Climatic Shifts in the Availability of Contested Waters: A Long-Term Perspective from the Headwaters of the North Platte River

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Early summer snowmelt from mountains in northern Colorado and southeastern Wyoming supplies the North Platte River, supporting nationally important agriculture, energy production, and urban development. Repeated decisions from the U.S. Supreme Court have fully apportioned Platte River waters among Colorado, Wyoming, and Nebraska, underscoring societal strains on this system. Now, climate change threatens the regional allocation of water. Tree-ring records indicate that past centuries contained multidecadal “megadroughts” far more severe than those of the historic period. However, the potential for even more persistent droughts, as the result of climate change, is poorly known. We document and evaluate the severity of recent and prehistoric droughts via a combination of data sources: modern temperature, precipitation, and stream gauge data; evidence of low lake-level stands; and related estimates of past hydroclimate change. Modern climate and stream data show an increase in spring temperatures of 2.21°C since 1916, an increase in the frequency of peak spring runoff before 1 May, and a reduction in winter precipitation. Lakes, however, that have only experienced minor hydrologic changes historically were desiccated during prehistoric dry periods during the past 12,000 years. Prehistoric lake shorelines indicate that water supplies were substantially reduced over centuries and millennia, such as from >8,000 to <5,000 years before present. The magnitude of these droughts likely also resulted in ephemeral river flows and thus indicates the potential for persistent shifts in regional hydrology. Such shifts should, therefore, be considered as part of long-term economic and legal planning. Key Words: climate change, drought, lake levels, North Platte River, water supply.
de lagos; y estimativos relacionados con cambios hidroclimáticos pasados. Los datos modernos sobre clima y corrientes muestran un incremento de las temperaturas de primavera de 2.21°C desde 1916, un incremento en la frecuencia del tope de escorrentía antes del 1 de mayo y una reducción de la precipitación invierno. Sin embargo, los lagos, que habían experimentado solo cambios hidrológicos insignificantes en tiempos históricos, se secaron en períodos secos prehistóricos durante los pasados 12,000 años. Las líneas de costa de lagos prehistóricos indican que el suministro de agua fue sustancialmente reducido durante siglos y milenios, por ejemplo de >8,000 a <5,000 años antes del presente. Es probable que la magnitud de estas sequías resultara en flujos efímeros de ríos, indicando así el potencial de cambios persistentes en la hidrología regional. Tales cambios deben ser consecuentemente considerados como parte de una planeación económica y legal a largo plazo. Palabras clave: cambio climático, sequía, niveles lacustres, Río North Platte, abasto de agua.

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ater in the Western United States has long been a source of conflict within the region, with lessons from the past century (e.g., overallocation of the Colorado River) revealing the value of a long-term perspective on the variability of water resources (MacDonnell, Getches, and Hugenberg 1995). Climate change is likely to exacerbate uncertainties in water supplies (Bates et al. 2008; Milly et al. 2008), including the potential for hydroclimatic changes to persist beyond reasonable resource planning horizons (Seager et al. 2007; Barnett et al. 2008). Most Western waters derive from early summer snowmelt in the mountains, and much of the region is currently experiencing a shift to earlier snowmelt as a result of anthropogenic-forced warming (Stewart, Cayan, and Dettinger 2004). Superimposed on this trend, a nearly decade-long drought has contributed to declines in riverflows (Rood et al. 2005) and is the most recent manifestation of changes in precipitation detected over the last fifty years (Dai et al. 2009). At longer time scales, prolonged multidecadal “megadroughts” have been inferred from tree-ring records (Cook et al. 2004), but even these records might be unable to provide a full range of drought variability necessary for long-term planning, especially in the context of future climate change. The past 12,000 years provide an opportunity to examine how water resources respond to global climate forcing different from the past few centuries and thus might provide a wider range of contingencies to consider for the future (Shuman et al. 2009; Shuman et al. 2010).

We focus here on the hydrologic history of the North Platte River in Colorado, Wyoming, and Nebraska as an illustrative example of legally contested waters affected by climate change. The river has been a source of multiple interstate lawsuits arbitrated by the U.S. Supreme Court between 1911 and 2001 (see later). The 12,000-year history of water supplies in the river’s headwaters is used to demonstrate the potential for climate change to radically affect the current legal consensus. The headwaters’ region covers approximately 72,520 km$^2$ in the mountains of northern Colorado and southeastern Wyoming and is an important source of water for irrigation, energy production, and urban development (Figure 1). The smallest portion of the watershed is in northern Colorado, with the majority in southeastern Wyoming. However, primary state water rights on the North Platte are held by Nebraska through prior appropriations.

The goal of this article is to examine recent trends in temperature, moisture balance, and streamflow in the

Figure 1. Map of the North Platte River Basin in Colorado and Wyoming. The Northgate stream gauge is shown on the Colorado–Wyoming border and a dashed line denotes the watershed above the gauge. Filled circles represent AMS-dated lake-level study sites: (A) Hidden Lake, (B) Creedmore Lake, (C) Little Windy Hill Lake. Open squares represent additional sites with ground-penetrating radar data: (D) Long Lake, (E) Teal Lake, (F) Tiago Lake. Black bars indicate location of dams.
North Platte drainage in a 12,000-year context. We pursue three main questions:

1. How has recent climate change affected water supply in the region?
2. How do recent hydrologic trends compare to those related to past climate change?
3. What are the implications of these past changes in water supply?

In answering these questions, we place the current drought in a context that reveals that the historical range of variability in water supplies can be woefully inadequate for considering possible futures. We focus on past aridity, but our evidence also indicates prolonged wet periods outside the range of historic experience.

The North Platte River Basin: The Regional–Legal Context

The North Platte River and its main tributaries, the Laramie and Sweetwater rivers, originate in high elevations of northern Colorado and Wyoming, turning southeast toward Nebraska with several impoundments and diversions, mostly in Wyoming (Figure 1). Currently, the river water is fully appropriated by legal agreement with water rights used primarily for agriculture, followed by industrial and energy production, municipal and domestic use, and recreation. The allocation has been continuously contested, however.

The first interstate lawsuit challenging allocation of North Platte waters was filed in 1911 by Wyoming against Colorado related to usage of the Laramie River. The U.S. Supreme Court ruled in the 1922 Laramie River Decree (Wyoming v. Colorado, 259 U.S. 419 [1922], amended in 1957) to set a specific limit (15,500 acre-feet/year) on Colorado diversions with the rest allocated to Wyoming. Such a ruling assumes that 15,500 acre-feet/year has been and will be continuously available from the Laramie River, but the claim has never been validated. Historic climate variability, however, challenges this assumption. During the 1930s, severe regional drought led Nebraska to sue, claiming that diversions in Wyoming were preventing priority water rights downriver. The U.S. Supreme Court decision in 1945 (Nebraska v. Wyoming, 108 (Orig.), 325 U.S. 589, 665) then set limitations on the appropriations of North Platte water in Wyoming, although litigation continued in 1953, 1993, and 1995.

The most recent modification to this ruling, the Modified North Platte Decree of 2001 (Nebraska v. Wyoming & Colorado, 534 U.S. 40 [2001]), declared that sections of the North Platte River originating in Wyoming are divided for consumptive use during irrigation season (May–September) between Nebraska (75 percent) and Wyoming (25 percent). The hydrologic assumptions for this allocation arise from the documented availability of water over any ten consecutive years during the period from 1952 to 1999 as determined by agricultural consumptive use and climate data (see Exhibit 6 of Nebraska v. Wyoming & Colorado, 534 U.S. 40 [2001]). This decree also allows Colorado to claim 1.28 million acre-feet of water over any ten-year period. The proportional allocation of water is based on the recognition of variable flows, such as during drought years, but the assumption remains that natural declines in flow are likely to be short lived (Milly et al. 2008).

Climate change and other environmental issues (e.g., endangered species; local resource extraction) have raised new concerns about the allocation of water. The climate of the North Platte Basin has historically been semiarid, which limits water supplies throughout much of the watershed where annual evapotranspiration is greater than annual precipitation despite a slight peak in precipitation in May (Shinker and Bartlein 2010). The majority of surface water in the region, therefore, comes from a single source: winter snowpack that falls mostly above 3,000 m in a small fraction of the watershed along its southwestern and northwestern margins. Reduced average annual snowpack in these mountain ranges can have large downstream consequences, and an increase in springtime temperatures has advanced the timing of spring snowmelt and peak river discharge throughout the West (Cayan et al. 2001; Stewart, Cayan, and Dettinger 2004). Early spring snowmelt, in turn, threatens to indefinitely reduce runoff, leaving less water available later in the summer than in past decades (Barnett and Pierce 2008).

Data and Methods

Modern Climate and Streamflow Data

Continuous climate and stream gauge data from 1916 through 2007 were used to characterize temperature, precipitation, and streamflow trends. Temperature and precipitation data from Wyoming Climate Division 10 represent the Upper Platte region (National Climatic Data Center 1994). Trends were examined in time series of mean annual and spring (March, April, and
May [MAM]) temperatures with spring temperatures used specifically to assess rates of change during peak snowmelt and maximum riverflows. Annual and winter (December, January, and February [DJF]) precipitation anomalies (1971–2000 base period) were also examined for comparison with riverflows. Winter precipitation anomalies were analyzed specifically because winter precipitation (via snowpack) is a strong indicator of variability in streamflow (Changnon, McKee, and Doesken 1991). Stream gauge data, including annual flow, magnitude of peak runoff, and timing of peak discharge, were examined for the North Platte River at the Northgate stream gauge near the Colorado–Wyoming border; data were obtained through the U.S. Geological Survey (USGS) National Streamflow Information Program (NSIP). Simple linear regressions were used to establish temporal trends, and residuals were statistically assessed for normality. Additionally, the frequency of events of certain magnitude (e.g., years with mean annual discharge of <6 m$^3$s$^{-1}$, which is less than 50 percent of the mean historic flow) was calculated using a ten-year moving window (i.e., the number of events per decade centered on each year in the record). We use the term mean historic flow to refer to the average of the mean annual discharge over the period of record.

**Holocene Lake-Level Reconstruction**

In much the same way that data from local meteorological stations can be compared to assess weather patterns, arrays of lakes (via sediment deposits) can be studied to reconstruct past climate conditions. Submerged shorelines in lakes are indicative of periods of drier-than-present conditions (e.g., Dearing 1997; Shuman and Finney 2006). Stratigraphic analyses of small lakes, therefore, can provide accurate records of hydroclimatic change (Digerfeldt, Almendinger, and Bjørck 1992).

When lake levels are low, sandy inorganic substrates expand toward the center of the lake, and sediment accumulation becomes nonconstant (~10 cm/1,000 years or less) toward shore (Dearing 1997; Shuman 2003). As a result, sandy layers and hiatuses (erosion surfaces) extend out from shore, and deepwater sediments “pinch out” near shore. Our studies of such evidence from lakes in the North Platte watershed were conducted with (1) ground-penetrating radar (GPR) to identify past shifts in shoreline position and associated changes in sediment geometry and (2) coring and trenching to sample and date submerged and buried shoreline deposits. Plots of sediment type, age, and elevation provide constraints on the water-level history. GPR data were collected with a GSSI, Inc., SIR-3000 GPR with 200 and 400 MHz antenna towed in rafts on the lake surface. GPR surveys were conducted at more than ten lakes in the region and representative data are shown here. Sediment cores and samples from near-shore trenches were collected from Hidden Lake, Jackson County, Colorado (40.50°N, 106.61°W, 2,728 m elevation); Creedmore Lake, Larimer County, Colorado (40.86°N, 105.59°W, 2,515 m); and Little Windy Hill Lake Carbon County, Wyoming (41.43°N, 106.33°W, 2,980 m). Core analyses include loss-on-ignition (Shuman 2003) and radiocarbon dating, conducted at the W. M. Keck Carbon Cycle Accelerator Mass Spectrometry (AMS) Laboratory. AMS radiocarbon dates were calibrated to account for atmospheric radiocarbon variations using CALIB 5.0.2 (Reimer et al. 2004). Here we provide new data for Creedmore and Little Windy Hill lakes and review published data from Hidden Lake (Shuman et al. 2009).

**Calculation of Impacts on Water Resources**

Differences between historic and Holocene riverflows at the Northgate gauge were calculated based on estimates of Holocene lake drawdown. The magnitude of drawdown was inferred from the difference in the past and modern elevations of sandy inorganic deposits (near shore). These elevational differences were multiplied by lake area to calculate a volume of water withdrawn from each lake in the past compared to today and then were divided by the area of each lake’s watershed to determine the annual change in precipitation minus evapotranspiration (P – E; lake inputs versus lake outputs) across the watersheds. Our P – E estimates, therefore, represent anomalies from the conditions associated with ca. 2008 lake levels. P – E values in mm/day were then calculated iteratively by dividing the annual total P – E for each lake by a range of 46 different lake-climate equilibration times from 0.5 to 5 years (182.5–1,825 days) in 0.1 year increments (see Shuman et al. 2010). Table 1 lists the means and standard deviations of these P – E estimates.

We cannot differentiate between changes in precipitation and evapotranspiration because each lake’s water budget depends on the balance of both factors. Groundwater in each watershed is a product of the balance of P – E and is not an additional source of lake water (i.e., derived from outside the watershed) because each of the watersheds is rimmed by bedrock with limited permeability: Precambrian quartz monzonite and granite at Creedmore Lake; Cretaceous Dakota Sandstone...
Table 1. Moisture balance and river flow estimates

<table>
<thead>
<tr>
<th>Lake</th>
<th>Area (ha)</th>
<th>Watershed (ha)</th>
<th>Drawdown (mbmls at 8-5 ka)</th>
<th>Volume change (m$^3$)</th>
<th>$\Delta P - E$ mm/year/watershed</th>
<th>$\Delta P - E^a$ mm/d/watershed</th>
<th>$\Delta$flow at North Gate (m$^3$/s)</th>
<th>$\Delta$flow (10$^5$ acre-ft/year)</th>
<th>$\Delta$flow (% of mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hidden Lake</td>
<td>6.50</td>
<td>94.00</td>
<td>3.5</td>
<td>227,500</td>
<td>$-242$</td>
<td>$-0.35 \pm 0.27$</td>
<td>$-14.9 \pm 6.9$</td>
<td>$-7.27$</td>
<td>$-124 \pm 58$</td>
</tr>
<tr>
<td>Creedmore Lake</td>
<td>3.62</td>
<td>17.04</td>
<td>1.2</td>
<td>36,234</td>
<td>$-255$</td>
<td>$-0.37 \pm 0.28$</td>
<td>$-15.8 \pm 7.3$</td>
<td>$-7.67$</td>
<td>$-131 \pm 61$</td>
</tr>
<tr>
<td>Little Windy Hill Lake</td>
<td>2.21</td>
<td>10.64</td>
<td>1.4</td>
<td>30,940</td>
<td>$-291$</td>
<td>$-0.42 \pm 0.32$</td>
<td>$-18.0 \pm 8.2$</td>
<td>$-8.74$</td>
<td>$-149 \pm 69$</td>
</tr>
</tbody>
</table>

Top 5 low flow years since 1948

<table>
<thead>
<tr>
<th>Year</th>
<th>$\Delta$flow</th>
<th>$\Delta$flow</th>
<th>$\Delta$flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>$-9.5$</td>
<td>$-2.41$</td>
<td>$-78$</td>
</tr>
<tr>
<td>1977</td>
<td>$-8.7$</td>
<td>$-2.23$</td>
<td>$-72$</td>
</tr>
<tr>
<td>1934</td>
<td>$-8.5$</td>
<td>$-2.19$</td>
<td>$-71$</td>
</tr>
<tr>
<td>1954</td>
<td>$-7.9$</td>
<td>$-2.03$</td>
<td>$-66$</td>
</tr>
<tr>
<td>1981</td>
<td>$-7.6$</td>
<td>$-1.94$</td>
<td>$-63$</td>
</tr>
</tbody>
</table>

Note: Mbmls = meters below modern lake surface; ka = thousands of years before 1950; $\Delta P - E =$ change in the balance of precipitation minus evapotranspiration.

$^a$Standard deviations are based on forty-six estimates of $\Delta P - E$ using lake-equilibrium times in 0.1 year steps from 0.5 to 5.0 years.
underlain by Proterozoic granitic rocks and pelitic schist at Hidden Lake; and Proterozoic Deep Lake Group quartzite and other metasediments, and Archean mafic intrusive rocks at Little Windy Hill Lake (USGS 2005). Low lake levels would also be associated with reduced hydrostatic head and groundwater outflow from each watershed. Thus, by assuming no change in groundwater loss over time, we are making conservative estimates of the changes in P – E.

The annual change in P – E was multiplied by the area of the North Platte drainage (3,706 km²) above the Northgate stream gauge to heuristically estimate an annual volume of water removed from the river system in the past. We present these values as flow rates (as m³s⁻¹ by dividing by the number of seconds per year; and as acre-feet per year, by converting the volume to the commonly and legally used hydrologic unit of acre-feet) and as a percentage deviation from the mean historic flow rate (12.0 m³s⁻¹). Our calculated values are compared with values for the five lowest flow years since 1916 based on USGS NSIP data.

Results
Recent Trends in Climate and Streamflow

The modern (1916–2007) climate time series illustrates trends in temperature (Figure 2A) consistent with global and regional patterns (Intergovernmental Panel on Climate Change 2007) with an increase in both mean annual and MAM temperatures. The rate of change in spring temperatures exceeds that for any other time of the year. Based on the linear regression (Figure 2A), mean annual temperatures in the North Platte River Basin have increased approximately 1.44°C over the ninety-two-year record (R² = 0.322, p < 0.001). Mean MAM temperatures in the region increased 1.5 times as fast as the mean annual temperatures at approximately 2.21°C over the same time (R² = 0.230, p < 0.001).

The increase in mean temperatures corresponds with an increase in the frequency of early spring peaks in discharge at Northgate (Figure 2B). For example, peak runoff before 1 May (Julian Day 120) has only taken place since 1960, and three of the four occurrences have taken place since 1989 (Figure 2B). A linear regression explains 45.0 percent of the variance in the frequency of early flow years per moving ten-year window. Linear regression of peak discharge dates, however, is not significant (R² = 0.012, p = 0.289) but qualitatively confirms the change in frequency of early runoff events, with peak runoff occurring now 0.114 days per year earlier than at the beginning of the record. The trends equal an advance in the timing of peak runoff by approximately 10.5 days over the record or an advance of 4.75 days per 1°C increase in MAM temperatures. Peak timing has not advanced smoothly but experienced both interannual and interdecadal variation (Figure 2C). The rate of change tending toward early
runoff is consistent with other regional studies (e.g., Stewart, Cayan, and Dettinger 2004; Mote et al. 2005).

In addition to the shift in timing of peak runoff (Figure 2B), annual riverflow from the North Platte headwaters has decreased approximately 3.4 m$^3$s$^{-1}$ (25 percent of the mean; Figure 2C). Annual river discharge dropped to only 21.5 percent of the mean discharge in 2002 and averaged 75.6 percent for the decade (1999–2008). Although the apparent linear trend ($R^2 = 0.035$, $p = 0.074$) in mean annual discharge depends on the time period analyzed and is driven by late runoff and high flows before 1930, the residuals of the trend have a near-normal distribution. A linear trend in the frequency of low flow years (with mean annual discharge $< 6$ m$^3$s$^{-1}$; $R^2 = 0.433$) is also not dependent on the time period considered and indicates a significant change in hydrologic regimes ($p < 0.03$).

Peak discharge has similarly declined by approximately 58 m$^3$s$^{-1}$ (52 percent) from 122 m$^3$s$^{-1}$ for the decade centered around 1925 to 64 m$^3$s$^{-1}$ for the decade centered around 2004. The frequency of both low mean annual and low peak flow years, therefore, is greater since 1977 compared to the earlier portion of the historic record. For example, low mean annual flow years were recorded in 1934 and 1954 and seven years since 1977 (including three years since 2001; Figure 2C). Linear regression explains 69.3 percent of the variance in the frequency of low peak flow years (with peak annual flow $< 40$ m$^3$s$^{-1}$). Of the low peak flow years, 62.5 percent have taken place since 1977. Years with anomalously low DJF precipitation (e.g., 2002, 1981, 1977, 1954, and 1931) correspond to the lowest annual streamflow, and also increase in frequency after 1980 (Figure 2D). The rate of precipitation change is slightly over the period (based on our linear regression, $R^2 = 0.176$, $p < 0.001$).

Based on the changes in the frequency of low mean and peak runoff, and runoff timing, we conclude that meaningful hydrologic change has affected the North Platte headwaters—even if such changes are only qualitatively captured by our linear regressions (Figure 2). Importantly, the changes in frequency are not dependent on the inclusion of the pre-1930 period. All regressions (Figure 2) also have normally distributed residuals except for those calculated for peak runoff timing (Figure 2B) and the annual flow at Northgate (Figure 2C). Additionally, the trends of all climatological and hydrological variables examined in this study are consistent with similar hydroclimatic trends identified in other studies from Western North America (see Mote et al. 2005; Rood et al. 2005; Barnett et al. 2008). The last decade was the warmest and driest on record, with 2002 as the driest year. These results indicate a trend toward less water in the system.

Lake-Level Variations

The past decade of drought has caused low lake levels at Creedmore Lake (Figure 3A) and other lakes in the region. GPR and sediment core data, however, reveal the presence of submerged paleoshorelines and thus evidence of drier episodes than the recent drought. GPR profiles show dense near-shore deposits and erosion/nondeposition surfaces, which represent paleoshorelines (Figure 3B). A sediment core from 120 cm of water in Creedmore Lake terminated in 30 cm of sandy sediment (12–87 percent sand) comprising one of the paleoshorelines. A calibrated radiocarbon age on sedimentary charcoal from the base of 9 cm of organic-rich silt (>15 percent loss-on-ignition) above the sands (Figure 4A) indicates that the sands accumulated before 158 to 303 calibrated years before 1950 (cal year BP). The lake level before 1792–1647, therefore, was >120 cm lower than in 2008, consistent with dendroclimatic evidence of regional “megadroughts” (Cook and Krusic 2004). Profiles of sediments exposed near the beach of Creedmore Lake contain fine-grained intervals (Figure 3C; <75 percent sand and >5 percent loss-on-ignition), which date to 503–471, 934–834, 2,055–1,991, 3,878–3,778, and before 7,965–7,938 cal year BP as though the water level were at least as high as modern during those times (Figure 4A). Note that little evidence exists for higher than modern levels between ca. 7,900 and 3,900 cal year BP and that evidence for high levels is most frequently from recent millennia.

Examination of a regional network of lakes shows extensive evidence of prolonged low-water intervals including inorganic near-shore layers and associated nondeposition or erosion surfaces at lakes in the North Platte River headwaters (Figure 5). The inferred positions of ancient shorelines indicate significant reduction in the surface area of these lakes (Figure 5, right column). For example, from ca. 8,400 to 4,400 cal year BP, Hidden Lake was approximately 3.5 m below the modern lake surface with a change in volume of approximately 227,500 m$^3$ (Table 1; Shuman et al. 2009).

Sediment cores from Creedmore, Hidden, and Little Windy Hill lakes (Figure 4) contain inorganic sediment layers, which appear to represent repeated dry periods since ca. 8,000 cal year BP. The layers interrupt periods...
Recent low water levels at Creedmore Lake in May 2008 (A) illustrate the hydrological impacts of the past decade of drought. Subsurface geology (B), however, captured by ground-penetrating radar (GPR) and sediment core data reveal that the lake has been much lower in the past. Paleoshorelines submerged within the lake date from before ca. 200 years before present (BP), and shovel pits (inset photo) show no evidence of higher than modern lake levels from ca. 7,950–3,750 years BP. Bold numbers in B indicate ages and positions of radiocarbon ages on sedimentary features.

of organic sediment deposition near shore and are associated with reductions in net sediment accumulation consistent with periods of shallow water (see Shuman et al. 2009). At Hidden Lake, cores collected near shore in five and six meters of water (cores E and C respectively; Figure 4B) contain inorganic paleoshoreline deposits (<15 percent loss-on-ignition) with very low net sedimentation rates (~3.8 cm/1,000 years in core E) between dates of 2,043–1,993 and 1,262–1,179 cal year BP when tree-ring drought reconstructions reveal repeated periods with more than fifty drought years per century (Cook and Krusic 2004). These core locations also accumulated no sediment and were likely desiccated, before ca. 4,400 years ago. Similarly, at Little Windy Hill Lake, net sediment accumulation even in the center of the lake (core 1A; Figure 4C) was more inorganic than recently and was reduced to 9.0 cm/1,000 years between dates of 2,341–2,210 and 1,694–1,613 cal year BP as though it were also shallow at that time. Earlier periods with similar sediment characteristics (e.g., net sedimentation rates below ~10 cm/1,000 years) at Creedmore, Hidden, and Little Windy Hill lakes indicate other periods of prolonged drought or frequent extreme droughts, particularly from ca. 3,700–2,900 and 7,900–5,000 cal year BP. The low elevations of inorganic paleoshorelines deposits from these periods provide a constraint on changes in lake volumes (Table 1).

Estimated Holocene Water Supply Reductions

Overall, we find that all of the lakes we studied were commonly low from >7,900 to <5,000 years ago. To sustain these low levels, we estimate that precipitation minus evaporation (P − E) dropped by 0.35 to 0.42 mm/day (Table 1). These estimates are consistent with climate model simulations of the region for 6,000 cal year BP (Diffenbaugh et al. 2006) and indicate regional aridity more intense in magnitude than in 2002 (and yet far longer in duration).

The change of flow at Northgate, calculated by multiplying the estimated P − E anomalies by the
Figure 4. Sediment stratigraphies and inferred water-level histories from (A) Creedmore Lake, Larimer County, Colorado; (B) Hidden Lake, Jackson County, Colorado; and (C) Little Windy Hill Lake, Carbon County, Wyoming. Dark gray curves (at right) indicate the water-level history as inferred from the elevations of inorganic deposits with slow sediment accumulation rates. Left columns show percentage loss-on-ignition (LOI) data versus elevation relative to the modern water surface from two sediment cores or near-shore sediment profiles from each lake; the LOI indicates the amount of organic matter in the sediments, which is low in shallow, near-shore environments (Shuman 2003). Gray bars denote inorganic intervals thought to represent paleoshorelines. Dashed lines indicate points of correlation between cores. Right graphs show the age–depth relationships for the cores and profiles based on the elevation and ages of calibrated radiocarbon dates (closed circles; Table 2). Light gray lines indicate inorganic sediment intervals, and relatively horizontal lines indicate periods of low net sediment accumulation consistent with shallow water. Gray circles in (A) indicate calibrated radiocarbon ages from sediment profile V2, which provides replication of sediment profile V1. Open circles (right) denote the top of the sediment sequences.

Here, however, they numerically result from the estimated change in lake volumes (Table 1) and thus indicate that groundwater, as well as surface flows, would have been depleted. The river channel was likely dry—except perhaps during spring snowmelt. Therefore, if the Holocene reconstructions are accurate, the North Platte River experienced (repeated or prolonged) reductions in flow over several thousand years that were much more severe than the historic low flow years (Table 1).
Figure 5. Lakes throughout the region contain submerged erosion surfaces at their margins that indicate prolonged periods of low water levels. Representative ground-penetrating radar profiles from a geographically diverse selection of lakes are shown. White indicates areas of high-density contrast within the vertical radar profiles. The middle column shows the interpretation of the profile with black lines denoting the submerged lake sediments, dashed lines marking erosion surfaces, and thin black lines showing truncated layers. At the right, the inferred positions of the most prominent ancient shorelines (based on the erosion surfaces) are shown. Where dated at Little Windy Hill, Creedmore, and Hidden lakes, the inferred shoreline positions were occupied from 8,000 to 5,000 years ago.
Discussion

Historic climate data indicate that regional climate change is affecting regional hydrology and water supplies, but our lake-level reconstructions suggest that much more dramatic changes in water resources have taken place in the past. P – E and riverflow reconstructions indicate streamflow at the Northgate stream gauge could have been ephemeral (assuming some seasonal flow from snowmelt) from ca. 8,000 to 5,000 years before present. Similarly, dune activity in Nebraska indicates that extended drought periods in the past likely led to a “perennially dry” North Platte River Valley (Muhs et al. 2000, 214); dune activity in Nebraska spanned from 9,900 to 6,600 years before present (Miao et al. 2007). Such changes coincide with extensive regional evidence of severe aridity (e.g., evidence of low water at more than fourteen lakes across the Rocky Mountains [Stone and Fritz 2006; Shuman et al. 2009]; evidence of aridity from fossil pollen records [Thompson et al. 1993]) and probably relate to major changes in global climate controls during the Holocene (Bartlein et al. 1998; Diffenbaugh et al. 2006). Legal water allocation, therefore, could be severely strained by the effects of similar changes in global climate controls in the future (i.e., high greenhouse gas concentrations).

How reasonable are our riverflow inferences (i.e., seasonally dry riverbeds)? In 2002, the lowest flow year on record, flow at Northgate dropped to 21.5 percent of the mean annual flow and was fed by groundwater sources that had probably not equilibrated to the single year of severe drought (e.g., Winter, Rosenberry, and LaBaugh 2003). Despite the lack of hydrologic equilibrium, areas of the North Platte River channel were dry during ninety-four days in 2002 at the Wyoming–Nebraska border based on USGS NSIP data and were also commonly dry in the nineteenth century (Williams 1978; Muhs and Holliday 1995). Therefore, persistent shifts in regional moisture balance that lasted for centuries or millennia, such as before ca. 5,000 years BP (Figure 4), could be reasonably expected to reduce flows to ephemeral levels given that the low lake levels indicate substantial reductions in groundwater. Groundwater would have had time to reach equilibrium with the persistently low precipitation, high evapotranspiration rates, or both, especially given sufficient time for paleoshoreline formation. Consistent with these ideas, the lakes were only minimally drawn down during

### Table 2. Ages of radiocarbon samples.

<table>
<thead>
<tr>
<th>Lab</th>
<th>Sample #</th>
<th>Core</th>
<th>Depth (cm)</th>
<th>Material dated</th>
<th>Radiocarbon age (Years before AD 1950)</th>
<th>SD</th>
<th>Maximum</th>
<th>Median</th>
<th>Minimum</th>
</tr>
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<tbody>
<tr>
<td>Little Windy Hill Lake</td>
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<td>1A</td>
<td>53.5</td>
<td>&gt;125 µm charcoal pieces</td>
<td>1735</td>
<td>20</td>
<td>1694</td>
<td>1651</td>
<td>1613</td>
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<td>2316</td>
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<td>69.5</td>
<td>&gt;125 µm charcoal pieces</td>
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<td>20</td>
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<td>3267</td>
<td>3218</td>
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<tr>
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<td>91.5</td>
<td>&gt;125 µm charcoal pieces</td>
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<td>20</td>
<td>5045</td>
<td>5010</td>
<td>4972</td>
<td></td>
</tr>
<tr>
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<td>105.5</td>
<td>&gt;125 µm charcoal pieces</td>
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<td>20</td>
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<td>5921</td>
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<td>126.5</td>
<td>&gt;125 µm charcoal pieces</td>
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<td>25</td>
<td>7566</td>
<td>7530</td>
<td>7506</td>
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<td>9888</td>
<td>9799</td>
<td>9709</td>
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<td>195</td>
<td>&gt;125 µm charcoal (0.12 mgC)</td>
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<td>10494</td>
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<td>834</td>
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<td>20</td>
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<td>n/a</td>
<td>n/a</td>
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<tr>
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<td>&gt;125 µm charcoal pieces</td>
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<tr>
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<td>7965</td>
<td>7953</td>
<td>7938</td>
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</tbody>
</table>

Note: UCI = University of California, Irvine (W. M. Keck Carbon Cycle Accelerator Mass Spectrometry [AMS] Laboratory).
* Out of order; not used.
recent droughts (Figure 3) but show evidence of multiple meters of drawdown during the mid-Holocene (Figures 3–5). Net erosion in uplands and small valleys produced alluvial terraces on the North Platte (Condon 2005), which is also consistent with large changes in riverflow regimes.

The current flow regime changes are both temperature related (e.g., increasing temperatures leading to early spring runoff) and precipitation related (e.g., decreasing winter precipitation reducing annual flow). The flow-regime trends are sensitive to the time period examined, but the regional temperature trend is consistent in sign and becomes stronger after 1948 and indicates that flow regimes could continue to shift (Stewart, Cayan, and Dettinger 2004). Even in the absence of any anthropogenic trends in the climate and river data, our Holocene results indicate that major shifts in hydrological regimes, although not frequent, have taken place in the North Platte watershed (Figure 4). The region, since settlement, therefore has not experienced the full range of possible drought severity, frequency, or duration that can result from variability intrinsic to the climate system. Our specific flow calculations are overly simplified, but Holocene flow reductions must have been greater than in 2002, when flows were reduced at Northgate by more than 75 percent (Table 1), because paleoshorelines were lower than historic levels (Figure 3) and associated with sufficient time for groundwater and base river flows to equilibrate to the climatic conditions (Figure 4).

The reductions have important implications for the allocation of river water. For example, the 1922 Laramie River Decree limited Colorado’s usage of the Laramie River (which joins the Platte substantially downstream of the Northgate gauge) to 15,500 acre-feet per year. However, if we apply the P – E anomalies estimated from the lake-level reconstructions to the 1,124 km² watershed of the Laramie River above Woods Landing, Wyoming (near the Colorado–Wyoming border and near Creedmore Lake) in the same way as for the Platte above Northgate (Table 1), we find that the Laramie River would also be reduced by much more than 15,500 acre-feet per year to ephemeral or zero flow. Such a reduction would enable Colorado to take all of the flow of the river (if any existed) and severely impact water use in municipalities, such as Laramie, Wyoming, where 50 percent of the water supply derives from the Laramie River.

The basis for the current legal allocations of the North Platte River, therefore, might not be applicable in the context of zero or near-zero flow, such as took place 5,000 to 8,000 years ago. The allocation of 1.28 million acre-feet to the state of Colorado over any consecutive ten-year period (per the Modified North Platte Decree of 2001) might account for annual variations within the system including short-term droughts, but our evidence shows that severe and persistent droughts have occurred over multiple decades to millennia. Such persistent aridity would prohibit the Colorado allocation over a ten-year time frame and similarly affect water delivery to the other states. Our results, therefore, confirm the importance of a ten-year reevaluation of the allocation of North Platte River water, as prescribed by the 2001 decree, because the hydrologic assumptions of the decree might not be met under climate conditions that differ from those of 1952 through 1999.

Ephemeral flows across the Wyoming portion of the North Platte River system would similarly have broad socioeconomic impact on cities and industries, such as Casper, Wyoming, where the regional fossil fuel industry is centered. Wyoming’s ability to produce enough coal, oil, and natural gas to account for 17.9 percent of energy produced in the United States, which is approximately as much as Texas and more than any other individual state or nation (U.S. Energy Information Administration 2009), depends on historic levels of availability of water (U.S. Department of Energy 2006). For example, industrial users of water in the Platte River Basin in Wyoming include Chevron Environmental Services, Conoco-Phillips, and BP North America, which together are permitted to use 8,366 gallons per minute for oil exploration, refining, and reclamation (Wyoming Water Development Commission 2009). Ephemeral river flows and low groundwater could substantially impact such uses. Our results indicate that contingency plans for future energy production, municipal uses, agriculture, and other societal sectors should therefore consider extreme possibilities, including persistent absence of major surface water flows. Indeed, the current inability of many federal reservoirs on the Great Plains to store water (Brikowski 2008) demonstrates that Holocene-based scenarios are not unwarranted.

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References


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