THESIS

THE ECOLOGY OF AN IRRIGATION SYSTEM:

WETLAND CREATION IN AN AGRICULTURAL LANDSCAPE

Submitted by

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ABSTRACT

THE ECOLOGY OF AN IRRIGATION SYSTEM:

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Irrigation has increased the agricultural productivity of the arid American West, but has also greatly altered the natural landscape. Irrigation canals transport water to 17 million ha of currently irrigated land. Because water is a limited resource in the west, and irrigated agriculture uses approximately 90% of all the water diverted from rivers, much attention has been paid to the efficiency of irrigation systems. Irrigation canals have been shown to leak up to 50% of the water they transport, affecting both groundwater recharge and return flows to rivers, though little work has been done documenting the ecological effects of irrigation canal seepage on wetland ecosystems. This study sought to identify the hydrologic processes linking canals and reservoirs to wetlands, identify the types of wetlands supported by irrigation canal seepage, and document the area of wetlands supported by irrigation within the service area of an irrigation company. All wetlands within the North Poudre Irrigation Company service area in Larimer County were mapped and their hydrologic source determined from visual clues. Groundwater monitoring wells were installed in wetlands adjacent to canals and reservoirs to identify the hydrologic influence of canal seepage on wetland hydrologic regime. To further demonstrate the hydrologic source of wetlands, stable oxygen isotopes were analyzed within wetlands and possible adjacent water sources. Vegetation characteristics and species percent composition was related to environmental variables to highlight the types of wetlands supported by an irrigation infrastructure. A total of 176 wetlands covering 652 ha were mapped, 92% of which were visually connected to the irrigation infrastructure. Wetland water tables fluctuated with adjacent canal flow, with increases in the water table when canals started transporting water, and decreases in water table depth during times when canals did not carry water. Isotopic data indicate that canal leakage is the hydrologic source for adjacent wetlands within the study area. The isotopic

signature of canal water matched that of wetlands closer to canals, with evaporatively enriched isotopic signatures in wetlands further from canals. Wetland vegetation composition was related to both salinity and groundwater depth, with salt flats dominated by *Atriplex spp.* forming in areas with high salinity, marsh communities dominated by *Typha latifolia and Schoenoplectus acutus* forming in areas with low salinity and deeper standing water, and meadow communities dominated by *Carex nebrascensis and Schoenoplectus pungens* forming in areas with low salinity and water tables closer to the ground surface. Though land conversion and water diversions have led to dramatic reductions in historic wetland area in some places, it is clear from this study that current agricultural landscapes create wetlands that rely on excess irrigation water for their hydrologic maintenance. Any future changes in irrigation practices or water distribution may have negative consequences on wetland ecosystems.

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1. INTRODUCTION

Early settlers of the American West relied on irrigation for agricultural productivity, diverting river water through small, hand dug canals to irrigate pastures and croplands (Morgan 1993). Because of the regional aridity in most intermountain basins, irrigation was necessary to support agriculture. As larger areas of land were settled, canals became larger and longer, and transported water further from rivers. By 1900, three million ha of land were irrigated across the west (Pisani 2002). This figure has grown to over 17 million ha of irrigated land today (Gollehon and Quinby 2000). Not only have irrigation canals enhanced the productivity of the American West, they have also greatly altered the landscape of the region (Morgan 1993).

Water in the American West is limited in availability and highly variable in timing. The majority of annual precipitation falls as snow in high mountain ranges during the winter, with large runoff events during the spring and small amounts of rain and runoff during the summer. Because evapotranspiration exceeds precipitation by ten times during the summer in many areas (Dunne and Leopold 1978), agricultural production for most crops west of the 100th meridian is limited to areas that can be irrigated. To accomplish this, water diversions capture peak river discharge in the spring and store it in reservoirs for use during the summer. The South Platte River, for example, originates on the eastern slope of the Colorado Rocky Mountains and has more than 1000 dams and reservoirs (Strange et al. 1999), as well as nearly 7,000 km of canals to transport and store spring runoff (Colorado Division of Water Resources, 2011). Because a portion of irrigation water returns to the river after it is diverted and can thus be “reused”, the amount of water diverted from the South Platte River exceeds annual river discharge. Irrigated agriculture accounts for 78% of water withdrawals and 90% of water consumption in the western United States (Western Water Policy Review Advisory Commission 1998), and contributes to 48% of the harvested US crop sales that are consumed all over the world (USDA 2001).

Irrigation canals across the American West are known to have water losses up to 50% due to leakage (Luckey and Cannia 2006). Negative impacts of water diversions on rivers are well documented (Strange et al 1999; de Fraiture et al. 2010), but the environmental changes created by irrigation canal leakage remain understudied (Wiener et al. 2008). Canal leakage may increase groundwater recharge (Kendy and Bredehoeft 2006), elevate regional groundwater tables (Harvey and Sibray 2001), and alter groundwater flows to increase return flow to rivers (Fernald and Guldan 2006). Although some authors have suggested a direct competition for water between irrigated agriculture and wetland ecosystems (de Voogt et al. 2000; Lemly et al. 2000; Brinson and Malvarez 2002), others have mentioned the possibility of canal leakage creating and maintaining wetland and riparian ecosystems (Kendy 2006; DiNatale et al. 2008), yet evidence for the connection between irrigation canal leakage and wetland creation remains anecdotal (Crifasi 2005), or based on inferences made from aerial photographs (Ekstein and Hygnstrom 1996).

Wetlands are an important part of a landscape, yet estimates of historical wetland loss due to land conversion in some western states range between 50 and 90% (Yuhas 1996). Due to the conveyance of water away from riparian corridors to upland areas, historical proportions of wetland types have also changed (Kath et al. 2010). Because wetlands provide habitat to a disproportionate number of animal species and perform essential ecosystem services related to water quantity and quality (Zedler 2003), the United States instituted a "no net loss" policy goal to keep the current acreage of wetlands from declining. As irrigation canals are a ubiquitous feature on the landscape of the American West and may alter wetland characteristics, understanding the influence of irrigation canals on the hydrologic regime of wetlands is necessary. The present study sought to answer three questions: (i) Are there hydrologic processes linking canals and reservoirs to wetlands, (ii) What types of wetlands are supported by irrigation canals, and (iii) What is the area of wetlands linked to irrigation within the service area of an irrigation company?

2. STUDY AREA

The study area is located in the South Platte River Basin on the plains and foothills north of Fort Collins, in Larimer and Weld Counties, Colorado (4501473 N, 492866 E). The area has an agricultural economy consisting mostly of irrigated hay pastures, and the raising of various high value crops (USDA 2009). The climate is semi-arid with mean annual precipitation of approximately 40 cm and an annual total potential evapotranspiration exceeding 100 cm. The majority of water in the region arrives as mountain snow, with snowmelt runoff in late spring and early summer. Most agricultural producers rely on water deliveries from river diversions for crop irrigation through the summer. The South Platte Basin supports 25% of Colorado's irrigated land and has an annual total water use of approximately 1.9×10^9 m^3.

North Poudre Irrigation Company (NPIC) is one of many irrigation water delivery companies in northern Colorado. NPIC has a total service area of 23,300 ha and delivers water to 9,700 ha of irrigated land utilizing 16 holding reservoirs and approximately 250 km of canals (Fig. 1), 89% of which are unlined earthen canals that have been in place for over a century. Water diverted from the North Fork and main stem of the Cache la Poudre River is transported through the canal system from April through September to upland areas away from river corridors. In 2010, NPIC diverted approximately 1.1×10^8 m^3 of water (89,400 acre feet), 45% of which was lost to evaporation and canal seepage (pers. comm. NPIC manager). Previously measured NPIC canal water losses ranged from 0% to 50% per canal (Riverside Technology, Inc. 2005).

3. METHODS

3.1 WETLAND MAPPING AND HYDROLOGY

3.1.1 Wetland Mapping

Wetlands were mapped using ArcMap 10.0. National Wetland Inventory maps from 1975 were refined using aerial images (i-cubed Nationwide Prime with 1 m resolution) as well as site visits during the summer of 2011. NPIC infrastructure layers were obtained from the Colorado Decision Support System as well as information specific to NPIC from the North Poudre Service Area Feasibility Study (Riverside Technology, Inc. 2005).

The hydrologic source of each mapped wetland was visually determined with aerial photographs by tracing surface water flow paths or subsurface flow paths as detected by increased primary productivity back to a source. Hydrologic sources included irrigation canal seepage, intentional water deliveries to wetlands created by the Colorado Division of Parks and Wildlife, tailwater from excess water applied to irrigated fields, outlets and dam seepage from ponds and reservoirs, and reservoir fringes. Wetlands that had no visible connection to a hydrologic source were separated into two categories based on whether they were uphill or downhill of adjacent irrigation canals.

For analysis, canals were classified according to the amount of water they typically lose using the previously measured percent water loss data for each NPIC canal (Riverside Technology, Inc. 2005): low loss (<7%), moderate loss (7-17%), and high loss (>17%). The Euclidean distance of each wetland to the nearest canal, as well as the elevation difference between canals and wetlands was determined using ArcMap 10.0.

3.1.2 Hydrologic Data Collection

A stratified sample of wetlands representing the most common types of wetlands in the study area were chosen for groundwater monitoring well installation. A total of 70 monitoring wells were installed in 20 wetlands that were chosen based on proximity to canals and reservoirs as well as landowner permission. One groundwater monitoring well was installed to represent a typical and homogenous portion of each vegetation community in each wetland. Wells were dug with a hand auger to approximately 1 m depth, cased with 1.5” schedule 40 PVC pipe with holes drilled approximately every 5 cm and backfilled with native soil. Both the top and bottom of the well were capped, with a hole drilled in the bottom cap to ensure water drainage from the well if the water table dropped below the casing. Water tables were measured approximately every two weeks from May through November 2011. Pressure transducers (In-Situ Rugged Troll 100) were installed in 6 monitoring wells, each in a different plant community and in different wetlands, to represent the most common plant communities across the landscape. Pressure transducers were hung with Rio Powerflex 0.016” 20lb Knottable Wire Bite Tippet to a depth of approximately one m below the ground surface to record hourly water table depths. One barometric pressure logger (In-Situ Baro Troll 100) was hung in a tree adjacent to a centrally located wetland to account for barometric pressure variations recorded by the water pressure transducers.

Daily canal flow through the summer of 2011 was estimated from the daily irrigation order records from NPIC customers along each canal. Though the actual amount of flow volume was determined by ditch riders each morning and may differ slightly from daily orders, the use of daily orders provided a realistic estimation of daily canal flow.

Precipitation data were collected from six precipitation stations in the Community Collaborative Rain, Hail & Snow Network (www.cocorahs.org). Daily precipitation amounts, collected and recorded by private landowners, were obtained for the measurement location nearest to each instrumented wetland.

3.2 ISOTOPIC ANALYSIS

Water samples for isotope analysis were collected in polyethylene bottles from wetlands, canals, and rainstorm events during the summer of 2011. Groundwater samples from 40 wetlands were collected by digging a hole approximately 10 cm deep and allowing the inflowing water to fill the bottle. Wetland water samples were paired with canal water samples collected from the nearest canal by emersion of the bottle into the canal. Rain samples were collected during storm events in June, July, and August 2011 until the bottle was full or rain ceased falling. After collection, each bottle was sealed with a screw cap and parafilm, and stored in a 37° F refrigerator until processed. All samples were processed within one month of collection.

The stable oxygen isotope ratio (δ^{18}O) of all water samples was determined by CO_2 equilibration using a VG Microgas Injector coupled to a VG Optima Isotope Ratio Mass Spectrometer (Natural Resource Ecology Laboratory, Colorado State University, Fort Collins). δ^{18}O results are reported as parts per thousand (‰) using the δ notation as follows:

$$\delta^{18}\mathrm{O}(‰) = [(R_{sample} / R_{standard}) - 1] \times 1000$$

where R_{sample} and $R_{standard}$ are the molar abundance ratios (^{18}O/^{16}O) of the sample and Vienna Standard Mean Ocean Water, respectively (Clark and Fritz, 1997). More negative δ^{18}O values indicate higher amounts of lighter isotopes, while more positive values indicate evaporative enrichment of heavier isotopes in sampled water, relative to the standard. Because water subjected to higher rates of evaporation has more positive δ^{18}O values (Kray et al. 2012), wetlands sustained by canal seepage closer to the canal will have similar isotopic signatures to the adjacent canal water than wetlands further away.

Electrical conductivity (EC) for each wetland instrumented with monitoring wells was taken as a proxy for salinity (Rhoades et al. 1999). The electrical conductivity of each groundwater monitoring well was measured in August, 2011 using a Hach CO150 Conductivity Meter. EC measurements were taken by inserting the electrode far enough into the well to be submerged in the ground water.

3.3 VEGETATION

Vegetation was characterized in ArcMAP 10.0 using aerial images (i-cubed Nationwide Prime with 1 m resolution) for every wetland in the study area. Because aerial images were not precise enough to identify vegetation to the species level, vegetation was separated into three categories within each wetland. "Marsh" communities contained at least seasonally standing water and were dominated by *Typha latifolia* and/or *Schoenoplectus acutus,* visible in the image as tall, dense vegetation. "Meadow" communities represented areas dominated by sedges such as *Carex nebrascensis* and other herbaceous species such as *Schoenoplectus pungens,* and were visible as shorter stands of dense vegetation. "Salt flats" had sparse vegetation adapted to highly saline conditions caused by evaporative upflux, often dominated by *Atriplex* spp*.,* and were visible due to the presence of white salt on the land surface*.* Each community was mapped with aerial images, and ground-truthed with site visits to each wetland during the summer of 2011.

At each wetland fitted with groundwater monitoring wells, vegetation composition at the species level was also analyzed. Within a 2 m radius of each well, the percent canopy cover of each species was visually estimated.

3.4 STATISTICAL ANALYSIS

Wetland groundwater table decline was related to canal flow using linear regression in SigmaPlot 10.0. The midnight reading from the pressure transducer was used for each day's water table depth and was related to a 7-day running average of the adjacent canal flow. The lag time between the water table depth and the canal flow was calculated by identifying the point when the water table started to drop and the canal flow started to decline. To ensure the correct lag time between water table and canal flow decline, corresponding dates of wetland and canal flow decline were varied four days on either side, with the final lag time having the highest r^2. An 8-day window was deemed appropriate to allow for the correct determination of the date of water decline.

Wetland, canal and rain $\delta^{18}O$ were compared with a Kolmogrov-Smirnov test using SAS, as the data failed the normality and equality of variance assumptions of associated parametric tests. Wetland and canal $\delta^{18}O$ were related using linear regression. Wetland $\delta^{18}O$ was related to the distance of each wetland from the adjacent canal using linear regression to determine if there was a linear change in isotopic signature with distance from the adjacent canal.

Canonical correspondence analysis (CCA) was used to relate vegetation plot floristic composition to measured environmental variables (ter Braak and Smilauer 1998) using PC-ORD 5.10 (McCune and Mefford 2006). Environmental variables included plot distance from canal, plot distance from uphill wetland edge, elevation below the canal, average, median, and maximum adjacent daily canal flow, number of days the adjacent canal transported water during the 2011 irrigation season, average, median, minimum, maximum, and standard deviation water table depth recorded in the monitoring well for that plot, and electrical conductivity.

4. RESULTS

4.1 CANAL PHYSICAL AND HYDROLOGIC CHARACTERISTICS

Of the 250 km of canals within the study area, 223.4 km (89.2%) were unlined earth, 7.1 km (2.8%) were concrete lined, 4.0 km (1.6%) were rock lined, and 15.9 (6.3%) km were piped underground. Small canals transported water for as little as 8 days during the irrigation season and had maximum flows of 2 m^3/s. Many large canals carried water every day with maximum flows of 24 m^3/s. According to previously measured canal water loss data, 127 km (50.6%) of canals had high percent water loss greater than 17%, 91.5 km (36.5%) had moderate water loss between 7% and 17%, and 32.2 km (12.8%) had low water loss less than 7% (Table 2).

4.2 WETLAND MAPPING

A total of 176 wetlands covering 652.3 ha were mapped within the NPIC boundary (Table 1). Of these, 56 wetlands covering 173.7 ha were associated with irrigation canal leakage. The majority of wetlands associated with canals were below high water loss canals with percent water losses greater than 17%. Seventeen wetlands were below canals with moderate water loss and only 3 wetlands were located downhill of canals with percent water losses less than 7%. Along with canal seepage, pond and reservoir dam seepage was a major hydrologic source for wetlands, sustaining 52 wetlands totaling 186.7 ha. Wetlands created for wildlife with intentional water deliveries totaled 98.5 ha. Wetlands located on the fringes of reservoirs totaled 128.1 ha. Tail water from excess irrigation application was a hydrologic source for 7 different wetlands. The source of 18 wetlands totaling 51.1 ha could not be visibly detected, though all were located below irrigation canals. Only two wetlands, combining for 1.1 ha, were located in ephemeral stream channels directly adjacent and uphill from an irrigation canal. Within the study area, agricultural water storage, conveyance losses, and application were visually attributable for 89% of the number of wetlands, and 92% of the total wetland area.

4.3 HYDROLOGIC PROCESSES IN CANALS AND WETLANDS

Wetland water table depths adjacent to canals with high water loss were heavily influenced by changes in canal flow (Table 2). The highest wetland water table depth change recorded from when a canal was flowing to when it stopped flowing was 131.4 cm. Only one wetland adjacent to high water loss canals did not have water table depths that responded to adjacent canal flow. Though water visibly came from the canal, this wetland was located in an artificially impounded depression which kept the water table at a consistent depth through the summer. Both instrumented wetlands adjacent to low water loss canals fluctuated with adjacent canal flow. The largest water table change adjacent to low water loss canals was 83 cm. All three wetlands adjacent to canals with moderate water loss did not have fluctuating water levels with adjacent canal flow. Instrumented wetlands located below ponds or reservoirs had stable water table depths through the year.

Though most groundwater monitoring wells were not installed prior to irrigation canal transport of water in the spring, a large response was measured when the canals ceased transporting water in the fall. The Buckeye Main canal recorded the highest flows through the irrigation season and groundwater levels increased in a wetland adjacent to it as flow increased throughout the summer, and declined by 60 cm once the canal ceased to carry water (Figure 2). The water table decline in the *C. nebrascensis* community was significantly correlated to the canal flow decline, with a 50 day lag between the flow in the canal and the response in the groundwater table (Figure 3, $r^2 = 0.9141$, $P < 0.0001$). Wetland water table depths were not responsive to precipitation.

Wetland water table response to changes in adjacent canal flow can be characterized with examples from four sites (Figure 4). Wetlands adjacent to both the Munroe and Livermore canals, two canals diverted directly from the Cache la Poudre River with consistent daily flow and estimated water losses of 20%, showed rising water tables once the canals started flowing, and decreasing water tables once the canals ceased transporting water (Figure 4a). Wetlands adjacent to smaller canals that flowed intermittently had fluctuating water tables corresponding to times when the canal was flowing (Figure 4c), with increasing water levels when the canal flowed, and declining water tables when the canal was dry. One particular wetland responded more to irrigation application than it did to adjacent canal flow. The water table in this wetland rose rapidly on days when the landowner applied water to the irrigated pasture adjacent to the wetland (Figure 4b). While the majority of wetlands instrumented with groundwater monitoring wells adjacent to canals had water tables that fluctuated with canal flow, the water table in four wetlands did not respond to changes in adjacent canal flow (Figure 4d).

4.4 WETLAND AND CANAL ISOTOPIC ANALYSIS

Rain samples collected during the summer of 2011 had an average $\delta^{18}O$ of -0.30, and ranged from -6.69 to +9.70 (Figure 5). Canal water had an average $\delta^{18}O$ of -16.50 and ranged from -19.09 to -2.78. Wetland ground water had an average $\delta^{18}O$ of -15.00 and ranged from -19.07 to -5.14. Differences between all three groups were statistically significant ($P < 0.05$).

Wetland $\delta^{18}O$ values were weakly associated with the paired canal $\delta^{18}O$ values (Figure 6a, $r^2 = 0.2874$ $P = 0.0005$). However, wetland $\delta^{18}O$ values within distinct topographic drainages were highly significantly correlated to distance from the adjacent canal (Figure 6b), with different rates of evaporative enrichment of $\delta^{18}O$ for each drainage as distance from the canal increased.

4.5 VEGETATION

Within the study area 43% (279 ha) of the wetland area was marsh, 40% (263 ha) meadow and 17% (111 ha) salt flats. Canonical Correspondence Analysis of plot vegetation composition data indicated the importance of hydrologic variables and ground water salinity in driving variation in wetland vegetation. The analysis revealed a gradient from stands dominated by *Atriplex* spp. and *Triglochum maritima* in salt flats on the left side of the ordination space, to stands dominated by *Typha* *latifolia* in marshes on the lower right side of the ordination space and stands dominated by *Eleocharis macrostachya, Schoenoplectus pungens, Carex nebrascensis,* and *Juncus arcticus* located in wet meadows on the upper right side of the ordination space (Figure 7). Total variance in the species ordination was 9.89 standard deviation units, the eigenvalue of Axis 1 was 0.768, and 0.412 for Axis 3. Axis 1 was negatively correlated with electrical conductivity ($r = -0.887$). Salt flats with higher electrical conductivities occurred on the left side of the ordination space, while marsh and wet meadow sites with lower electrical conductivities occurred on the right. Axis 3 was negatively correlated to wetland hydrologic variables, including the highest recorded water table depth ($r = -0.704$), and the average water table depth ($r =-0.611$), with higher water tables located at the bottom of the plot. Marsh plots were located in areas with higher water tables, while wet meadow plots were located in areas with water tables closer to the ground surface. The standard deviation of the recorded water table depth was also negatively correlated with Axis 1 ($r = -0.464$), with more variable water tables located on the left side of the ordination space.

5. DISCUSSION

The functions of agricultural ditches running through areas already saturated and those traveling across arid land are fundamentally different. For already saturated land, ditches are used to lower water tables and manipulate it for the benefit of crops (Krause et al. 2007). In arid and semi-arid regions ditches are used to convey water from river corridors, ground water pumping stations, and reservoirs to uplands where it is applied to arid lands. In 1990, 2.2×10^{11} m^3 (180 million acre-feet) of water were diverted from rivers in the American West (Western Water Policy Review Advisory Commission, 1998), approximately 80% of which was diverted for agricultural purposes (DiNatale et al. 2008). Although intended to irrigate arid lands to produce livestock forage and crops, not all diverted water is consumptively used by plants (Fernald et al. 2010). The remaining water recharges alluvial aquifers (Kendy and Bredehoeft 2006), or is returned to rivers as overland flow or shallow groundwater (Fernald and Guldan 2006), creating wetlands along the way (Kendy 2006).

Reservoirs that hold water for dry years are a common feature in many arid regions, with over 12,750 reservoirs in Colorado alone (Colorado Division of Water Resources, 2011). The transport of water from streams and reservoirs in irrigation canals and ditches, some with seepage rates exceeding 50% (Luckey and Cannia 2006), and the excessive amount of water applied to some irrigated fields (Fernald et al. 2010) has resulted in the unintentional creation of a wide range of wetland types in many parts of the western US. Though some authors suggest that competition for water occurs between wetlands and agriculture (Lemly et al. 2000), irrigated agriculture appears to have played an important role in the redistribution of water and the creation and maintenance of a large proportion of the total wetland area in many western landscapes (Peck et al. 2001).

Wetland response to canal seepage

Though agriculturalists have become increasingly more efficient in their water use, with estimates as high as 90% (USDA 2001), Fernald et al. (2010) demonstrated that only seven percent of water diverted from the Rio Grande in one agricultural system of New Mexico was consumptively used by crops. The majority of water not consumed by crops in many irrigation systems seeps out of canals (Luckey and Cannia 2006), or runs off irrigated fields as excess water (Fernald et al. 2010). The present study demonstrated the importance of this excess water in creating and maintaining wetland ecosystems. The hydrologic and geochemical methods used in this study highlighted the direct coupling between irrigation canals with high water loss and wetland hydrologic regime. These findings are corroborated by other studies that found increases in local water tables during the irrigation season (Kendy et al. 2004), with subsequent declines when canals ceased transporting water (Fernald and Guldan 2006). Canal seepage has also been shown to be of international importance when the lining of the All-American Canal in the American southwest resulted in aquifer declines in Mexico (Hayes 1991) leading to detrimental impacts to both Mexican farmers and wetland ecosystems (Reis 2008).

Non-riparian wetlands have groundwater as a primary water source (Mitsch and Gosselink 2000) and are generally independent of precipitation in arid regions (Laubhan 2004). Kendy et al. (2004) found that changes in groundwater had large impacts on wetland ecosystems. This is consistent with results from this study showing that high rates of canal seepage led to groundwater level rises in wetlands when canals were transporting water, and little influence of precipitation events on wetland water levels. Although some wetlands at distances exceeding 1 km from canals in the NPIC study area could not be visually linked hydrologically to canals, Wurster et al. (2003) found that wetlands were surface expressions of the water table, and could be linked to ground water recharge by streams many kilometers away. Canals may therefore act analogously to streams in arid regions (Wiener et al. 2008), and influence or control water table position through hyporheic flow (Francis et al. 2010). Because canal seepage can raise local water tables (Harvey and Sibray 2001), the current wetland distribution in many agricultural areas is likely a function of the location and functioning of the irrigation infrastructure (Kendy 2006).

The use of stable isotopic signatures to identify wetland water sources

The evaporative enrichment of $\delta^{18}O$ in water as it leaked from canals and flowed as surface and groundwater away from canals identified irrigation canal seepage as the primary source of water for wetlands, and influenced wetlands over 2 km away. Stable isotopes are an important tool in many environmental studies, and have been used to identify the impact of water from the Everglades on municipal water supplies in Florida (Wilcox et al. 2004), the extent of water leakage in a landslide dam in Italy (Petitta et al. 2010), and to successfully quantify irrigation canal leakage in Nebraska (Harvey and Sibray 2001). Isotope ratios were similar between canals and wetland waters adjacent to the canal, with a linear enrichment of heavier isotopes as water moved through wetlands further from canals. These results are consistent with other studies showing evaporative enrichment in wetlands as the distance from their recharge source increased (Wurster et al. 2003). The use of stable isotopes remains a key tool in identifying the connections to and impacts of water management on wetland ecosystems.

Wetland types supported by irrigation

The hydrologic regime is often identified as the key determinant of wetland structure and function (Mitsch and Gosselink 2000). This study has highlighted the importance of canal seepage in influencing the hydrologic regime of wetlands, and its control over the types and functions of wetlands in an agricultural landscape. Wetlands can be formed by the impoundment of agricultural water (Rumble et al. 2004) and can increase habitat for migratory birds (Erwin 2000). However, many impoundments can be dominated by exotic plant species with fewer ecological benefits (Anteau 2012) and are often the type of wetland created in lieu of meadows and other more uncommon wetland types (Kath et al. 2010). Similar to previous accounts (Crifasi 2005) many wetlands in this study were found on hill slopes directly below irrigation canals, and were dominated by wet meadow plant species, including members of the genera *Juncus* and *Carex*. Slope wetlands are often the first wetland type to be lost due to land use change (Skalbeck et al. 2008), but are thought to support high biodiversity (Stein et al. 2004), and may be some of the more resistant wetlands to future climate change (Winter 2000). Wetlands that have been created by irrigation water may be indistinguishable in form and floristic composition from wetlands with more natural water sources (Peck and Lovvorn 2001) and may provide greater ecosystem services due to their longer hydroperiods (Kendy 2006), such as biodiversity support (Rumble et al. 2004), flood abatement (Zedler 2003) and water quality improvements (Fennessy and Craft 2011).

Land use changes and river diversions have led to historical wetland losses (Yuhas 1996), but the complete restoration of natural hydrologic regimes in human dominated landscapes is not feasible (Strange et al. 1999). Because wetlands in agricultural landscapes are directly controlled by irrigation practices, wetland conservation in these areas necessitates an understanding of the complex hydrologic interactions between irrigated lands and wetlands (Lovvorn and Hart 2004). Irrigation canals in some areas may function analogously to important riparian habitat (DiNatale et al. 2008) and provide refuge for threatened species (Crifasi 2005). Along with vegetation along the canal, water seepage from canals creates important habitat (Wiener et al. 2008). Lining canals, transferring irrigation water to cities, or altering current irrigation practices in the name of increased efficiency, could have detrimental impacts on both wetland functions (Fernald and Guldan 2006) and biodiversity (DiNatale et al. 2008).

6. CONCLUSIONS

Water in the American West is a limited resource, and its use is contentious between agriculture, growing municipalities, and the environment. Though agricultural practices are often viewed as inefficient, large wetland complexes are maintained through seepage from canals and pond and reservoir dams, tailwater from irrigated fields, as well as through interactions with shallow aquifers. Hydrologic data and stable oxygen isotope comparisons were essential to identify canal seepage as a primary water source that determines agricultural wetland characteristics and hydrologic regimes. As many rivers in Colorado are augmented by trans-basin water transfers, wetland acreage has likely increased in some basins due to irrigated agriculture and declined in others due to the diversions. Because water quality and biodiversity support are growing concerns in many landscapes, future work should focus on the functions and services of agricultural wetlands, as well comparisons between the location of historic wetlands and those currently in existence. Water transfers and changing agricultural practices to increase water efficiency put existing wetlands at risk, necessitating an understanding of policy and management implications on agricultural wetland ecosystems. Results from studies such as this could be used to identify and prioritize specific wetland complexes to focus our preservation efforts. Current wetlands may only be as permanent as the irrigation practices that sustain them.

7. TABLES AND FIGURES

Table 1. Census of mapped wetland attributes corresponding to their hydrologic source. Canals are separated by percent water loss as previously measured from Riverside, Inc. The number of wetlands, the total wetland area, average distance to the source, and average height to the source are reported for each infrastructure category. "Intentional Water Delivery" refers to managed wetlands with water deliveries. The hydrologic source for 18 wetlands located below multiple irrigation canals could not be determined, and are reported as "unknown source, below canal." Only two wetlands were located above irrigation canals. "Tail water" refers to wetlands located at the low point of irrigated fields. "Pond/reservoir outlet" refers to wetlands downhill of ponds or reservoirs. "Reservoir Fringe" refers to wetlands along the banks of NPIC reservoirs.

Wetland hydrologic source	Number of Wetlands	Total Wetland Area (ha)	Average Wetland Size (ha)	Average Distance to Canal (m)	Average Height to Canal Bank (m)
<7% Loss Canal	3	7.1	2.4	85.6	6.9
7-17% Loss Canal	17	31.8	1.9	42.6	3.7
>17% Loss Canal	36	134.8	3.7	151.4	4.6
Intentional Water Delivery	12	98.5	8.2	664.9	9.4
Unknown Source, Below Canal	18	51.1	2.8	1313.7	13.1
Above Canal	2	1.1	0.5	0	-0.3
Tail Water	7	13.1	1.9	-----	-----
Pond/Reservoir Outlet	52	186.7	3.6	-----	-----
Reservoir Fringe	29	128.1	4.5	-----	-----

Table 2. Hydrologic characteristics of NPIC canals and reservoirs as well as the instrumented wetlands associated with them. The length of each canal and the percent of total canals are reported for each canal percent loss category as well as the total surface area of ponds and reservoirs. Data for specific canals having instrumented wetlands adjacent to them within each category include their average daily flow and the number of days they had flowing water. Characteristics of the instrumented wetlands associated with each category include the distance and height to the associated canal, as well as the wetland water table response to the stopping of the adjacent canal flow.

Infrastructure Category	Category Amount	Canals			Instrumented Wetlands		
		Name	Average Daily Flow (m^3/s)	Flow Days	Distance to Source (m)	Height to Source (m)	Water Table Change (cm)
< 7% Loss	32.2 km 13% of total	Lower #1	0.8	85	13.5	3.7	83
					135	5.8	50.6
7 - 17% Loss	91.5km 36 % of total	Lower 10	2	102	30.2	3.7	None
		Upper 10	0.9	78	9.8	2.4	None
					41.7	4.6	None
> 17% Loss	127km 51% of total	Buckeye	12.5	122	16.6	2.1	103.6
		Livermore	2.4	177	13.2	5.5	14.6
					10.3	2.7	12.4
					6.8	2.4	17.7
					10.7	2.7	51.3
					11.7	3.4	None
		Munroe	3.4	142	50	6.1	131.4
					58.8	4	59.3
					23.9	4.3	102.7
					70	1.8	120.5
					15.7	4.3	52.7
Pond/Reservoir	1571.2 ha	-----	-----	-----	16.4	3	None
					20.8	4.6	None
					49.4	4.9	None

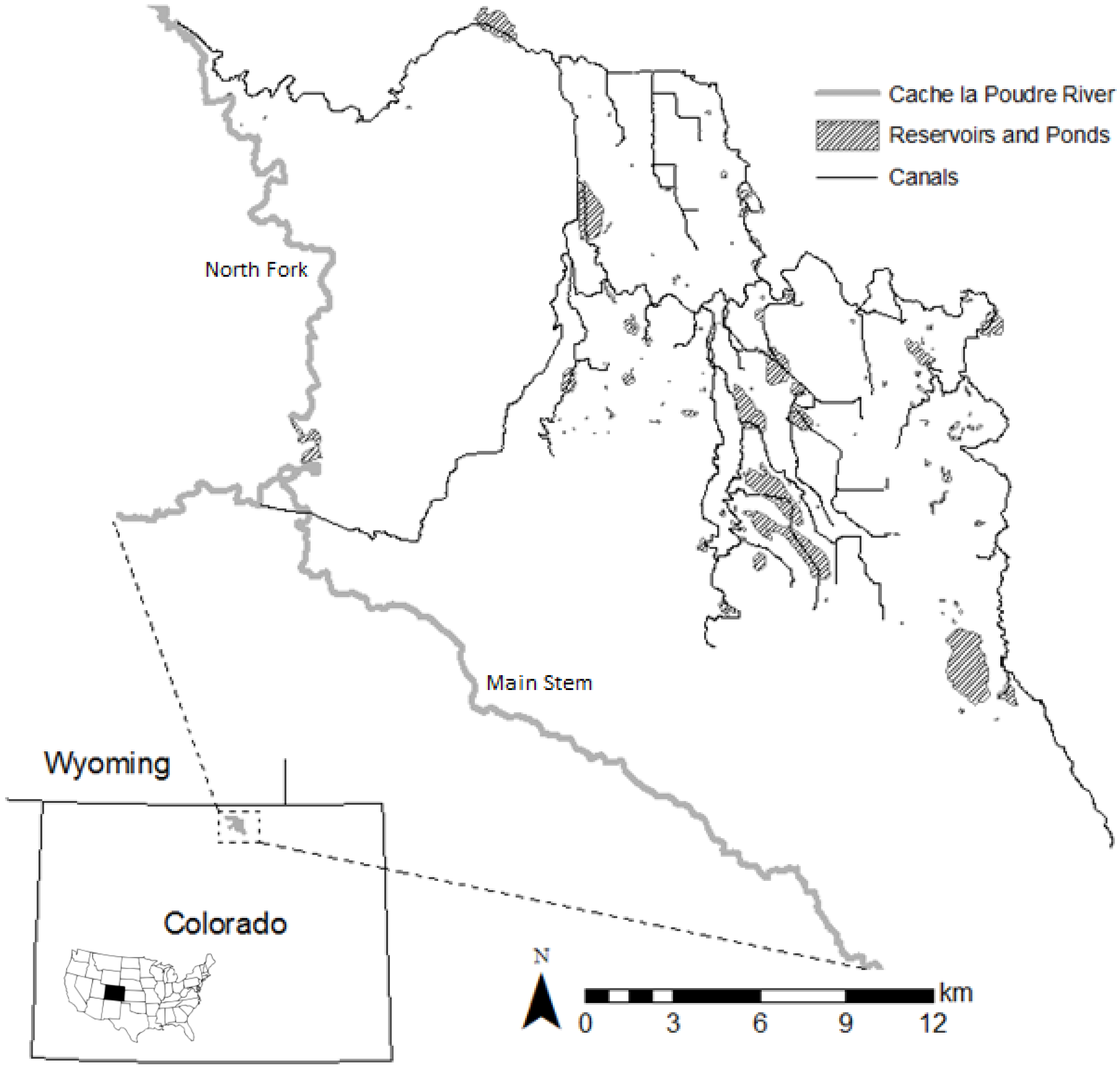

Figure 1. Study area map of North Poudre Irrigation Company canals and reservoirs adjacent to the Cache la Poudre river in northern Colorado.

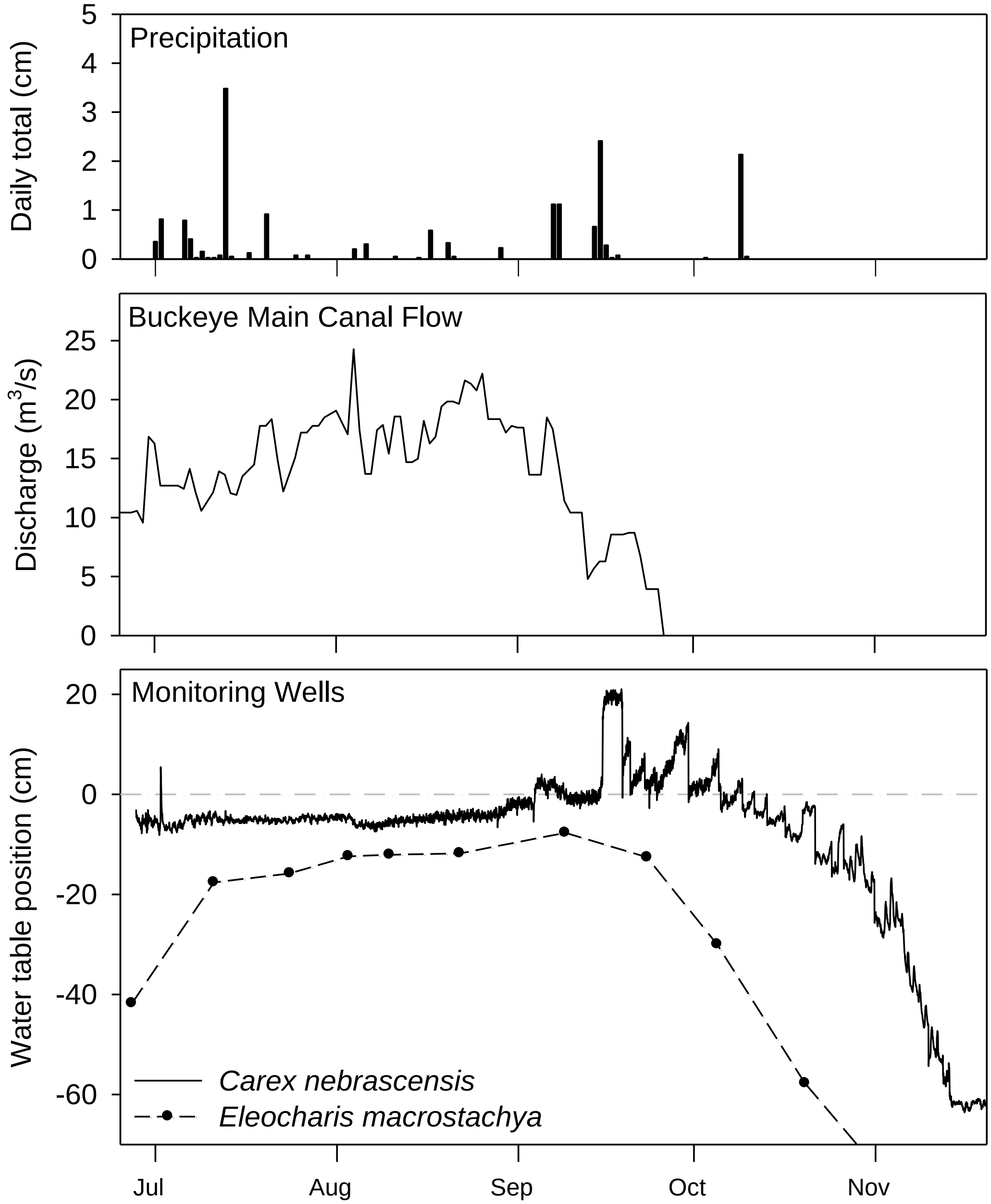

Figure 2. The effect of daily precipitation and adjacent canal flow on water tables from one wetland. Monitoring wells were located in two vegetation communities in a wetland adjacent to the Buckeye Main canal during the summer of 2011. The dominant plant species occurring at each well is used as that well's name. Water levels represent hourly data within a *Carex nebrascensis* community (solid line) and bi-weekly data within an *Eleocharis macrostachya* community (dashed line). Points along the dashed line represent specific measurements. A 50 day lag occurred between the declining flow in the canal and the declining groundwater level for the *C. nebrascensis* community, with a shorter lag for the *E. macrostachya* community.

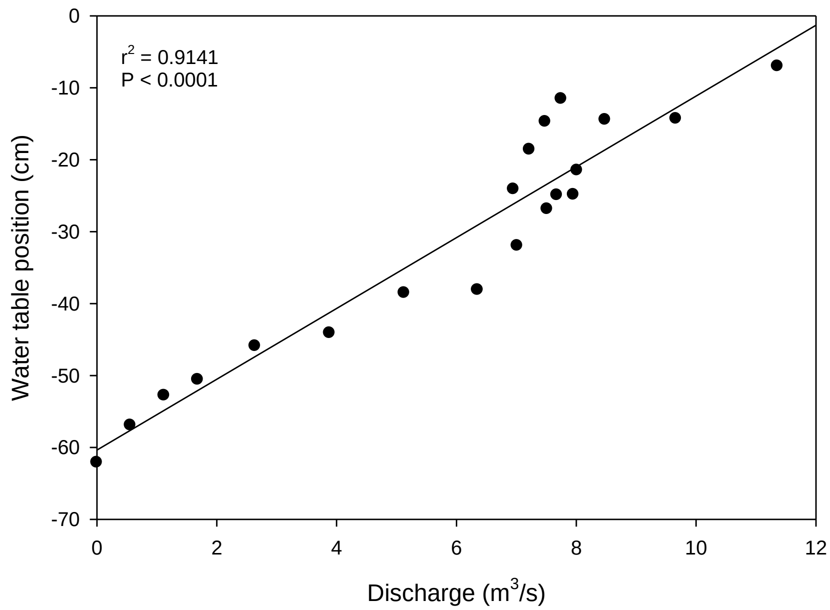

Figure 3. Regression of the wetland water table and canal flow from the site depicted in Figure 2 (r^2 = 0.9141, P < 0.0001). Due to the lag time between the decline of the canal and the response of the wetland water table, the water table data is offset by 50 days for this analysis. As leakage from canal flow for one particular day will be attenuated by the time that water reaches the wetland, a 7 day running average of canal flow is represented here.

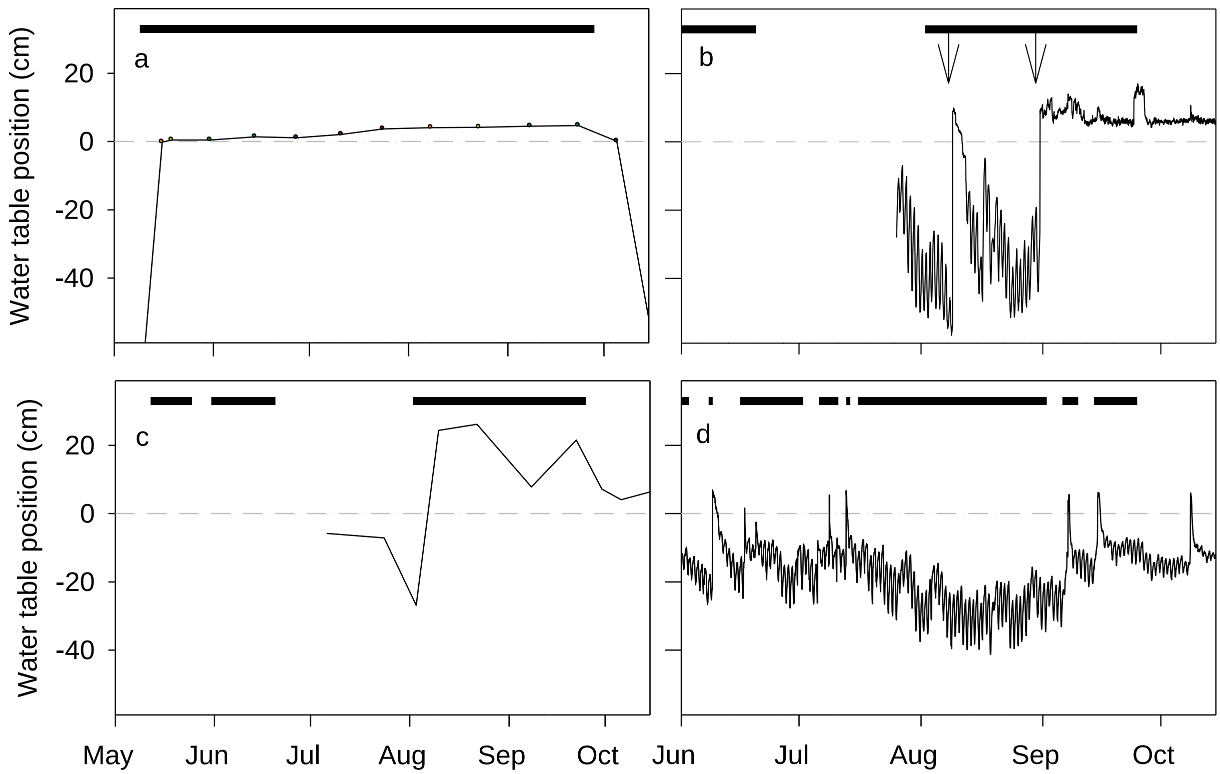

Figure 4. Four types of wetland water table position response to adjacent canal flow from four different wetlands. Straight thick lines represent days when adjacent canals had flowing water over the study period. Thin lines represent groundwater depths in a monitoring well for a specific vegetation community type. (a) *Carex* nebrascensis community adjacent to a daily flowing canal. (b) *Scirpus nevadensis* community located within an irrigated pasture. Downward arrows represent times when the landowner applied water to the pasture. (c) *Typha latifolia* community adjacent to an intermittently flowing canal. (d) *Shoenoplectus pungens* community adjacent to a near daily flowing canal.

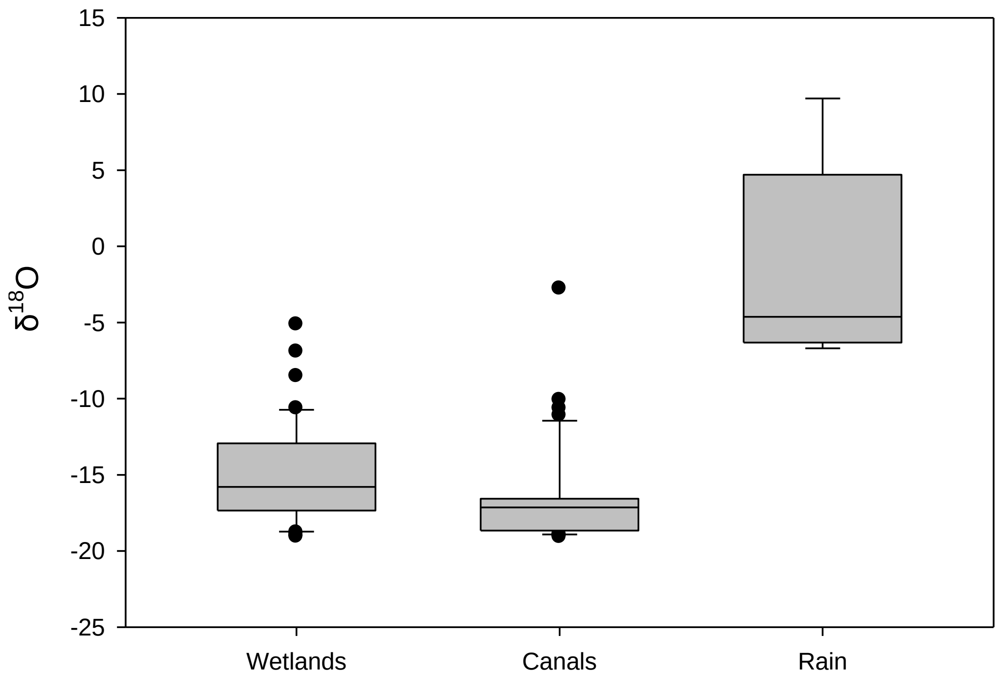

Figure 5. Stable Oxygen isotopic ratio summary data for wetlands, canals, and rain. Though rain $\delta^{18}O$ was markedly higher than the $\delta^{18}O$ for either canals or wetlands, all three were significantly different at $P < 0.05$.

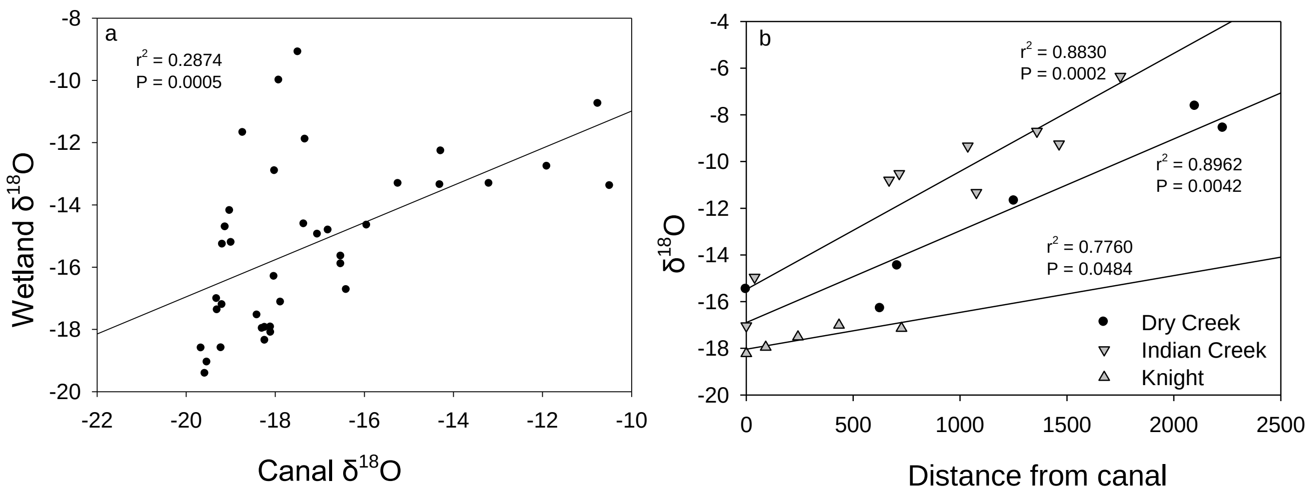

Figure 6. Stable oxygen isotopic ratio comparison between wetlands and canals. (a) Wetland $\delta^{18}O$ as a function of canal $\delta^{18}O$ for July 2011. (b) Wetlands are separated into distinct topographic drainages with $\delta^{18}O$ values as a function of distance from the nearest uphill canal. Canal $\delta^{18}O$ for each drainage is shown at distance 0. Evaporative isotopic enrichment within each drainage was significantly related to distance from the adjacent canal.

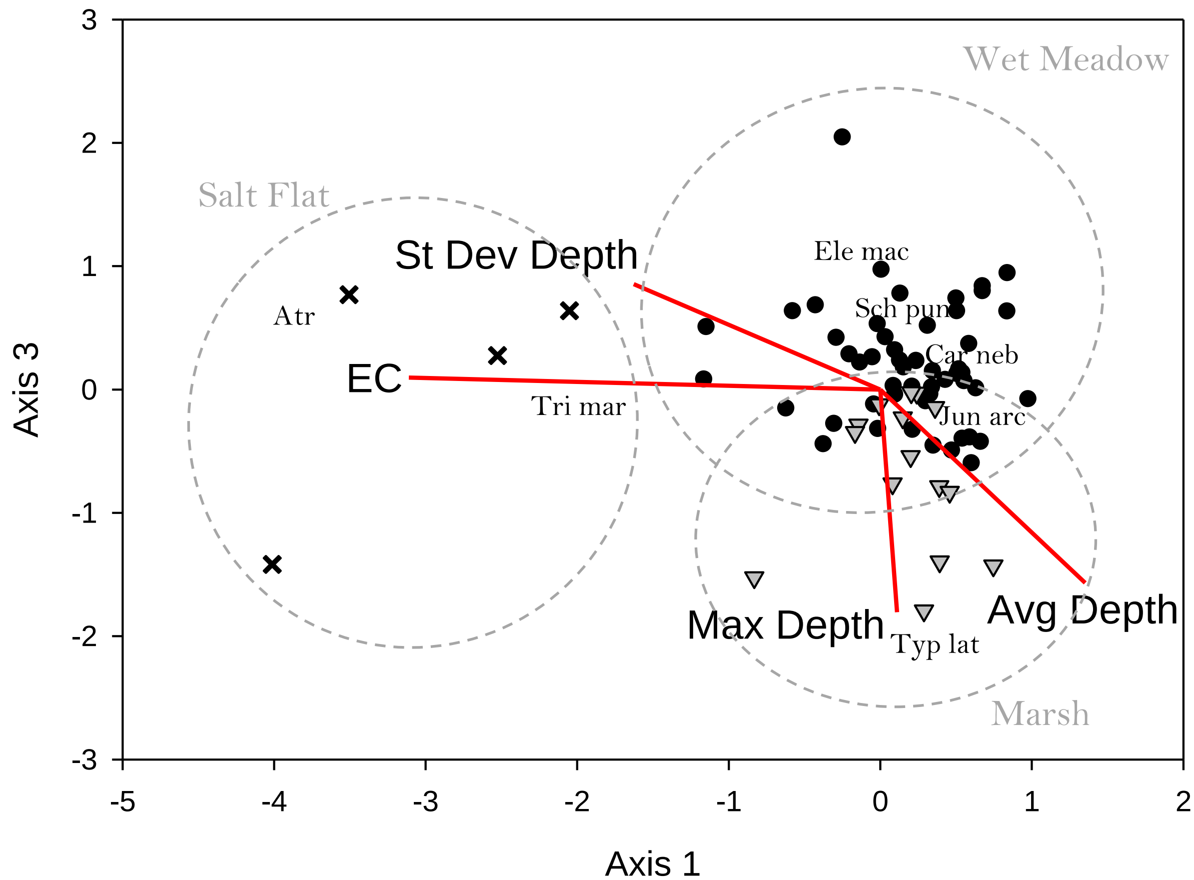

Figure 7. Canonical Correspondence Analysis for vegetation plots. Lines represent environmental variables, with the length of each line proportional to its effect on species distribution. "Average depth" is the average water table depth measured over the course of the summer for that plot. "Max depth" is the highest recorded water table depth. "St Dev Depth" is the standard deviation of the water table depth over the course of the summer. "EC" is the electrical conductivity of the water as measured in each groundwater monitoring well for each plot. Dashed circles outline plots that fall into each of the three vegetation communities mapped. "Salt" outlines those plots that were located within salt flats, denoted by the x. Salt flats represented 17% of the total wetland area mapped. "Marsh" outlines plots that were within a marsh community, denoted by grey inverse triangles. Marsh communities represented 43% of the total wetlands area mapped. "Meadow" outlines plots that were within a meadow community, denoted by black circles. Meadow communities represented 40% of the total wetland area mapped. Seven of the most common plant species are included. *Atriplex* (Atr), *Triglochum maritima* (Tri mar), *Typha latifolia* (Typ lat), *Juncus arcticus* (Jun arc), *Carex nebrascensis* (Car neb), *Schoenoplectus pungens* (Sch pun), and *Eleocharis macrostachya* (Ele mac).

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9. APPENDICES

APPENDIX A. Wetland Hydrograph Comparisons to Canal Discharge and Precipitation

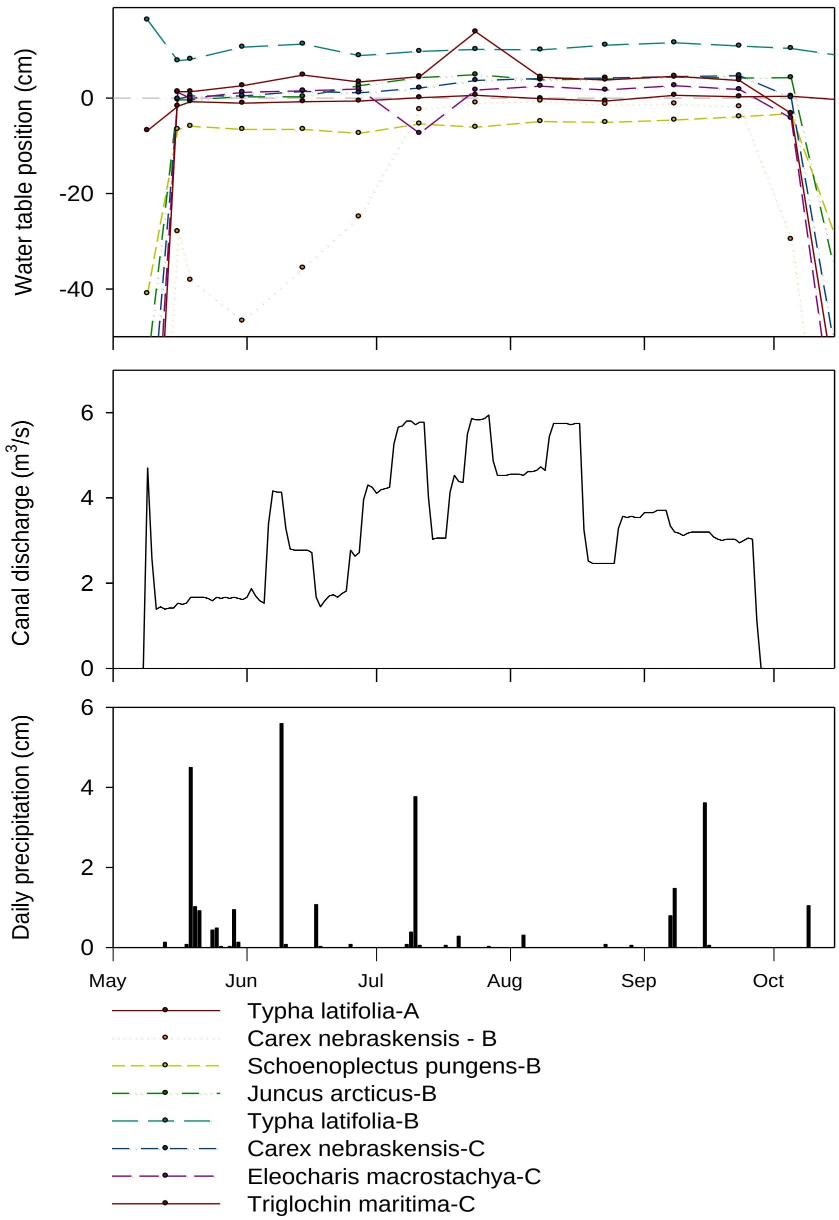

Figure A1. Upper Plot: Water level in 8 monitoring wells in a wetland adjacent to the Munroe canal. The name of each well refers to the dominant plant species occurring at that well. Three distinct drainages are part of this wetland, denoted here by (a), (b), and (c). The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Munroe canal. Lower Plot: Daily precipitation.

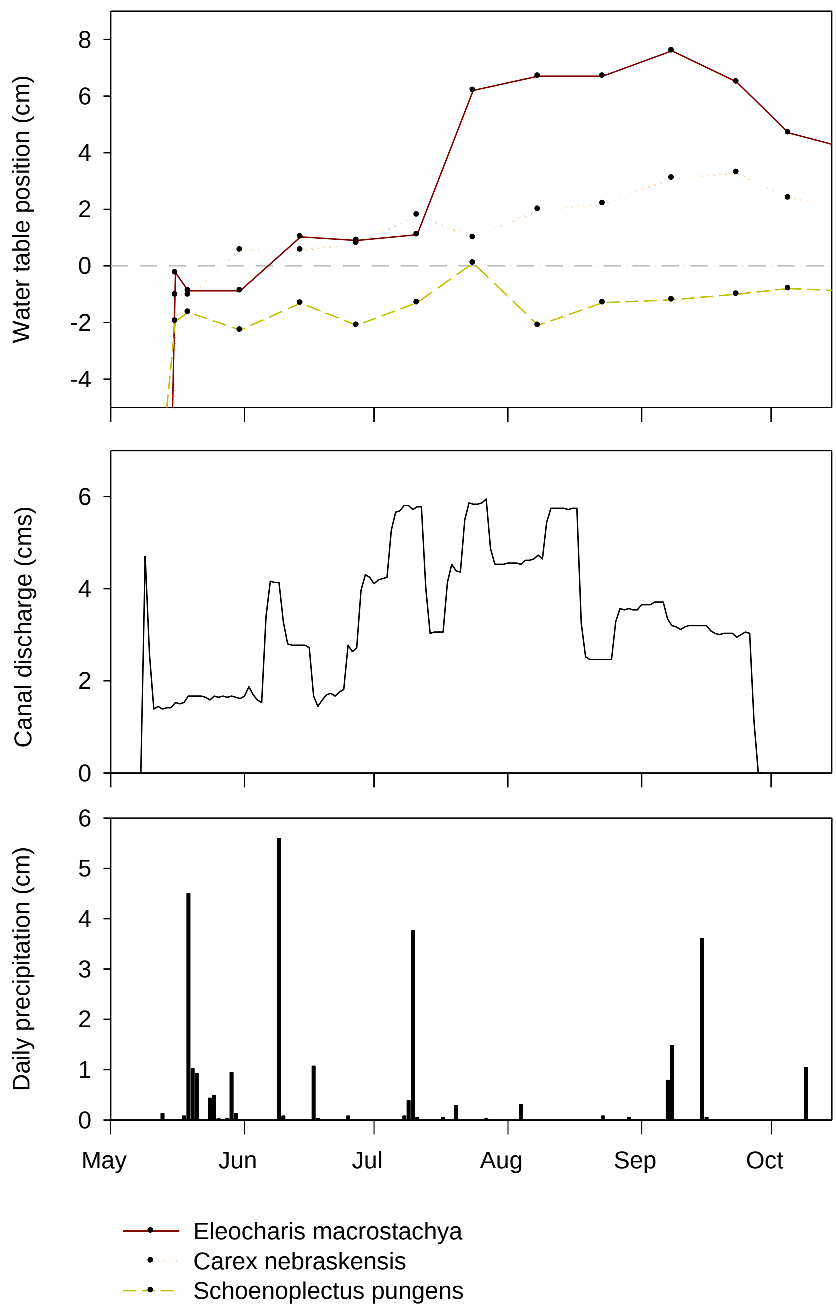

Figure A2. Upper Plot: Water level in 3 monitoring wells in a wetland adjacent to the Munroe canal. The name of each well refers to the dominant plant species occurring at that well. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Munroe canal. Lower Plot: Daily precipitation.

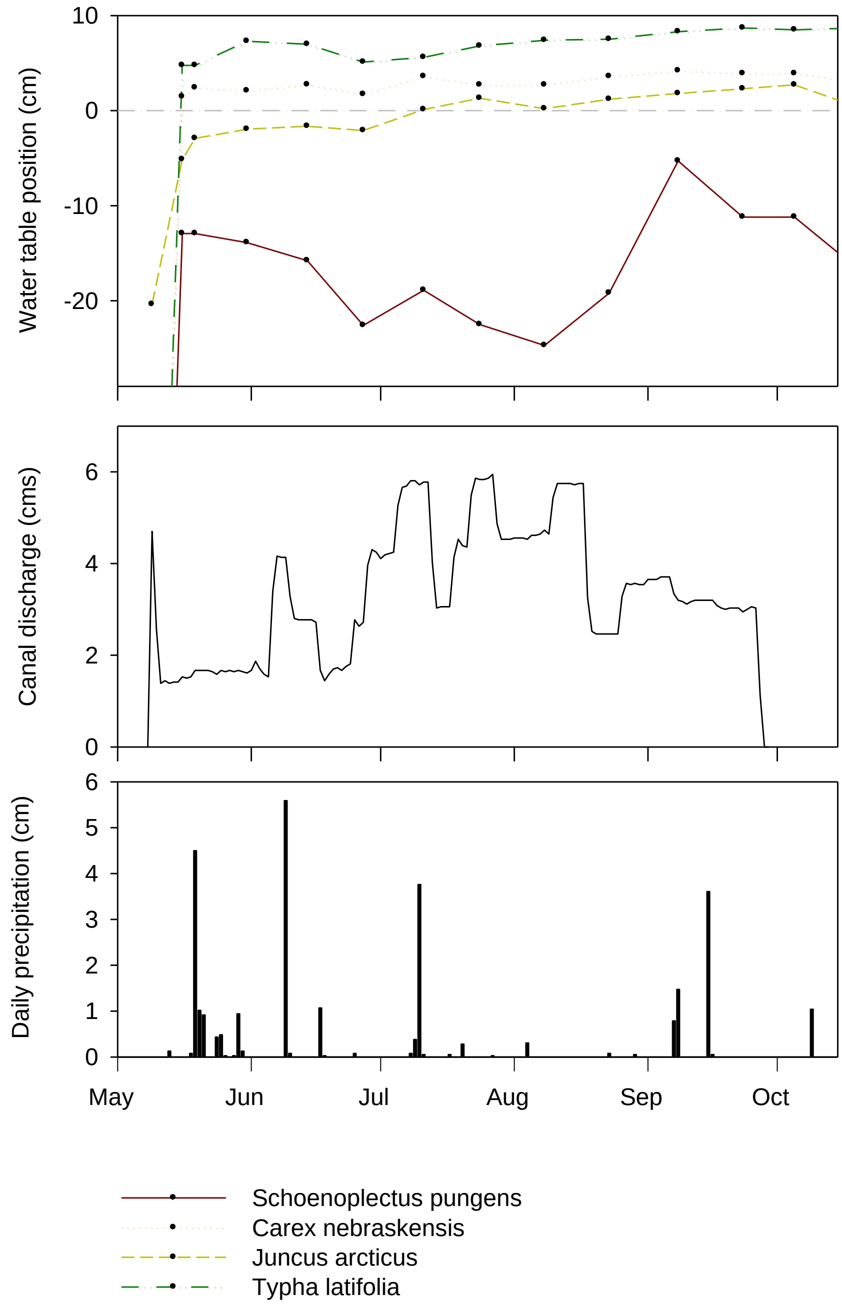

Figure A3. Upper Plot: Water level in 4 monitoring wells in a wetland adjacent to the Munroe canal. The name of each well refers to the dominant plant species occurring at that well. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Munroe canal. Lower Plot: Daily precipitation.

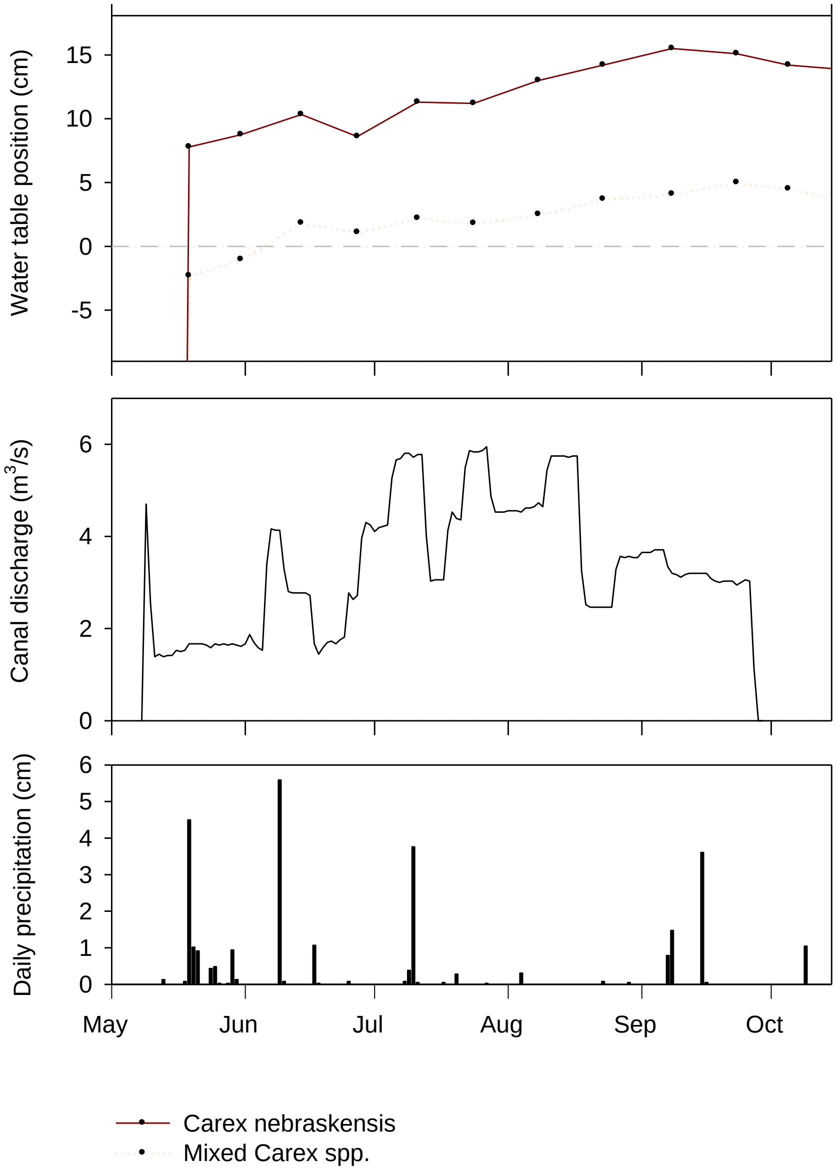

Figure A4. Upper Plot: Water level in 2 monitoring wells in a wetland adjacent to the Munroe canal. The name of each well refers to the dominant plant species occurring at that well. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Munroe canal. Lower Plot: Daily precipitation.

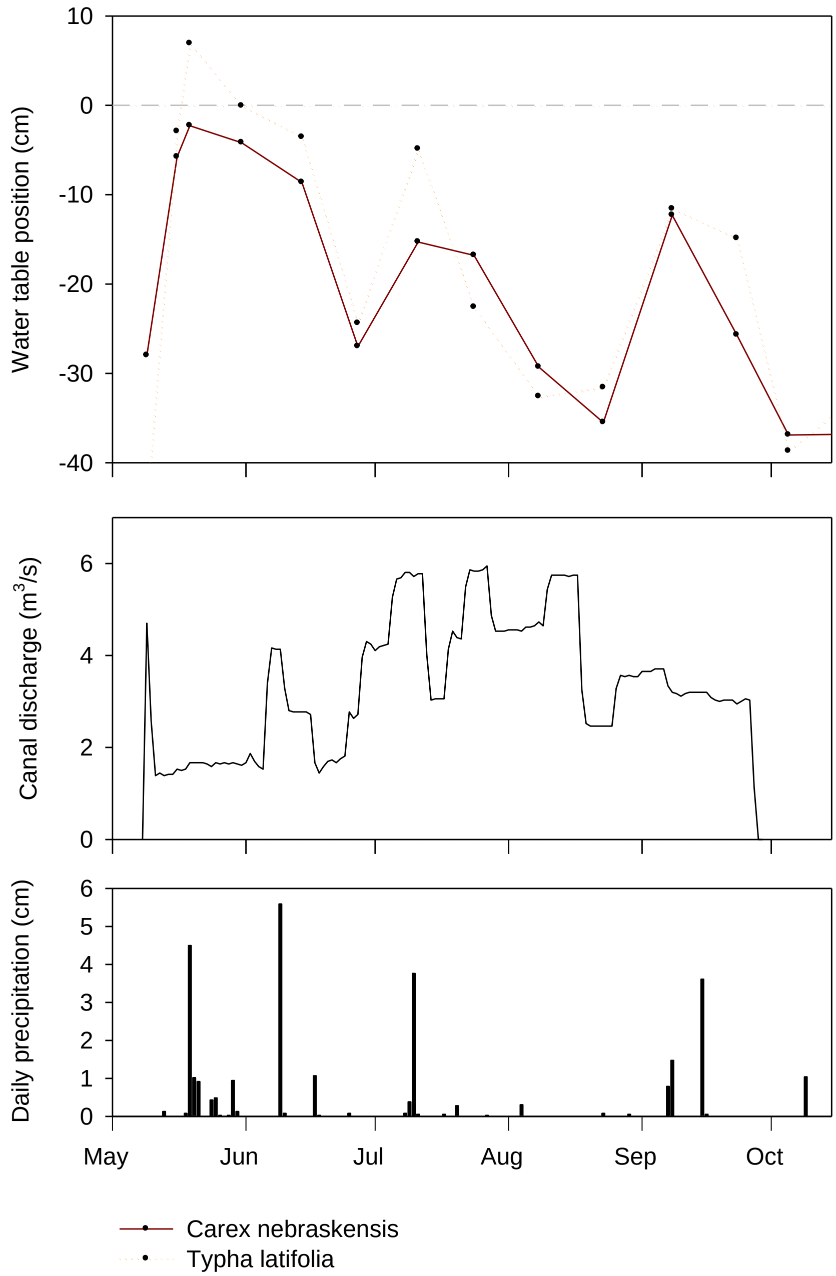

Figure A5. Upper Plot: Water level in 2 monitoring wells in a wetland adjacent to the Munroe canal. The name of each well refers to the dominant plant species occurring at that well. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Munroe canal. Lower Plot: Daily precipitation.

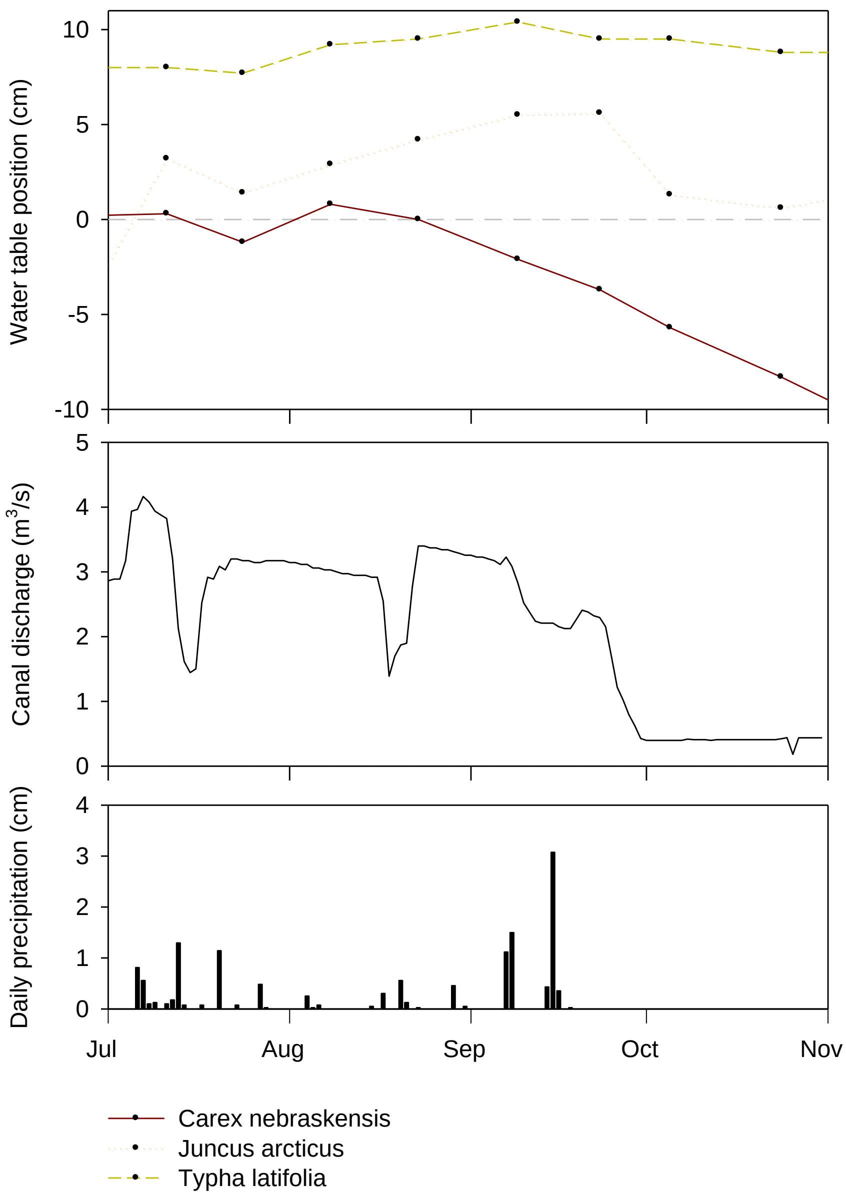

Figure A6. Upper Plot: Water level in 3 monitoring wells in a wetland adjacent to the Livermore canal. The name of each well refers to the dominant plant species occurring at that well. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Munroe canal. Lower Plot: Daily precipitation.

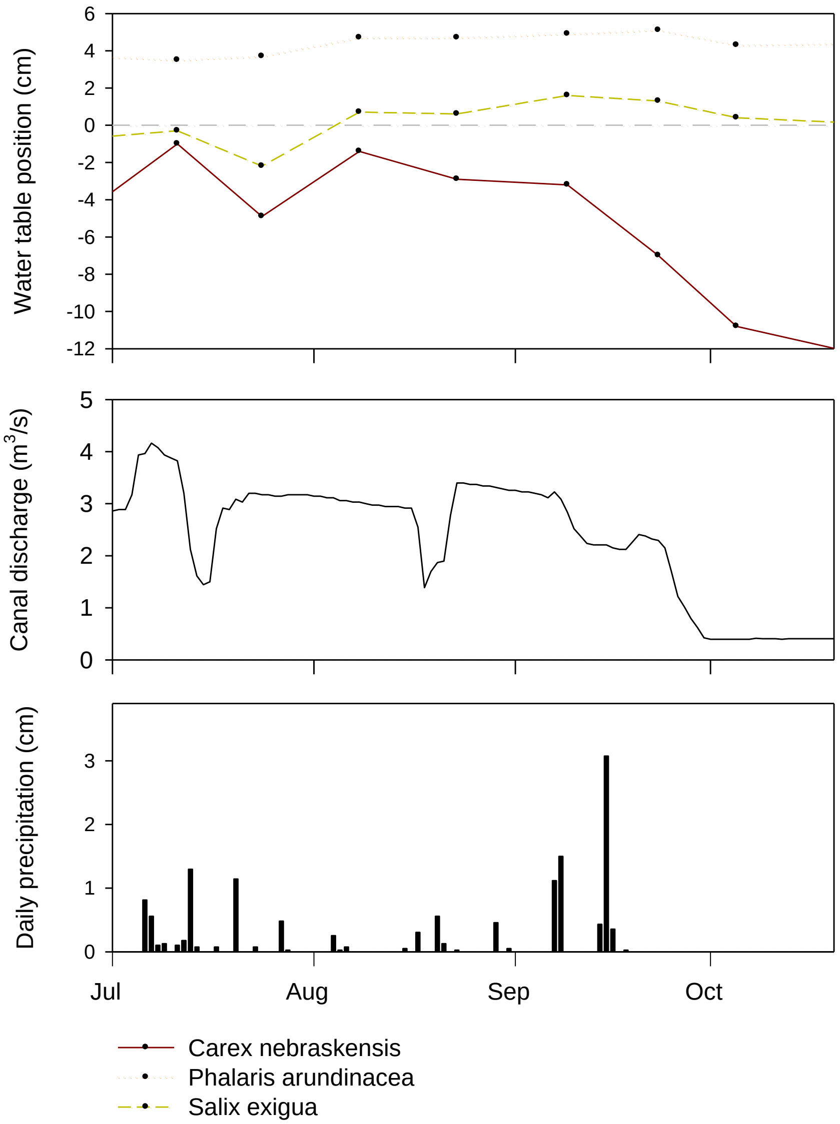

Figure A7. Upper Plot: Water level in 3 monitoring wells in a wetland adjacent to the Livermore canal. The name of each well refers to the dominant plant species occurring at that well. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Munroe canal. Lower Plot: Daily precipitation.

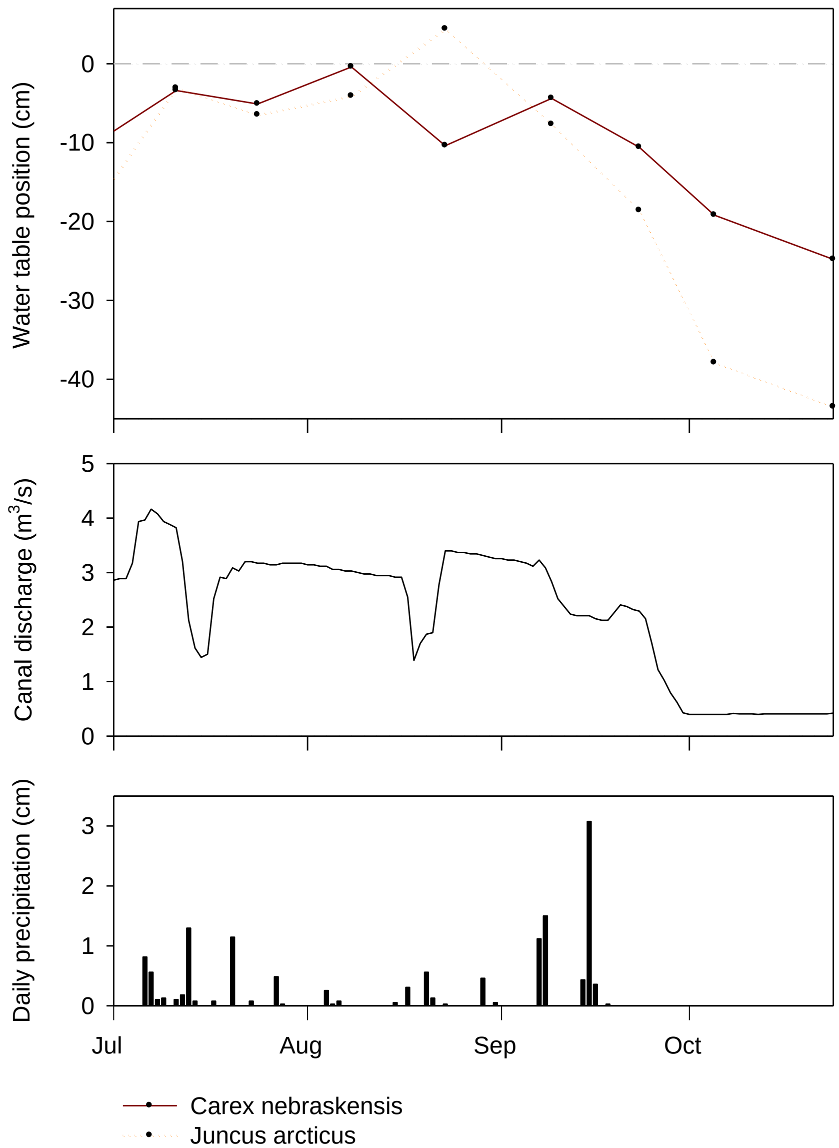

Figure A8. Upper Plot: Water level in 2 monitoring wells in a wetland adjacent to the Livermore canal. The name of each well refers to the dominant plant species occurring at that well. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Munroe canal. Lower Plot: Daily precipitation.

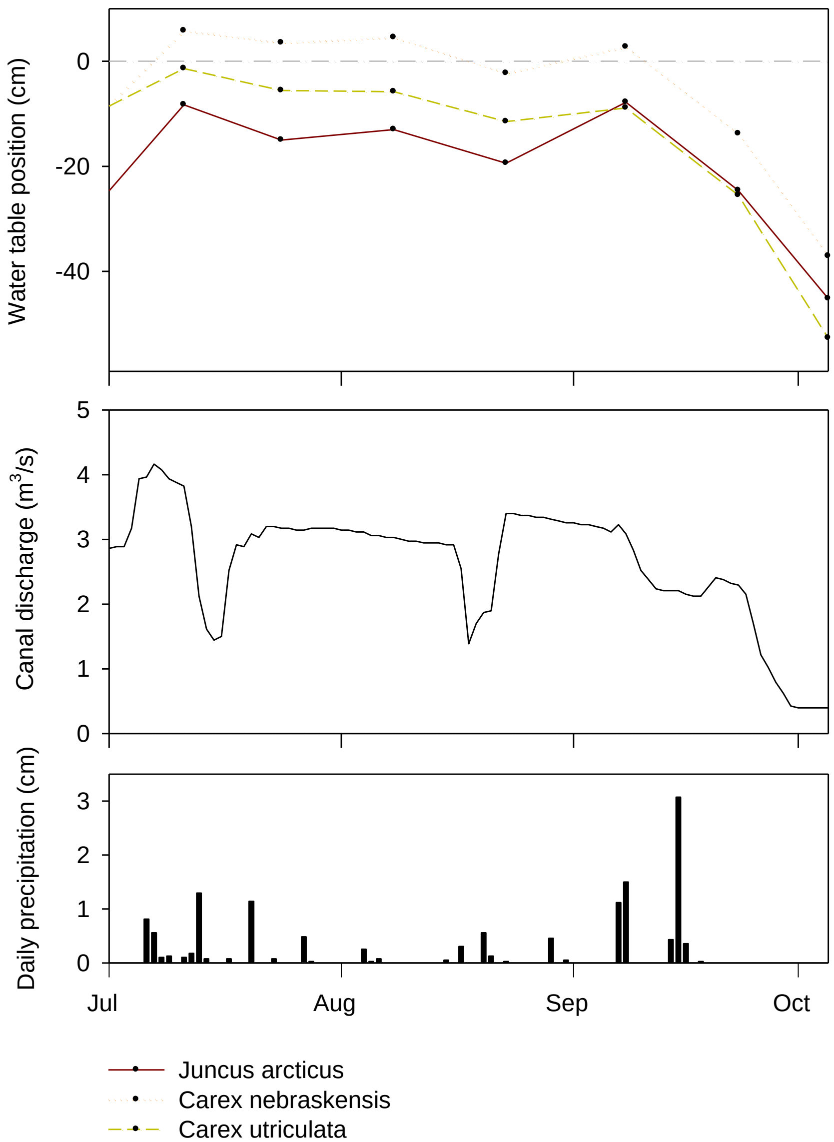

Figure A9. Upper Plot: Water level in 3 monitoring wells in a wetland adjacent to the Livermore canal. The name of each well refers to the dominant plant species occurring at that well. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Munroe canal. Lower Plot: Daily precipitation.

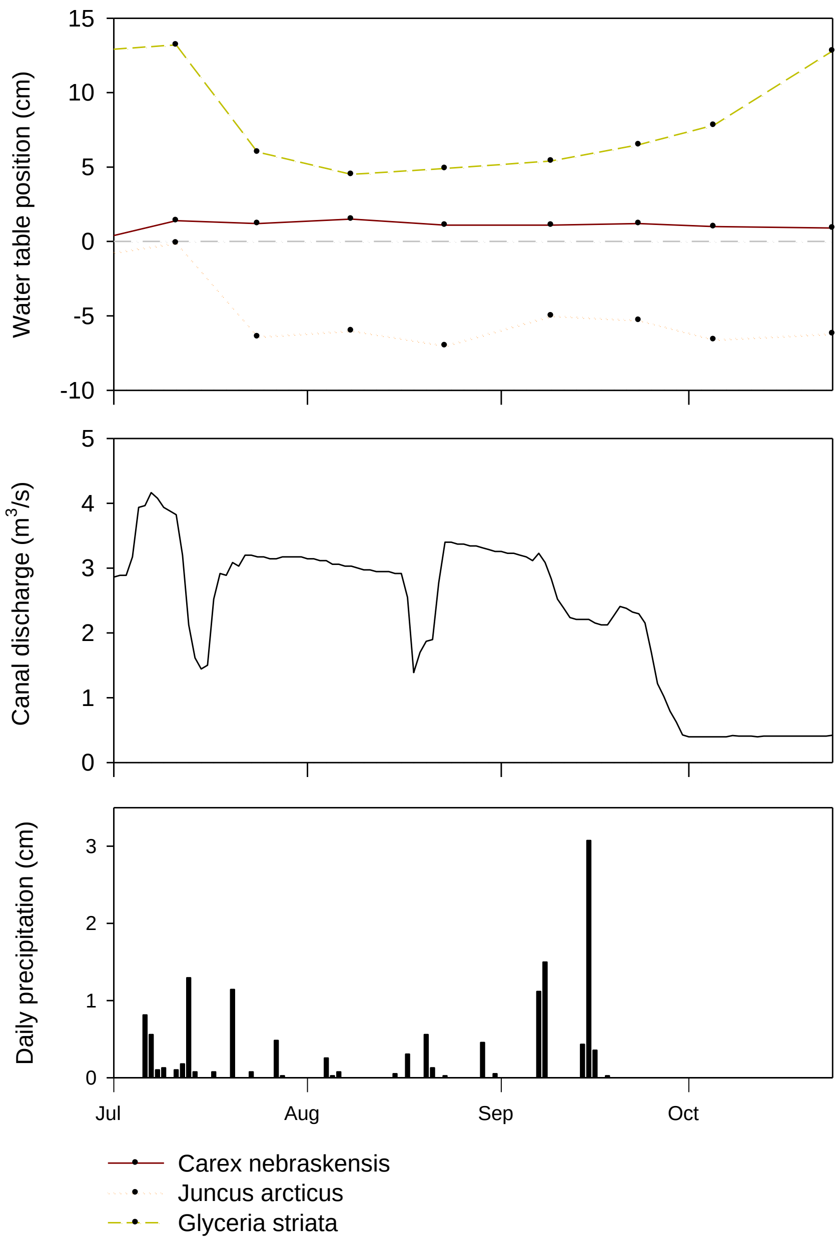

Figure A10. Upper Plot: Water level in 3 monitoring wells in a wetland adjacent to the Livermore canal. The name of each well refers to the dominant plant species occurring at that well. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Munroe canal. Lower Plot: Daily precipitation.

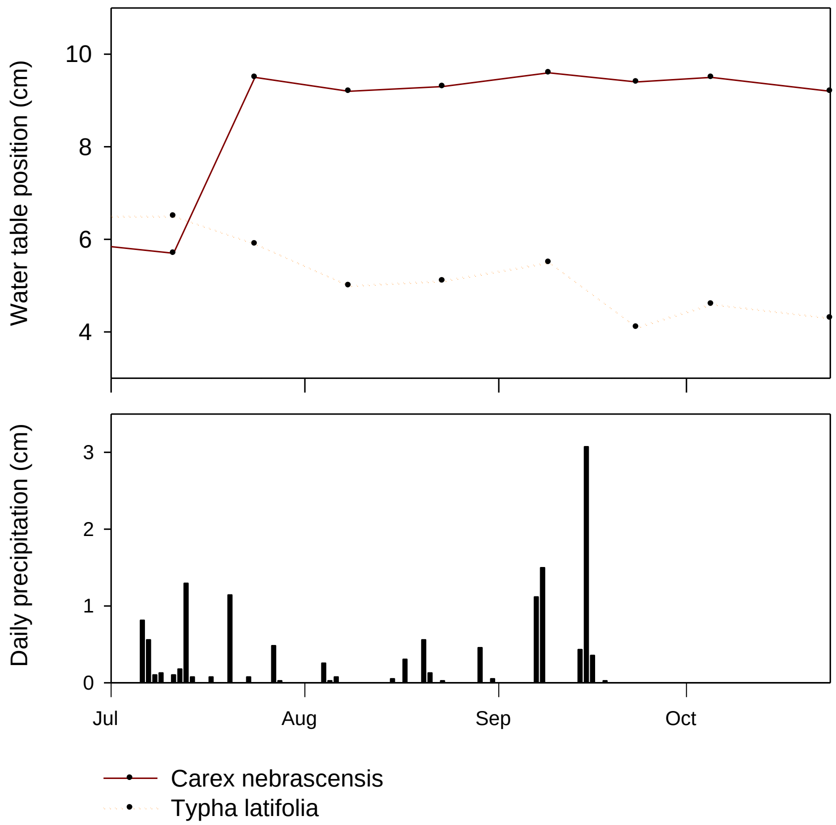

Figure A11. Upper Plot: Water level in 2 monitoring wells in a wetland adjacent to a pond that is supplied by the Livermore canal. The name of each well refers to the dominant plant species occurring at that well. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Lower Plot: Daily precipitation.

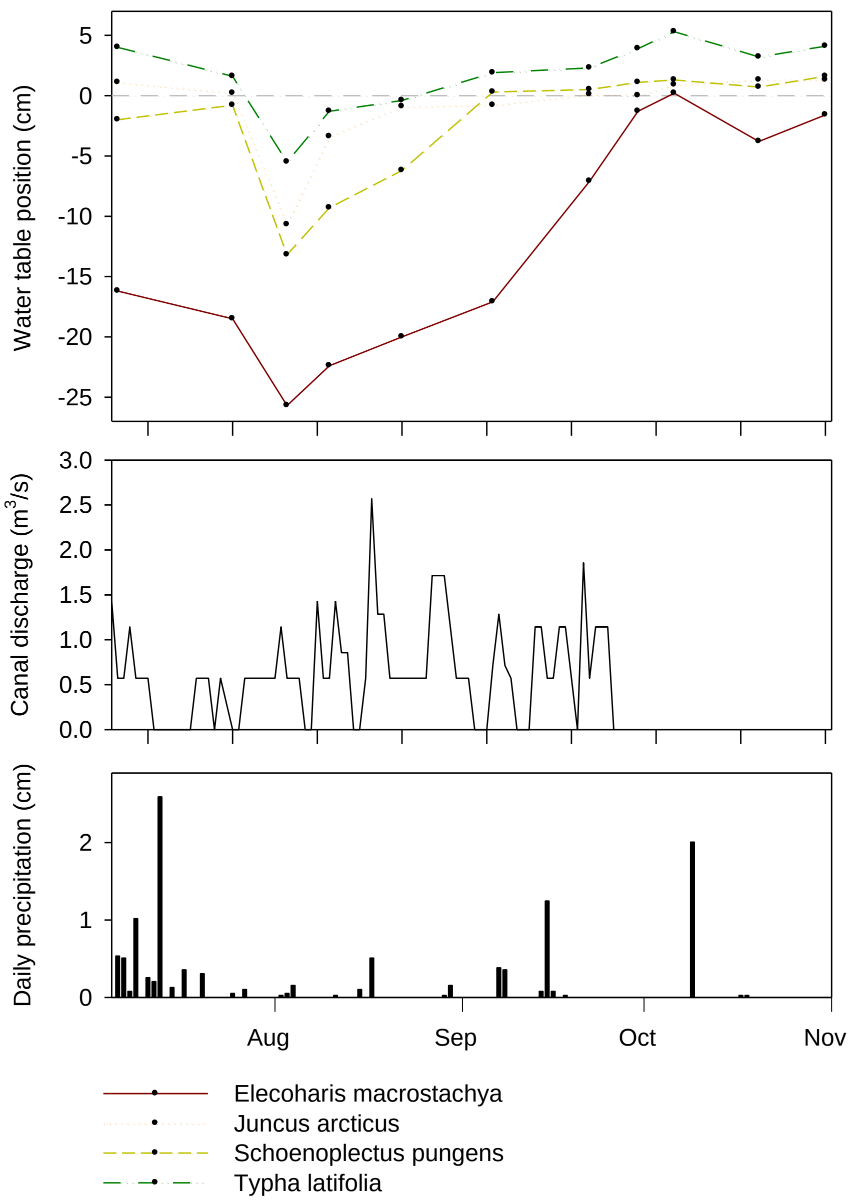

Figure A12. Upper Plot: Water level in 4 monitoring wells in a wetland adjacent to the Upper 10 canal. The name of each well refers to the dominant plant species occurring at that well. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Munroe canal. Lower Plot: Daily precipitation.

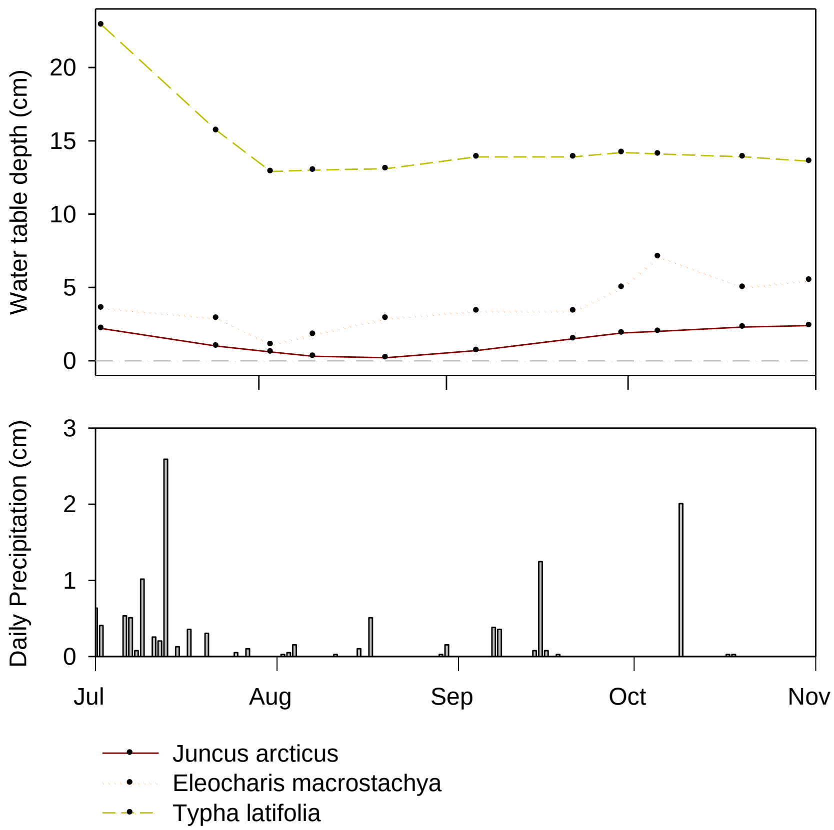

Figure A13. Upper Plot: Water level in 3 monitoring wells in a wetland adjacent to a pond that is supplied by the Upper 10 canal. The name of each well refers to the dominant plant species occurring at that well. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Lower Plot: Daily precipitation.

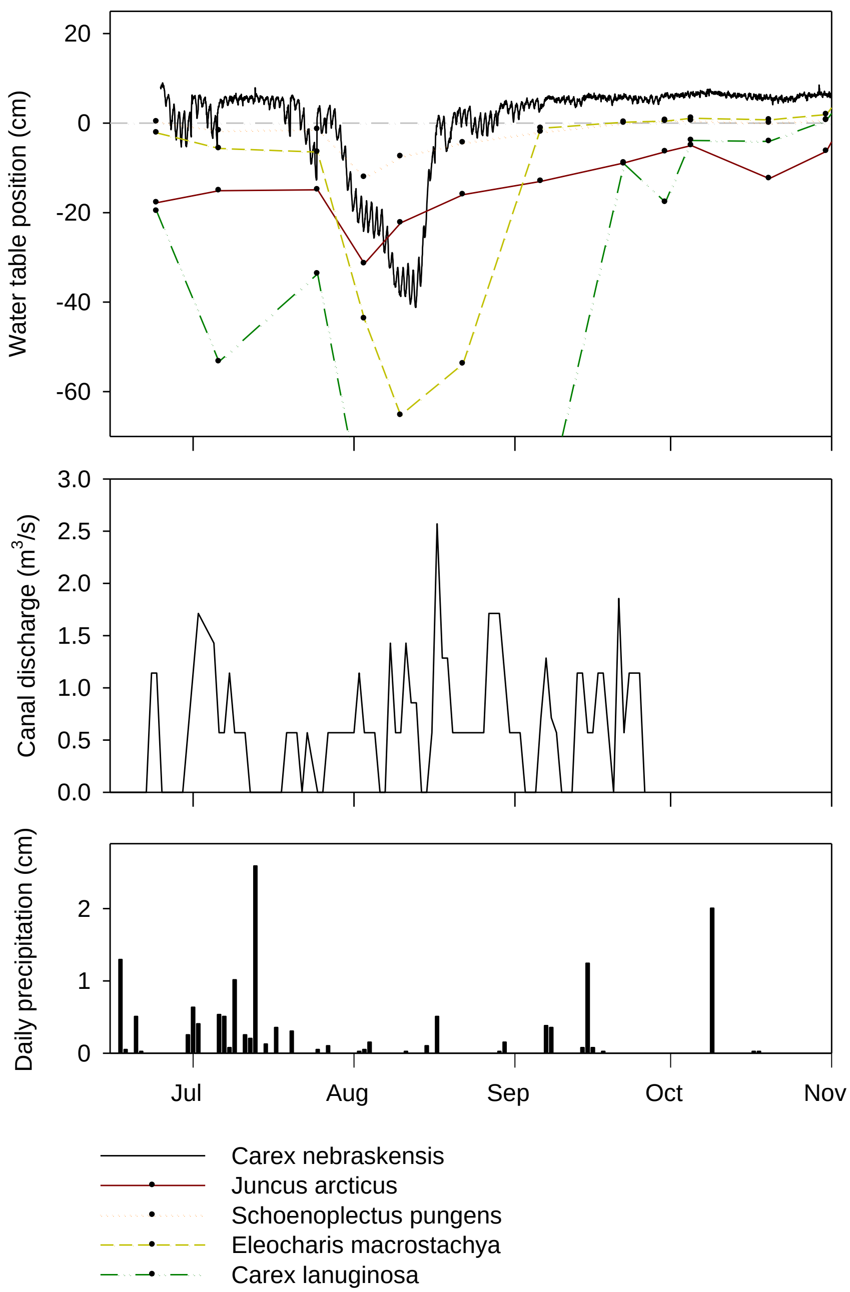

Figure A14. Upper Plot: Water level in 5 monitoring wells in a wetland adjacent to the Upper 10 canal. The name of each well refers to the dominant plant species occurring at that well. Monitoring wells measured every other week are shown with dashed lines, and dots on dates of measurement. The water table for the Carex nebrascensis well was measured hourly with a pressure transducer. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Upper 10 canal. Lower Plot: Daily precipitation.

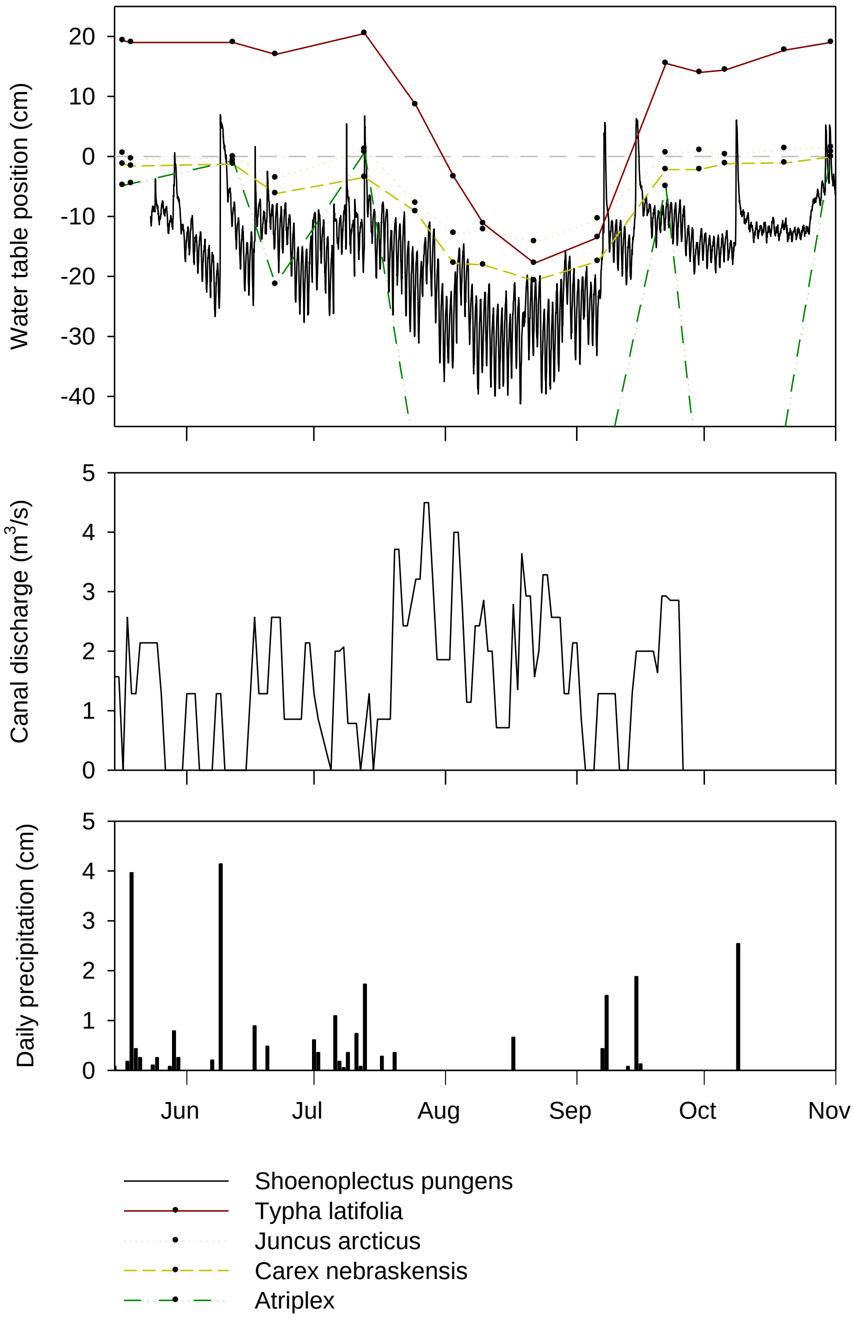

Figure A15. Upper Plot: Water level in 5 monitoring wells in a wetland adjacent to the Lower 10 canal. The name of each well refers to the dominant plant species occurring at that well. Monitoring wells measured every other week are shown with dashed lines, and dots on dates of measurement. The water table for the Schoenoplectus pungens well was measured hourly with a pressure transducer. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Lower 10 canal. Lower Plot: Daily precipitation.

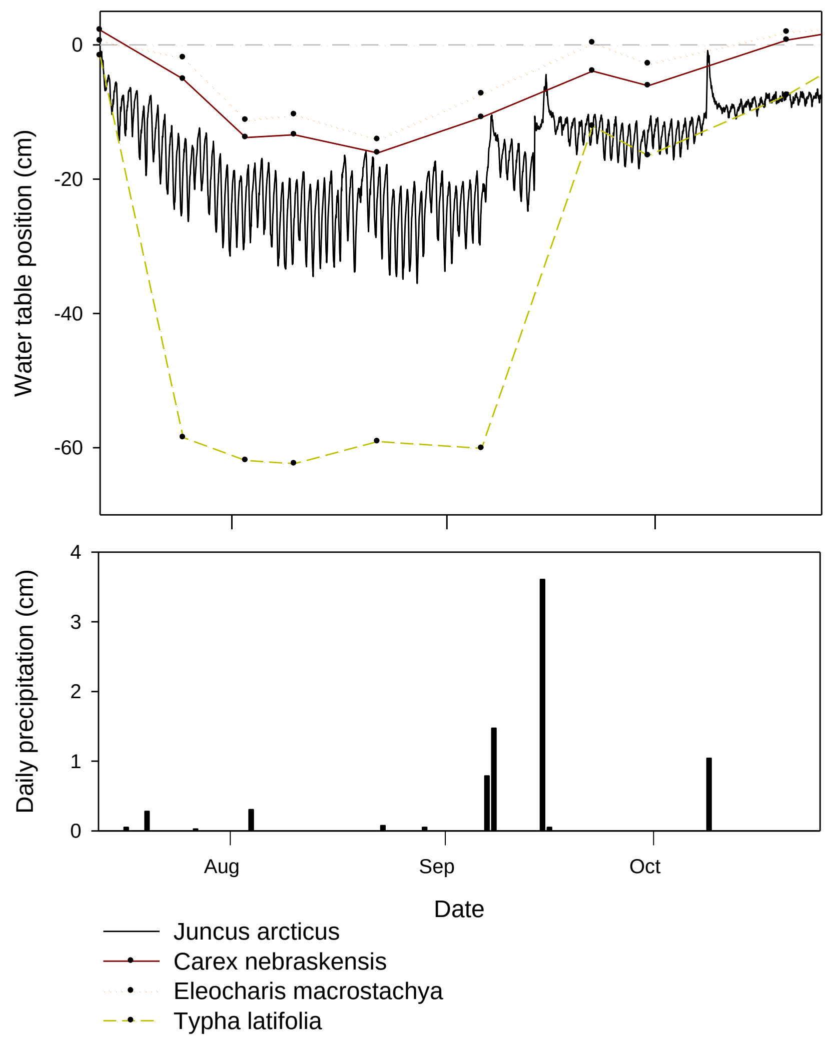

Figure A16. Upper Plot: Water level in 4 monitoring wells in a wetland adjacent to the Indian Creek Reservoir. The name of each well refers to the dominant plant species occurring at that well. Monitoring wells measured every other week are shown with dashed lines, and dots on dates of measurement. The water table for the Juncus arcticus well was measured hourly with a pressure transducer. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Lower Plot: Daily precipitation.

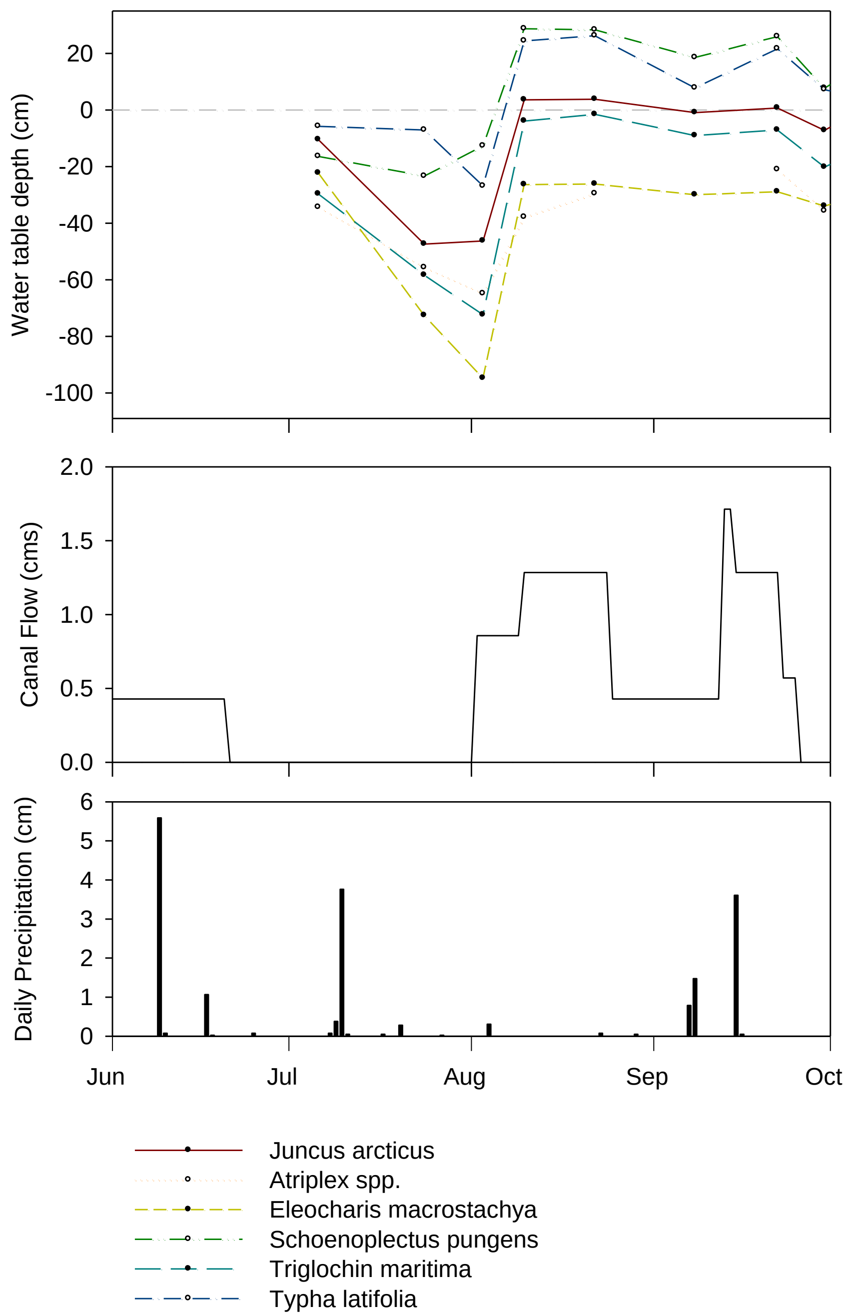

Figure A17. Upper Plot: Water level in 6 monitoring wells in a wetland adjacent to the Lower #1 canal. The name of each well refers to the dominant plant species occurring at that well. Monitoring wells measured every other week are shown with dashed lines, and dots on dates of measurement. The first and last measurements were taken when no water was present in the canal. All other measurements were taken when water was flowing in the canal. Ground level is at 0 cm on the y-axis and is represented by the horizontal grey dashed line. Middle Plot: Daily canal flow in the Lower 10 canal. Lower Plot: Daily precipitation.

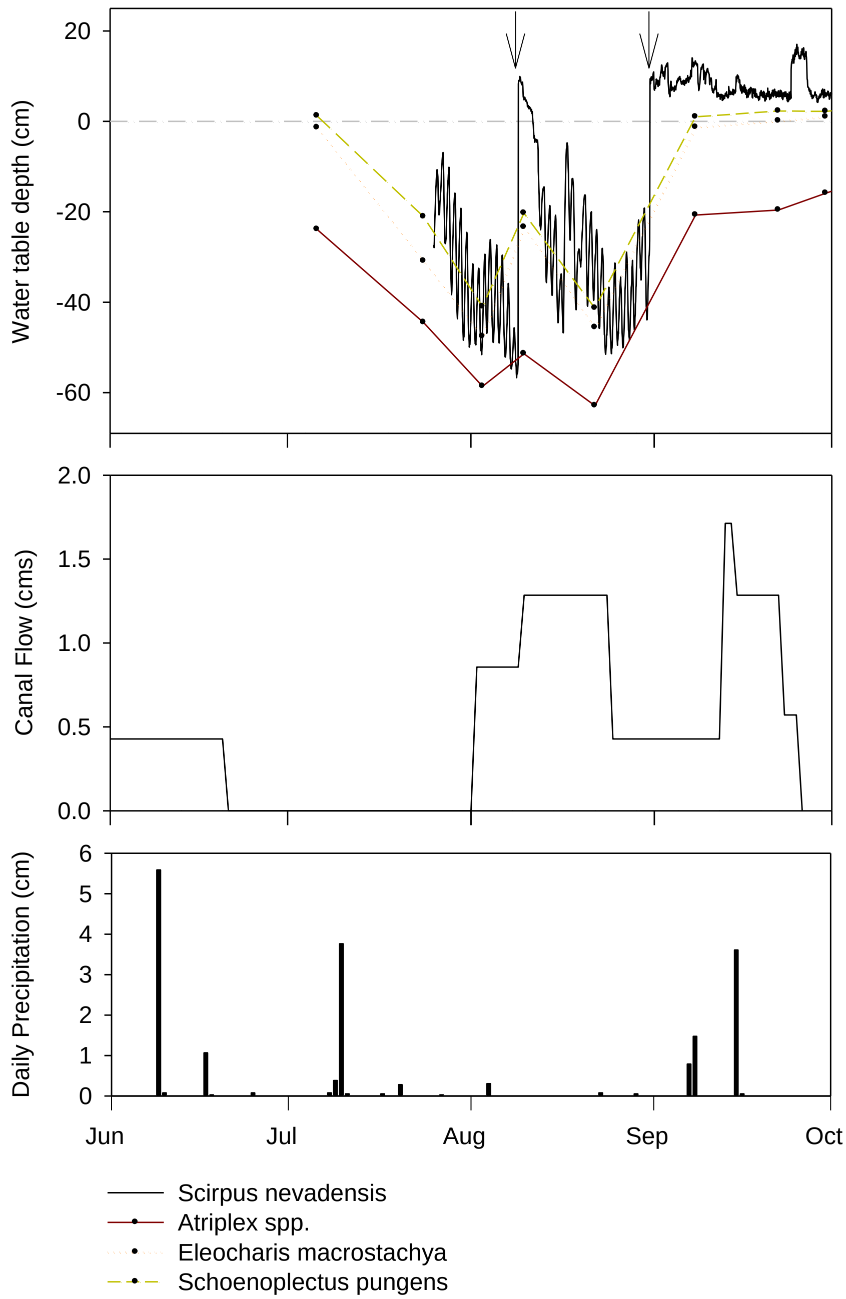

Figure A18. Upper Plot: Water levels in 4 monitoring wells for a wetland located in an irrigated pasture adjacent to the Lower #1 canal. The name of each well refers to the dominant plant species occurring at that well. Monitoring wells measured every other week are shown with dashed lines, and dots on dates of measurement. The water table for the Scirpus nevadensis well was measured hourly with a pressure transducer. The ground level for the top plot is represented by the grey dashed line at 0 cm. The two arrows above the upper plot identify times when water was applied to the pasture around the study wetland. Middle Plot: Daily canal flow in the adjacent canal. Lower Plot: Daily precipitation.

APPENDIX B: Water Chemistry

Methods.

From water samples already collected for stable isotope analysis, a smaller group of water samples representing wetlands, canals, rain, groundwater springs, and rain were sent in for cation and anion analysis performed by the Soil, Water, and Plant testing lab at Colorado State University. Cations were analyzed by inductively coupled plasma atomic emission spectroscopy (EPA Method 200.7) using a TJA Solutions IRIS Advantage radial view. Anions were measured by ion chromatography (EPA Method 300.0) using a Dionex 2000i/SP. Carbonate and bicarbonate analysis were done by titration (EPA Method 310.1).

Results

Major anions and cations varied between wetlands, irrigation canals, rain, groundwater springs, and the Cache la Poudre River (Fig.B1). The Piper diagram of the averages of the anion and cation data points show chemical similarity between rain, canals, and wetlands, with the river and natural groundwater springs very similar to each other. Variations between samples were largest in the anions, with high bicarbonate levels in the samples from the Cache la Poudre River and natural groundwater springs, and high sulfate levels in wetlands, canals, and rain samples.

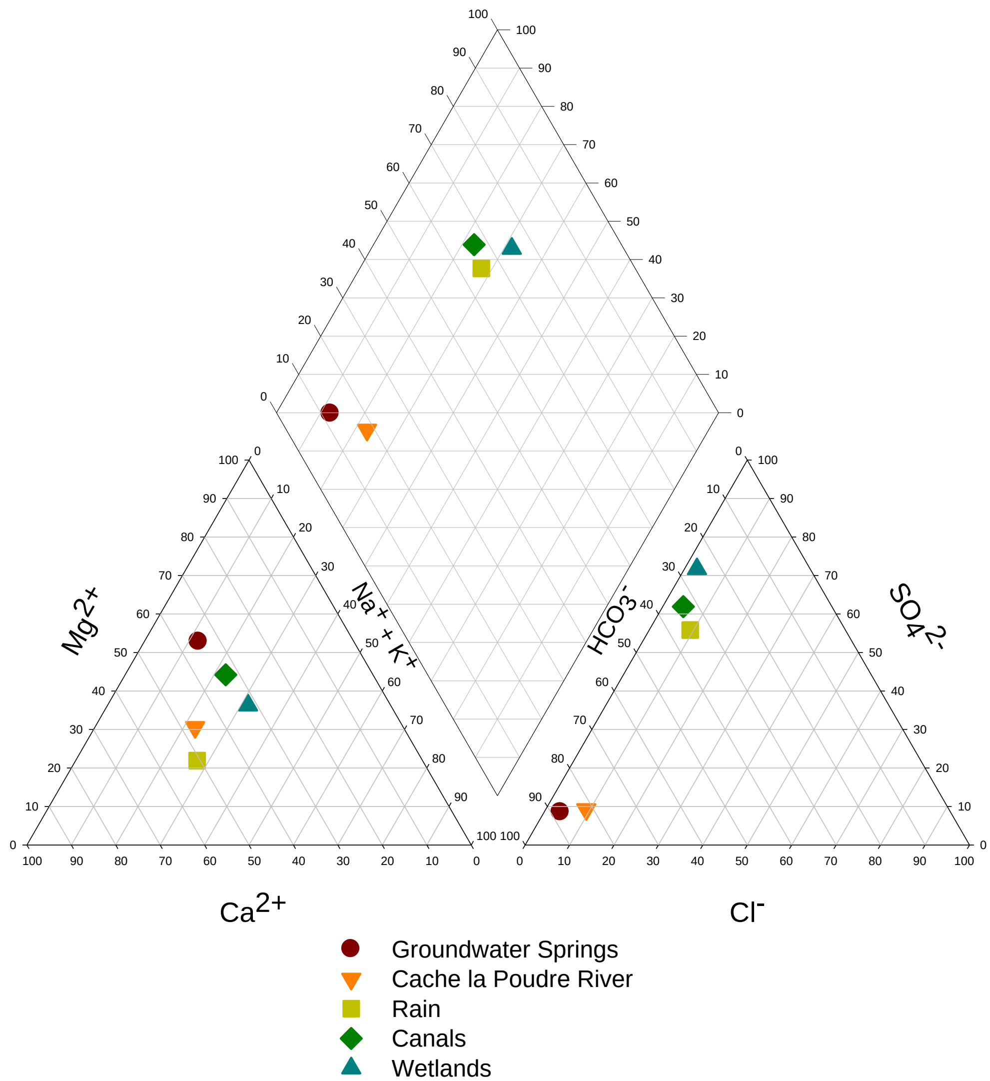

Figure B1. Piper plot of water chemistry data. Points reflect the averages for each category.