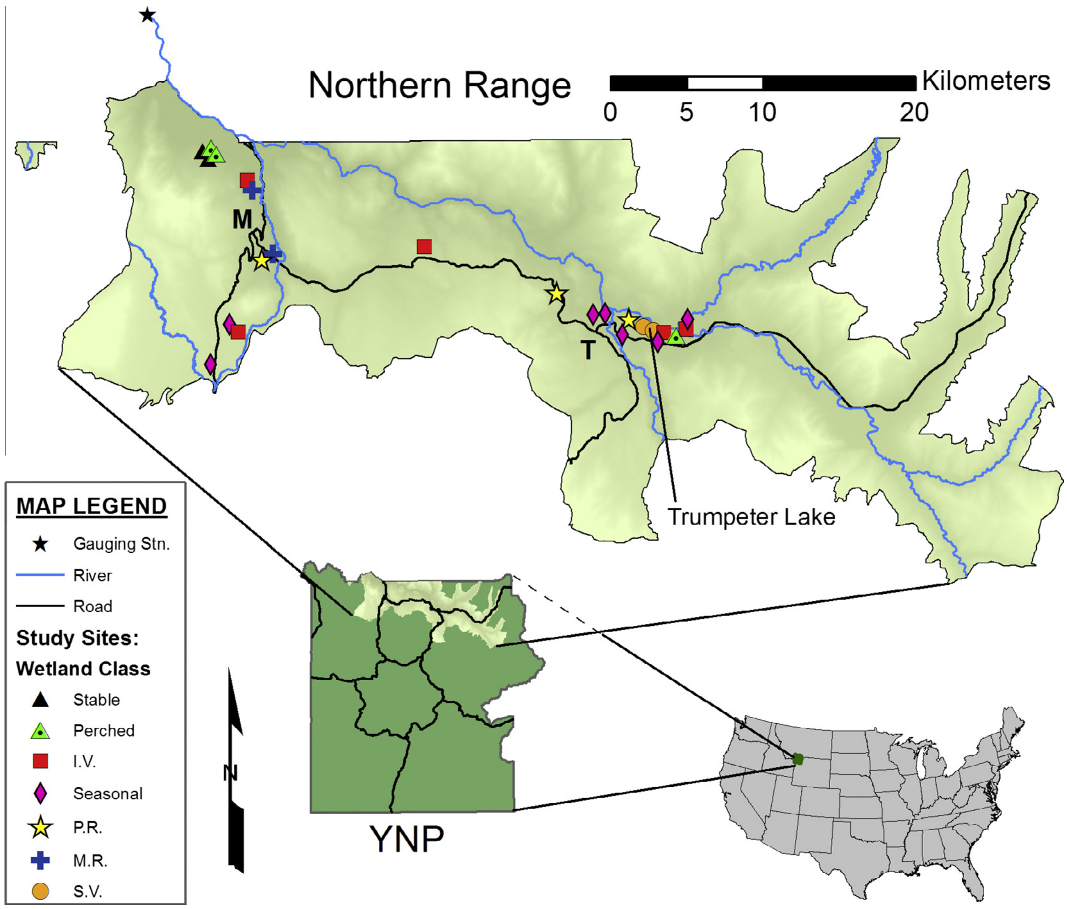

Fig. 1. The Northern Range within Yellowstone National Park, Wyoming and Montana, USA. Study sites are coded by wetland class. The Yellowstone River gauging station and Mammoth (M) and Tower (T) weather stations are included.

3. Methods

3.1. Wetland characteristics and classification

3.1.1. Hydrologic data collection

One hundred and three shallow groundwater monitoring wells were installed in the 24 wetland study sites in 2009, and 18 wells were added in 2010. Wells were installed across the major topographic gradients and used to measure water table depth on all sides of each study wetland and to characterize the hydrologic niches of dominant plant species in the wetlands. Staff gauges were used to measure surface water depth. Monitoring wells were hand-augered using a 10 cm diameter bucket auger to a depth below the anticipated water table low where possible. Wells were constructed from 4.2 cm I.D. schedule 40 PVC pipe that was continuously slotted throughout the zone of water table fluctuation. Holes were backfilled with native soil. A rotating laser level was used to measure the relative elevation of all instruments and notable geomorphic features within a wetland. An average of two nested piezometers, constructed from 2.1 cm I.D. PVC, were installed adjacent to each well within the top two meters of soil. Water depth was measured manually with an electric tape biweekly in 2009 and weekly in 2010. Weekly values were interpolated to permit statistical comparison. In 2011, hourly water table data were collected at a subset of 14 wells using automated pressure transducers (Rugged Troll 100, In-Situ Inc.). Seven wells logged data during the winter of 2011–2012 and through summer 2012.

3.1.2. Wetland classification

Wetlands were classified into groups based on seasonal water table depth variance. Instruments installed in late 2009 or 2010 and those that dried too early to provide data throughout each summer were not included in the analysis. Each well's water table reading for 3 June 2009 was used as its base datum, and all subsequent measures were relative to this datum. This standardization permitted the analysis of surface and groundwater changes independent of their depth relative to the ground-surface (van der Kamp and Hayashi, 2009).

Two distinct well types were classified *a priori*. One group had stable water levels with less than 3 cm of water level variation during the two-year study period. A second group had perched water tables with surface water that disappeared abruptly and piezometers that never contained water, indicating an unsaturated layer below surface water. The 12 wells with these hydrologic regimes were distinct from other wells, which contained transient water levels connected to groundwater systems.

For the remaining 83 wells, we conducted a two-step "shape-magnitude" cluster analysis to produce a composite classification by separately analyzing the timing (shape) and total seasonal variance (magnitude) of water table variations (Hannah et al., 2000). This approach has been used to group patterns of rainfall (Bower et al., 2004), stream discharge (Laize and Hannah, 2010), and water table depth (Upton and Jackson, 2011). To classify shape, each well's weekly water table data were transformed to z-scores to isolate the timing and rate of water table change independent of their magnitude. Transformed data were analyzed using hierarchical agglomerative cluster analysis with Euclidian distance as the similarity metric and Ward's group linkage as the clustering method (Bower et al., 2004) with the program PC-ORD (McCune and Mefford, 2006). The resultant dendrogram was pared at 40% information remaining to produce three well groups having distinct hydrograph shapes.

For the magnitude analysis, we combined seven z-score transformed water table deviance variables: minimum, mean, and standard deviation of each 2009 and 2010 water table elevations, and 2010 maximum water table elevation (Hannah et al., 2000). A cluster analysis was performed on the magnitude data using the procedure described above and pruned at 0% information remaining, which produced two groups. The three shape and two magnitude classes were crossed to yield six possible well hydrograph classes, five of which occurred in the study wetlands. The five shape-magnitude groups, along with perched and stable groups, comprised the seven well classes (Fig. 2). Wells at most wetlands fell within a single class, allowing wetlands to be grouped by well class. A mixed wetland class was created for two sites that contained wells from three or four classes.

To analyze the wetland classification in relation to the local environment, we compared wetland classes to 14 environmental variables. Chi-squared analysis was used for the six binary categorical variables: surface water inflow, surface water outflow, peat presence, organic matter in basin, clay in basin, and hardstem bulrush (*Schoenoplectus acutus*) as the dominant wetland plant species. One-way ANOVA was used to test wetland class against the eight quantitative variables: elevation, average annual precipitation, maximum observed surface water area, watershed size, duration to slowest piezometer's equilibration, maximum piezometer positive head, electrical conductivity (EC) in the basin, and EC of groundwater inflow.

Water table data from 2011 were used to assess the two-year classification in a very large snow year. Five of the well classes ($n = 14$ wells) had at least two wells with complete 2009–11 data, and we assessed the consistency of water table responses within these classes.

3.1.3. Historic wetland area analysis

At 16 study basins the maximum elevation of wetland soils could be identified using the hydric soil indicator protocol in the Western Mountains and Valleys Regional Supplement to the Corps of Engineers Wetland Delineation Manual (USACE, 2010). The boundary between wetland and upland soil was determined in soil pits using morphological indicators including chroma ⩽2 and the presence of oxidized root channels and mottling. The elevation between modern water surface and the hydric soil boundary was analyzed among wetland classes using ANOVA and between outlet vs. closed-basin wetlands using a *t*-test.

Aerial photographs from 1954, 1969, 1991, 1994, 1998, 2001, 2006, and 2009 were used to measure ponded area through time for each basin. Emergent vegetation obscured the identification of surface water perimeters in 10 study basins, so only 14 wetlands were analyzed. Photos were georectified to 2009 NAIP imagery using 2nd and 3rd degree polynomials, and wetland surface area was delineated in ArcMap v. 10.0 (ESRI, 2010). To standardize wetland area, each wetland's maximum area was assigned 1, and other years represented a fraction of 1. Wetland area was compared to annual precipitation at the closer weather station (Fig. 1). We conducted a multiple regression comparing each wetland's proportion of the maximum to percent of average precipitation for time steps of the past 2, 4, and 8 years in SAS (SAS Institute, 2010). A wetland's best correlated time step is reported for all $p < 0.10$.

3.2. River discharge

The Yellowstone River drains 6783 km^2 above the Corwin Springs gauging station (USGS gauge #06191500), where mean daily discharge data were available for 1911–2012. The shape-magnitude framework was used to analyze Yellowstone River discharge trends. Magnitude was classified using maximum, minimum, mean, and standard deviation of monthly discharge. The Palmer Drought Severity Index (PDSI), was also analyzed using data from the Yellowstone River drainage basin for 1895–2012 (NCDC, 2013).

3.3. Vegetation

Vegetation is arranged in concentric zones around study wetlands and is influenced by water depth and duration. In 2009 we estimated the canopy cover of each plant species present in a 2 × 0.5 m plot centered on each well to quantify vegetation composition. To determine the hydrologic conditions supporting common plant species, we calculated the mean weekly water table depth for all species comprising ⩾20% cover at four or more wells. The species included were *Carex aquatilis*, *C. atherodes*, *C. pellita*, *C. utriculata*, *Eleocharis palustris*, *Phleum pretense*, *Poa pratensis*, *Schoenoplectus acutus*, and four *Salix* species, *S. boothii*, *S. drummondiana*, *S. geyeriana*, and *S. pseudomonticola*. The *Salix* species all

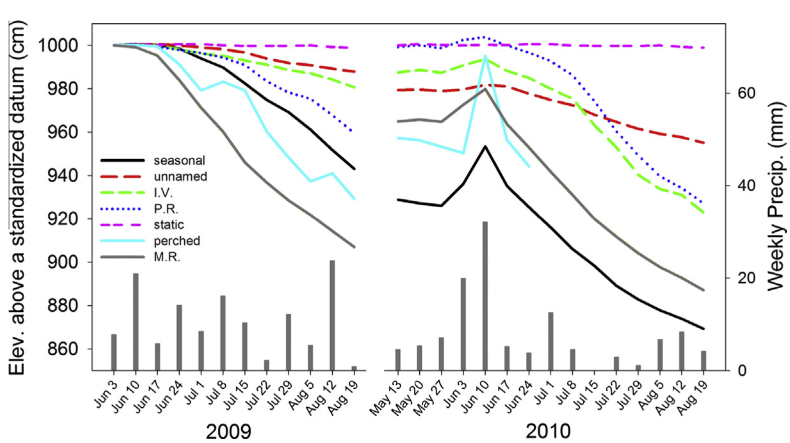

Fig. 2. Summer 2009 and 2010 water table elevations for the seven well classes. Lines are average weekly water table values for all wells in each class, except for the perched class which shows an example well that dried in June 2010. Each well class was developed into a unique wetland class except "unnamed", which was too uncommon ($n = 6$) to constitute its own class. The S.V. wetland class included wells from at least three of these well types. Bars depict weekly precipitation.

grew in peatlands, had similar hydrologic niches, and were combined for this analysis.

3.4. Trumpeter Lake intensive study site

Because of its ecological significance and importance to the public, Trumpeter Lake was chosen as an intensive study site. A lichen trim line was present from when surface water drowned lichens. This line is easily seen on glacial erratics high above the current lake water level suggesting that lake stage was higher in the past (Hale, 1974; Marsh and Timoney, 2005). We used a total station to survey elevation differences among surface water, lichen lines, eroded shorelines, relict bulrush stands, and a surface outlet constraining maximum lake stage. Existing bathymetric data was used to estimate the land surface elevation below water (Jones et al., 1978). Data were imported to ArcMap 10.0 where a triangulated irregular network (TIN) surface was created. Polygons of surface water area were delineated from each air photo and superimposed on the TIN to determine lake depth in each photo. To minimize area bias from photo dates, we analyzed lake sizes on a common day of year. We accounted for changes in lake stage between the photo date and August 15 by subtracting measured precipitation from evaporative loss, which was estimated using historic monthly (Pochop et al., 1985) and annual pan evaporation measurements. 2010 lake stage was measured in the field. We conducted regression analyses comparing lake area and volume to cumulative precipitation over the previous 1, 2,…, 10 years.

The time lag between precipitation input and subsequent water level changes in a wetland basin is influenced by aquifer saturated hydraulic conductivity (K_s). Two methods were used to calculate K_s: (1) the Hvorslev slug test was used in monitoring wells (Fetter, 1994), and (2) double-ring infiltrometer tests (ASTM, 2003) were used at ground surface and at 50 cm below ground on lake-margin and upland till environments. Water samples from the Trumpeter Lake watershed were analyzed for Ca^{2+}/Na^{+} ratios using a TGA Solutions Iris Advantage, with differences in the ratio reflecting flow paths.

4. Results

4.1. Hydrologic regimes and wetland change

Northern Range wetlands exhibited several geomorphic indicators of surface water decline. Lichen trim lines occurred 95–250 cm above existing wetland surface water levels at four study sites, suggesting that a high water period occurred in the past few dec-

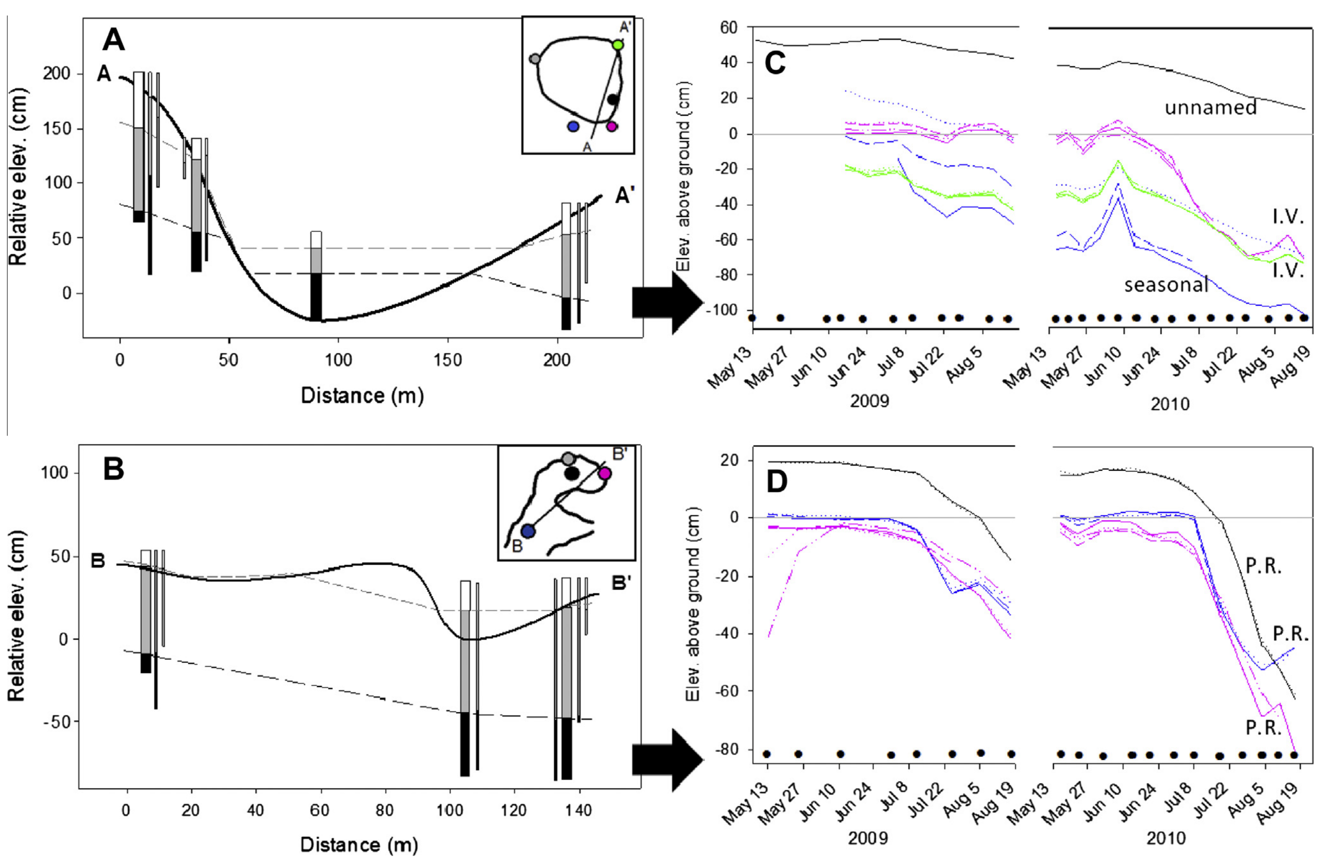

Fig. 3. Detailed examples of instrument setup and data recorded at wetlands LT (panels A and C) and DC (panels B and D). Solid lines in cross-sections represent ground surface, and dashed lines are water table elevations on 10 June 2010 (grey) and 5 August 2010 (black), interpolated from groundwater monitoring wells (thick bars). Piezometers (thin bars) nested with wells reveal vertical hydrologic gradients. Note that piezometers at left in (A) show an upward gradient, but all other piezometers show negligible vertical gradients. Well and piezometer bar filling represents water levels on 10 June (grey) and 5 August (black). (C) and (D) are hydrographs showing water level in each well and piezometer during summers 2009 and 2010. Solid lines are wells, and dotted and dashed lines are piezometers nested with the well of the same color. Hydrograph colors correspond to the same colored wells illustrated as dots on plan view insets. Labels in (C) and (D) correspond to well types; wetland LT was a S.V. wetland and DC was a P.R. wetland. Hydrographs revealed characteristics of site hydrology, including locations that: strongly respond to rain (blue in C and D), declined earlier in the drier 2010 (pink in C, all in D), had a strong positive hydraulic gradient (blue in C), had slowly-equilibrating piezometers that revealed a low K_s layer (pink dash-dot in D), and did not change in response to early summer rain because of surface outflow (all in D). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ades (Timoney and Marsh, 2004). At three of these sites, eroded former shorelines occurred >200 cm above the 2009–2010 maximum surface water elevation. A third indication of former water elevation was the presence of dead stands of bulrush, a tall emergent wetland plant, at least 180 cm above the highest measured surface water levels at wetlands OR, LT, and TL (names in Appendix, Table A1).

During the study period, surface water levels declined through the growing season at 22 of the 24 study wetlands, and all of these sites had lower water levels in 2010 than 2009. Wetlands DW and RL had persistent inflow and outflow, and water level changed by less than 3 cm during the study period. In contrast, surface water level in BD, BG, and CP averaged 115 cm higher in 2009 than 2010.

Rain events triggered groundwater and surface water levels to rise synchronously (Fig. 3), as highlighted in a subset of continuously monitored wells (Appendix, Fig. A1). Some wetland water tables were recharged by winter groundwater inflow, while others responded more to spring snowmelt and rain. Nineteen wetlands had groundwater inflow from one side and outflow on the opposite side and are flow-through systems. Hydraulic gradient reversals, where the relative elevation of groundwater and adjacent surface water switch, occurred at seven sites (Fig. 4c). For example, following heavy rain, LT switched from being a flow-through wetland to having ground water inflow on all sides (Fig. 3a). Three wetlands were perched above the regional water table and filled only by snowmelt, rain, and surface runoff.

Vertical hydrologic gradients were small and near-surface groundwater flows were predominantly horizontal. Only 17 of 217 piezometers had positive gradients $\geqslant 5$ cm relative to their nested monitoring well. Groundwater discharge at DW and TF had substantial positive gradients of 22–48 cm. Twelve of 17 piezometers with positive gradients took longer than one week (median 10 weeks) to equilibrate following installation, suggesting they had extremely low K_s and transmitted little water to the wetland. Seven piezometers consistently had $\geqslant 5$ cm of downward gradient, indicating that downward flow was also uncommon. The three perched wetlands had at least one piezometer that never contained water even when surface water was present, revealing an unsaturated zone below the pond.

Basins with surface outflows typically had inflowing groundwater, and their outlets constrained maximum surface water level. Five of seven wetlands with outlets had peat soils, while the other two were a large deep lake and a perched basin that was often dry. Wetlands with outlets had less water table rise in response to early summer rains ($\bar{x} = 2$ cm) than closed-basins ($\bar{x} = 13$ cm; $p = 0.005$, Fig. 3c and d). Sites with outlets responded to late summer rain events only if surface water outflow had ceased (Fig. 3d).

Trumpeter Lake is a flow-through system, with groundwater inputs from the south during most of the growing season (Fig. 4). In late summer 2010, the lake surface was higher than adjacent groundwater in all monitoring wells, and the lake recharged groundwater on all sides (Fig. 4d). Na^+/Ca^{2+} ratios of groundwater samples indicated that two aquifers contributed to the watershed. Groundwater discharging from a bedrock aquifer had a Na^+/Ca^{2+} ratio of 13, while discharge from the glacial till aquifer had a ratio of 3. Double-ring infiltrometer and slug tests in the Trumpeter Lake watershed indicated that K_s values ranged from 0.003 to 1.7 m/day. The double-ring infiltrometer yielded K_s values roughly an order of magnitude higher than the slug tests, similar to the measures in till by van der Kamp and Hayashi (2009). These low conductivity val-

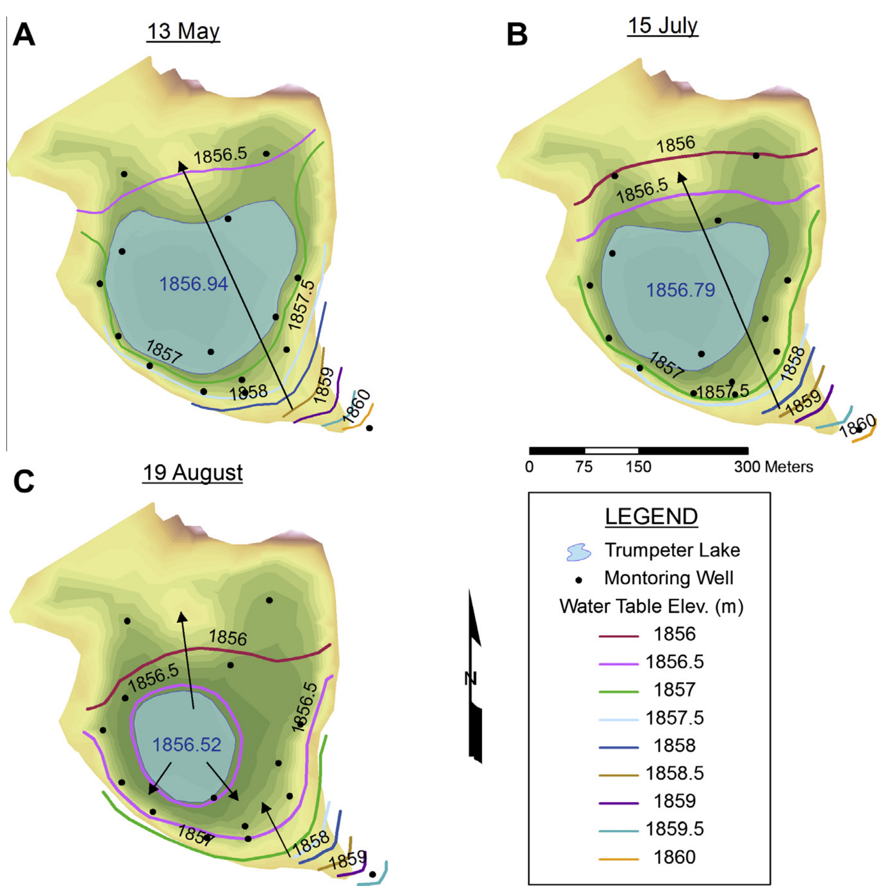

Fig. 4. 2010 Trumpeter Lake water table contours (m.a.s.l.), interpolated from 15 monitoring wells. (A) and (B) Trumpeter Lake was a flow-through wetland through mid-July, with the water table gradient from south to north (arrows). (C) In late summer the water table gradient reversed and surface water locally recharged groundwater on all sides.

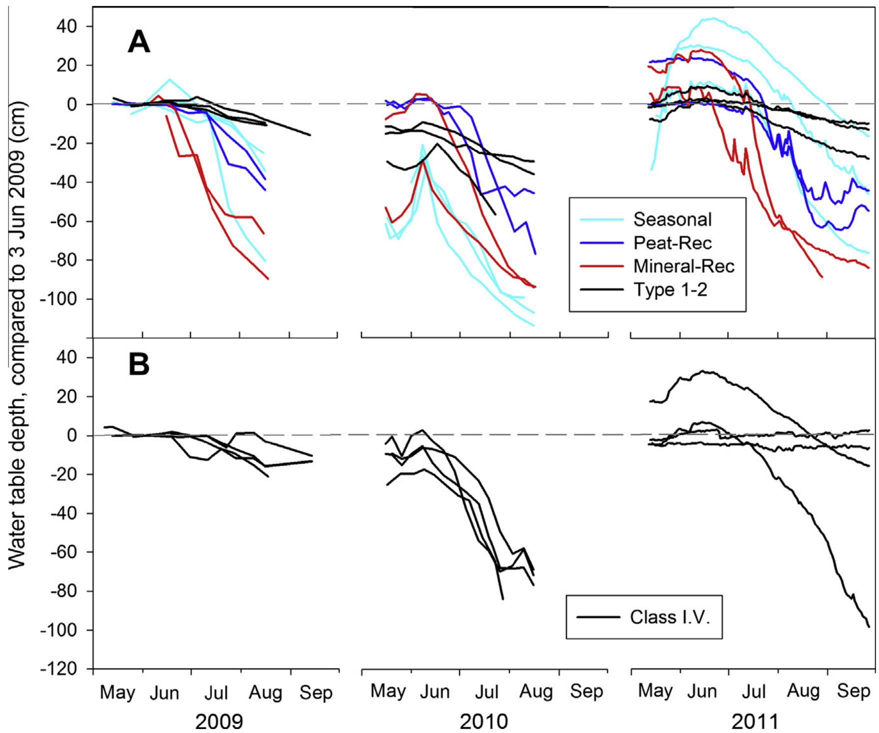

Fig. 5. Water table variation for the five well classes having three summers of data for multiple wells. (A) Wells in four classes continued to support similar hydrologic regimes in 2011, while (B) shows that wells in the fifth class examined had similar hydrographs in 2009–10, but they diverged in the very wet 2011.

ues indicate that it can take years between water's input to the watershed and its arrival to the lake.

4.2. Wetland classification

Seven wetland classes were identified using water table variance measured in 2009 and 2010. These are: (1) "*Stable*" wetlands DW and RL had a surface water elevation that changed less than 3 cm over the study period due to consistent inflow and a defined surface outflow elevation. Air photo analysis indicated that the ponded area has remained stable for decades. (2) "*Perched*" wetlands BP, MC, and WA had water perched above an underlying aquifer. Piezometers installed in these basins never contained water even though their associated monitoring well or staff gauge did, indicating that the piezometer was in or below a confining layer. Surface water was recharged by snowmelt and overland flow, and water levels steadily declined through the growing season until the pools were dry. (3) "*Seasonal*" wetlands BD, BG, BM, BW, CP, CR, and SV had highly varying water table levels that differed between years. 2010 water levels averaged 75 cm lower than in 2009, more than double the between-year difference of any other class. Winter snowpack created flow-through or recharge basins, and the water table rose following rain events, indicating a close connection between precipitation and water table elevation. (4) "*P.R.*" (peat-recovery) wetlands DC, RP, and SN are fens supported by groundwater discharge. Water levels declined by up to 80 cm in late summer and recovered to the ground surface by the following spring. 2009 water level declines occurred later in the summer and were smaller than those of 2010. All sites had surface water outlets that limited water level rise in response to early summer rain. (5) "*M.R.*" (mineral-recovery) wetlands MB and US had mineral soils with water tables recovering between growing seasons. These wetlands had the largest water table declines, approximately 100 cm each summer. (6) "*I.V.*" (interannually variable) wetlands BE, IP, OR, SG, and TF water tables changed substantially between summers. The average within-summer water table decline was 20 cm in 2009 and 65 cm in 2010. Water table variation was relatively small and responded minimally to precipitation events. Soil type and outlet presence varied among sites. Excluding their similar water table changes, I.V. wetlands appeared the most inconsistent of any class. (7) "*S.V.*" (spatially variable) wetlands TL (Trumpeter Lake) and LT had wells classified into at least three different well types. Water table variations were distinct in different parts of each wetland, indicating that a combination of hydrologic processes occur and create spatial complexity. When tested during the exceptionally large 2011 snow year, the classification successfully grouped study sites in four of the five wetland classes tested (Fig. 5).

Landscape position and watershed condition influenced the formation of wetland hydrologic regimes and classes. Wetland class was correlated with the highly linked variables surface water outflow ($\chi^2 = 16.03$, $p = 0.014$) and peat soil ($\chi^2 = 15.77, p = 0.015$), conditions common to wetland classes P.R. and I.V. At these sites, surface water outlets constrained maximum wetland water levels,

Table 1
Relationship between environmental variables and wetland hydrograph classes. Chi-squared analysis was performed on categorical variables, and one-way ANOVA tested quantitative variables.

Variable	Cat. vs. quant.	χ^2	*F*-statistic	*P*
Surface water outflow	C	16.03		0.014
Thick peat	C	15.77		0.015
Basin size	Q		3.5	0.02
Clay in basin	C	14.1		0.03
Piezo. time to equilib.	Q		2.1	0.11
Watershed size	Q		1.92	0.14
Maximum piezo. gradient	Q		1.75	0.17
Organic soil in basin	C	8.72		0.19
Elevation	Q		1.45	0.25
Precipitation	Q		1.15	0.37
Surface water inflow	C	6.24		0.4
Bulrush dominant	C	5.49		0.48
Basin EC	Q		0.9	0.52
Inflowing EC	Q		0.84	0.56

dampened water table changes, and supported peat formation. Basin size differed among wetland classes ($F = 3.5, p = 0.02$), a function of the largest two wetlands both being members of the S.V. class. Presence of a clay layer was most prominent in the perched class ($\chi^2 = 14.1$, $p = 0.03$, Table 1).

4.3. Wetland area through time

Surface water extent for studied basins varied by up to 400% on air photos from 1954 to 2009. Wetland area was greatest in 1969 following the wettest decade preceding any air photo, and in 1998 following two years with very large snowpack that produced the two highest Yellowstone River runoff years on record. Surface water area at BD, IP and CR was correlated with total precipitation over the two years prior to photo date, while LT, TL, BM, and CP surface water area was correlated with precipitation over the previous eight years ($p < 0.10$; Table 2). The other seven wetlands were not correlated with precipitation patterns. Significance between precipitation and wetland class was not tested because only seven wetlands were found to vary with precipitation. Wetland surface area was more strongly correlated with total precipitation than to snowfall alone ($p < 0.01$).

Trumpeter Lake surface area was largest at 12.8 ha in 1969 and lowest at 3.0 ha in 2006. A topographic survey found that lake volume was highly correlated with surface water area using the power function $Volume = 8 * 10^{-7} * Area^{2.251}$ ($R^2 = 0.999$). The survey permitted Trumpeter Lake to be the one wetland where we can directly calculate lake area and volume as a function of measured stage. Lake volume was more highly correlated with precipitation over the previous 5–10 years (mean $R^2 = 0.85$) than the previous 1–4 years (mean $R^2 = 0.67$), suggesting that groundwater contributions from several years sustain lake levels.

For the 16 wetlands where we could identify an upper hydric soil boundary, its height above the maximum 2009–10 surface water level differed significantly among wetland classes ($F = 3.29$, $P = 0.04$). Hydric soil boundaries at basins with outlets were near the surface water peaks ($\bar{x} = 31$ cm ± 4 cm SE above 2009–10 mean peak, $n = 7$) while in closed-basins they were significantly higher ($\bar{x} = 128 \pm 24$ cm SE, $t = 3.31$, $n = 9$, $p = 0.005$).

4.4. Climate

4.4.1. Trends in Yellowstone River discharge

The 5-year mean discharge of the Yellowstone River was positively correlated with wetland area calculated from air photos ($R = 0.89$). Cluster analyses of monthly discharge produced three magnitude classes. These were years with mean June discharge of 460, 370, and 250 m^3/s. Four shape classes resulted, corresponding to annual runoff peaks in May, late May-early June, mid-June, and late June-early July. From 1985 to 2012 there was only one late (June–July) peak but ten early (May) peak years, compared to their relatively equal distribution from 1911 to 1984 (Appendix, Fig. A2). Prior to 1984, average peak runoff occurred on June 11, but after 1985 it occurred on May 31 ($t = 4.15$, $p < 0.001$). The decade most similar to the early discharge peak 1990s and 2000s was the drought period of the 1930s. In contrast, the 1940s had the most late peak years. The early peak 1990s, however, was followed by a second successive early peak decade. Unlike discharge timing, the volume of mean annual discharge did not change after 1984 ($t = 0.01$, $p = 0.99$).

Table 2
Relationship between wetland area and cumulative precipitation, determined from air photo analysis. Wetland area was compared to precipitation from the 2, 4, and 8 years previous to photo date using forward-step multiple regression for the eight photo years. Results for a wetland's most significant time step are reported if $p < 0.10$. No wetlands were most closely related to the last 4 years.

Wetland	Time step (yrs)	*F*-value	*P*-value
BD	0–2	8.32	0.028
IP	0–2	6.36	0.045
CR	0–2	3.92	0.095
LT	0–8	19.28	0.005
TL	0–8	58.19	0.0003
BM	0–8	9.17	0.023
CP	0–8	6.73	0.041
BG	None	–	–
BP	None	–	–
BW	None	–	–
WA	None	–	–
OR	None	–	–
DW	None	–	–
RL	None	–	–

4.4.2. Long-term climate trends

The relative highs and lows in Yellowstone River discharge and PDSI have co-occurred over the last 100 years. Since 1970 river discharge has remained around the mean of the past century, while increased temperature has produced consistently low PDSI values (Fig. 6). Although PDSI indicates that the past four decades have been drier than the early to middle 20th century, tree ring data indicate that the dry conditions of recent decades have occurred several times in the past 800 years in YNP (Fig. 6d; Gray et al., 2007). Additionally, the relatively dry second half of the 20th century was preceded by the most prolonged wet period of the past 800 years, lasting approximately 80 years from the late 19th through the early 20th centuries (Gray et al., 2007). This wet period may have resulted in the expansion of Northern Range wetlands to their largest extent of the past several centuries.

4.5. Vegetation

The nine most common plant species in study wetlands occupied habitats with distinct hydrologic regimes (Fig. 7). *Carex aquatilis* and *C. utriculata* occupied sites with the highest water tables. *Carex pellita*, *Schoenoplectus acutus*, and *Salix* spp. were found in sites with water tables above or near the soil surface in early summer 2009. However, these three species lacked standing water during summer 2010, in contrast to *C. aquatilis* and *C. utriculata* which had standing water through late June in both years. *Eleocharis palustris* occurred in locations that were saturated in early 2009, but the water tables dropped substantially in both summers. *Carex atherodes* experienced similarly large summer variation as *E. palustris* and occupied seasonal wetlands whose mean water tables differed by 60 cm between years. *Phleum pratense* and *Poa pratensis* occupied the driest locations and were not indicative of wetland conditions.

5. Discussion

5.1. Wetland function and hydrology

Air photographs, hydric soils, geomorphic indicators, PDSI, and river discharge analyses all indicated that growing season surface water abundance in YNP's Northern Range has declined in recent decades. The decades-to-century scale perspective indicates that wetland area has been abnormally small in recent decades, however the first decades after YNP's designation as a national park were in one of the most prolonged wet periods of the past 800 years (Gray et al., 2007). Therefore, the late 1800s may represent a period with unusually abundant surface water instead of an average reference state. Even though wetland areas as large as those of the late 19th or small as the early 21st centuries probably

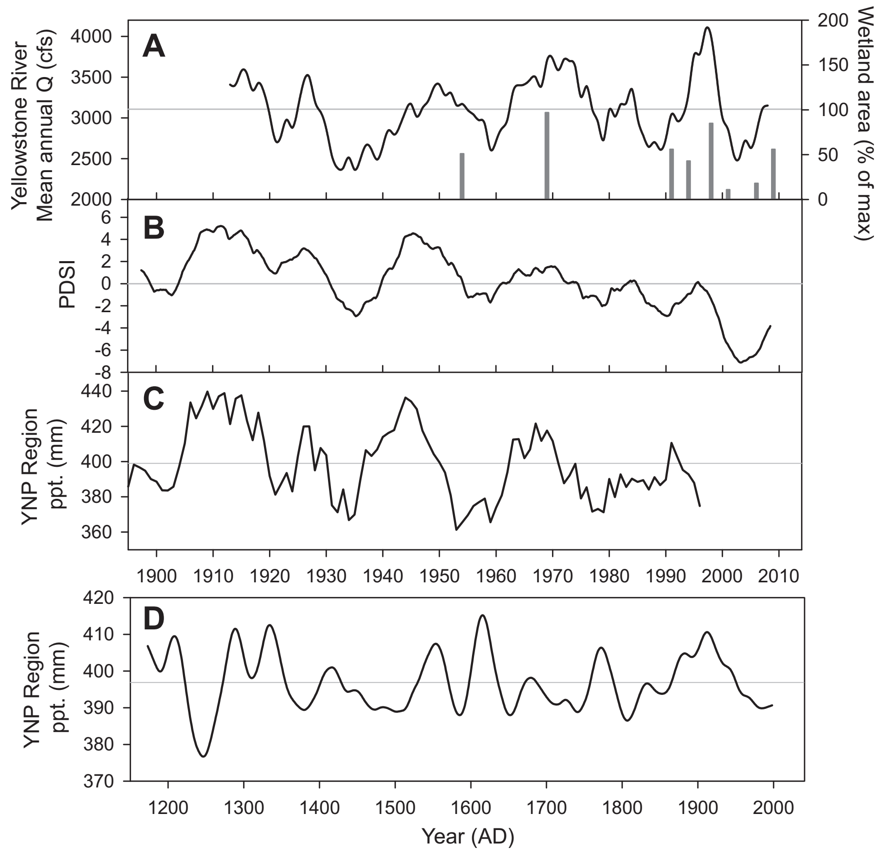

Fig. 6. Climate indices for YNP. (A) Solid line is the 5-year mean for annual discharge of the Yellowstone River at Corwin Springs. Bars depict wetland surface area delineated from air photos. (B) 5-Year mean PDSI for the Yellowstone River drainage, Wyoming. (C) 20th century 5-year mean tree-ring reconstructed precipitation for the YNP region. (D) Tree-ring reconstructed precipitation since 1173 AD, displayed as a 60-yr cubic smoothing spline (data in (C) and (D) from Gray et al., 2007). Horizontal grey lines represent means during the plotted period. Note the unique *x*-axis in (D).

occurred in the past, projected further warming will likely surpass this natural range of variation (Westerling et al., 2011) and lead to unprecedentedly small wetland area. Recent wetland declines have reduced or eliminated habitat for native species (Proffitt et al., 2010), and continued drying could adversely affect other species and alter plant distributions to create novel communities (Bartlein et al., 1997). When properly functioning, the near-surface water table in fens promotes high plant production, low decomposition rates, and peat formation. Under climate change, some fens could have reduced water delivery and lower water tables, shifting them from carbon sinks to sources (Chimner and Cooper, 2003).

Water table variation indicates that multiple hydrologic processes affected the study wetlands in this region that lacks direct anthropogenic modifications. At most sites rain produced a rapid water table rise, while snow seasonally recharged aquifers and supplemented surface water to initiate the growing season. Groundwater discharge mitigated water level decline in most study wetlands, similar to wetlands in Argentina's Monte Desert (Jobbágy et al., 2011) and Nebraska's Sandhills (Winter, 1986). At some wetlands, such as those in classes P.R. and M.R., summer water table decline was counteracted by groundwater recharge over winter, a process that minimized interannual variation. However, groundwater inputs at other sites, such as seasonal class wetlands, have fast flow paths that did not contribute water throughout the year. Perched wetlands lacked groundwater contributions, similar to playas in the southern Great Plains of the USA (Smith, 2003) and vernal pools in Mediterranean climates in western North America, Chile, South Africa, and Australia (Keeley and Zedler, 1998). Surface outlets limited maximum water level and increased hydrological and ecological stability.

5.2. Wetland classes

Our hydrologically based wetland classification provides a framework for comparing Northern Range wetlands, and each of the seven classes includes complementary yet distinct habitats within the region. Seasonal class wetlands provide habitat for YNP's four native amphibians that require ephemeral surface water. The S.V. wetland class included large wetlands with multiple water sources and could support nesting trumpeter swans if surface water expands. Consistent saturation has allowed P.R. wetlands to accumulate organic matter and sequester large amounts of carbon in peat soils. Wetlands in the stable class were uncommon across the Northern Range but may serve a critical role as isolated habitat refuges for wetland-dependent flora and fauna during exceptionally dry times.

Our wetland classification was based on water table variation over two years, and any classification should be re-evaluated as more data become available. The addition of 2011 water table data, collected in an anomalous snow year, substantiated four of the five classes assessed. However, 2011 had divergent patterns within the I.V. class, which included basins that were ecologically, geomorphically, and pedologically inconsistent. On much longer timescales, hydric soil analysis indicated that wetlands within classes changed similarly. Thus, two years of hydrologic data appear suitable for creating a basic wetland classification that provides a useful

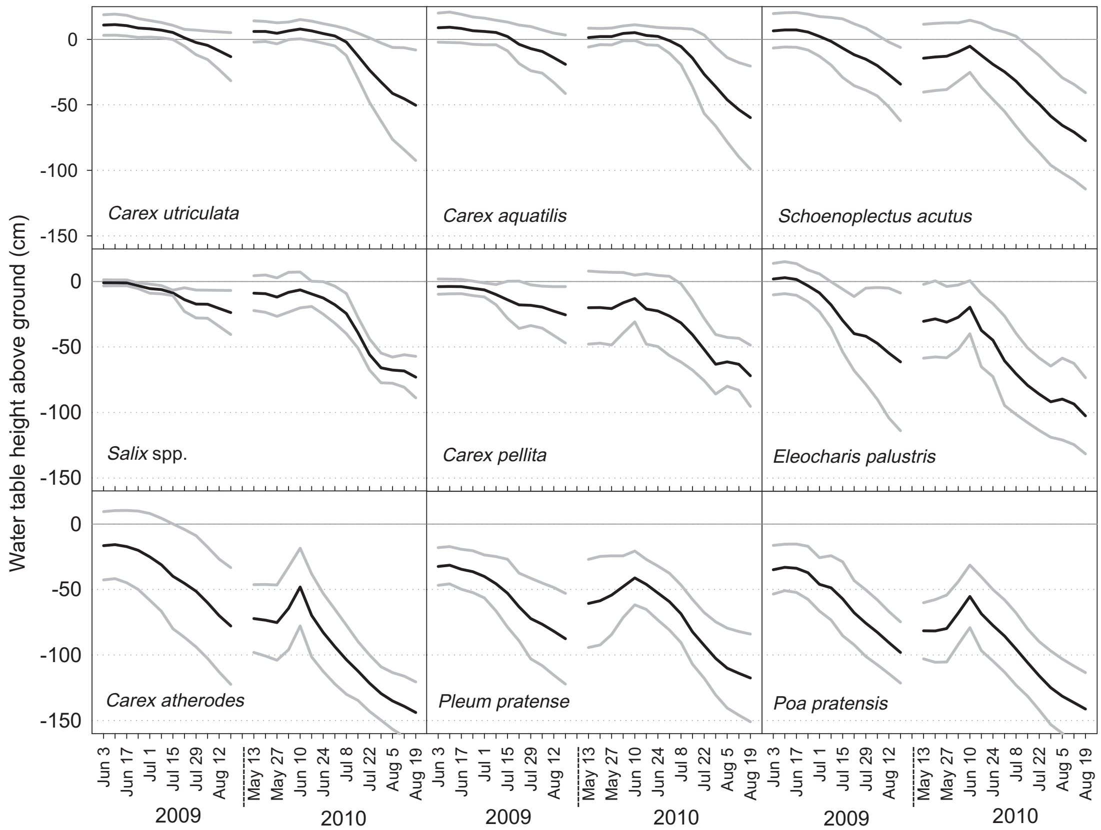

Fig. 7. Water table hydrographs for the nine most common plant species. Graphs illustrate water table means ±1 standard deviation. Data are derived from averaging water tables for all wells with ⩾20% cover of the identified species.

conceptual framework for understanding long-term wetland processes.

5.3. Hydrologic controls of wetland vegetation

Dominant wetland plant species occupied distinct zones of water table depth and duration. *Carex utriculata* and *Poa pratensis* are the biotic endpoints on the wet–dry scale, with other species' hydrologic niches falling in between. Because species occupy distinct hydrologic niches relative to each other, this information can be used to approximate water table dynamics in other areas supporting these species. Plant community structure differs in areas of groundwater discharge and recharge (Cook and Hauer, 2007; Hunt et al., 1999) and can indicate the spatial distribution of these hydrologic processes in a wetland. Wetland vegetation is predicted to change with climate (Johnson et al., 2010; Poiani et al., 1996), and monitoring the plant species composition of Northern Range wetlands is critical to identify the ecological effects of climate change in YNP.

5.4. Trumpeter Lake watershed dynamics

Lichen trim lines, relict hydric soils, dead bulrush stands, eroded shoreline, and a temporal sequence of air photos reveal that a 2.5 m surface water decline has occurred at Trumpeter Lake over the last half century. Sediment cores have shown that surface water levels were highly variable and the lake has dried completely at least once within the last century (Engstrom et al., 1991). This water table change parallels the "drought and deluge" conditions in semi-permanent wetlands of the prairie potholes (Johnson et al., 2004). Chemical analyses indicated that two distinct aquifers fed Trumpeter Lake, one in andesite bedrock and one in till. Both contribute water to Trumpeter Lake, yet climate change will likely affect the flow paths differently.

In the 21st century the Northern Range bison population has been the highest since YNP's inception (Meagher, 1973; Wallen, 2010). The resulting heavy use area around Trumpeter Lake has denuded vegetation, triggered soil erosion, and altered water infiltration. Glacial erratics located between the former and current lake perimeters have rust-colored stains ringing their bases, suggesting that soil erosion has exposed formerly buried portions of the rocks. In addition, dead bulrush 2.0 m above the modern lake surface occurs in isolated clumps that are elevated above the surrounding ground surface. All robust Northern Range bulrush stands are comprised of homogenous clones that cover the ground in dense continuous stands, suggesting that the dead isolated clumps have resisted erosion, but soil loss will ensue in these areas over time. Trumpeter Lake provides an example of how interacting climatic and biological agents can cause rapid habitat change that is detrimental to native species.

5.5. Climate and wetland area changes through time

Although watershed properties play an integral role in creating a wetland's hydrologic regime, on larger time scales climate can interact with the watershed to initiate wetland change. Data from the past century support the idea that climate change is responsible for Northern Range wetland loss. In general, 2009–11 water tables varied according to annual precipitation. Air photo analysis indicated that water levels were well correlated with cumulative precipitation over the past two years at some basins and the past 5–10 years at others. In Alaska (Klein et al., 2005) and Siberia

(Smith et al., 2005) air photo analyses have revealed wetland decline concurrent with air temperature increases. Warming has recently occurred in YNP, and changes have intensified since the 1980s (McMenamin et al., 2008; Wilmers and Getz, 2005). Johnson et al. (2010) modeled climate change effects on wetlands of variable permanence, finding that more permanent sites, such as our S.V. and P.R. classes, are more susceptible to climate change than ephemeral wetlands, such as our seasonal class. We showed that groundwater inputs to wetlands can persist through the year, but a future climate might yield lowered groundwater contributions that fail to resupply wetland water levels. Seasonal class wetlands can change from water filled to dry within a couple of years, and the flora and fauna at these sites are likely adapted to this variability. However, water level declines at P.R., S.V., and I.V. wetlands may have more lasting effects in a changing climate.

Wetland changes in most regions of the world have been poorly documented because of the multitude of wetlands on the landscape, the effort required to monitor them, and the complexity of data analysis. Basin wetlands and perennial rivers, although inherently different, are both influenced by climate-driven hydrologic processes. Our Yellowstone River flow analysis revealed that the last three decades have experienced a proportion of early discharge peaks that is unprecedented in the gauge record, indicating that snowpack is melting earlier than at any time in the past century. Earlier snowmelt produces a longer growing season and increased evapotranspiration, further depleting water. Other Rocky Mountain rivers have also experienced earlier runoff (Stewart et al., 2005), a regional trend that is projected to continue (Stewart et al., 2004). This hydrologic shift could initiate additional changes to wetlands, habitats where the water table position relative to the land surface is critically important.

6. Conclusions

Basin wetlands on Yellowstone's Northern Range have declined in area during the past century, but the current conditions are within the natural range of variation for the last millennium. Weather patterns naturally vary between warm–dry and cool–wet conditions, and the warmer and drier conditions of the last several decades have reduced wetland area and surface water levels. If the recent climate trajectory continues, wetlands will dry further, eliminating critical habitat for native species. Wetland persistence is critical to ecosystem integrity in YNP, one of the last places in the conterminous United States where natural ecosystem processes dominate. Under projected climate changes the growing season initiation and onset of summer water table decline will likely occur earlier, leading to additional drying, organic matter decomposition, and wetland destabilization. Non-linear or threshold responses may lead to irreversible effects. Understanding, communicating, and managing these valuable habitats is essential moving forward, and wetland classification can facilitate reaching all of these goals. Wetlands serve a critical role in YNP and worldwide, and they should be monitored in the future to facilitate our recognition of vital ecosystems undergoing change.

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Appendix A.

See Figs. A1 and A2 and Table A1.

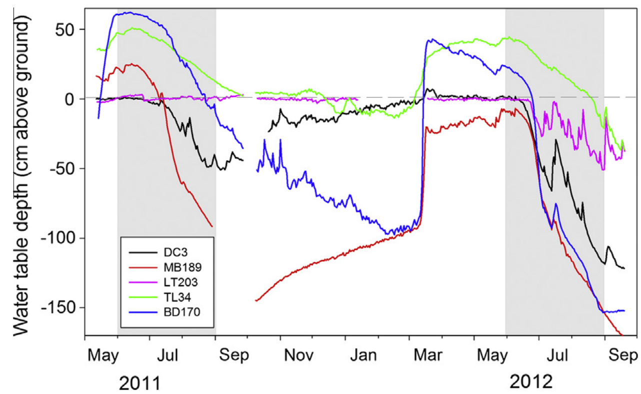

Fig. A1. Water tables at five wells where pressure transducers collected data from May 2011 to September 2012. Hydrographs illustrate differences among sites, including that some water tables recharge over winter while others lower, water table spikes from rain differ by well and season, interannual consistency varies among wells, and the onset of summer water table declines varies by year. Well names are in legend and grey background highlights June–August.

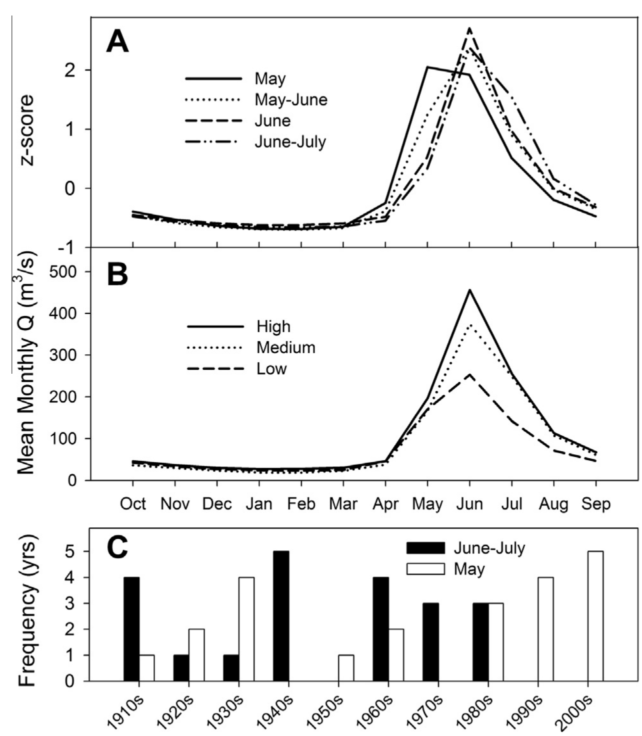

Fig. A2. Yellowstone River discharge shape-magnitude analysis classes and their occurrence throughout the past century. (A) Mean annual hydrograph of all wells in each of the four shape classes, termed after the timing of peak discharge, (B) mean annual hydrograph of the 3 magnitude classes, (C) chronology of the earliest vs. latest discharge years, showing a "slingshot" from late- to early-peaks since the 1970s.

Table A1
The 24 study wetlands. Coordinates are in UTM zone 12N. Basin size is the ponded area in the 1998 aerial photo, and *n* wells is the number of monitoring wells installed at the wetland.

Wetland name	Wetland acronym	UTM E	UTM N	Elev. (m)	Basin size (ha)	*n* Wells	Wetland class
Big D	BD	546592	4974876	1875	0.2	4	Seasonal
Bighorn Marsh	BM	547949	4973587	1904	0.8	6	Seasonal
Blue–Green	BG	545970	4974936	1905	0.2	5	Seasonal
Brown Pond	BP	520612	4985821	1765	0.4	3	Perched
Bunsen East	BE	522447	4973863	2218	1.7	5	I.V.
Bunsen West	BW	522035	4974291	2228	1.3	5	Seasonal
Chorus Pond	CP	520797	4971697	2241	0.2	4	Seasonal
Copper Rock	CR	550268	4973075	1887	0.5	5	Seasonal
Dead Willow	DW	520432	4985701	1776	0.4	7	Stable
Double Cub	DC	543547	4976370	2009	0.6	4	P.R.
Island Pond	IP	552001	4974167	1890	0.6	5	I.V.
Little Trumpeter	LT	549423	4973951	1861	3.1	5	S.V.
Mammoth Bowl	MB	524980	4978500	1824	0.7	4	M.R.
Meadowlark Commons	MC	520777	4985721	1769	0.4	5	Perched
Old Road	OR	523300	4983570	1791	0.7	5	I.V.
Rainbow Lake	RL	520423	4985457	1792	2.1	3	Stable
Rye Pond	RP	524180	4978560	1887	0.3	5	P.R.
Sandhill Nest	SN	548510	4974510	1864	1.7	5	P.R.
Self-Guiding	SG	534864	4979149	2047	0.8	5	I.V.
Slough View	SV	552075	4974492	1888	0.6	5	Seasonal
Trumpeter Feeder	TF	550155	4973559	1863	0.4	4	I.V.
Trumpeter Lake	TL	549898	4973760	1860	3.7	14	S.V.
Upper Slide	US	523565	4983271	1752	0.2	4	M.R.
The Wallows	WA	551342	4973520	1884	2.1	6	Perched

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