THESIS

# CLIMATIC AND HYDROLOGIC PROCESSES LEADING TO RECENT WETLAND LOSSES IN YELLOWSTONE NATIONAL PARK, USA


Submitted by

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ABSTRACT

CLIMATIC AND HYDROLOGIC PROCESSES LEADING TO RECENT WETLAND LOSSES IN YELLOWSTONE NATIONAL PARK, USA

Wetlands both provide vital habitat within functioning environments and act as landscape indicators by integrating catchment-scale hydrologic processes. Wetland drying during the past few decades in Yellowstone National Park's Northern Range has caused concern among National Park managers and the public at large. My research was initiated to develop an understanding of the processes controlling wetland water levels and contributing to wetland decline in the Northern Range. To do this I integrated analyses of hydrology, climate, soils, and vegetation. In 2009 I selected 24 study wetlands and instrumented each with an average of five shallow groundwater monitoring well-and-piezometer nests. To quantify historic wetland area I mapped hydric soils, analyzed aerial photographs, and identified geomorphic indicators of higher water. Vegetation was sampled to characterize wetlands and plant-water relationships, and I also conducted a soil seed bank study. The Trumpeter Lake focal site revealed groundwater changes through time and was used to identify the timescale on which an important wetland varies. Climate data indicated that warming and drying occurred during the 20$^{th}$ century, but that this pattern was within the natural range of variation for the study region during the past 800 years. 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. Wetland classes exhibited variable hydrologic permanence within and between the two study summers. Aerial photographs and hydric soil delineation both confirmed formerly greater wetland abundance. These changes were linked to the wetland classes and the presence or absence of surface water outlets. Wetland plant species inhabited

areas of distinct water table depth and variation, and can be used to infer subsurface hydrologic regime in the absence of extensive monitoring well networks. Continued monitoring of these wetland basins and their watersheds is critical to expanding our understanding of the processes supporting Northern Range wetlands and allowing us to better manage these valuable habitats.

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## 1. INTRODUCTION

Wetlands are among the most valuable yet vulnerable habitats on Earth (Poff et al., 2002; Bates et al., 2008; Winter, 2000). Hydrologic processes, which are influenced by climate, geology, and landscape setting, are the dominant mechanisms creating and sustaining wetlands (Mitsch and Gosselink, 2000; Hunt et al., 1996). Located at low points in their watersheds, wetlands integrate catchment-scale processes and reflect environmental conditions (Williamson et al., 2008; Bates et al., 2008; Long and Nestler, 1996). Additionally, the close proximity of the water table and land surface in wetlands leaves these habitats susceptible to changing hydrologic, landscape, and climatic conditions (Brooks, 2009; Bates et al., 2008).

Interactions among precipitation, evapotranspiration, groundwater, and surface water create a wetland's hydrologic regime. Distinguishing surface- from groundwater processes is often complex because they interact at multiple spatial and temporal scales (Winter, 1999; Schot and Winter, 2006; Devito et al., 2005). Subsurface stratigraphy and its hydraulic properties play important roles in influencing wetland hydrologic processes (van der Kamp and Hayashi, 2009; Winter, 1999; Todd et al., 2006). Adjacent wetlands that appear similar can vary in permanence (Brooks, 2000), and recent modeling in the prairie pothole region of the northern American Great Plains has shown more permanent wetlands to be more susceptible to climate change than temporary wetlands (Johnson et al., 2010). Further complicating hydrologic assessments, groundwater sources sustaining a wetland may originate hundreds of kilometers away, such as those that support Argentine desert oases (Jobbágy et al., 2011) and Death Valley, California springs (Belcher et al., 2009). Groundwater flow paths also affect surface water chemistry (van der Kamp and Hayashi, 2009; LaBaugh, 1987) and salinity (Jolly et al., 2008; LaBaugh et al., 1998), factors that influence wetland species composition.

Basin wetlands found throughout the world exhibit a range of hydrologic regimes (Winter, 1999). For example, playa wetlands of the southern Great Plains (Tiner, 2003; Tsai et al., 2007) and vernal pools across the USA (Brooks, 2004; Pyke, 2004; Zedler, 2003) are dependent on precipitation and evapotranspiration (ET) processes. These wetlands are considered hydrologically isolated from ground- and surface waters. In contrast, Nebraska's Sandhills and Colorado's Great Sand Dunes support wetland complexes that are connected via groundwater flows in highly conductive soil (Winter, 1986; Wurster et al., 2003). Cook and Hauer (2007) described wetlands in the Northern Rocky Mountains that formed in a dead-ice glacial moraine, with some wetlands connected by near-surface flow and others being hydrologically isolated. Fluxes between ground- and surface water in prairie pothole region wetlands are highly variable temporally and spatially, and the direction of groundwater flow may change seasonally (Woo and Rowsell, 1993; Rosenberry and Winter, 1997; Winter and Rosenberry, 1995). The high degree of spatial and temporal variability in wetlands illustrates that generalizing wetland function in an unstudied region can yield inaccurate assumptions.

Temperature and precipitation strongly influence wetland habitats and are forecasted to change in the coming decades (Carpenter et al., 1992; Brooks, 2009). Past changes in climate have been correlated with wetland disappearance in Alaska and Siberia (Klein et al., 2005; Smith et al., 2005), and the trend is predicted to continue (Sorenson et al., 1998; Bates et al., 2008). Understanding the effects of climate change on wetland biotic and hydrologic processes is challenging due to the inherent spatial and temporal complexity in these habitats (Pilon and Yue, 2002; Bates et al., 2008; Brooks, 2009).

Regional climate models for Yellowstone National Park (YNP) forecast an ecological shift unprecedented in the Quaternary, yielding an uncertain future for the park's water-based ecosystems (Westerling et al., 2011; Bartlein et al., 1997). Many wetlands in YNP's glaciallyinfluenced Northern Range have exhibited pronounced surface water declines during the past four decades. However, these changes are poorly quantified (e.g., McMenamin et al., 2008), and no previous research has investigated the processes causing these changes. Recent wetland loss has already affected YNP's native wetland species, including causing the loss of trumpeter swan nesting habitat (Proffitt et al., 2010). Although some effects of wetland decline on key species have been identified, the underlying processes altering the wetlands themselves remain unknown and are important to guiding future conservation efforts.

The geologic diversity of YNP has created high environmental heterogeneity, precluding a broad characterization of wetland processes. To address this variation, I used concepts from other classifications (e.g., Acreman et al., 2009; Dahl, 2011; Rains, 2011; Junk et al., 2011) to create a framework for grouping wetlands according to their hydrologic processes. This research addressing wetland change was framed within the following objectives: (1) classify wetlands according to their hydrologic regime, including climatic and geomorphic processes, (2) determine the patterns and magnitude of water level decline that occurred during the late 20$^{th}$ and early 21$^{st}$ centuries and assess whether this change is within the natural range of variation, and (3) investigate a focal site that has experienced dramatic water level changes to gain a more complete understanding of wetland processes. The upper Yellowstone River watershed provides a unique opportunity to investigate hydrologic processes in a relatively pristine hydrologic setting. To address the study objectives I integrated wetland and watershed hydrology, climate, soils, and vegetation to create an integrated view of the processes supporting Northern Range wetlands.

## 2. STUDY AREA

### 2.1 Site Description

The 1,400 km$^2$ Northern Range is located in Wyoming and Montana and comprises much of YNP's northern quarter (Fig. 1). Douglas fir (*Pseudotsuga menziesii* Mirbel) and lodgepole pine (*Pinus contorta* Loudon) dominate the higher elevation forests, while lower elevations are dominated by sagebrush steppe (*Artemisia tridentata* Nutt; nomenclature follows USDA PLANTS (NRCS, 2011)). Lower elevations (1800-2000 m) receive 41 cm average annual precipitation, with over half falling as snow (NCDC, 2011). Most of the study area was covered by glaciers during the Pinedale Glaciation, which ended approximately 15 kya. Today's environment is heavily influenced by glacial scouring and till deposition that has created a heterogeneous landscape with abundant depressions that support today's wetlands. Clay rich mollisols and inceptisols surround the study sites (YCR, 2009). In recent years, park staff and visitors have observed a pronounced lowering of surface water levels in these wetlands, but quantitative and process-based information explaining the phenomenon is lacking.

In 2009, 24 non-riparian wetlands were selected as study sites to characterize Northern Range wetland types (Table 1). Study sites ranged from 1783 – 2284 m elevation. Sites included both mineral and organic soils, and common plant species included *Carex atherodes, C. utriculata, Juncus arcticus, Eleocharis palustris* and *Schoenoplectus acutus*. Study wetlands receive water from direct precipitation, groundwater, and overland flows. Through the 20$^{th}$ and early 21$^{st}$ centuries, some Northern Range wetland water levels were stable, while others varied greatly (Engstrom et al., 1991). Several wetlands exhibited distinct indicators of former high water levels, including relict vegetation, lichen trimlines, and eroded shorelines. Biotic factors including high large herbivore density can disturb vegetation and soils, especially in wetlands. Northern Range bison populations are the highest on record and elk populations have been nearly twice as high during the past three decades compared to the previous four (YNP, 1997; Wallen, 2010; Wyman, 2011).

The Trumpeter Lake focal site was selected for a more detailed analysis because it has purportedly undergone major water level declines and trumpeter swans formerly nested here. However, lower water levels have changed the lake's habitat structure, leaving it unsuitable for nesting today. The lake is located near the confluence of the Lamar and Yellowstone Rivers in dead-ice moraine terrain. Its watershed has hummocky topography comprised of low-permeability unconsolidated glacial till with a high density of granitic glacial erratics (Pierce, 1979). Upland soils were identified as loam and lake-bottom soil as clay-loam using the hydrometer method particle size analysis (Gee and Bauder, 1979), suggesting that porosities were approximately 46% (Rawls et al., 1982).

### 2.2 Study Period weather

Weather patterns during the study period influenced the measured wetland water levels. 2009 and 2010 annual temperatures were both within 0.3° C of the post-1931 average. Total precipitation in water year 2009 (1 Oct 2008 – 30 Sep 2009) was 97% and snowfall 120% of average, while 2010 total precipitation was 83% and snowfall 53% of average (NCDC, 2011). Early June through early July was the wettest period in 2009, while late May through mid-June was the wettest period in 2010 (Appendix A). Weather station comparison for 2010 data indicated that sites throughout the study area experienced similar precipitation conditions. Pearson's R correlation coefficients among the three rain gauges within the study area ranged from 0.84 to 0.97.

## 3. <u>METHODS</u>

## 3.1 WETLAND CHARACTERISTICS AND CLASSIFICATION

### 3.1.1 Hydrologic Data collection

103 shallow groundwater monitoring wells were installed at the 24 wetland study sites in 2009, and 18 wells were added in 2010 (Appendix B). Wells were distributed to measure water tables on all sides of each study wetland and to characterize the hydrologic niches of dominant plant species. Staff gauges were installed in all wetlands with ponded surface water to measure its depth. Monitoring wells were hand-augered using a 10 cm diameter bucket auger to a depth either below the anticipated water table low or as deep as possible in rocky soils. Wells were constructed from 4.2 cm I.D. schedule 40 PVC pipe that was continuously slotted throughout the anticipated zone of water table fluctuation. Augered holes were backfilled with native soil. To measure hydraulic head in various soil layers, an average of two nested 2.1 cm I.D. PVC piezometers were placed adjacent to each well within the top two meters of soil. Water depth was measured manually with an electric tape approximately biweekly in 2009 and weekly in 2010 (Shaffer et al., 2000), and readings were used to interpolate weekly values. A rotating laser level was used to determine the relative elevation of wells within a wetland.

### 3.1.2 Wetland Water Table Classification

Classifying monitoring wells based on measured water tables was the first step toward wetland classification. The majority of wells were installed in May 2009, and I used 3 June 2009 as the first date for analyzing well, staff gauge, and piezometer data. I excluded from analysis instruments installed in late 2009 or in 2010 along with those that dried too early to provide data throughout each summer. For classification, each well's initial water level was standardized to a common datum, and subsequent readings were relative to this point. Standardization permitted the ecologically significant analysis of surface and groundwater changes independent of their absolute ground-surface elevations (van der Kamp and Hayashi, 2009).

I grouped wells with similar water table variations using a hierarchical combination of multivariate statistics and well-nest informed assignment. Wells with two distinctive hydrologic regimes were first identified by analyzing hydrologic patterns. Wells in a stable group had less than 3 cm of water level variation during the two-year study period. Secondly, wells in a perched group had surface water that disappeared abruptly and nested piezometers that never contained water, revealing an unsaturated layer below surface water. These groups were deemed unique from all other wells, which contained transient water levels connected to groundwater systems.

For the remaining 83 wells, I conducted a two-step “shape-magnitude” cluster analysis to produce a composite classification by separately analyzing the timing (i.e. shape) and magnitude of water table variations. This approach has been used for analyzing weather patterns and stream discharge (Laize and Hannah, 2010; Bower et al., 2004; Hannah et al., 2000), and recently groundwater (Upton and Jackson, 2011). To classify shape, each well’s weekly water table data were standardized to a common degree of variation using a *z*-scores transformation (mean = 0, st. dev. = 1). This transformation isolated the seasonality and rate of water table change independent of its magnitude. Transformed data were grouped using hierarchical agglomerative cluster analysis using Euclidian distance and Ward’s group linkage method (Laize and Hannah, 2010; Bower et al., 2004) with the program PC-ORD (McCune and Mefford, 2006). The resultant dendrogram was pared at 40% information remaining, producing three groups of wells, each with distinct hydrograph characteristics.

For the magnitude analysis, I combined seven water table variables: minimums, means and standard deviations for each 2009 and 2010, and maximum elevation for 2010 (Bower et al. 2004, Harris et al. 2000). All magnitude indices were standardized by conversion to z-scores to eliminate uneven weighting of classes (Hannah et al., 2000; van Tongeren, 1987). A second cluster analysis was performed on the magnitude data using the procedure described above but pruned at 0% information remaining, which produced two groups, one with larger and one with smaller water table changes (Fig. 2). The three shape and two magnitude classes were then crossed to yield six possible well hydrograph classes, five of which occurred in the study wetlands. The five shape-magnitude classes combined with the perched and stable well groups identified previously produced seven well classes (Fig. 3). Wells within most wetlands were in a single class, allowing wetlands to be grouped by these classes. A unique wetland class was created to accommodate the two sites that contained wells from three or four well classes.

To compare the wetland classification to local environments, I compared wetland classes to 14 environmental variables. Chi-squared analysis was conducted on the six binary categorical variables: surface water inflow, surface water outflow, peat presence, organic matter in basin, clay in basin, and bulrush (*Schoenoplectus acutus*) as the dominant wetland plant species. I define a wetland “basin” as a depression with surface water, not synonymous with a wetland’s watershed. One-way ANOVA, similar to chi-square analysis but used for quantitative variables, was conducted on eight 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. To supplement these analyses, I created a classification tree via CART analysis (De’ath and Fabricius, 2000) in the rpart package (Therneau and Atkinson, 2009) using the statistical program R 2.10.1 (R Development Core Team, 2009).

### 3.1.3 Wetland area analysis

*Hydric soils:* At 16 of the 24 study sites the maximum elevation of wetland soils could be identified using the hydric soil indicators protocol in the Corps of Engineers’ Wetlands

Delineation Manual (USACE, 2010). The boundary between wetland and upland soil was determined using soil pits and morphological indicators including chroma less than two, oxidized root channels, and mottled matrices. The distance between modern water level and the hydric soil's upper boundary was analyzed among wetland classes using an ANOVA and between outlet vs. closed-basin wetlands using a t-test.

*Aerial photograph analysis:* Aerial photographs from 1954, 1969, 1991, 1994, 1998, 2001, 2006, and 2009 were used to quantify the ponded area through time (photo dates in Appendix C). Dense vegetation obscured the identification of surface water perimeters at ten of the study sites, so 14 wetlands were used in the analysis. Photos were georectified to 2009 NAIP imagery using 2$^{nd}$ and 3$^{rd}$ degree polynomials, and wetland surface area was delineated in ArcMap v. 10 (ESRI, 2010). To standardize wetland area (Niemuth et al., 2010), each wetland's maximum area was assigned 1, and other years represented a proportion of 1. Wetland areas were compared to annual precipitation totals (NCDC, 2011) at either the Tower or Mammoth weather station, depending on proximity. I used regression models between the two stations to estimate missing monthly precipitation values (Iglesias et al., 2006; Pegram and Pegram, 1993). SAS (SAS Institute, 2010) was used to conduct a multiple regression comparing each wetland's proportion "full" to percent of average total precipitation for time steps of the past 2, 4, and 8 years. A wetland's best correlated time step is reported for all $p < 0.10$.

## 3.2 CLIMATE

### 3.2.1 2009-2010 weather

I analyzed daily precipitation records for May through August of 2009 and 2010. Climate data are available since 1931 for the Mammoth and Tower weather stations (NCDC, 2011). All study wetlands are located within 12 km of one station and 350 m elevation of both stations

(Fig. 1). In 2010 a HOBO tipping bucket rain gauge (Onset Computer Corp.) was installed (UTM Zone 12N 549867 E, 4973438 N) to measure precipitation near Trumpeter Lake. I performed linear regression analysis on 2010 weekly precipitation data among the Tower, Mammoth, and HOBO rain gauges to analyze spatial variability among study sites.

#### 3.2.2 Historic datasets

The Yellowstone River above the Corwin Springs gauging station (USGS gauge #06191500) drains 6783 $km^2$, including the entire Northern Range within YNP. Mean daily discharge data are available for the period 1911-2010. The shape-magnitude framework described above was used to analyze Yellowstone River discharge trends. To classify magnitude from each year, the maximum, minimum, mean, and standard deviation of monthly discharge data were used for annual hydrographs. The Palmer Drought Severity Index (PDSI), a metric of dryness (Dingman, 2002), is also reported for the Yellowstone River drainage basin from 1895-2010 (NCDC, 2011).

### 3.3 VEGETATION

#### 3.3.1 Plant-hydrology relationship

Vegetation in the study basins was typically distributed in concentric zones controlled by water depth and duration. In 2009 I estimated the canopy cover of each plant species present in a 2 m x 50 cm plot centered on each well and oriented parallel to vegetation zones. To determine the hydrologic conditions supporting common plant species, I calculated the mean weekly water table depth for all species comprising ≥ 20% cover at four or more wells. This included *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* were all found in peatlands, had similar hydrologic niches, and were combined for analysis.

### 3.3.2 Soil seed bank study

Soil seed banks were investigated to assess a wetland's ability to revegetate if higher water levels return. Although some wetland plants reproduce asexually through rhizomes, many species produce persistent seed banks that stay viable for decades. The soil seed bank was analyzed at 12 wetlands that represented a variety of Northern Range environments. Soil samples were collected along two transects beginning at either the middle of the wetland basin or approximately 40 cm below surface water in deep wetlands. Transects extended to the surrounding upland vegetation. Each transect included five to seven plots spaced at 30 to 60 cm elevation intervals, corresponding to the vertical relief between wetland bottom and upland. A 25 x 25 x 5 cm thick soil block was collected from each plot at the ground surface, air dried, and sieved to remove roots and rhizomes. Each sample was spread onto sterile Pro-Mix BX soil in a Colorado State University greenhouse and analyzed using the seedling emergence method (Roberts, 1981). Soils were subjected to waterlogged conditions, which have been shown to be superior to ponding for eliciting germination of wetland species (Boedeltje et al., 2002). Vega and Sierra (1970) found that 83% of seedlings emerging in three years germinated in the first year. For this study all plants identifiable within 14 months were included.

For statistical analysis, plots on each transect were assigned a value from 0 to 1, representing their proportional elevation from the wetland's interior to the surrounding upland. This method produced a relatively even distribution of a given wetland's plots among elevation classes, and it preserved the role of scale in variously-sized watersheds. All 140 plots were stratified into seven elevation classes that were analyzed using Kruskal-Wallis and Mann-Whitney U tests with the program SAS (2010).

## 3.4 TRUMPETER LAKE FOCAL SITE

### 3.4.1 Surveying and aerial photograph analysis

Because of its ecological significance and importance to the public, Trumpeter Lake was chosen as a focal site. A lichen trimline on glacial erratics around the lake indicates that lake stage was higher in the recent past (Marsh and Timoney, 2005; Hale, 1974). In northern Alberta, Marsh and Timoney (2005) showed that trimlines can persist 33-65 years. The declined lake water level has triggered soil erosion and habitat alteration detrimental to trumpeter swans and other native species. I used a total station to survey the zone between the water's edge and the maximum possible Trumpeter Lake stage. An existing bathymetric dataset was used to estimate land surface's elevation under surface water (Jones et al., 1978). Data were imported to ArcMap 10.0 where a triangulated irregular network (TIN) surface was created. Surface water polygons were derived from each of the eight air photos and superimposed on the TIN to determine lake stage in each photo. The topographic survey allowed me to analyze lake volume in addition to area (Hayashi and van der Kamp, 2000). To minimize seasonality bias, I analyzed lake sizes on a common day of year by calculating changes in lake stage between the photo date and August 15. To do this I subtracted the measured precipitation from evaporative loss, which was estimated using historic monthly (Pochop et al., 1985) and annual (WCA, 2008) pan evaporation measurements. This value was added to lake stage if the photo was taken before August 15, or subtracted from photo stage if taken after August 15. The calculated stage superimposed on the TIN produced lake sizes for a common day of the year. 2010 lake size was measured in the field.

To investigate the time scale on which Trumpeter Lake functions, regression analysis was used to compare lake area and volume to precipitation totals over the previous 1, 2, …, 10 years.

**3.4.2 Aquifer flow paths**

The time lag between precipitation input and subsequent water level changes in the wetland basin is influenced by aquifer saturated hydraulic conductivity ($K_s$). Two methods were used to calculate $K_s$, the Hvorslev slug test (Fetter, 1994) measured water's return rate in groundwater monitoring wells in the Trumpeter Lake watershed. A double-ring infiltrometer (ASTM, 2003) was used to calculate $K_s$ at the ground surface and at 50 cm depth on lake-margin and upland till environments. Water samples taken in the Trumpeter Lake watershed were analyzed for $Ca^{2+}/Na^{+}$ ratios. Differences in this ratio reflect different flow paths.

**4. <u>RESULTS</u>**

**4.1 WETLAND HYDROLOGIC REGIMES**

**4.1.1 Wetland hydrology**

Northern Range wetlands exhibited several indicators of surface water decline. At three sites, OR, LT, and TL, eroded former shorelines occurred > 200 cm in elevation above the 2009-2010 maximum surface water level (see Table 1 for wetland acronyms). Lichen trimlines, created when surface water drowned established lichen colonies (Marsh and Timoney, 2005; Hale, 1974), occurred on rocks surrounding wetland basins at BM (95 cm above maximum measured water), CR (105 cm), LT (230 cm), and TL (250 cm). These rocks had little or no visible lichen colonization below the trimline, suggesting that the high water period occurred within the past few decades (Timoney and Marsh, 2004). A third indication of former water depth was the location of dead stands of bulrush, an emergent marsh species. These slowly decaying plants occurred on highly organic soils 20-30 cm thick and were 180, 185, and 200 cm above the study period's highest surface water at OR, LT, and TL.

During my 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 during 2010 than 2009 (Fig. 4). In 2009 all 24 study sites supported surface water in early summer and 15 retained it through mid-August, while in 2010, 22 sites had surface water in early summer and 9 did in mid-August. Water table variance during the summer differed by site. Wetlands DW and RL had persistent inflow and outflow, and surface water levels varied < 3 cm during both summers. In contrast, surface water level in BD, BG, and CP averaged 111-119 cm higher in 2009 than 2010.

Groundwater level patterns resembled those of surface water levels for most wetlands (Fig. 4d). Each summer's most intense two-week rain period, 29 mm in 2009 and 52 mm in 2010, triggered groundwater rises (Fig. 3, Fig. 4c). In some sites groundwater levels varied more than surface water (e.g. TL, BW), while at other sites the opposite occurred (e.g. BD, SV). 19 wetlands most frequently experienced groundwater inflow from one side and outflow to the opposite side, and thus were considered flow-through systems (Dingman, 2002). Hydraulic gradient reversals, where the relative elevations of groundwater and surface water reverse, were documented at seven sites (Fig. 5e). Following the periods of heaviest rain (e.g., the first two weeks of June 2010), LT and other wetlands switched from flow-through wetlands to having groundwater inflow on all sides (Fig. 4a). Wetlands MC, BP, and WA were perched above the regional water table.

Piezometric head data revealed that vertical gradients were small and groundwater flows were predominantly horizontal. Only 17 of 217 piezometers had significant upward gradients, characterized by a hydraulic head ≥ 5 cm from water table elevation. A spring supporting DW had 22-23 cm of positive gradient, and one supporting TF and TL had 25-48 cm of positive gradient. 12 of 17 piezometers with positive gradients took longer than one week (median 10 weeks) to equilibrate following installation, suggesting they had low $K_s$ and produced little upward flow into the wetland. Seven piezometers consistently had more than 5 cm of negative gradient, indicating that downward flow is uncommon. The three perched sites all had at least one deep piezometer that never contained water even when surface water was present, revealing an unsaturated zone below surface water.

Wetlands containing surface water outflow at any time during the study period were distinct from closed basins. These wetlands typically had inflowing groundwater, and their surface outlets maintained relatively stable maximum water levels. They had similar early summer water table levels in both study years. Five of the seven wetlands with outlets had peat soils and are fens (Lemly and Cooper, 2011), and the other two are a large and deep lake (RL) and a perched site (MC) that was often dry. Wetlands with outlets had less water table response to early summer rains (mean 2 cm) than closed-basins (13 cm; $t = 2.87$, $p = 0.005$, Fig. 4c&d). Sites with outlets responded to rain events in late summer only if surface outflow had ceased (Fig. 4d).

The Trumpeter Lake wetland is a flow-through hydrologic system, with groundwater inputs from the south and southeast (Fig. 5, Fig. 6). $Na^{+}/Ca^{2+}$ ratios from groundwater samples indicated that two separate aquifers contribute to water tables in the watershed. A spring from the bedrock aquifer had $Na^{+}/Ca^{2+}$ ratios around 13, while ratios from the surficial till aquifer springs were around three. Trumpeter Lake stage declined by 23 cm in 2009 and 45 cm in 2010. Seasonal water table maxima occurred in early June in both years. By late summer 2010, surface water was higher than groundwater on all sides of the lake and recharged groundwater on all fronts (Fig. 6d). 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 (Appendix D). The double-ring infiltrometer yielded $K_s$ values roughly an order of magnitude higher than the slug tests, commensurate to the findings in till by van der Kamp and Hayashi (2009). These low conductivity values indicate that it can take years between water's arrival in the watershed and its interaction with the lake.

### 4.1.2 Wetland Classification

Seven wetland classes were identified from water table variation patterns. Description of these classes follows:

*Stable surface water ,"stable"*: DW, RL. Basins maintaining surface water within 3 cm of constant due to consistent inflow and outflow. Dense emergent vegetation bordered the surface water. Aerial photograph analysis indicated that wetland area has remained stable for decades.

*Perched water tables, "perched"*: BP, MC, WA. Wetlands with perched water. Water levels steadily declined before disappearing. Some piezometers never contained water even though a nested monitoring well did, indicating the piezometer was completed in or below a confining layer.

*Seasonally and yearly variable water tables, "seasonal"*: BD, BG, BM, BW, CP, CR, SV. Wetlands with large water table decline during and between summers. 2010 water levels averaged 75 cm lower than in 2009, more than double the between-year decline of any other class. Winter snowpack created flow-through or recharge basins, and pronounced water table rises following rain events indicated a close connection between precipitation and water tables.

*Peat soils with recovering water tables, "P.R."*: DC, RP, SN. Fens supported by groundwater discharge with water levels declining in late summer and recovering during the winter.

Recovering is defined by water tables increasing between study summers due to recharge processes. 2009 water level declines occurred later in the summer and were smaller than in 2010. All sites had surface water outlets that limited the water table's response to early summer rain.

*Mineral soils with recovering water tables, "M.R."*: MB, US. These mineral soil basin wetlands had the largest water table declines, approximately 100 cm each summer. Water tables recovered during the 2009-2010 winter.

*Interannually variable water table persistence, "I.V. "*: BE, IP, OR, SG, TF. Water tables declined minimally in 2009 but much more in 2010. Sites included those with and without outlets and having mineral and organic soils. Water table variation was relatively small and unresponsive to precipitation events.

*Spatially variable water table patterns, "S.V."*: TL, LT. Wetlands containing wells from at least three of the well types described above. Water tables in different areas of these wetlands varied distinctly, indicating that a combination of hydrologic patterns converge and create spatial complexity.

Wetland class assignment was influenced by the interaction between each wetland and its surrounding environment. Wetland class was correlated with the highly linked variables of surface water outflow ($x^2 = 16.03$, $p = 0.01$) and peat soil ($x^2 = 15.77$, $p = 0.02$), variables that were indicative of wetlands in classes P.R. and I.V. Surface water outlets constrained maximum wetland water levels, dampened water table changes, and supported peat formation. The most parsimonious classification tree in CART analysis contained only one split, divided at peat presence or absence, a variable 92.5% correlated with surface water outflow. The overall CART misclassification rate was 12.5%, compared to the majority misclassification rate of 29.2%.

Therefore, the model reduced misclassification by 16.7%. Basin size differed among wetland classes ($F = 3.5$, $p = 0.02$) and appeared to be driven by the largest two wetlands being both members of the S.V. class. Presence of a clay layer beneath the wetland basin ($x^2 = 14.1$, $p = 0.03$, Table 2) was most prominent in the perched class.

### 4.1.3 Wetland size through time

Aerial photographs from eight years for the period 1954 to 2009 indicated that surface water extent has varied up to 400% at study sites. Wetland areas were greatest in 1969 and 1998. 1969 followed the wettest decade preceding any air photo, and 1998 followed the two highest runoff years of record for the Yellowstone River. Wetlands with inlets and outlets (DW and RL) maintained constant area during the photo study period. Other sites varied substantially, with 10 of 14 wetlands completely lacking surface water in some years.

Surface area at BD, IP and CR was correlated with total precipitation over the two years prior to the photo date, while LT, TL, BM, and CP were correlated with precipitation over the previous eight years (Table 3). The remaining seven wetlands were not clearly correlated with precipitation patterns. Wetland surface area was more strongly correlated with total annual precipitation than with snowfall alone ($t = 2.70$, $p = 0.007$).

Trumpeter Lake's August 15 area peaked at 12.8 ha in 1969 and declined to 3.0 and 3.5 ha in 2006 and 2010 (Appendix E). A topographic survey revealed that Trumpeter Lake's volume was highly correlated with its area by a power function ($R^2 = 0.999$, Fig. 7). Lake volume was more highly correlated with precipitation over the previous 5-10 years than the previous 1-4 years alone (Table 4), suggesting that groundwater accumulated over several years sustains the lake.

For the 16 wetlands with an identified relict hydric soil, this soil's upper boundary differed significantly among wetland classes compared to the current surface water level ($F = 3.29$, $P = 0.04$). This finding provides a longer-term perspective supporting the wetland classification, which was developed from two summers of hydrologic data. Hydric soil boundaries at wetlands with an outlet were more similar to the 2009-10 water levels ($n = 7$, mean = 31 cm ± 4 cm SE above 2009-10 mean peak) compared to closed-basin sites ($n = 9$, mean = 128 ± 24 cm SE, Student's t-test, $t = 3.31$, $p = 0.005$). The presence of hydric soils in locations beyond the surface water elevations measured during field study provided evidence suggesting that wetlands occupied greater areas in the past.

## 4.2 CLIMATE

### 4.2.1 Trends in Yellowstone River discharge

The 5-year mean discharge of the Yellowstone River was positively correlated with wetland area over time ($R = 0.89$; Fig. 8a), suggesting that the river's discharge record from 1911-2010 may be a good proxy for wetland area. Cluster analyses of annual Yellowstone River discharge data produced three magnitude and four shape classes, the latter corresponding to annual runoff peaks occurring in May, June-May, June, and June-July (Fig. 9). In the 26 years since 1984 there have been no late peak and 10 early peak years, compared to their relatively equal distribution of runoff timing in the decades prior to the 1980s (Fig. 10). The ratio of May (early) to June-July (late) peaks in the last three decades is unprecedented in the discharge record. Prior to 1984 the mean annual discharge peak occurred on June 11, but from 1985-2010 it occurred on May 30 (t-test, $t = 4.67$, $p < 0.001$). The decade most similar to the early peak-dominated 1990s and 2000s was the drought period of the 1930s. This decade was followed by the 1940s, which had the most late peak years on record. 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 pre- and post-1984 (Student's t-test, $t = 0.38$, $p = 0.70$).

### 4.2.2 Long-term climate trends

For the last 100 years, relative highs and lows in Yellowstone River discharge and PDSI have co-occurred (Fig. 8). Since 1970 river discharge has oscillated around the mean of the past century, while increased temperatures have produced consistently lower PDSI values. Although PDSI trends suggest that the past four decades have been drier than most of the last century, tree ring data indicate that conditions at least as dry as the past 40 years have occurred in YNP several times in the past 800 years, for example *circa* 1250, 1500, 1700, and 1800 AD (Fig. 8d; Gray et al., 2007). The relatively dry second half of the 20$^{th}$ century was preceded by the most prolonged wet period of the past 800 years, lasting approximately 80 years from the late 19$^{th}$ through the early 20$^{th}$ centuries (Gray et al., 2007). This wet period may have resulted in the expansion of Northern Range wetlands to their largest extent in the past several centuries.

## 4.3 VEGETATION

### 4.3.1 Vegetation-hydrology relationship

The nine most common plant species in study wetlands occupied distinct hydrologic regimes (Fig. 11). *Carex aquatilis* and *C. utriculata* occurred in locations with the highest water tables in both years, having surface water throughout the first half of each summer. *Carex pellita*, *Schoenoplectus acutus*, and *Salix* spp. were also found in wet locations with water tables near the soil surface through mid-June in 2009. In 2010 their water tables were 10-20 cm below ground in early summer and dropped to approximately 75 cm in late summer. *Eleocharis palustris* occurred in locations that were saturated in early 2009, but the water tables dropped substantially in both years. *Carex atherodes* experienced similarly large summer variation as *E. palustris*. It occupied sites with mean 2009 and 2010 water tables differing by 60 cm. *Phleum pratense* and *Poa pratensis* occupied the driest locations. The mean water level at sites supporting *Poa pratensis* was 42 cm lower in 2010 compared to 2009, while *Phleum pratense's* was 23 cm lower. *Poa pratensis* inhabited zones of fluctuating hydrologic conditions, while *Phleum pratense* inhabited more consistently dry sites.

*Carex*-dominated wetlands, excluding fens, had outlets within 1 m of measured surface water maxima. In contrast, bulrush-dominated sites lacked outlets within 1 m (*non-significant*, p = 0.12). During large water periods bulrush sites can support much deeper water levels than those dominated by *Carex*. Bulrush sites had less water table difference between study years indicating that wetlands supporting this species may have greater year-to-year stability. Aerial photos, hydric soils, and outlet elevations all suggest that bulrush tolerates larger decadal water level changes compared to *Carex*. *Carex*-wetlands were often members of the seasonal wetland class.

This study identified two wetland plants not previously recorded in YNP. *Scirpus nevadensis* S. Watson was found at wetlands LT and IP, and *Alopecurus geniculatus* L. was found at WA.

#### 4.3.2 Soil seed bank study

46 plant species germinated from soils collected at the wetland study sites. Six species were obligate wetland species (OBL) and nine were facultative wetland species (FACW; Appendix F). In a given plot, some species were represented by one germinant, while others had hundreds of germinants. The relative elevation-based classification produced a marginally significant unimodal curve for the distribution of OBL and FACW wetland species (Kruskal-Wallis

test, chi-square = 11.76, df = 6, p = 0.07). Significantly more wetland species germinated just above the midpoint of the wetland bottom and upland boundary compared to the lowest three and highest classes (Mann Whitney U test, z = 2.00-2.88, p = 0.01-0.05; Fig. 12).

## 5. DISCUSSION

Multiple lines of investigation helped identify the patterns and processes driving wetland losses on YNP's Northern Range. Wetland area and water level is clearly linked to weather and climate patterns, and the wetland sizes measured in this study have likely occurred multiple times during the past millennium. The first decades after YNP's designation as a national park coincide with the most prolonged wet period of the past 800 years, which may have produced unusually large wetlands. YNP's climate has also warmed and dried during the last century, and continued warming could surpass the natural range of variation that occurred within the tree ring record and could lead to unprecedentedly small wetland areas. Wetlands serve a valuable role in maintaining ecosystem integrity in YNP, which is one of the last places in the conterminous United States where natural ecosystem processes dominate. Declines in YNP's native species have been linked to wetland reduction (McMenamin et al., 2008; Proffitt et al., 2010) and continued drying will endanger additional species and cause further environmental changes, such as shifting fens from carbon sinks to carbon sources (Chimner and Cooper, 2003).

Each study wetland's local watershed controlled its hydrologic regime. This is distinct from the influence of the broader regional hydrologic patterns identified in other wetland settings (Florin et al., 1993; Merkey, 2006; Fig. 1). Wetland areas vary with climate, including those in YNP, the prairie potholes (Johnson et al. 2004, Niemuth et al. 2010), southern Alaska (Klein et al. 2005), and Siberia (Smith et al. 2005). Similar to wetlands in Argentina's Monte Desert (Jobbágy et al., 2011) and Nebraska's Sandhills (Winter, 1986), groundwater sustained many YNP study wetlands. A few wetlands lacked groundwater contributions, similar to playas of the southern American Great Plains (Smith, 2003) and vernal pools in California (Keeley and Zedler, 1998). Two study wetlands have apparently maintained stable water levels for decades, while others have varied substantially. Rarely do wetlands in such close proximity function as differently as has been documented here. The various hydrologic regimes of Northern Range wetlands influence local ecosystem processes including soil microbial environments and lichen, vascular plant, and animal communities.

## 5.1 HYDROLOGICALLY-BASED WETLAND CLASSIFICATION

Classification was a practical tool for creating a conceptual framework to compare Northern Range wetland hydrologic regimes. Study wetlands differed to a degree approaching the national-scale variability documented in classifications from the United States (Brinson et al., 1993; Cowardin et al., 1979), Spain (Florin et al., 1993) and Amazonia (Junk et al., 2011). The shape-magnitude framework incorporated the important roles of timing and degree of water table changes to identify seven wetland hydrologic classes. Hydric soils analysis substantiated the wetland classification by showing that the identified classes have functioned distinctly for decades. Wetlands from the seasonal class provide habitat for species adapted to changing surface water abundance, such as *Carex atherodes, Carex utriculata* and YNP’s four native amphibians. The S.V. wetland class included large wetlands with multiple water sources. Consistent saturation has allowed P.R. wetlands to accumulate organic matter and create peat soils. Three of the five wetlands in the I.V. class were peatlands with groundwater inputs that persisted for longer than those in the P.R. class. The two other I.V. sites were both closed basins with mineral soil, but they differed from the M.R. and seasonal classes by having more persistent groundwater inputs. Wetlands in the stable class were uncommon across the

Northern Range but may serve as isolated habitat refuges for wetland-dependent flora and fauna during exceptionally dry times.

### 5.2 HYDROLOGIC PROCESSES CONTROLLING YELLOWSTONE'S WETLANDS

Inputs to wetland water budgets consisted of surface water, groundwater, and precipitation. Rain produced a relatively rapid response in wetland sizes, while snow slowly recharged aquifers and wetted soils to initiate the growing season. The groundwater discharge supporting 21 of 24 study sites stabilized water tables, presumably producing longer growing seasons and increasing vegetative production (Rains, 2011; Cook and Hauer, 2007; Hunt et al., 1999). Groundwater flow paths were not fully characterized because land surface watersheds can differ from groundwater watersheds (Devito et al., 2005) and multiple wetlands shared nested watersheds in the study area's poorly developed land surface drainages.

Watershed characteristics including topography, lithology, and infiltration capacity strongly influence hydrologic processes in wetlands (Florin et al., 1993) and vary on small scales in the Northern Range. Peat soil and the presence of a surface water outlet were the two environmental variables most closely correlated with wetland class in this study. Surface outlets limited maximum water level and increased hydrological and ecological stability. The resulting near-surface water table promoted high plant production, low decomposition rates, and peat formation. Merkey (2006) incorporated outlet presence into a wetland classification for Michigan, finding that sites with both inlets and outlets exhibited unchanging water tables, as occurred in my stable wetland class. At study wetlands DC and SG, surface water inflow and outflow existed seasonally, but limited inputs caused water tables to decline by late summer.

### 5.3 HYDROLOGIC CONTROLS OF WETLAND VEGETATION

The distribution of common wetland plants indicated both past and present hydrologic regimes. Robust bulrush stands were found only where relatively stable standing water levels occurred in both study years. Decomposing dead bulrush stands with thick organic soil occur at three sites > 2 m above the highest measured surface water level. Two of these sites are classified into the S.V. wetland type and responded to the long-term patterns of precipitation. Bulrush appears to be a good indicator of wetland basins whose water levels change slowly, but that can change substantially in different climate periods.

Dominant wetland plant species occupied distinct zones of water depth and seasonal variation. Because each species occupied a distinct hydrologic niche, point measurements from monitoring wells in patches dominated by common species can be used to extrapolate hydrologic processes to other areas where the species are found. Plant community structure differs in areas of groundwater discharge and recharge (Cook and Hauer, 2007; Hunt et al., 1999; Humphries et al., 2011) and can indicate the spatial distribution of these hydrologic processes at a wetland. Wetland vegetation will change as the climate changes (Johnson et al., 2010; Poiani et al., 1996), therefore monitoring plant distribution at study sites may help identify the ecological effects of climate change. Plants germinating from the soil seed bank indicated that when higher water levels occur in the future, viable seed banks can promote rapid wetland vegetation adjustment.

**5.4 TRUMPETER LAKE WATERSHED DYNAMICS**

Lichen trimlines, relict bulrush stands, and an eroded shoreline reveal a 2.5 m surface water decline at Trumpeter Lake during the past few decades. Sediment cores have been used to show that water levels are highly variable and suggest that the lake has been dry at some point in 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). $K_s$ values in the Trumpeter Lake watershed were on the order of dm/d at the land surface and cm/d at 1-2 m depth, similar to values recorded in glacial till in the United Kingdom (Cuthbert et al., 2010) and the prairie pothole region (van der Kamp and Hayashi, 2009). Higher $K_s$ surface values may result from the abundance of near-surface macropores created by root channels and burrowing animals (Cuthbert et al., 2010; Todd et al., 2006). Near-surface $K_s$ values encompass only a fraction of the till's thickness (K. Pierce, *pers. comm*.), but the bulk of water movement is likely within this section due to decreasing $K_s$ with depth in till aquifers (van der Kamp and Hayashi, 2009). Groundwater discharging southeast of Trumpeter Lake may be emerging where a zone of thin till permits water expulsion from the underlying bedrock (Todd et al., 2006). However, chemical analysis of this water indicated that its origin is more likely from the surficial till aquifer. A model of the lake's water budget would help to analyze lake volume variations, but a robust model calls for greater resolution of aquifer thickness, $K_s$ variability, and watershed ET.

The highest recorded population of Northern Range bison (Wallen, 2010) appears to be having destructive effects on the Trumpeter Lake area vegetation and soil, likely driving vegetation changes, denuding and eroding the land surface, and altering water infiltration. Bison hooves sink > 30 cm into lake edge soil, promoting erosion. Rocks located between the former and current lake perimeters have rust-colored stains on their bases, suggesting they were recently beneath the soil surface and have been exposed by erosion. In addition, dead bulrush 2.0 m above the modern lake surface occurs in isolated clumps 20 cm above the surrounding ground surface. All contemporary bulrush stands are comprised of homogenous clones that cover the ground in dense continuous carpets, not clumps, indicating that a strong root system and slow decomposition have prevented soil erosion at the dead bulrush locations. Additionally, vegetation colonizing the zone between former and current Trumpeter Lake perimeters consists of low-diversity stands of invasive *Hordeum jubutum*, *Cirsium arvense*, and *Argentina anserina*.

### 5.5 WEATHER, CLIMATE, AND WETLAND AREA CHANGES THROUGH TIME

Evidence on the Northern Range indicates that wetland water levels have declined, but the processes of drying have varied by wetland. Seasonal wetlands had the greatest stage changes during 2009-2010 and responded to early summer rains with >50 cm water table increases. In contrast, wetlands in the stable, P.R., and I.V. classes exhibited little response to rain events. These sites either had surface water outlets or were closed basins that buffered response to individual precipitation inputs. Aerial photograph analysis indicated substantial variability in water abundance, suggesting that in the future air photos should be taken over broad spatiotemporal scales and at the same time each year (Niemuth et al., 2010). Some wetlands revealed undetectable connections to precipitation in aerial photograph analysis, even though it undoubtedly affects them. This could be due to the time scale on which a wetland's hydrologic regime functions being outside of the scale analyzed in aerial photos, or due to interacting landscape factors. For example, WA is a basin located at the base of a bedrock outcrop that may accumulate wind-blown snow (e.g., Rains, 2011).

Although watershed properties play an integral role in creating a wetland's hydrologic regime, it is likely that at larger time scales climate is more important (Laize and Hannah, 2010). Data from the past century support the idea that climate change is responsible for wetland loss. A warming trend has occurred in YNP, including exacerbated changes since the 1980s documented here and by others (McMenamin et al., 2008; Wilmers and Getz, 2005). Johnson et al. (2010) modeled climate change's effects on wetlands of variable permanence, finding that the less permanent sites (e.g. seasonal) are more resilient to climate change than more permanent ones (e.g., S.V. and P.R.). This was because of the latter's support from groundwater and increased evapotranspiration losses from surface water persisting through summer. Seasonal class wetlands can change from their maximum water extent to dry within 1-2 years, but their flora and fauna are adapted to this variability. However, it is likely that during the recent multi-decadal drying, P.R., S.V., and I.V. class wetlands have become drier as well. Under projected climate changes, the growing season's start and the timing of seasonal water table decline will occur earlier, leading to additional drying, organic matter decomposition, and wetland destabilization. Non-linear or threshold responses (Burkett et al. 2005) may limit fens' ability to sequester carbon. Climate data reveal that during the past 115 years YNP has warmed and dried, but tree ring data from Gray et al. (2007) through 1998 show that the recent dry spell has been surpassed multiple times in the past 800 years. Since 1998 the Northern Range has recorded a mean of 86% of historic annual precipitation, revealing further drying since this dataset was collected. However, it is unlikely that 12 moderately dry years have shifted the system to an unprecedented state. Gray et al. (2007) also document that the late 19$^{th}$ and early 20$^{th}$ centuries experienced the most prolonged wet cycle of the last 800 years. This suggests that efforts to revert Northern Range wetland abundance to the pre-climate change era may be a misguided attempt to reclaim an exceptionally wet "reference state".

Wetland changes have been poorly documented because of the multitude of wetlands on the landscape and the investment required to monitor even a single site. Lentic wetlands and lotic waterways, although inherently different, each are driven by groundwater regimes that are influenced by climate. This study suggests that Yellowstone River discharge data is a useful proxy for wetland surface water area on the Northern Range. Comparison in other regions should investigate the generality of this relationship. This study and others (McMenamin et al., 2008; Stewart et al., 2005) have shown Rocky Mountain river hydrographs shifting to earlier peaks, and Stewart et al. (2004) projected further advancement by 30-40 days throughout the West. This hydrologic shift would initiate major ecosystem changes in wetlands, where the water table position relative to the land surface is critically important to ecological processes.

## 6. CONCLUSIONS

Wetlands on Yellowstone's Northern Range have declined in area during the recent past, but the evidence suggests that current conditions are within the natural range of variation for the past 800 years. Furthermore, it is often assumed that when Westerners arrived, YNP's landscape was in a relatively pristine state of equilibrium. However, this was a period of water abundance. Weather patterns naturally oscillate 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, removing critical habitat for native species.

The research approach taken here has created a multifaceted perspective of YNP's recently dried wetlands. A combination of hydrology, soils, vegetation, and climate investigations were used to synthesize why, how, and to what degree wetland changes have occurred. Monitoring well data, aerial photographs, hydric soils, bulrush vegetation, and lichen trimlines all illuminated the patterns and magnitudes of wetland changes. The hydrologic wetland classification aided in creating an understanding of why these patterns have occurred. Wetlands in different classes are differentially vulnerable to forecasted climatic changes, and this should be considered in management. Wetlands from classes I.V., S.V., M.R., and P.R. were relatively resilient to the different 2009 and 2010 weather patterns, indicating that longer-term climatic processes more likely affect their water levels. If YNP climate continues to warm and dry, wetlands in these classes and their associated ecological functions (e.g. carbon sequestration, amphibian breeding, trumpeter swan nesting, etc.) will be vulnerable.

Preservation of landscape-scale ecological processes is a primary goal of the National Park Service, and wetland health serves a central role in this endeavor. Two years of data were collected in this study, but a thorough hydrologic study necessitates longer-term data collection and analysis. My analyses indicate that wetland conditions such as those in the S.V. class may be relatively common; however, decadal changes have affected our perception of the significance of their drying. Wetlands from the seasonal, P.R., and I.V. classes formed a continuum from low to high permanence. If these wetlands shift down a permanence class it could have dramatic ecosystem consequences, including loss of peatlands that formed over millennia.

Climate change was the primary candidate causing wetland change addressed here, but other factors should also be considered. YNP’s dynamic geology is a force underlying all surficial processes in the Northern Range, and unprecedentedly high bison populations affect wetlands by increasing the rate of soil erosion and vegetation change. Topsoil erosion should be monitored in the Little America area because losing this relatively fertile soil may further degrade these wetland ecosystems. Wetlands serve a critical role on the Northern Range landscape, and we should continue to monitor them to recognize if-and-when conditions surpass the ecosystem’s capacity to adjust.

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## 8. FIGURES AND TABLES

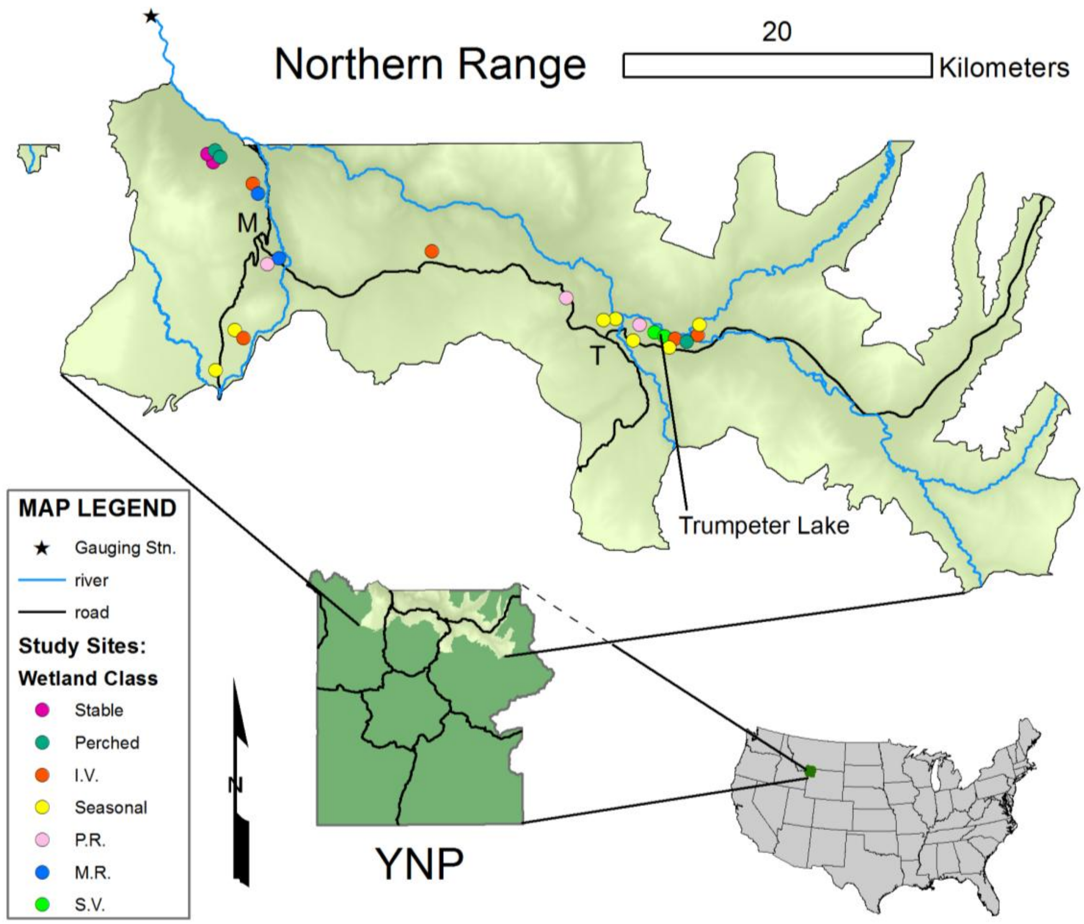



**Figure 1.** The Northern Range within Yellowstone National Park, Wyoming and Montana, USA. Study sites are represented by dots and colored according to their water table hydrograph classification. Mammoth and Tower weather stations are represented by M and T.

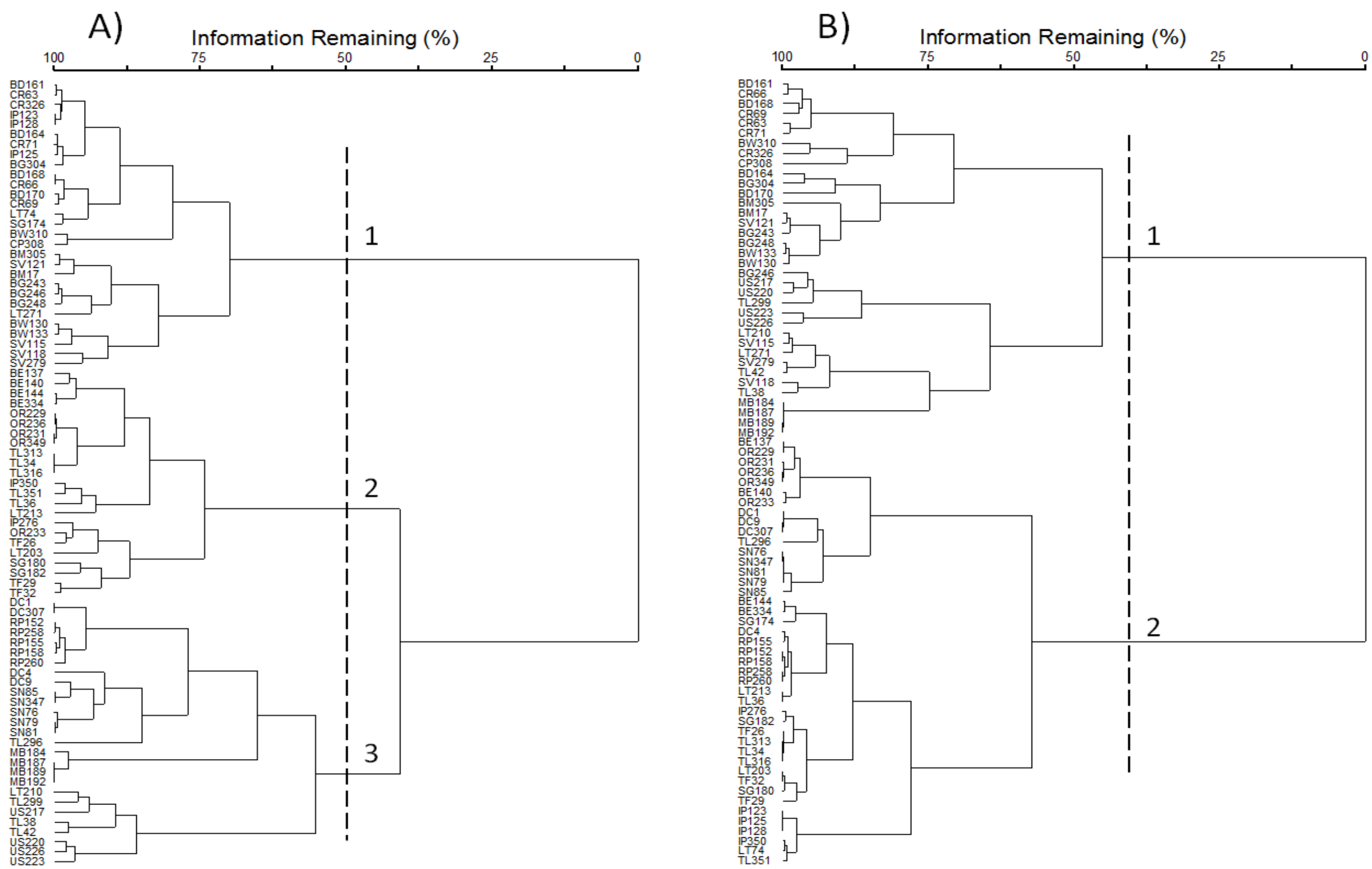



**Figure 2.** Cluster analysis results for the 80 wells analyzed using the shape-magnitude framework. A) dendrogram of hydrograph shape with pruning at 50% similarity which produced 3 classes. B) dendrogram of magnitude with pruning at 40% similarity which produced two classes. Note that the first two letters in well names are wetland IDs.

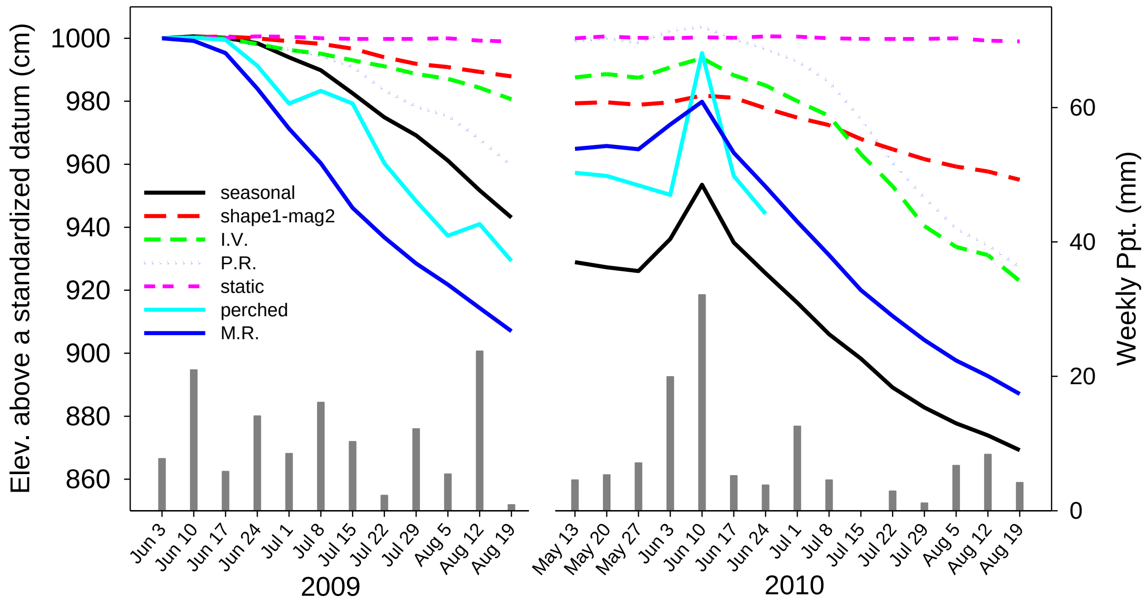
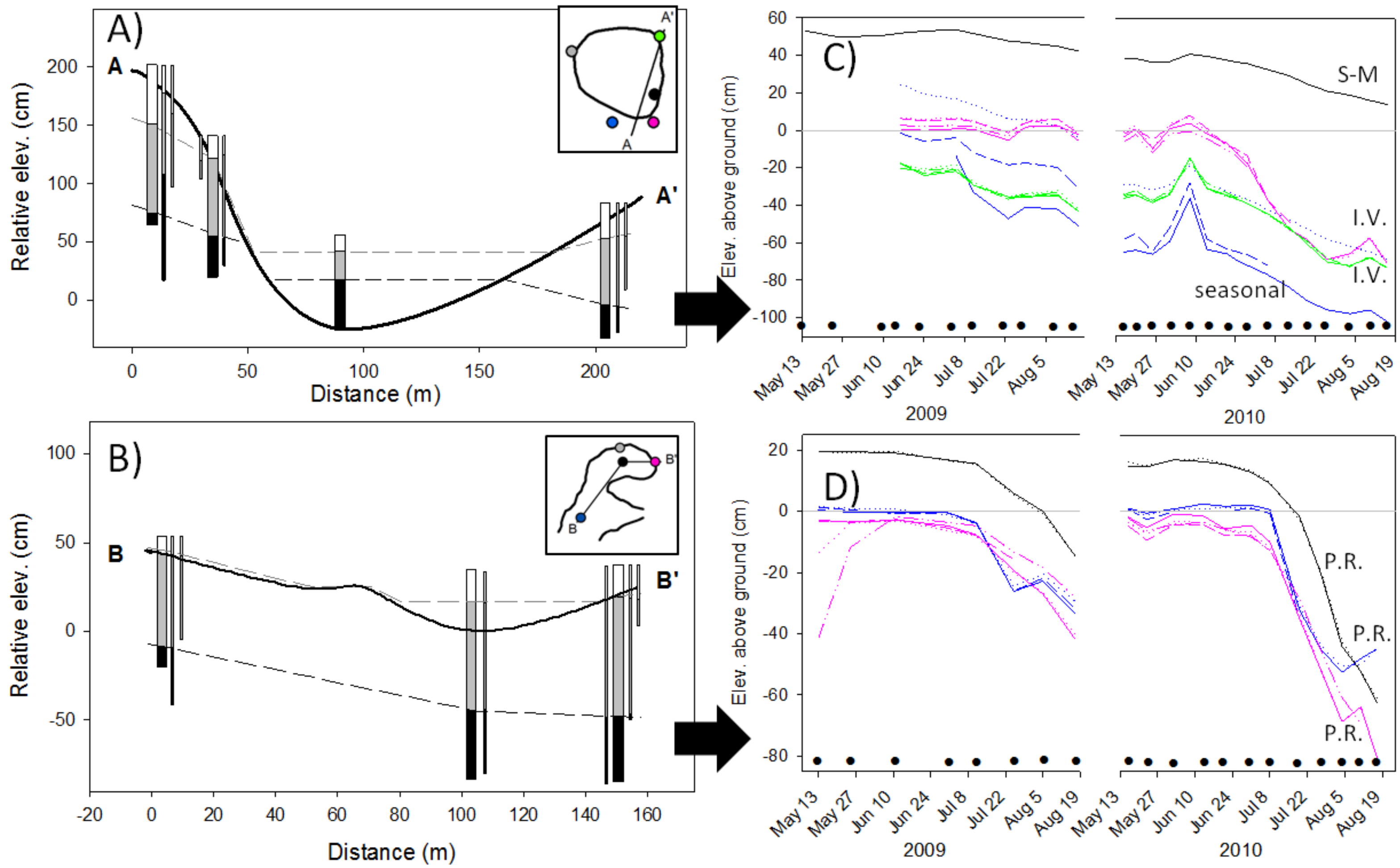



**Figure 3. Water table elevations** for the seven well classes during summers 2009 and 2010. Lines are average weekly water table values for all wells in each class, except for the perched class which depicts an example well that dried in June 2010. The S.V. wetland type described in the Results was comprised of at least three of these well types. Each of these well classes was developed into a unique wetland class except shape1-mag2, which was too uncommon (n = 6) to constitute its own class. Bars represent weekly precipitation.



A)
B)
C)
D)
Relative elev. (cm)
Distance (m)
Elev. above ground (cm)
A
A'
B
B'
S-M
I.V.
I.V.
seasonal
P.R.
P.R.
P.R.
2009
2010
May 13
May 27
Jun 10
Jun 24
Jul 8
Jul 22
Aug 5
Aug 19

**Figure 4.** Panes A & B show cross sections of wetlands LT and DC. Solid lines represent ground surface, and dashed lines are water table elevations on 10 June 2010 (grey) and 5 August 2010 (black). Water tables were interpolated from groundwater monitoring wells (thick bars). Piezometers (thin bars) nested with wells reveal vertical hydrologic gradients. Note that piezometers at left in pane A show an upward gradient, but all other piezometers show nominal vertical gradients. Bars indicate water level on 10 June (gray) and 5 August (black). Panes C and D are hydrographs showing water level in wells and piezometers from A and B 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 in panes A and B. 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: spiked in response to rain (blue in C and D), declined earlier in the drier 2010 (pink in C, all in D), had strong positive head (blue in C), had slowly-equilibrating piezometers that revealed a low hydraulic conductivity layer (pink dash-dot in D), and did not spike in response to early summer rain because of surface outflow (all in D).

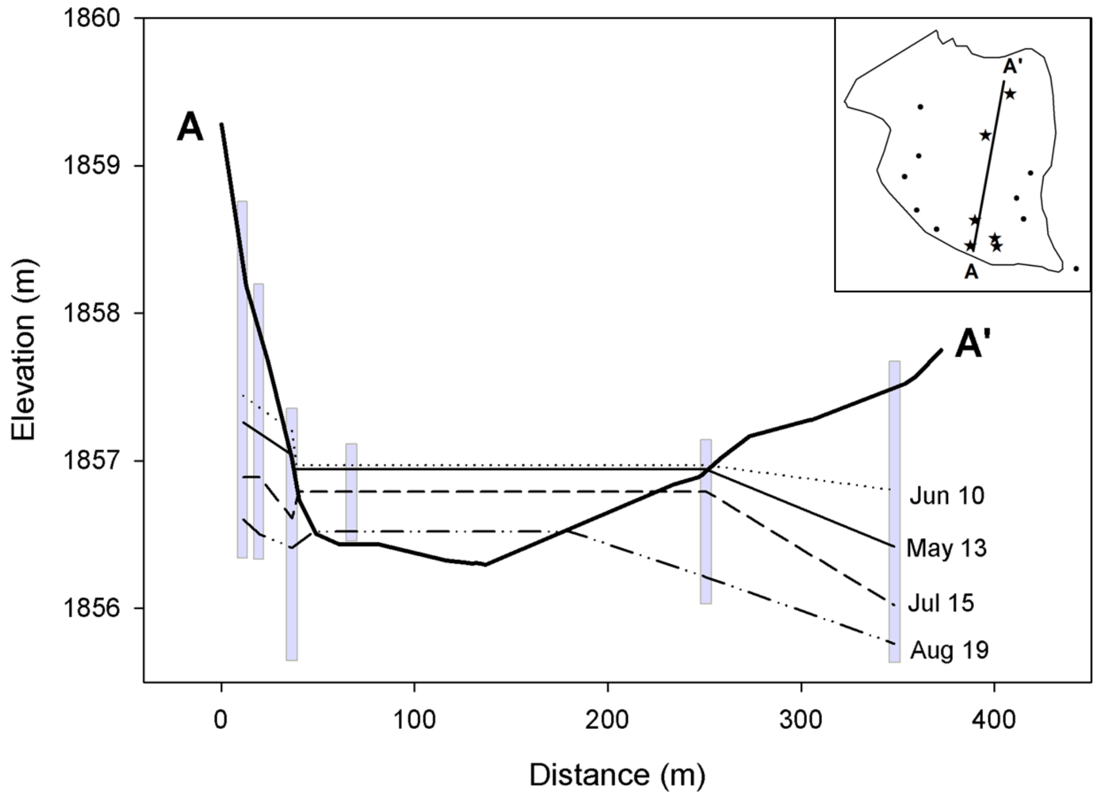



**Figure 5.** Cross section of Trumpeter Lake illustrating the water table on four dates in 2010. Ground surface, the thick line, was determined from a topographic survey. Grey bars represent monitoring wells, identified with stars on plan view inset showing all wells, which were used to interpolate water tables. Trumpeter Lake had groundwater inflow from the south in early summer, but by late summer a near-shore groundwater trough appeared. This indicates that the lake shifted from a groundwater flow-through system to groundwater recharge on all sides. Vertical exaggeration is 80:1.

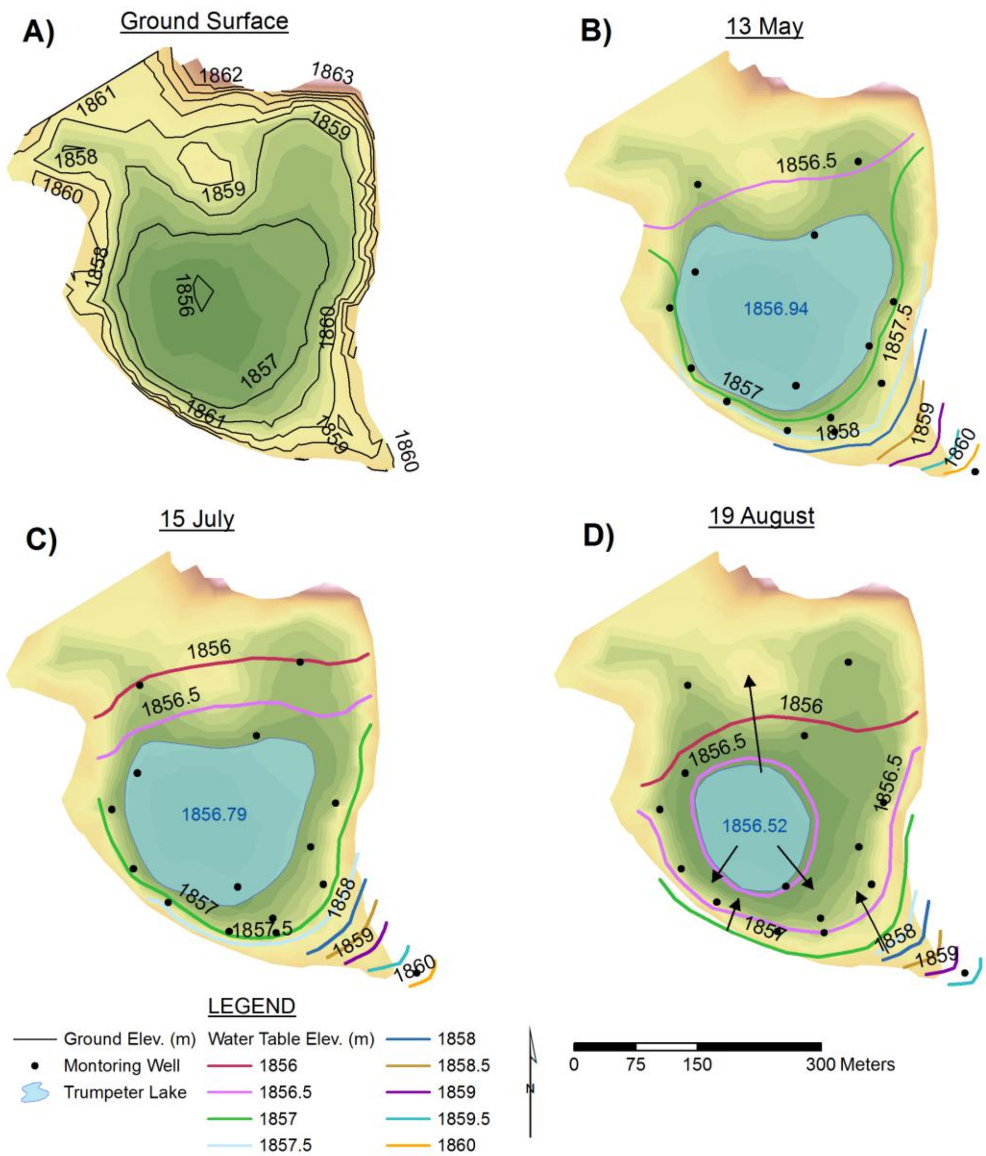



**Figure 6.** Trumpeter Lake water table contours (m.a.s.l.) for summer 2010, interpolated from 15 monitoring wells. Through 15 July this was a flow-through wetland, with the water table gradient from south to north. D) shows that in late summer surface water locally recharged groundwater (black arrows), even though the larger flow system was still flow-through. Water table elevation declined as the summer progressed beyond the early-June peak. Multiple groundwater interpolation methods were explored (e.g. IDW, kriging, spline), however, I manually delineated water table contours as this method is frequently more accurate (Bill Sanford, *pers. comm.*).

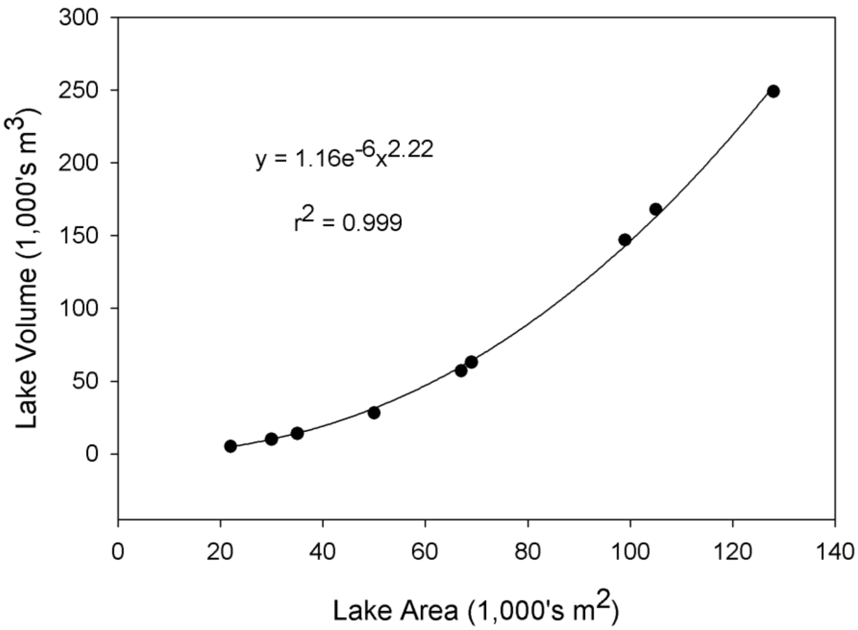



**Figure 7.** Surface area-volume relationship at Trumpeter Lake during nine years. Areas were derived from aerial photography (n = 8) and field data (n = 1). Corresponding volumes were calculated by overlaying the lake area on a TIN.

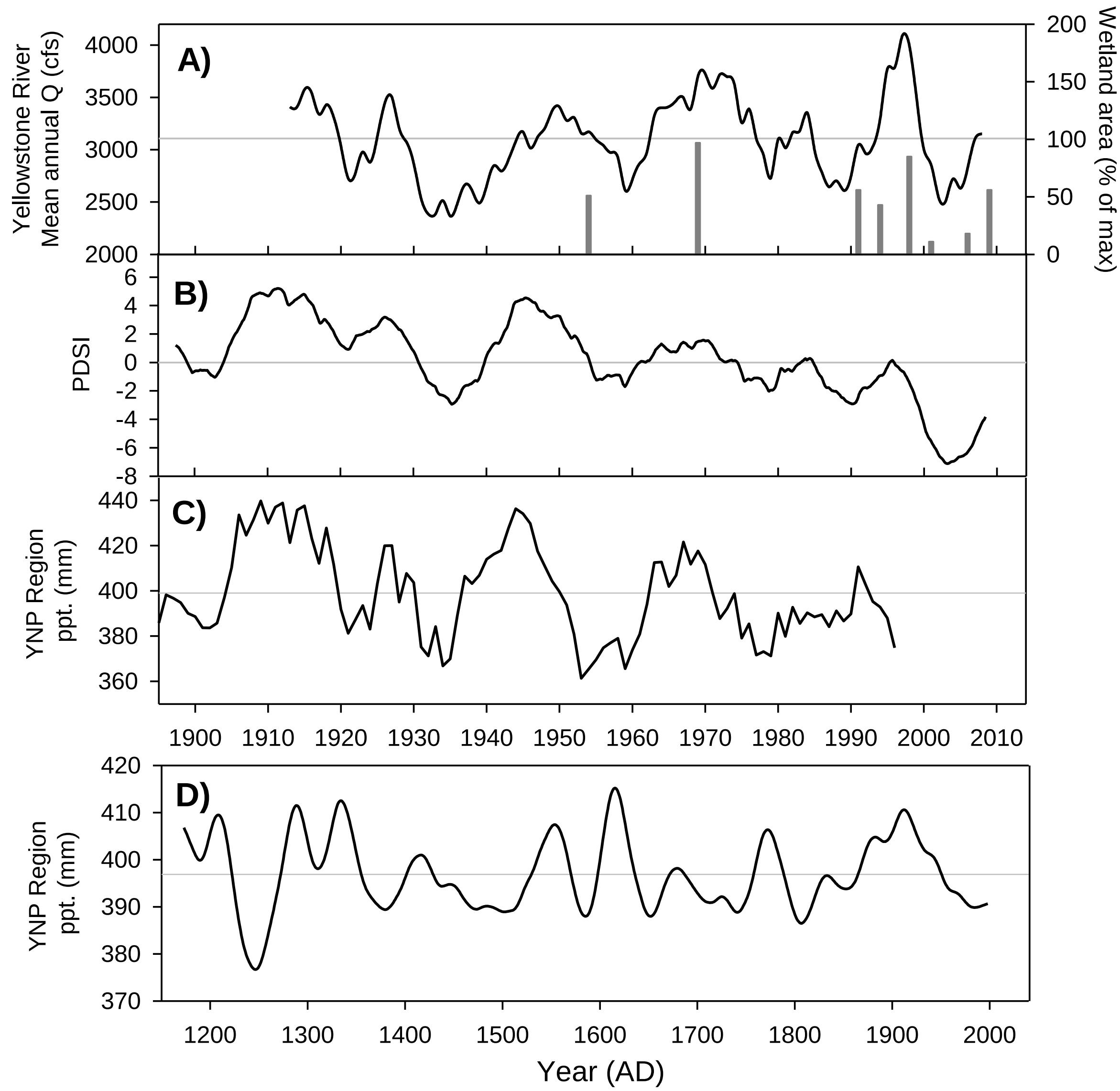



**Figure 8. Multiple climate indices for YNP.** A) Bars depict the across-wetland average % of maximum wetland surface area seen on air photos from a given year. Solid line is the 5-year running mean for annual discharge of the Yellowstone River at Corwin Springs. B) 5-year mean Palmer Drought Severity Index (PDSI) for the Yellowstone River drainage, Wyoming. C) 20th century 5-year mean tree-ring reconstructed precipitation for the YNP region (data from Gray et al. 2007)). D) Tree-ring reconstructed precipitation since 1173 AD, displayed as a 60-yr cubic smoothing spline (reproduced from Gray et al. 2007). Horizontal grey lines represent means

during the plotted period in A, C, and D, while in B it depicts the PDSI average by definition, 0. Note the unique x-axis for D.

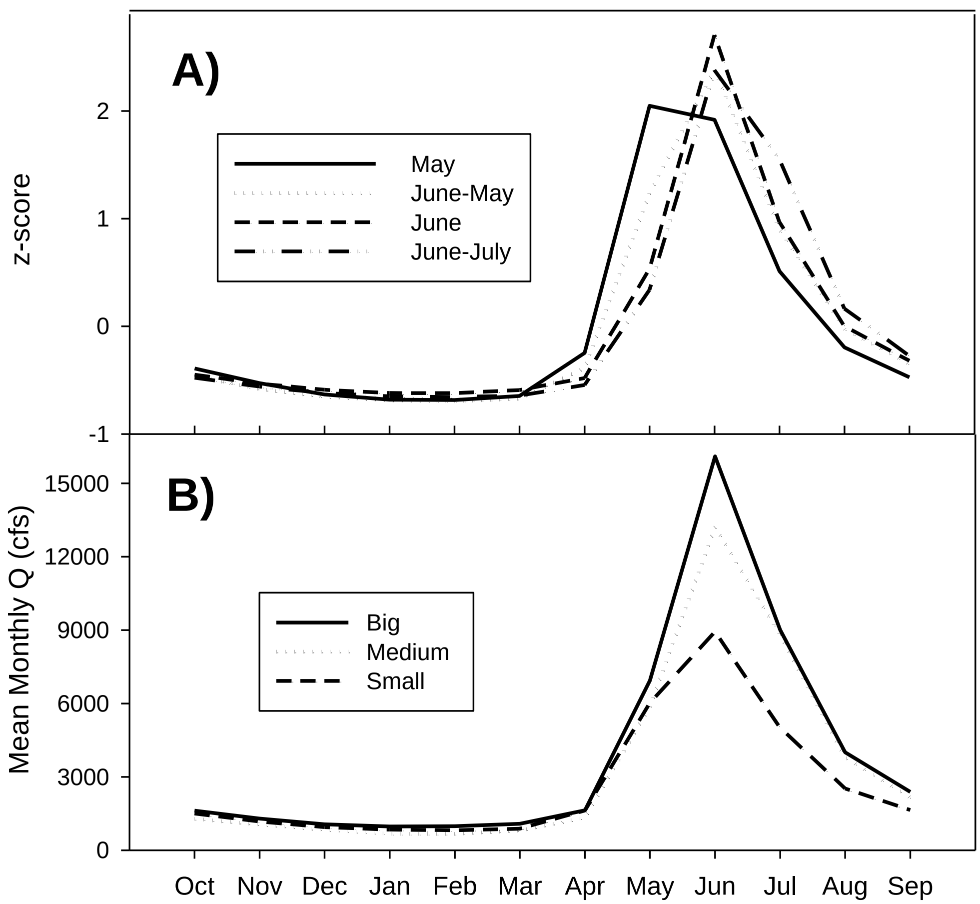



**Figure 9.** Yellowstone River discharge shape-magnitude analysis classes. A) Mean annual hydrograph of all wells constituting each of the four shape classes, termed according to their timing of maximum discharge. B) Mean annual hydrograph of the 3 magnitude classes, big, medium, and small.

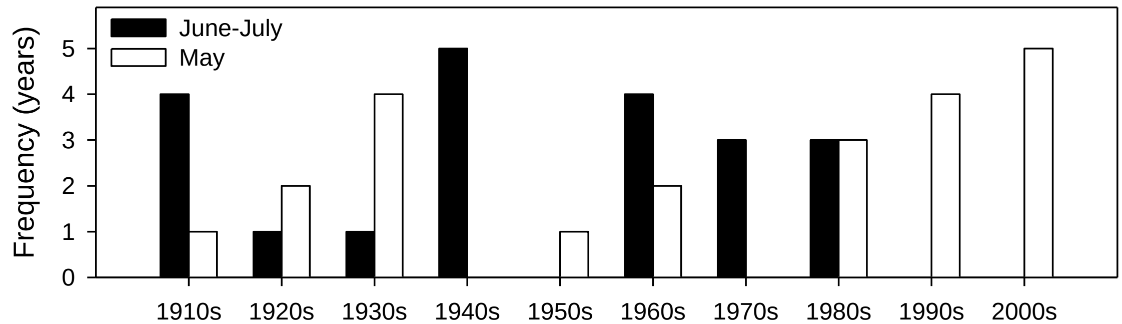



**Figure 10.** Chronology of the earliest and latest Yellowstone River runoff years, showing that early runoff has been unusually prevalent recently. Note: 1) Bars do not sum to 10 because the two middle classes were omitted for clarity; 2) The decade most closely resembling the 1990s and 2000s is the 1930s, the Dust Bowl years; 3) There is substantial inter-decadal fluctuation and no apparent 100-year trend. However, the 1970's forward reveals a "slingshot" from late to early peaks, presumably inciting wetland decline.

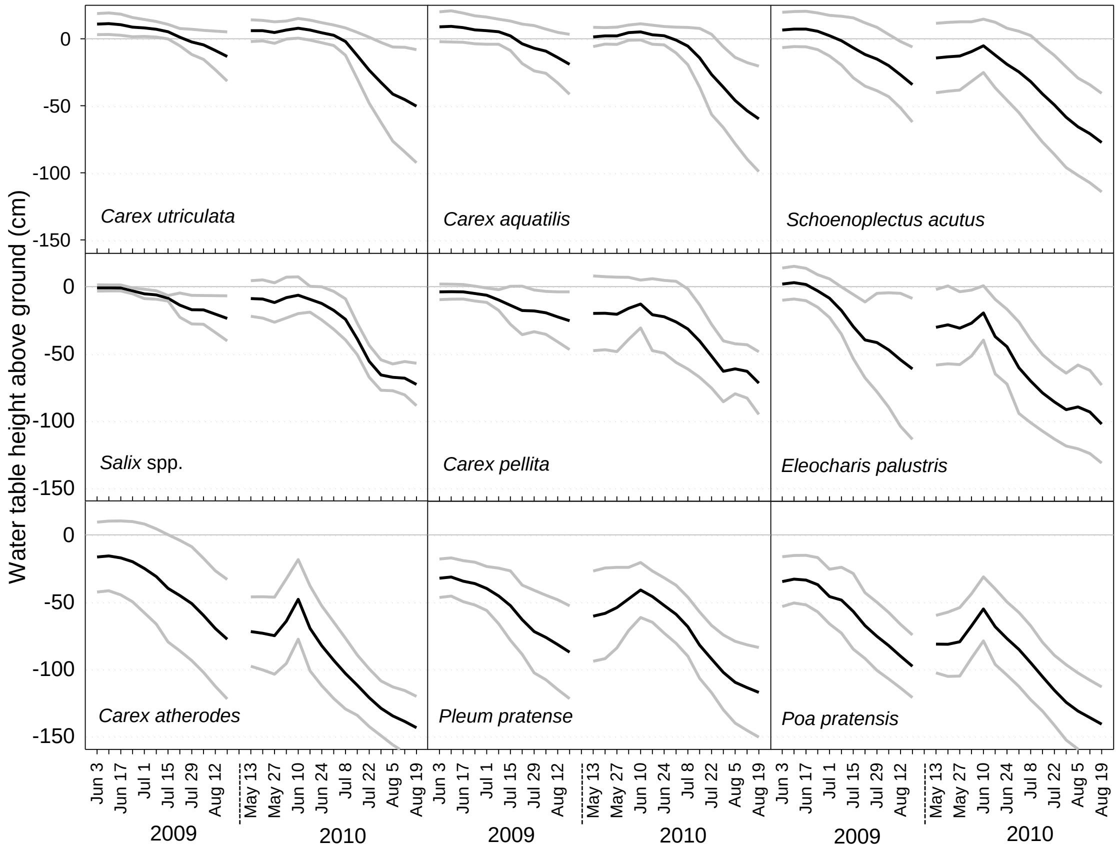



**Figure 11.** Water table hydrographs for the nine most prevalent plant species. Graphs illustrate species' water table means ± 1 standard deviation. Data are derived from averaging water tables for all wells with ≥ 20% cover of the identified species.

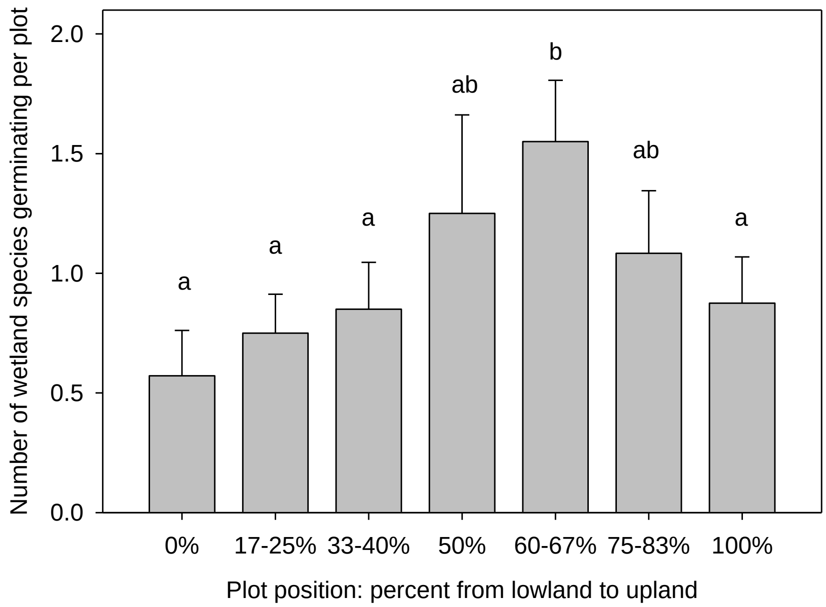



**Figure 12.** Mean number of wetland species ± se germinating per plot in the soil seed bank study. Bars represent the seven elevation classes, with the x-axis stratifying plots by their percent from wetland bottom to upland. Mann Whitney U tests revealed that plots in the 60-67% class germinated significantly more ($p < 0.05$) wetland plants than plots in the lowest three and highest elevation classes.

**Table 1.** The 24 Northern Range study sites.

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

**Table 2.** Relationship between environmental variables and wetland hydrograph classes. Chi-squared analysis was performed on categorical variables, and one-way ANOVA produced an F-stat for quantitative variables. Both tests produced comparable p-values (J. zumBrunnen, *pers. comm.*)

| Variable | Categ/Quant | $Chi^2$ | F-Stat | 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 |
| Pz. time to equilib. | Q | | 2.1 | 0.11 |
| Watershed Size | Q | | 1.92 | 0.14 |
| Highest pz. head | 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 |

**Table 3.** Relationship between wetland area and cumulative precipitation, determined from aerial photo analysis. Wetland area and precipitation from the 2, 4, and 8 years previous to photo date were compared via 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 | - | - |

**Table 4.** Relationship between total precipitation and Trumpeter Lake's area and volume for time steps of the last 1, 2, … 10 years. Data were derived from lake sizes in nine years.

| **Ppt. time step** | **Area $R^2$** | **Vol. $R^2$** |
|---|---|---|
| 1 Yr | 0.33 | 0.47 |
| 2 yr | 0.57 | 0.65 |
| 3 yr | 0.78 | 0.79 |
| 4 yr | 0.79 | 0.77 |
| 5 yr | 0.86 | 0.81 |
| 6 yr | 0.9 | 0.82 |
| 7 yr | 0.92 | 0.87 |
| 8 yr | 0.95 | 0.94 |
| 9 yr | 0.89 | 0.87 |
| 10 yr | 0.81 | 0.77 |

## 9. APPENDICES

**APPENDIX A.** Addendum to 2009-2010 Weather Report

### Methods

*Annual Summaries*: Weather data are publicly available since 1931 for two Northern Range weather stations within the study area, Mammoth and Tower (Fig. 1, NCDC 2011). Water year 2009 and 2010 values for temperature, total precipitation, and snow were calculated from summing (total precipitation and snow) or averaging (temperature) monthly values. 2009 and 2010 values were compared to mean values since 1931, the first year in which both Mammoth and Tower have continuous weather data. To calculate weather values, I used all months with published monthly data to determine monthly and annual averages. In the two months of 2009 (June and December) where Tower lacked data for both total precipitation and total snowfall, I used a linear regression record extension technique calculated from Mammoth data to estimate values.

*Field Season Precipitation*: I analyzed daily precipitation records for both Mammoth and Tower for May through August of 2009 and 2010. Additionally, on May 16 2010 I installed a HOBO tipping bucket rain gauge in the Trumpeter Lake watershed (UTM Zone 12N 549867 E, 4973438 N). This rain gauge was installed to get a better sense of a) rain inputs at our focal study site, and b) precipitation spatial variability.

### Results

*Annual Summaries*: Both study years were near average temperature, but 2009 was a wetter year and 2010 a drier year (Table B1). 2009 surpassed the post-1931 average by 0.2°C, while 2010 was 0.3°C cooler than average. Total precipitation in 2009 was 97% and snowfall was 120% of average, while in 2010 total precipitation was only 83% and snowfall 53% of average.

*Field Season Precipitation*: Precipitation is correlated between the Mammoth and Tower weather stations (Pearson's R correlation coefficient = 0.72). The largest rain event recorded was 24 mm at Mammoth on 6 August 2009. Summer precipitation most frequently falls in the form of convective summer thunderstorms, which can deliver isolated rain. Between May 13 and Aug 19, 2010 the three Northern Range precipitation gauges recorded between 105 mm (Mammoth) and 123 mm (Tower). 48% of this precipitation fell between May 28 and June 10. A water table increase was detected at wetlands after rain events (Fig. 3). The tipping bucket rain gauge and the Tower weather station each recorded ≥ 1 mm rain event on the same day 19 times over the 96 day recording period. Additionally, the tipping bucket reached ≥ 1 mm 7 times where Tower did not, and Tower recorded ≥ 1 mm 8 times where the tipping bucket did not.

Table A1. Temperature and precipitation deviation from historic average, 2009 and 2010. Mam = Mammoth, Tow = Tower, NR = Northern Range value, the mean of Mammoth and Tower.

| | **2009** | **2010** |
|---|---|---|
| Mam Temp (°C) | +0.2 | -0.4 |
| Tow Temp (°C) | +0.2 | -0.2 |
| **NR Temp (°C)** | **+0.2** | **-0.3** |
| Mam Ppt | 97% | 81% |
| Tow Ppt | 97% | 85% |
| **NR Ppt** | **97%** | **83%** |
| Mam Snow | 111% | 45% |
| Tow Snow | 129% | 60% |
| **NR Snow** | **120%** | **53%** |

**APPENDIX B.** Location of all wells

Table B1. Log of all 138 wells used in the study.

| Well # | Wetland | Easting | Northing | Elev (m) | Well Type |
|---|---|---|---|---|---|
| 1 | DC | 543566 | 4976420 | 2047 | shape3-mag2 |
| 4 | DC | 543510 | 4976320 | 2047 | shape3-mag2 |
| 9 | DC | 543616 | 4976400 | 2048 | shape3-mag2 |
| 17 | BM | 547854 | 4973670 | 1942 | shape1-mag1 |
| 21 | BM | 547835 | 4973690 | 1943 | shape1-mag1 |
| 22 | BM | 547949 | 4973640 | 1943 | shape1-mag1 |
| 26 | TF | 550143 | 4973550 | 1898 | shape2-mag2 |
| 29 | TF | 550155 | 4973580 | 1898 | shape2-mag2 |
| 32 | TF | 550092 | 4973570 | 1898 | shape2-mag2 |
| 34 | TL | 549963 | 4973720 | 1897 | shape2-mag2 |
| 36 | TL | 549993 | 4973780 | 1897 | shape2-mag2 |
| 38 | TL | 549950 | 4973950 | 1897 | shape3-mag1 |
| 40 | TL | 549664 | 4973950 | 1897 | n/a |
| 42 | TL | 549747 | 4973700 | 1897 | shape3-mag1 |
| 44 | BP | 520591 | 4985781 | 1799 | stable |
| 45 | DW | 520435 | 4985686 | 1809 | perched |
| 47 | RL | 520381 | 4985529 | 1825 | perched |
| 48 | MC | 520841 | 4985700 | 1804 | stable |
| 51 | MC | 520834 | 4985770 | 1797 | stable |
| 53 | MC | 520784 | 4985780 | 1799 | stable |
| 56 | BP | 520594 | 4985770 | 1800 | stable |
| 57 | BP | 520597 | 4985873 | 1798 | stable |
| 59 | DW | 520413 | 4985700 | 1810 | perched |
| 63 | CR | 550195 | 4973120 | 1924 | shape1-mag1 |
| 66 | CR | 550294 | 4973029 | 1924 | shape1-mag1 |
| 69 | CR | 550305 | 4973068 | 1922 | shape1-mag1 |
| 71 | CR | 550357 | 4973140 | 1919 | shape1-mag1 |
| 74 | LT | 549470 | 4973915 | 1898 | shape1-mag2 |
| 75 | BD | 546614 | 4974912 | 1910 | shape1-mag1 |
| 76 | SN | 548471 | 4974500 | 1901 | shape3-mag2 |
| 79 | SN | 548509 | 4974500 | 1899 | shape3-mag2 |
| 81 | SN | 548466 | 4974540 | 1900 | shape3-mag2 |
| 85 | SN | 548505 | 4974560 | 1903 | shape3-mag2 |
| 92 | DW | 520460 | 4985610 | 1813 | Perched |
| 93 | DW | 520458 | 4985620 | 1812 | Perched |
| 96 | DW | 520449 | 4985650 | 1810 | shape2-mag2 |
| 100 | DW | 520451 | 4985700 | 1808 | Perched |
| 102 | DW | 520441 | 4985760 | 1806 | Stable |
| 105 | RL | 520428 | 4985370 | 1826 | Stable |
| 107 | RL | 520359 | 4985470 | 1825 | shape3-mag2 |
| 110 | CP | 520821 | 4971730 | 2284 | n/a |
| 112 | CP | 520764 | 4971670 | 2284 | n/a |

| | | | | | |
|---|---|---|---|---|---|
| 114 | CP | 520820 | 4971712 | 2284 | n/a |
| 115 | SV | 552100 | 4974480 | 1924 | shape1-mag1 |
| 118 | SV | 552055 | 4974550 | 1923 | shape1-mag1 |
| 121 | SV | 552070 | 4974460 | 1924 | shape1-mag1 |
| 123 | IP | 551940 | 4974190 | 1925 | shape1-mag2 |
| 125 | IP | 551941 | 4974190 | 1925 | shape1-mag2 |
| 127 | IP | 551978 | 4974125 | 1925 | shape2-mag2 |
| 128 | IP | 552033 | 4974130 | 1925 | shape1-mag2 |
| 130 | BW | 521983 | 4974430 | 2270 | shape1-mag1 |
| 133 | BW | 521972 | 4974280 | 2269 | shape1-mag1 |
| 136 | BW | 522072 | 4974220 | 2269 | n/a |
| 137 | BE | 522332 | 4973990 | 2260 | shape2-mag2 |
| 140 | BE | 522574 | 4973810 | 2260 | shape2-mag2 |
| 142 | BE | 522338 | 4973860 | 2260 | shape2-mag2 |
| 144 | BE | 522409 | 4973956 | 2260 | shape2-mag2 |
| 148 | FF | 532455 | 4978196 | 2054 | n/a |
| 152 | RP | 524225 | 4978480 | 1924 | shape3-mag2 |
| 155 | RP | 524176 | 4978560 | 1923 | shape3-mag2 |
| 158 | RP | 524135 | 4978540 | 1925 | shape3-mag2 |
| 161 | BD | 546619 | 4974870 | 1911 | shape1-mag1 |
| 164 | BD | 546578 | 4974890 | 1911 | shape1-mag1 |
| 168 | BD | 546619 | 4974920 | 1910 | shape1-mag1 |
| 170 | BD | 546615 | 4974900 | 1910 | shape1-mag1 |
| 172 | BM | 547937 | 4973570 | 1941 | n/a |
| 174 | SG | 534905 | 4979120 | 2089 | shape1-mag2 |
| 177 | SG | 534765 | 4979340 | 2080 | n/a |
| 180 | SG | 534880 | 4979270 | 2086 | shape2-mag2 |
| 182 | SG | 534835 | 4979260 | 2086 | shape2-mag2 |
| 184 | MB | 524875 | 4978880 | 1861 | shape3-mag1 |
| 187 | MB | 524953 | 4978980 | 1853 | shape3-mag1 |
| 189 | MB | 524943 | 4978880 | 1859 | shape3-mag1 |
| 192 | MB | 524926 | 4978910 | 1858 | shape3-mag1 |
| 195 | WA | 551200 | 4973610 | 1924 | n/a |
| 197 | WA | 551448 | 4973590 | 1921 | stable |
| 200 | WA | 551361 | 4973420 | 1921 | stable |
| 203 | LT | 549468 | 4973860 | 1899 | shape2-mag2 |
| 210 | LT | 549305 | 4974000 | 1899 | shape3-mag1 |
| 213 | LT | 549480 | 4974030 | 1896 | shape2-mag2 |
| 217 | US | 523563 | 4983270 | 1786 | shape3-mag1 |
| 220 | US | 523581 | 4983270 | 1785 | shape3-mag1 |
| 223 | US | 523595 | 4983300 | 1783 | shape3-mag1 |
| 226 | US | 523596 | 4983280 | 1784 | shape3-mag1 |
| 229 | OR | 523265 | 4983550 | 1825 | shape2-mag2 |
| 231 | OR | 523288 | 4983600 | 1826 | shape2-mag2 |
| 233 | OR | 523348 | 4983630 | 1823 | shape2-mag2 |
| 236 | OR | 523331 | 4983580 | 1824 | shape2-mag2 |
| 239 | FF | 532336 | 4978330 | 2054 | n/a |

| | | | | | |
|---|---|---|---|---|---|
| 242 | FF | 532293 | 4978280 | 2053 | n/a |
| 243 | BG | 545994 | 4974950 | 1945 | shape1-mag1 |
| 246 | BG | 545957 | 4974960 | 1944 | shape1-mag1 |
| 248 | BG | 545969 | 4974930 | 1945 | shape1-mag1 |
| 251 | BG | 545945 | 4974940 | 1944 | n/a |
| 254 | BG | 545950 | 4974946 | 1944 | n/a |
| 255 | CP | 520805 | 4971670 | 2284 | shape1-mag1 |
| 257 | BW | 522122 | 4974300 | 2271 | n/a |
| 258 | RP | 524215 | 4978540 | 1922 | shape3-mag2 |
| 260 | RP | 524176 | 4978540 | 1923 | shape3-mag2 |
| 267 | FF | 532390 | 4978272 | 2054 | n/a |
| 271 | LT | 549386 | 4973860 | 1899 | shape1-mag2 |
| 272 | MC | 520856 | 4985740 | 1799 | stable |
| 273 | MC | 520855 | 4985740 | 1799 | stable |
| 276 | IP | 551983 | 4974117 | 1925 | shape2-mag2 |
| 279 | SV | 552065 | 4974446 | 1925 | shape1-mag1 |
| 282 | TW | 549943 | 4972880 | 1946 | n/a |
| 283 | TW | 550079 | 4973150 | 1930 | n/a |
| 286 | TW | 549784 | 4973290 | 1925 | n/a |
| 288 | TW | 549803 | 4973320 | 1925 | n/a |
| 291 | TW | 549981 | 4972970 | 1936 | n/a |
| 295 | FF | 532324 | 4978310 | 2053 | n/a |
| 296 | TL | 549917 | 4973640 | 1897 | shape3-mag2 |
| 299 | TL | 549864 | 4973620 | 1897 | shape3-mag1 |
| 301 | TW | 549817 | 4973430 | 1915 | n/a |
| 303 | BM | 548011 | 4973580 | 1941 | n/a |
| 305 | BM | 547944 | 4973610 | 1942 | shape1-mag1 |
| 307 | DC | 543570 | 4976400 | 2047 | shape3-mag2 |
| 308 | CP | 520793 | 4971692 | 2284 | shape1-mag1 |
| 309 | BP | 520589 | 4985815 | 1798 | shape1-mag2 |
| 310 | BW | 522054 | 4974226 | 2269 | shape1-mag1 |
| 311 | SV | 552049 | 4974494 | 1924 | n/a |
| 313 | TL | 549752 | 4973812 | 1897 | shape2-mag2 |
| 316 | TL | 549897 | 4973857 | 1897 | shape2-mag2 |
| 320tf | TF | 550163 | 4973597 | 1900 | n/a |
| 320wa | WA | 551443 | 4973344 | 1924 | n/a |
| 322 | WA | 551430 | 4973573 | 1920 | stable |
| 323 | WA | 551280 | 4973564 | 1921 | shape1-mag1 |
| 326 | CR | 550294 | 4973090 | 1922 | shape1-mag1 |
| 328 | SG | 534790 | 4979319 | 2081 | n/a |
| 334 | BE | 522325 | 4973975 | 2260 | shape2-mag2 |
| 336 | BG | 545964 | 4974943 | 1944 | shape1-mag1 |
| 338 | TW | 550256 | 4973451 | 1908 | n/a |
| 341 | TL | 549755 | 4973918 | 1897 | n/a |
| 342 | TL | 549721 | 4973768 | 1897 | n/a |
| 343 | TL | 549790 | 4973655 | 1898 | n/a |
| 344 | TL | 549921 | 4973618 | 1897 | n/a |

| | | | | | |
|---|---|---|---|---|---|
| 345 | TL | 549978 | 4973677 | 1897 | n/a |
| 347 | SN | 548498 | 4974538 | 1900 | shape3-mag2 |
| 348 | TW | 550272 | 4973462 | 1908 | n/a |
| 349 | OR | 523303 | 4983572 | 1824 | shape2-mag2 |
| 350 | IP | 552004 | 4974165 | 1925 | shape2-mag2 |
| 351 | TL | 549888 | 4973651 | 1856 | shape2-mag2 |
| 352 | WA | 551429 | 4973574 | 1920 | shape1-mag1 |

**APPENDIX C**. Aerial photography dates

Table C1. Day, or window of days, on which air photos were taken in each year. Note that 1969 lacked photos for BD and BG so photos from 1971 were substituted.

| Year | Wetlands near Mammoth | Wetlands near Tower |
|---|---|---|
| 1954 | Aug 11-18 | Aug 11-18 |
| 1969 | Sep 8 | Sep 8 |
| 1971 | - | Sep 10 |
| 1991 | Jul 4 | Aug 3 |
| 1994 | Jun 26 | Aug 24 |
| 1998 | Aug 5 | Aug 5 |
| 2001 | Jul 1 | Jul 1 |
| 2006 | Sep 29 | Sep 29 |
| 2009 | Aug 27 | Aug 27 |

**APPENDIX D**. Hydraulic conductivity measurements in the Trumpeter Lake watershed

Saturated hydraulic conductivity ($K_s$) was calculated via the double-ring infiltrometer method and via the Hvorslev slug test. The two methods yielded quite different results, possibly a function of depth (van der Kamp and Hayashi 2009). This was unexpected in an unconsolidated till system with poor soil development, since vertical and horizontal $K_s$ to be roughly equivalent. Results from each location tested follow in these tables. Note that in Table G1 well 296 at 35 cm depth should equal the "TL lake seds." at 35 cm depth since these tests were performed in the same location. The values were 0.037 and 0.26 m/day, respectively. This narrow line of evidence suggests an error of one degree of magnitude. I am not sure where the error originated.

Table D1. $K_s$ calculated from the double-ring infiltrometer test.

| **Location** | **Depth** | **$K_s$ (m/day)** |
|---|---|---|
| Upland TW #2 | Surface | 0.8 |
| Upland TW | Surface | 0.87 |
| Upland TW | 50 cm | 0.56 |
| TW local depression, *Juncus* veg. | Surface | 1.7 |
| TL lake seds., well 296 | Surface | 0.13 |
| TL lake seds., well 296 | 35 cm | 0.26 |

Table D2. $K_s$ calculated from the Hvorslev slug test.

| Well | $K_s$ (m/day) |
|---|---|
| 341 | 0.011 |
| 38 | 0.043 |
| 342 | 0.025 |
| 343 | 0.003 |
| 299 | 0.016 |
| 296 | 0.037 |
| 344 | 0.0029 |
| 345 | 0.02 |
| 32 | 1.5 |
| 29 | 0.23 |
| 26 | 0.022 |
| 301 | 0.04 |

**APPENDIX E.** Trumpeter Lake focal site analysis

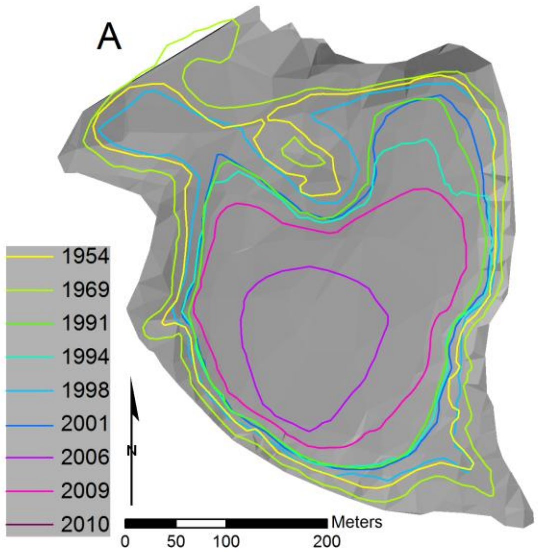



Figure E1. Trumpeter Lake surface water extent through time. A) shows lake perimeter delineated directly from air photographs. B) shows perimeter calculated by accounting for evaporation and precipitation between photo date and the standardization date, August 15. Land surface was produced by creating a TIN from a basin-wide topographic survey conducted in 2010. 2010 lake perimeter was calculated from field data directly in absence of an aerial photograph.

Table E1. Trumpeter Lake size derived from aerial photos. Volumes were calculated using the fill function in a TIN layer in ArcGIS. Since lake size changes throughout the summer and aerial photos were taken on different days in different years, I estimated lake size for the standardized date of August 15 by adjusting for the precipitation recorded at the Tower rain gauge (NCDC 2011) and the estimated lake evaporation (Pochop et al. 1985, WCA 2008)

.

| | Photo Date | | 15 Aug Standardization | |
|---|---|---|---|---|
| **Photo Date** | **Area ($m^2$)** | **Volume ($m^3$)** | **Area ($m^2$)** | **Volume ($m^3$)** |
| 11-18 Aug 1954 | 106,000 | 168,000 | 105,000 | 168,000 |
| 8 Sep 1969 | 126,000 | 249,000 | 128,000 | 249,000 |
| 3 Aug 1991 | 71,000 | 66,000 | 69,000 | 63,000 |
| 24 Aug 1994 | 68,000 | 61,000 | 69,000 | 63,000 |
| 5 Aug 1998 | 100,000 | 152,000 | 99,000 | 147,000 |
| 1 Jul 2001 | 72,000 | 69,000 | 67,000 | 57,000 |
| 29 Sep 2006 | 35,000 | 14,000 | 30,000 | 10,000 |
| 27 Aug 2009 | 48,000 | 27,000 | 50,000 | 28,000 |
| xx Xxx 2010 | n/a | n/a | 35,000 | 14,000 |

**APPENDIX F.** Soil seed bank study species list

Table F1. Plant species germinating in the soil seed bank study, listed with their wetland indicator status. n = number of wetlands, out of 12, from whose plots a species germinated. Nomenclature follows USDA PLANTS (2011).

| Species Name | Wetland Indicator Status | n |
|---|---|---|
| *Achillea millefolium* var. *lanulosa* | FACU | 1 |
| *Agrostis scabra* | FAC | 2 |
| *Agrostis stolonifera* | FAC | 3 |
| *Alyssum desertorum* | N/A | 4 |
| *Androsace septentrionalis* | FAC- | 3 |
| *Antennaria microphylla* | N/A | 1 |
| *Artemesia frigida* | N/A | 1 |
| *Astragalus agrestis* | FACW- | 2 |
| *Bromus japonicus* | UPL | 6 |
| *Bromus tectorum* | N/A | 1 |
| *Camelina microcarpa* | N/A | 1 |
| *Cerastium fontanum* | FACU | 1 |
| *Ceratocephala testiculata* | N/A | 3 |
| *Cirsium arvense* | FACU+ | 2 |
| *Collinsia parviflora* | N/A | 2 |
| *Collomia linearus* | FACU | 2 |
| *Corydalis aurea* | N/A | 1 |
| *Cryptantha ambigua* | N/A | 1 |
| *Dasiphora fruticosa* | FAC- | 1 |
| *Descurainia pinnata* var. *nelsonii* | N/A | 1 |
| *Descurainia sophia* | N/A | 2 |
| *Draba nemorosa* | N/A | 11 |
| *Epilobium ciliatum* | FACW- | 11 |
| *Erysimum inconspicuum* | N/A | 2 |
| *Festuca idahoensis* | FACU* | 1 |
| *Fragaria virginiana* | FACU* | 3 |
| *Gnaphalium palustre* | FAC+ | 3 |
| *Juncus arcticus* | FACW+ | 3 |
| *Juncus ensifolius* | FACW | 2 |
| *Juncus longistylis* | FACW | 1 |
| *Juncus nodosus* | OBL | 1 |
| *Juncus torreyi* | FACW | 1 |
| *Melilotus officinalis* | FACU | 1 |
| *Mentha arvensis* | FACW- | 3 |
| *Monolepis nuttalliana* | FAC- | 3 |
| *Myosurus minimus* | OBL | 2 |

| | | |
|---|---|---|
| *Poa palustris* | FAC | 12 |
| *Puccinellia nuttalliana* | FACW+ | 1 |
| *Ranunculus macounii* | OBL | 3 |
| *Ranunculus sceleratus* | OBL | 7 |
| *Rumex maritimus* | FACW+ | 6 |
| *Taraxacum officinale* | FACU | 7 |
| *Thlaspi arvense* | N/A | 5 |
| *Trifolium hybridum* | FAC | 1 |
| *Typha latifolia* | OBL | 2 |
| *Veronica peregrina* | OBL | 5 |

**APPENDIX G.** Soil seed bank study plot stratification procedure

I explored multiple ways to analyze soil seed bank data. As explained in the text, I resolved on a classification stratifying plot classes by their relative elevation from the lowest plot (0%) up to the surrounding upland elevation (100%). Elevation classes were chosen according to two criteria, 1) I attempted to lump percentages in close proximity to each other (e.g. given the percentages 0, 17, 20, and 25 I grouped 0's together and 17, 20 and 25's together), and 2) I attempted to create groups of similar size ($20 \leq n \leq 24$ for six of the seven classes). Table J1 shows the raw data for number of OBL and FACW species germinating in each plot, grouped by elevation class. The total number of wetland species germinating per plot was lower than desired.

An alternative classification that was rejected used each plot's elevation above the 2009 maximum water level in a particular wetland basin (cm). The advantage of this method was that it placed all wetlands on the same absolute scale, and elevation classes were described in centimeters rather than as percentages. This method incorporated the ecological importance of the seasonal high water level. However, the drawback to this classification was that it tended to decrease the diversity of wetlands represented in the plot elevation classes (e.g. only 7 of 12 wetlands were represented in the lowest class; Trumpeter Lake provided 8 of the 24 plots in the highest class). This classification revealed no strong trends in the distribution of germinating wetland species. In fact, wetland species starkly peaked in the highest elevation class, 140-342 cm above 2009 peak. Plots in this class were dominated by Trumpeter Lake plots, a particularly productive wetland. Thus, a high percentage of plots from one wetland and no pattern outside of this elevation class discounted my trust in this analysis.

Table G1. Raw data showing number of wetland species germinating per plot in the soil seed bank study. Plots are grouped in columns according to their relative wetland elevation, represented by percentage from wetland bottom to upland vegetation.

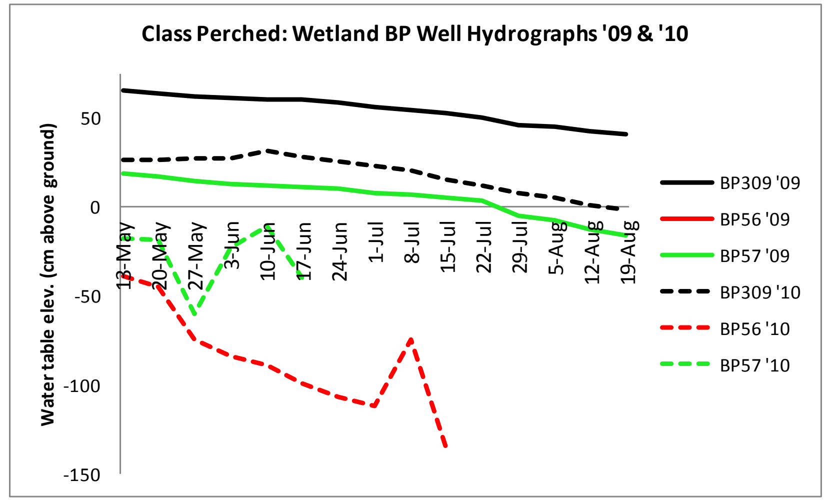
| | 0% | 17-25% | 33-40% | 50% | 60-67% | 75-83% | 100% |
|---|---|---|---|---|---|---|---|
| | 1 | 0 | 1 | 2 | 0 | 1 | 0 |
| | 0 | 0 | 0 | 2 | 2 | 1 | 0 |
| | 0 | 0 | 1 | 1 | 4 | 1 | 2 |
| | 1 | 1 | 1 | 0 | 1 | 0 | 1 |
| | 1 | 1 | 1 | 3 | 3 | 1 | 0 |
| | 0 | 0 | 0 | 2 | 1 | 0 | 1 |
| | 0 | 0 | 2 | 0 | 2 | 2 | 1 |
| | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| | 0 | 1 | 0 | | 1 | 1 | 1 |
| | 0 | 1 | 1 | | 1 | 1 | 1 |
| | 0 | 3 | 2 | | 3 | 0 | 2 |
| | 0 | 0 | 1 | | 1 | 0 | 0 |
| | 2 | 1 | 0 | | 0 | 1 | 1 |
| | 1 | 1 | 0 | | 0 | 1 | 0 |
| | 1 | 1 | 0 | | 2 | 4 | 2 |
| | 0 | 0 | 0 | | 2 | 0 | 4 |
| | 0 | 1 | 1 | | 2 | 0 | 1 |
| | 2 | 0 | 0 | | 0 | 0 | 0 |
| | 3 | 2 | 3 | | 3 | 2 | 0 |
| | 0 | 1 | 2 | | 2 | 2 | 0 |
| | 0 | 2 | | | | 2 | 1 |
| | | 1 | | | | 0 | 1 |
| | | 1 | | | | 5 | 1 |
| | | 0 | | | | 0 | 0 |
| **mean** | 0.6 | 0.8 | 0.9 | 1.3 | 1.6 | 1.1 | 0.9 |
| **SE** | 0.19 | 0.16 | 0.20 | 0.41 | 0.26 | 0.26 | 0.19 |

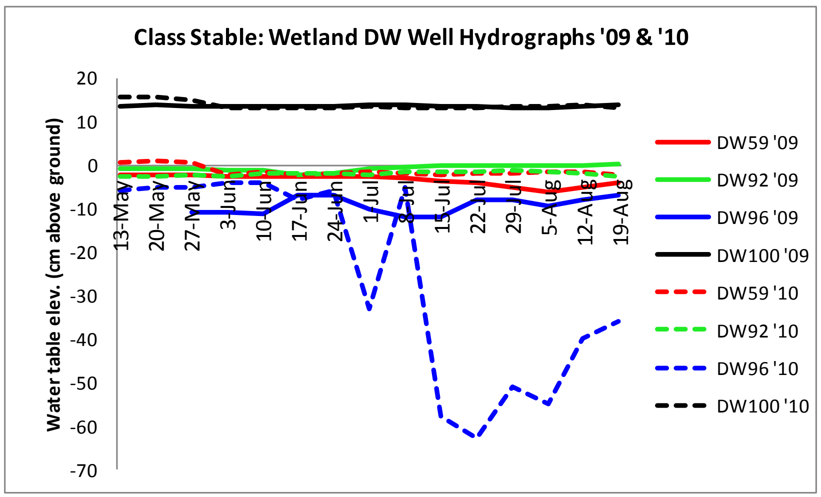
Table G2. Mann Whitney U test statistics from comparing each elevation class to all others. The top right triangle is the test z-score, while the bottom left triangle shows the associated p-values. Asterisks highlight significance at $p < 0.05$. See Fig. 12 for bar graph.

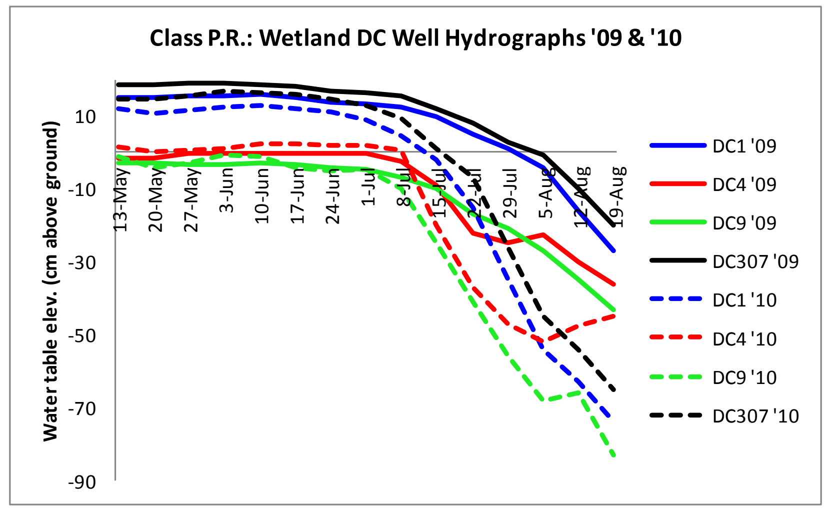
| Elev. Class | 0% | 17-25% | 33-40% | 50% | 60-67% | 75-83% | 100% |
|---|---|---|---|---|---|---|---|
| **0%** | | -1.04 | 1.23 | 1.51 | 2.88* | -1.57 | -1.36 |
| **17-25%** | 0.3 | | 0.33 | 1.09 | 2.45* | -0.7 | -0.38 |
| **33-40%** | 0.23 | 0.74 | | 0.83 | -2* | -0.34 | 0 |
| **50%** | 0.14 | 0.28 | 0.41 | | -0.53 | 0.57 | 0.89 |
| **60-67%** | 0.01* | 0.02* | 0.05* | 0.6 | | 1.64 | 2.13* |
| **75-83%** | 0.12 | 0.48 | 0.74 | 0.57 | 0.11 | | 0.35 |
| **100%** | 0.18 | 0.7 | 1 | 0.39 | 0.04* | 0.73 | |

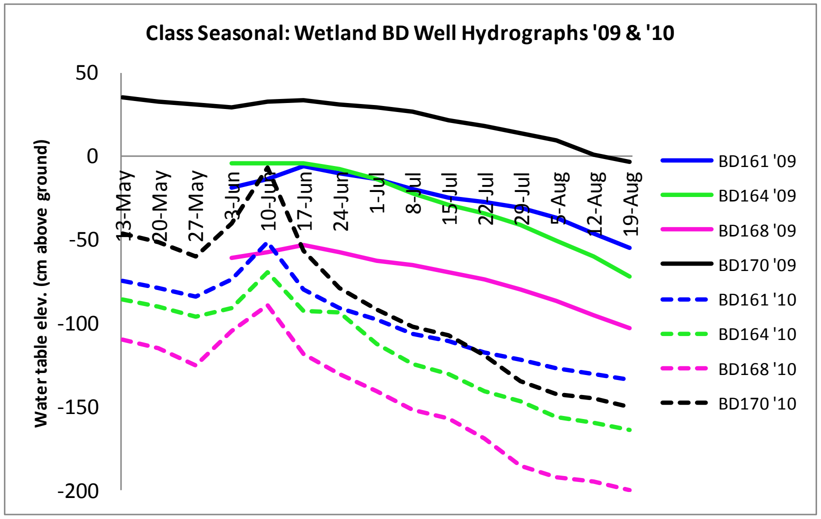
**APPENDIX H**. Example wetland hydrographs from the seven classes

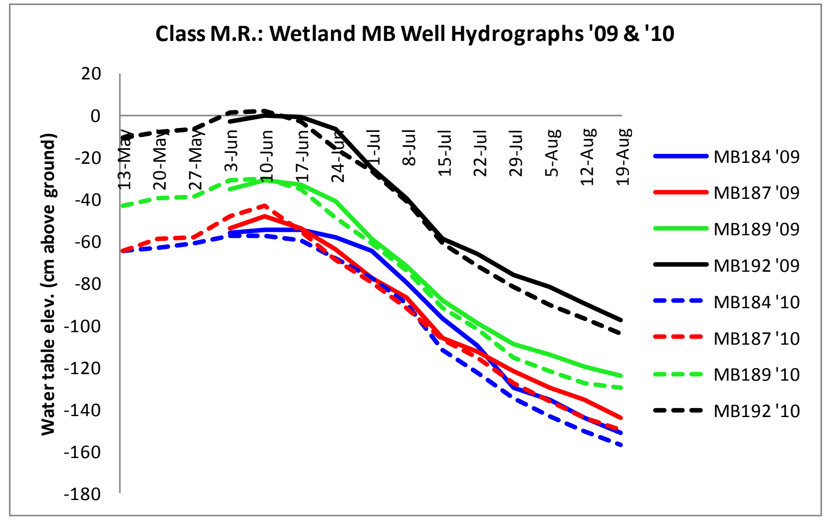
Figure H1. Illustrated are hydrographs of the seven wetland classes derived from well hydrograph analysis. Each pane is an example wetland from a given class. Summer hydrographs for all wells at a wetland are illustrated for both years. A given well is illustrated with the same color in each year. 2009 hydrographs are solid lines and 2010's are dashed. Black lines are staff gauges.

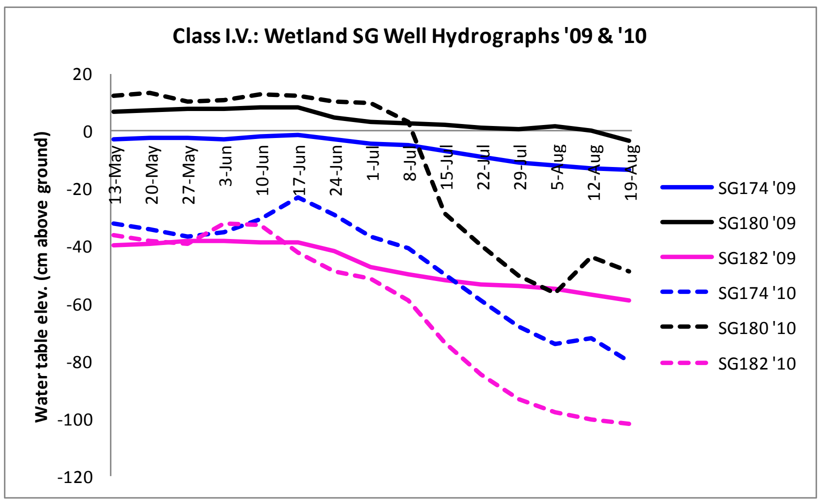


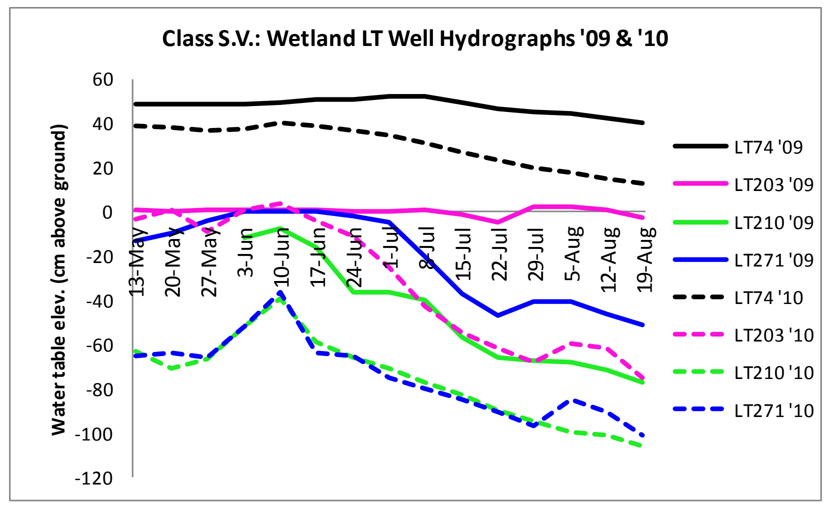




Class Seasonal: Wetland BD Well Hydrographs '09 & '10
Water table elev. (cm above ground)
50
0
-50
-100
-150
-200
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun
1-Jul
8-Jul
15-Jul
22-Jul
29-Jul
5-Aug
12-Aug
19-Aug
BD161 '09
BD164 '09
BD168 '09
BD170 '09
BD161 '10
BD164 '10
BD168 '10
BD170 '10


Class M.R.: Wetland MB Well Hydrographs '09 & '10
Water table elev. (cm above ground)
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun
1-Jul
8-Jul
15-Jul
22-Jul
29-Jul
5-Aug
12-Aug
19-Aug
MB184 '09
MB187 '09
MB189 '09
MB192 '09
MB184 '10
MB187 '10
MB189 '10
MB192 '10


Class I.V.: Wetland SG Well Hydrographs '09 & '10
Water table elev. (cm above ground)
20
0
-20
-40
-60
-80
-100
-120
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun
1-Jul
8-Jul
15-Jul
22-Jul
29-Jul
5-Aug
12-Aug
19-Aug
SG174 '09
SG180 '09
SG182 '09
SG174 '10
SG180 '10
SG182 '10


Class S.V.: Wetland LT Well Hydrographs '09 & '10
Water table elev. (cm above ground)
60
40
20
0
-20
-40
-60
-80
-100
-120
13-May
20-May
27-May
3-Jun
10-Jun
17-Jun
24-Jun
1-Jul
8-Jul
15-Jul
22-Jul
29-Jul
5-Aug
12-Aug
19-Aug
LT74 '09
LT203 '09
LT210 '09
LT271 '09
LT74 '10
LT203 '10
LT210 '10
LT271 '10

**APPENDIX I.** Yellowstone River annual discharge

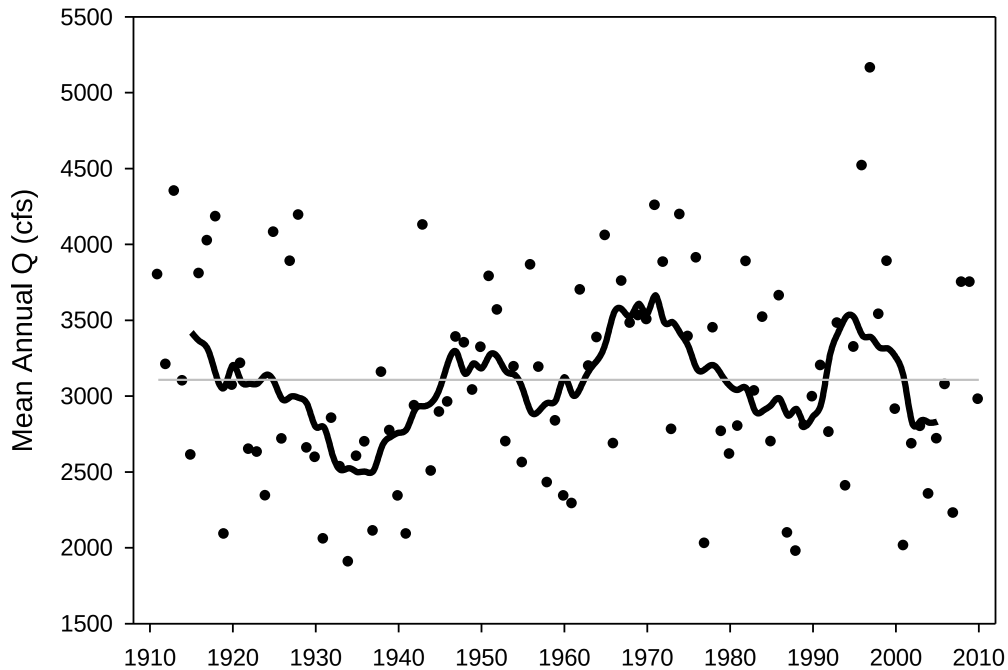



Figure I1. Mean annual discharge (Q) on the Yellowstone River at the Corwin Springs gauging station. Dots represent annual mean Q's for 1911-2010, black line represents the 10-year running average, and gray line is the mean. Data revealed an oscillating pattern of wetter and drier years, but no comprehensive trajectory over the past century. This figure's trends were extended back to the early 18$^{th}$ century by Graumlich et al. (2003). Their data indicated that the wettest period was circa 1900 and the longest prolonged dry spell was 1780-1870.

**APPENDIX G.** Photographs of one wetland from each class

Figure G1. Stable surface water class, wetland RL.

Figure G2. Perched water table class, wetland BP.

Figure G3. Seasonally and yearly variable water table class, wetland BD.

Figure G4. Peat soils with recovering water tables class, wetland DC.

Figure G5. Mineral soils with recovering water tables class, wetland MB.

Figure G6. Interannually variable water table persistence, wetland OR.

Figure G7. Spatially variable water table patterns, wetland TL.