Modeling inundation of sloughs to determine changes in suitable habitat for the Platte River caddisfly (*Ironoquia plattensis*)

Final Report

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Abstract—The Platte River caddisfly (*Ironoquia plattensis*) is a semi-terrestrial limnephilid caddisfly that inhabits off-channel aquatic habitats along the Platte River in central Nebraska, USA. It was discovered in the late 1990s, and the boundaries of its apparently limited distribution are unknown. The goal of this study was to determine what factors maintain water in sloughs (linear wetland depressions) during the aquatic phase of the insect's life cycle, both under past and present hydrologic conditions. We studied a relatively physically unaltered large island complex (Mormon and Shoemaker Islands) near Grand Island, Nebraska, that supports high densities of the Platte River caddisfly. We used a combination of aerial photographs, detailed topographic and groundwater elevation data, and historical river flow and precipitation data to 1) quantify changes in floodplain area occupied by inundated sloughs during the photographic record and 2) model the duration of slough inundation under different hydrological scenarios to determine potential changes in suitable habitat for the Platte River caddisfly. We evaluated long-term changes in slough inundation from two points in the photo series (May 1951 and May 1999) that had similar precipitation preceding photographs. Between those years, the area of inundated sloughs declined on both islands, even though river flows were ten times higher in 1999. This suggests that another factor, possibly declining groundwater stage, altered inundation patterns of sloughs. We then modeled the change in inundation area for sloughs and wet meadows as groundwater elevations increased and decreased relative to current (2010) conditions. We used these model outputs to estimate the duration of slough inundation for a subset of years (1997-2003) that encompassed both wet and dry periods. For the slough where the Platte River caddisfly was discovered, as well as most surrounding sloughs on Mormon Island, model results showed that sloughs contained water for an average of 340 days during wet years (1997-1999), whereas during dry years (2000 – 2003), sloughs only maintained water for an average of 249 days. These results suggest that ongoing hydrological alterations that diminish groundwater levels, and consequently, slough inundation, will reduce the amount of available habitat required for the Platte River caddisfly to complete the aquatic phase of its life cycle from October to May. Future studies should examine controls on groundwater elevations throughout the Platte River valley, especially the interacting influences of river flow, precipitation, and evapotranspiration, and how these apply to the Platte River caddisfly life cycle.

Introduction

The Platte River caddisfly (*Ironoquia plattensis*; Trichoptera: Limnephilidae; PRCF) was discovered along the Platte River in central Nebraska in the late 1990s (Alexander and Whiles 2000), and basic information about its life history and threats to its survival are not well understood. The confirmed distribution of the PRCF is limited to a 320-km length the Platte River, from Havens, NE (Merrick County) to Sutherland, NE (Lincoln County) (Vivian 2010). In addition, six populations of a similar caddisfly have been identified on the Loup and Elkhorn rivers (Vivian 2010), and species identification is in progress. The PRCF inhabits sloughs surrounded by both grasslands and riparian forests (Vivian 2010). It was discovered in an intermittent slough surrounded by wet, tallgrass prairie on Mormon Island (Hall County) (hereafter: type locality) in the late 1990s (Whiles et al. 1999, Alexander and Whiles 2000). These early surveys found the PRCF developing in the slough through five larval instars from November to late May/early June, moving to land to aestivate and pupate above ground during the summer, and emerging as adults during a brief period in late September/early October (Whiles et al. 1999). A subsequent survey found a large population of the PRCF 5.5 km from the type locality and observed earlier larval emigration from a slough to land in April, as well subterranean behaviors in upland soils during summer (Geluso et al. 2011).

Presence of PRCF in sloughs throughout the region is patchy (Goldowitz 2004, Vivian 2010), and it is unknown what factors directly or indirectly affect its presence. Hypothesized controls include: slough hydroperiod (i.e., number of days when water is present); predation by fish (Whiles and Goldowitz 2001, 2005); presence of key aquatic macrophytes (Whiles and Goldowitz 2005); types of land use, such as cattle grazing (Geluso and Harner *in review*); and slough biogeochemistry. In a detailed study of five sloughs, Trichoptera inhabited only one slough that was characterized by an intermediate hydroperiod (296 d) and a large biomass of macrophytes (Whiles and Goldowitz 2001, 2005). Sites with longer hydroperiods host predators of aquatic insects (e.g., fish), which may decrease in insect diversity and production, whereas sites with intermittent hydrology and few to no predators may promote insect diversity and production (Whiles and Goldowitz 2001, 2005). Another study found that loss of vegetation cover from cattle grazing reduced densities of PRCF larvae (Geluso and Harner *in review*).

Availability of slough habitat has decreased in the last century along the Platte River due to land use changes, including land leveling for agriculture, urban development, groundwater extraction for irrigation, and diversion of surface water flows (Williams 1978, Eschner et al. 1983). The overall width of the river channel from Overton to Grand Island, Nebraska, in 1969 was only 60-70% of the river channel width in 1865 (Williams 1978). Wetland meadows where sloughs occur declined by 23-45% between 1938-1982 along the North Platte and Platte rivers (Sidle et al. 1989). In addition to the loss of wet meadows and sloughs, inundation dynamics of sloughs also are subject to landscape modifications, which may have cascading effects on organisms like the PRCF. Inundation of sloughs is maintained by exposed groundwater or trapped surface run-in (Friesen et al. 2000), and these mechanisms have different effects on the slough's hydroperiod. Water reaching sloughs from surface run-in is spatially and temporally variable, often responding to pulses from rain, which can produce rapid wetting and drying cycles. In contrast, sloughs fed by groundwater have longer and more predictable hydroperiods, due to a continuous supply of water, as long as water table elevations are near the ground surface.

Conservation efforts for the PRCF are currently focused on understanding life history requirements to determine whether the species' apparent rarity, coupled with potential threats to its slough habitats, warrants protection of the species (USFWS 2009). Because the PRCF requires inundation of sloughs from autumn through spring, it is necessary to understand what hydrological factors influence and maintain the presence of surface water through this period at sites where ample slough habitat remains. As a first step in the process, we studied slough hydrology near the type locality on floodplain surfaces that have been largely unaltered physically during the last century and on lands protected by the Platte River Whooping Crane Critical Habitat Maintenance Trust (hereafter: Crane Trust) on Mormon and Shoemaker Islands (Hall County, Nebraska; Fig. 1). Herein we sought to link local hydrological dynamics to known life history attributes of the PRCF. Our specific objectives were 1) to quantify changes in the area of floodplain occupied by inundated sloughs during the historical photo record and 2) to model the duration of slough inundation (hydroperiod) under different hydrological scenarios to determine potential changes in availability of suitable habitat for the Platte River caddisfly.

Study Site

This study was conducted on lands owned and managed by the Crane Trust on Shoemaker and Mormon Islands, Hall County, Nebraska (40°47.660′N, 98°26.722′W; Fig. 1), 10 miles south of Grand Island. Here the Platte River flows eastward, and its relatively flat floodplain is traversed by numerous linear depressions (i.e., sloughs) that create a ridge/swale structure on the landscape (Henszey et al. 2004). Sloughs remain inundated for various time periods depending on precipitation, water table elevations, and river flow (Henszey et al. 2004, Whiles and Goldowitz 2001, 2005). As a result, the floodplain is comprised of a mosaic of grassland plant communities structured largely by the availability of soil moisture (Henszey et al. 2004, Meyer et al. 2010). The land is managed with rotational burning, cattle grazing, and resting to promote habitat heterogeneity and productive grasslands (Kim et al. 2008).

Researchers have studied the hydrology of the Platte River near our study site to document effects of flow regulation and increased irrigated agriculture that took place in the 20th century (Williams 1978, Eschner et al. 1983, Hurr et al. 1983, Sanders 2001). Pre-development flow conditions for the Platte River are considered to be pre-1930 (Sanders 2001), although humans had already utilized and modified the river corridor in the prior century (e.g., Eschner et al. 1983). Large-scale irrigated agriculture began in the mid-1950s, and the number of irrigated acres and active wells has increased dramatically since (Sanders 2001). The upstream Kingsley Dam (Keith County, Nebraska) was completed in 1941, and its operations affect river flows at our study site.

Records of river flow near the study site are available from a downstream gage near Grand Island, Nebraska (USGS Station #06770500: http://waterdata.usgs.gov) that began collecting data in 1934 (Fig. 2). Records of precipitation for Grand Island are available from the National Climatic Data Center (Grand Island Coop ID 253395; http://www.ncdc.noaa.gov/oa/ncdc.html) (Fig. 3). The region was recently affected by drought (2000-2004), and since, river flows and total annual precipitation have rebounded (Figs. 2 and 3).

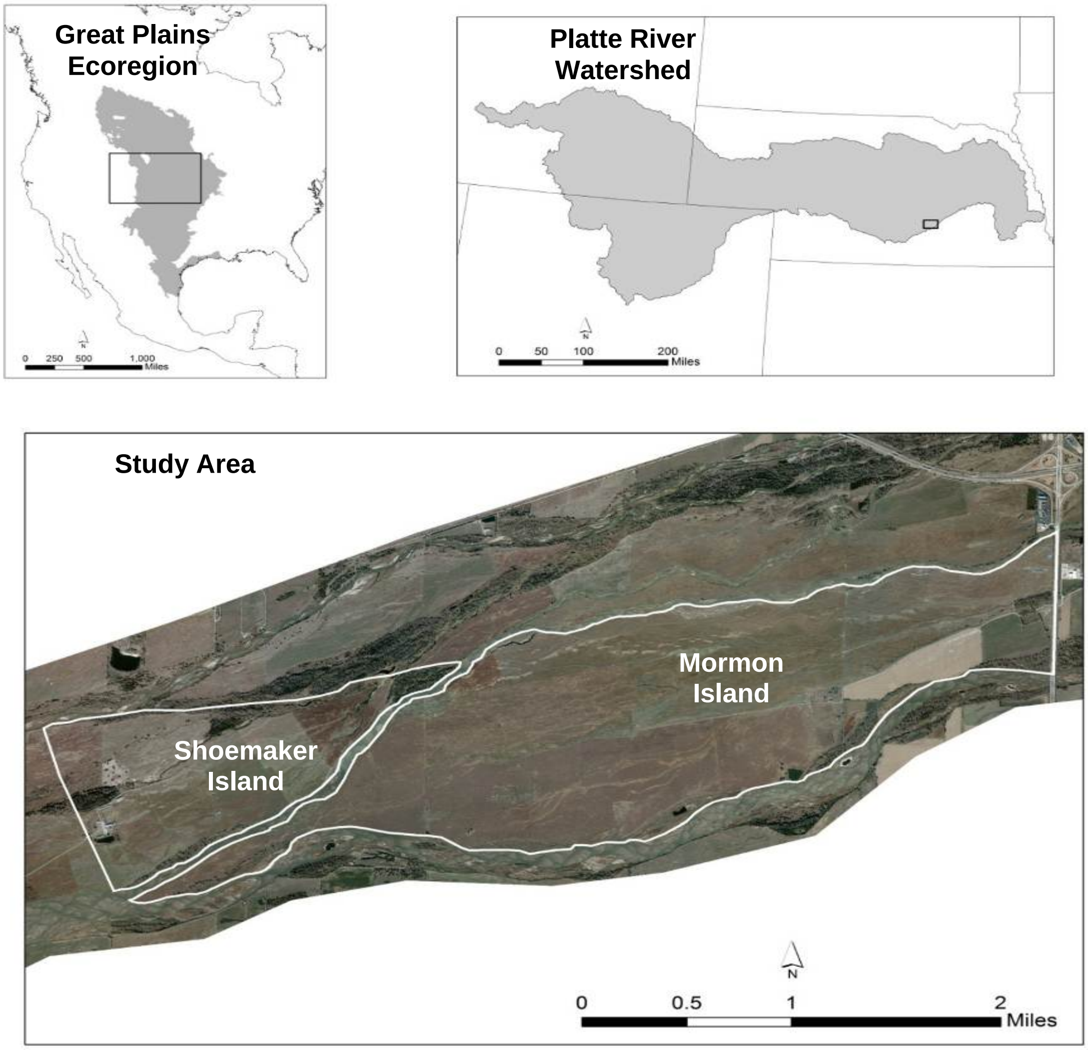


Figure 1. Location of Shoemaker and Mormon Islands along the Platte River in central Nebraska, USA. The Platte River lies within the Great Plains Ecoregion of North America, and its headwaters are in Colorado and Wyoming. Arial photograph taken on 28 October 2010.

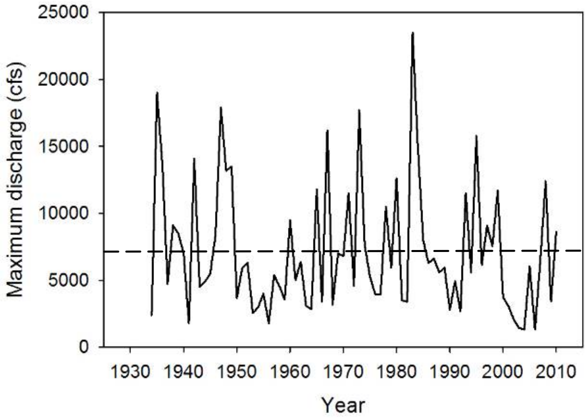


Figure 2. Platte River maximum annual discharge measured at Grand Island, NE. Dashed line denotes average peak flow over period of record (7,189 cfs).

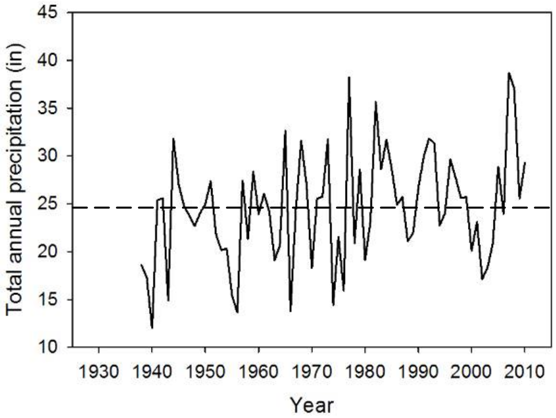


Figure 3. Total annual precipitation in Grand Island, NE. Dashed line denotes average annual precipitation (24.5 in) over period of record.

Groundwater monitoring wells have been installed on Mormon Island over the last 30 years. In 1980, the United States Geological Survey (USGS) monitored > 45 wells on the western end of Mormon Island to determine the effects of changes in water management on groundwater levels (Hurr 1983). They monitored groundwater levels and river stage for seven months to determine relationships between groundwater and surface water. They observed "groundwater levels beneath the island respond to changes in river stage, to recharge from snowmelt and precipitation, and to evaporation by riparian vegetation, and from areas where the water table is close to the land surface" (Hurr 1983). From 1988-1992, the U.S. Bureau of Reclamation (USBR) and U.S. Fish and Wildlife Service (USFWS) monitored ~30 wells in the central portion of Mormon Island to examine seasonal relationships between depth to groundwater and river stage, precipitation, evapotranspiration, and adjacent irrigation (Henszey and Wesche 1993, Wesche et al. 1994). They found that river stage and precipitation most influenced groundwater levels, with evapotranspiration also important from May through late September. Median groundwater levels usually peaked by March and gradually declined through September, with recharge beginning in October (Wesche et al. 1994). A USBR report by Sanders (2001) includes data from two well transects that were monitored on Mormon Island in 1999 and 2000. Sanders (2001) examined relationships among rainfall, river levels, and groundwater levels and concluded that wells close to the river channel responded to changes in river discharge, and that precipitation also exerted strong control on groundwater levels (Sanders 2001).

Hydrologist Robert Henszey, who had been involved in other Mormon Island hydrology studies (Wesche et al. 1994 and Henszey et al. 2004), monitored three wells on Mormon Island continuously within the period 1996-2004 (R. Henszey, *unpublished data,* archived in the Platte River Ecosystem Study Data Catalog, USGS Nebraska Water Science Center, Lincoln, Nebraska; http://data.usgs.gov/resources/platteriver/HenszeyPlatteData.zip). These wells indicate a change in the Mormon Island water table during the drought period early in the 21st century (Fig. 4). As the drought progressed, there was a declining trend in the annual peak water table elevations, and water table elevations were low for longer durations.

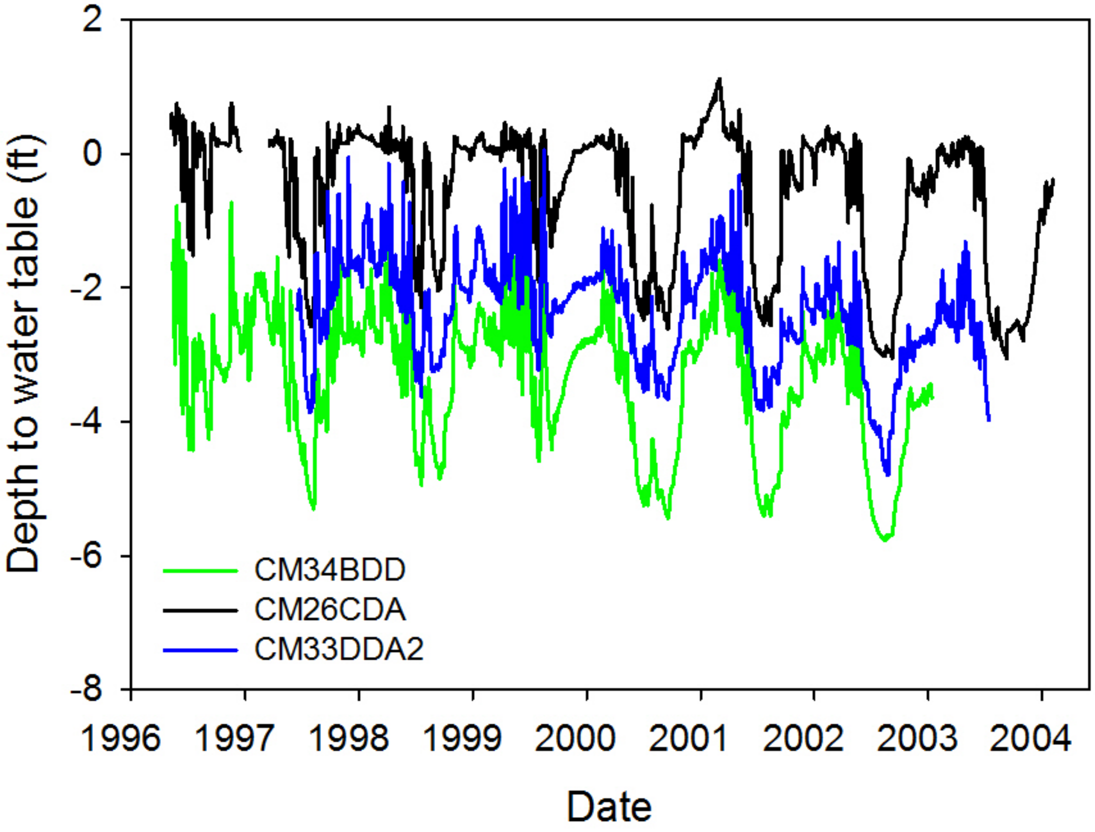


Figure 4. Depth to water table relative to ground surface measured from three wells on Mormon Island (R. Henszey *unpublished data*). Depth to water table was greater during summer than winter months. Peaks declined and low stages were of longer duration during a multi-year drought that began in 2000. The flat tops to the peaks in CM26CDA were likely due to water flowing away when the water table intercepted the ground surface.

The PRCF (Fig. 5) has been found at several locations on Mormon and Shoemaker Islands in forested and grassland sloughs (Fig. 6). Surveys have indicated inter-annual variation in the occurrence of the PRCF at these sites (e.g., Goldowitz 2004), and it is unknown whether the insect actually disappears from localities or declines to such limited numbers that they are difficult to detect. Observers may have failed to detect them during summer surveys, because they bury under ground (Geluso et al. 2011), and during autumnal surveys, because their emergence appears to be limited to several weeks (Goldowitz 2004) or days (Geluso et al. 2011).

Figure 5. Platte River caddisfly larvae. Photo by M. Harner.

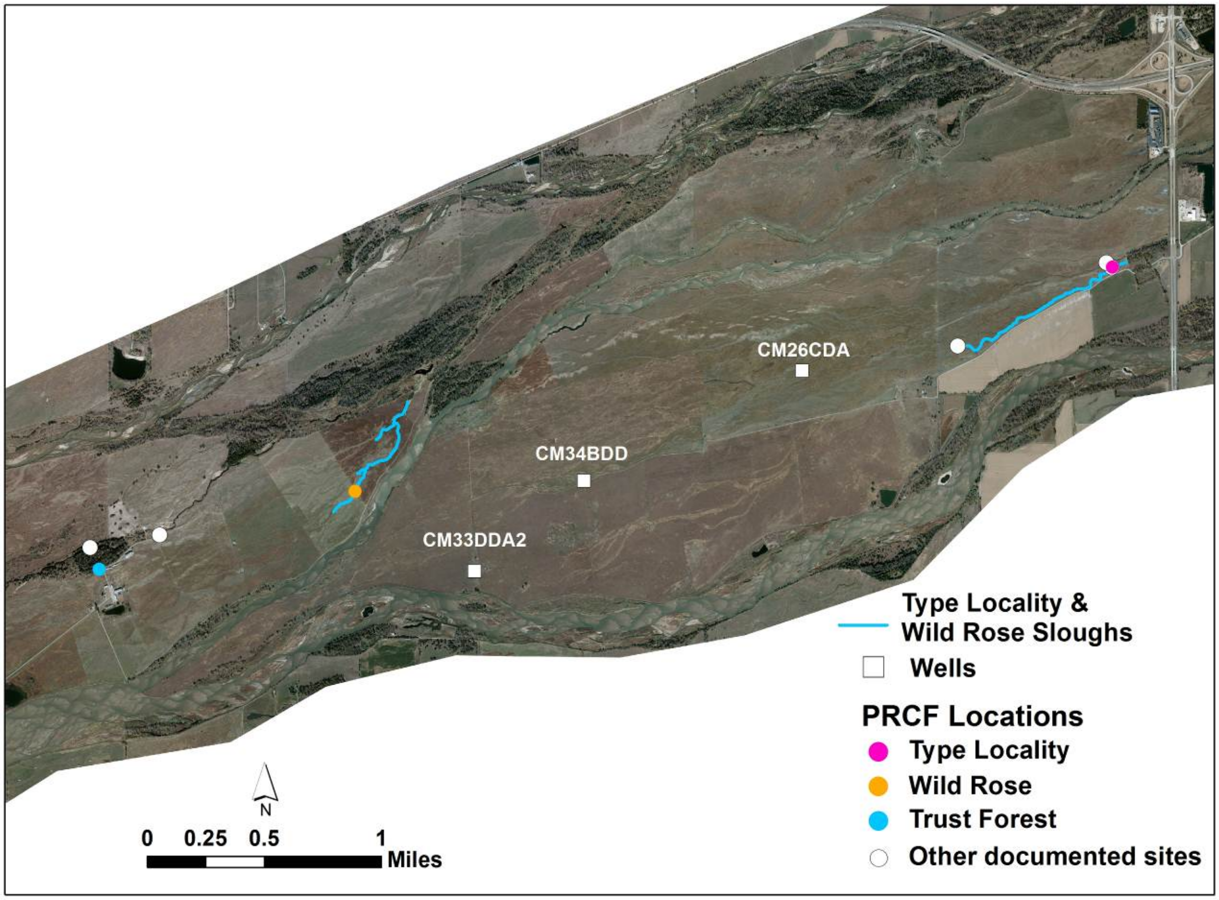


Figure 6. Locations of features on Mormon and Shoemaker Islands referenced in the report. The type locality (east) and Wild Rose (west) sloughs are key habitats for the Platte River caddisfly (PRCF). White dots indicate other known locations where the PRCF has been observed. The three wells recorded continuous data within the period 1996-2004 (R. Henszey, *unpublished data*). PRCF documentation: type locality: Whiles et al. (1999), Alexander and Whiles (2000), Whiles and Goldowitz (2001), Goldowitz (2004), Whiles and Goldowitz (2005); Geluso et al. (2011); Wild Rose slough: Meyer and Whiles (2008), Geluso et al. (2011), Geluso and Harner (*in review*); Trust Forest slough: Vivian (2010); and other localities: Goldowitz (2004) and K. Geluso (*unpublished data*).

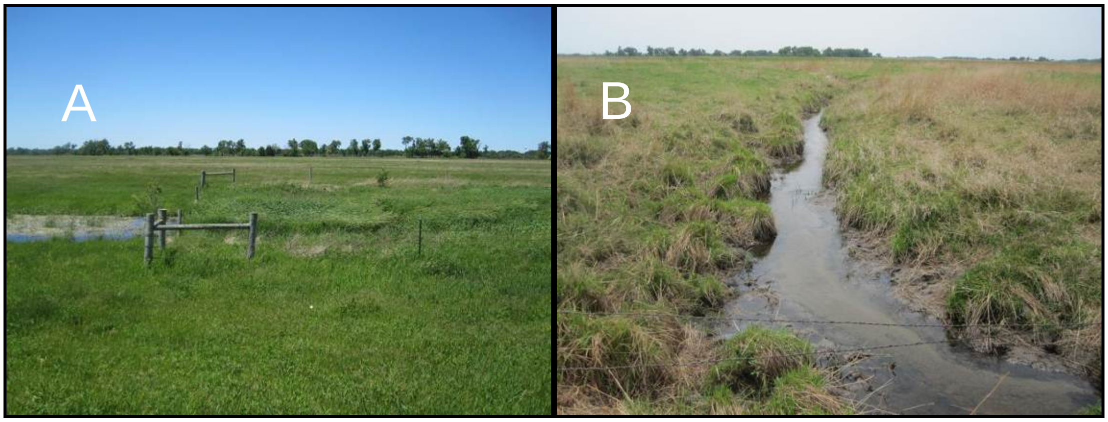


Figure 7. Grassland sloughs at the Crane Trust with high densities of the Platte River caddisfly. A) Type Locality on Mormon Island (note shallow topography) and B) Wild Rose slough on Shoemaker Island (note deeper, more entrenched channel). Photos by M. Harner 31 May 2011.

Densities of PRCF larvae differ among sites. The type locality (Fig. 7A) had the highest reported densities (725 larvae/m^2 on 5 April 1997; M. R. Whiles, personal communication, Whiles et al. 1999), followed by the western portion of Wild Rose slough (Fig. 7B; 553 larvae/m^2 on 29 April 2010, Geluso et al. 2011), and both of these sites have much higher larval densities than other sites along the Platte River surveyed in 2009 and 2010 (Vivian 2010). The type locality also had low larval densities in 2010 (Geluso et al. 2011). Some of this variation could reflect differences in sampling methodology. Whiles et al. (1999) sampled to a depth of 10 cm, while Vivian (2010) and Geluso et al. (2011) sampled to a depth of ~2.5 cm. It is possible that the Wild Rose slough densities are an underestimate, and they may approach historic densities reported for the type locality. Densities reported in Vivian (2010) are at least an order of magnitude smaller, with the exception of the Patrick site (Merrick County, NE) (126 larvae/m^2), further supporting that Mormon and Shoemaker islands host unusually high densities of the PRCF.

Methods

Overview of approach

Objective 1: Quantify changes in the area of floodplain occupied by inundated sloughs over the historical photo record.

We acquired aerial photographs from early in the photographic record (1938 and 1951) and recent times (1999-2010) and identified sloughs that had visible water within the channel. We measured the area of sloughs inundated and related that to precipitation and river flows preceding the photographs.

Objective 2: Model the duration of slough inundation (hydroperiod) under different hydrological scenarios to determine potential changes in availability of suitable habitat for the Platte River caddisfly.

With October 2010 imagery and Light Detection and Range (LiDAR) data, we developed a relative elevation model (depth of groundwater relative to ground surface) based on the difference between the groundwater slope and the general slope of the land. We then modeled how slough inundation changed as the water table elevation rose and fell by 0.25 ft increments. To link this inundation model with real space and time, we compared depth-to-water table measurements recorded in the field and modeled inundation patterns to determine the duration of hydroperiods for a subset of years (1997-2003). We determined the depth-to-water table at which the type locality and a majority of sloughs on Mormon Island would go dry and used this threshold to predict hydroperiods. This enabled us to link the modeled hydroperiods to the biology of the PRCF, which we did for two extreme years, 1999 (wet) and 2003 (dry), in the record. Detailed methods for each objective are described in the following sections.

Slough classification

We used historical aerial photographs and airborne imagery (Table 1) to quantify changes in the area of inundated sloughs (i.e., visible, standing water) over the historical photo record. We focused on Wild Rose slough (Fig. 6) because its deep channel was clearly visible and it held water throughout the photo series (Fig. 7B), in part due to an old dam at the mouth of the slough. The extent of slough inundation was delineated for the Wild Rose slough for all years and for 1951, 1999, and 2010 for a portion of Mormon Island; 1951 imagery only covered approximately 60% of Mormon Island, thus limiting our analysis of slough change for only part of the island. Although 1938 imagery was available (Fig. 8), poor image quality and multiple dates prohibited a robust delineation of slough inundation. Thus we used 1951 as our reference condition. For each year, extent of slough inundation was delineated using heads-up digitizing (i.e., manually drawing polygons around open water) in ArcMap, and the total area inundated was calculated. For Wild Rose slough, we examined associations among inundated slough area, river flow, and precipitation to the area of inundated slough with Spearman correlations (SPSS version 18).

Table 1. Dates and sources for aerial photographs and airborne imagery covering the study sites on Mormon and Shoemaker Islands, Hall County, Nebraska. Discharge denotes river flows at Grand Island. Images were from different seasons and river discharges, which affected slough inundation through the time series.

Year	**Day**	**Imagery Source**	**Discharge (cfs)**
1938	4-Jul	PRRIP[1]	351
1938	19-Nov	PRRIP	1500
1951	8-May	PRRIP	1080
1999	13-May	PRRIP	10800
2003	12-Sep	PRRIP	0
2004	31-Mar	PRRIP	0
2004	21-Aug	USFWS[2]	0
2006	23-Jul	USDA[3]	0
2010	28-Oct	PRRIP	1220

[1] Platte River Recovery Implementation Program, Kearney, NE
[2] United States Fish and Wildlife Service, Grand Island, NE
[3] United States Department of Agriculture, www.fsa.usda.gov

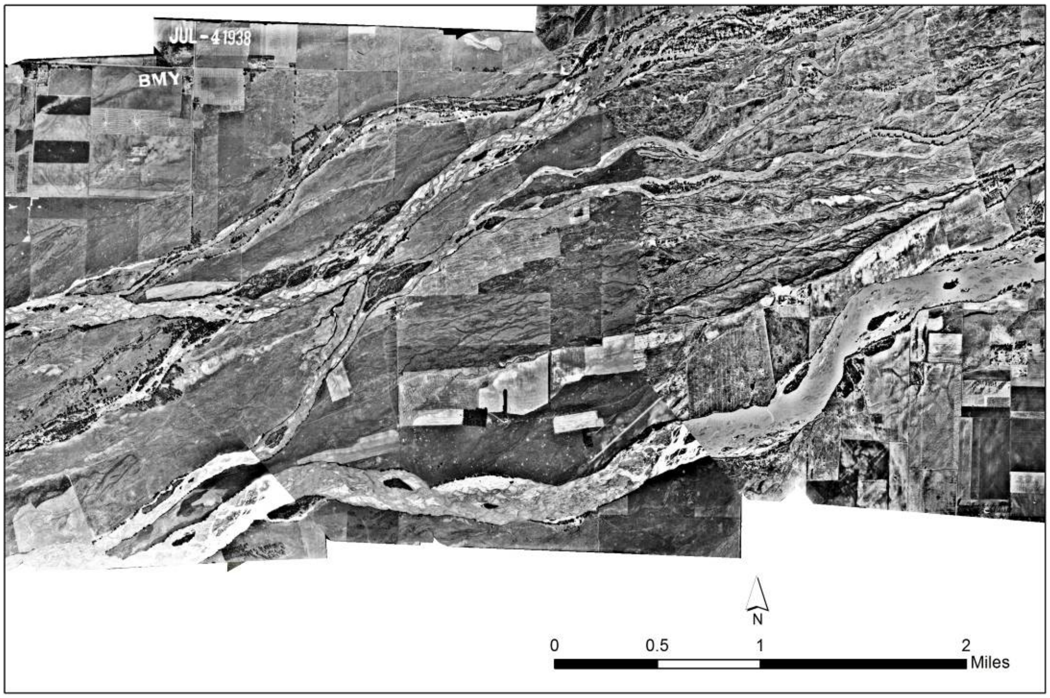


Figure 8. Aerial photography of Mormon and Shoemaker Islands from 1938. Western portion of image is from 4 July (river flow 351 cfs) and eastern portion from 19 November (river flow 1500 cfs). Delineation of sloughs on these photographs was unreliable due to low image resolution and differences in river flow between images.

Slough inundation modeling

We used the 28 October 2010 imagery (1 ft resolution) and the accompanying bare earth LiDAR data (3.3 ft resolution) to develop a groundwater relative elevation model (relative to ground surface) within Shoemaker and Mormon Islands. We assumed that visible water in sloughs represented the water table intercepting the sloughs, and used the distribution of slough water as our estimation of the slope of the water table. This was a relatively dry period, with little precipitation preceding the photograph (0.14 in 1-2 weeks prior), so presence of slough water was unlikely influenced by precipitation. Exposed water was delineated in the 2010 imagery by digitizing a line through the exposed water in the center of sloughs, and lines were converted to points at 6-ft spacing. Point elevations were then extracted from the LiDAR data to generate the slope of the water table. We recognize that slough water elevations may be a rough estimate of the adjacent water table because sloughs act as drains on the water table, thus their water level is often lower than the adjacent water table.

The groundwater slope was initially interpolated for each island using the Topo to Raster command in ArcMap to generate a coarse resolution (100 ft) raster to minimize effects of anomalies in the elevation data (e.g., erroneous elevation data might occur due to dense grass reducing penetration of LiDAR to reach the ground surface). One-ft contours were generated from the initial groundwater slope and reinterpolated to a final 3.3-ft resolution to match the resolution of the bare earth LiDAR data. The groundwater slope was then subtracted from the bare earth LiDAR to generate an initial groundwater relative elevation model. Because LiDAR does not penetrate the water surface or dense grass, additional analyses were conducted to model slough depths and account for overestimation of bare earth elevations in dense grass stands. Measurements of slough depths were needed to determine when the water table intercepts the bottom of the slough. To estimate slough depth, we visited sloughs and directly recorded the location and the depths of standing water in channels at the Wild Rose slough and the type locality on 3 and 4 June 2011. Data were collected using a Trimble GeoXT handheld GPS and post-processed to maximize positional accuracy. We adjusted measured slough depths by -0.4 ft to account for higher water in 2011. For example, if a field-measured slough depth was 1.6 ft, it was adjusted to 1.2 ft to account for slough stage between LiDAR acquisition and field measurements. This was based on a comparison of slough water surface and nearby road elevations between the GPS data and LiDAR data. Due to time and funding constraints, no other survey data were collected for other sloughs. To estimate depths for other sloughs, we used an estimate of an additional 0.75 ft (i.e., all other sloughs delineated in the 2010 imagery). A new groundwater relative elevation model was then interpolated using the estimates of slough depths.

Second, due to the inability of the LiDAR to penetrate dense grass, elevation values for upland pastures that were not recently burned or grazed were lowered. Approximately 200 random points were selected near pasture boundaries to determine differences in bare earth elevation estimations from dense grass stands and grazed/burned pastures uplands. A mean difference of 0.35 ft was calculated between the pasture boundaries. To create the final groundwater relative elevation model, uplands in non-grazed or unburned pastures were lowered by 0.35 ft. Exposed slough water surface elevations in dense grassland were assumed to be correct, due to the lack of vegetation in the exposed water, and were not adjusted.

The groundwater relative elevation model was then used to model changes in water table elevation and extent of slough/wet meadow as groundwater levels changed by 0.5 ft increments. Each island was modeled separately to minimize extrapolation errors. To validate our inundation models we visually ground-truthed our inundation extents throughout the first week of June 2011. Although the validation was purely qualitative, the model appeared to replicate current inundation reasonably well, with only minor problems in pastures with dense grass. In these areas the model seemed to minimally over-predict inundation. Despite these caveats, we feel that our inundation models reasonably portray inundation changes that occur on Mormon and Shoemaker Islands. A more robust validation would involve acquiring new imagery with coordinated well and slough stage data.

Although several steps were taken to produce a relatively accurate relative elevation groundwater model, some limitations still existed. For example, differences in pasture management (burning, grazing, and resting) affected the amount of visible water in sloughs (Fig. 9). Water is more easily detected in pastures that have been burned or grazed due to less grass cover and reduced rates of evapotranspiration (e.g., Wesche et al. 1994). In addition, an image acquired after a heavy rainfall will most likely capture standing water in shallow depressions and artificially increase the extent of visible water. Hence, when comparing modeled inundation extents to other photographs/images, these limitations must be considered.

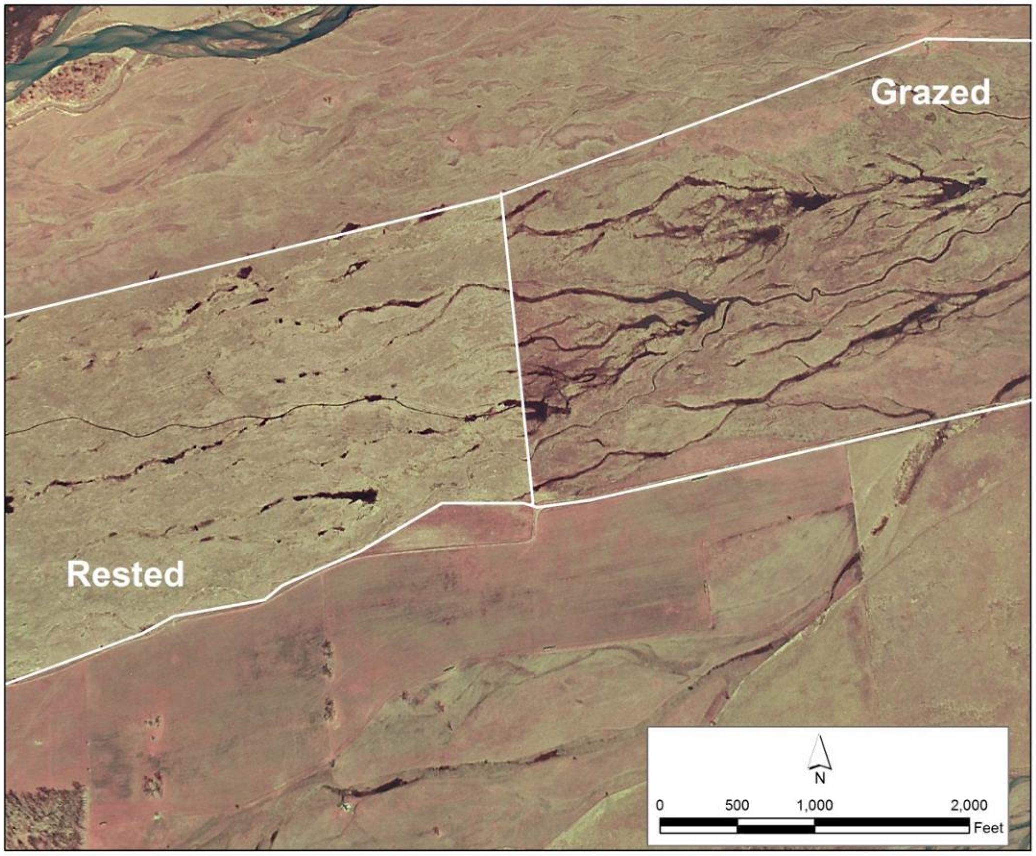


Figure 9. Example from Mormon Island (2004) of how grazing affects visibility of water in sloughs. Water is much more extensive in the grazed pasture compared to the pasture that was rested from grazing for two years. This is due to a reduction in grass cover obstructing the view of the channel and possibly reduced rates of transpiration in the grazed pasture. In addition, the rested pasture is up gradient and likely would have less surface water.

Hydroperiod modeling

To link our inundation model with real space and time, we used depth–to-water table measurements from well CM26CDA in conjunction with the inundation model available from 1997-2003 to model typical hydroperiods (# days sloughs held water) for relatively wet (1997-1999) and dry (2000-2003) periods. We used well CM26CDA in our analysis because it was the closest well to the type locality (Fig. 6) for which we had access to data (other wells are present near the type locality), and the water table was relatively shallow and therefore likely responsive to influences from precipitation. However all wells showed similar patterns of rising/dropping groundwater stage across time (Fig. 4), thus the relative rise and drop of the water table should be relatively consistent across Mormon Island.

First, we compared our modeled inundation results (based on the 28 October 2010 pattern) to the inundation extent from 13 May 1999 to determine what increase in groundwater stage would create the inundation (amount of visible surface water) in the 1999 image. An increase in groundwater elevation from the 2010 image by 0.5 ft best approximated the extent of inundation observed in 1999 (Fig. 10) (i.e., groundwater was ~ 0.5 ft lower when 2010 image flown). Second, by cross-referencing data from well CM26CDA on the same date of the imagery (13 May 1999), we determined that the water table elevation was 0.06 ft above the ground surface (based on R. Henszey's *unpublished data*). We used this figure (0.06 ft) as our reference depth-to-water table stage to calculate the relative drop and rise in the water table for 1999, and ultimately to determine when the type locality and the majority of sloughs on Mormon Island would go dry. The type locality slough is one of the wettest sloughs on Mormon Island, maintaining enough water to support fish communities (Whiles and Goldowitz 2001), thus the type locality slough provides a good barometer for potential drying of most sloughs on Mormon Island. If the type locality slough goes dry, then most other sloughs also are dry. From our modeled inundation patterns, it was determined that the type locality would go dry with a 1.5 – 2.0 ft drop in the water table. This would relate to a depth to water table of ~ 1.44 – 1.94 ft in well CM26CDA. We then used ~1.44 – 1.94 ft water stage as a threshold for drying of sloughs and estimated the yearly and mean hydroperiod for sloughs on Mormon Island for wet (1997-1999) and dry (2000-2003) years based on well CM26CDA data. Estimates of drying were calculated for each year for each depth (1.44 or 1.94 ft) and then averaged for the wet and dry periods.

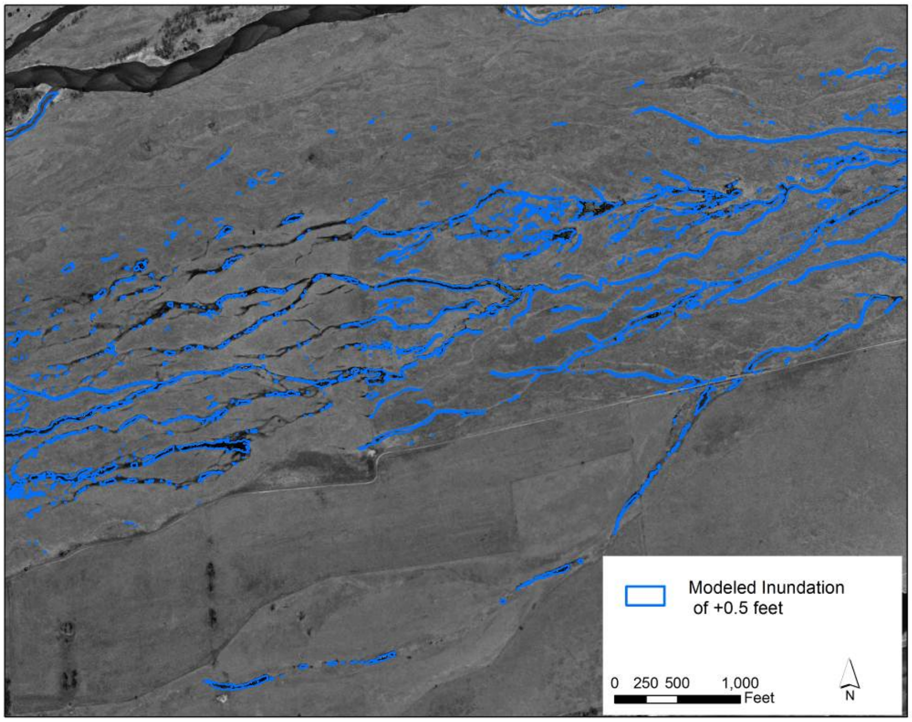


Figure 10. Base image from 13 May 1999 with modeled slough inundation, determined from 2010 imagery, overlaid. When groundwater elevations were increased by 0.5 ft relative to the 2010 imagery, the area inundated approximately matched the 1999 image, suggesting that the water table was ~0.5 ft lower in the 2010 image. This correction factor permitted extrapolation of the inundation model based on the 2010 image to 1999, a wet period in the record. There was some under-estimation of slough inundation (sloughs still appear black rather than blue) in the western portion of the image that was caused by the difficulties of bare earth elevation estimates for the 2010 LiDAR for this pasture with dense grass (see Fig. 9 for example).

Results

Changes in slough inundation through photographic record

The amount of inundated slough area varied widely across the photographic record of Wild Rose slough, ranging from only 0.9 acres to 5.0 acres (Table 2). When river flows approached 0 cfs, water was only visible in the far downstream segment (Fig. 11), likely due to pooling behind an obstruction. River flows varied by a factor of ten across the photo series (Table 2) and were positively correlated with slough inundation ($r_s = 0.852$, $p = 0.015$, $n = 7$). Correlation analysis, however, did not indicate an association between slough inundation and precipitation, measured one or two weeks prior to images. These correlations, or lack thereof, however, must be interpreted with caution, as the sample size was small, and there was a nearly 50-year gap in a portion of the photo record.

To compare slough inundation in the early and recent imagery, we focused analysis on May 1951 and May 1999 images because they were taken at the same time of year with similar antecedent precipitation (i.e., similar precipitation totals 1-2 weeks prior to image capture and during the months (January-April) preceding the photos). The dates, however, had very different river flows. The 1999 image had 10 times more discharge than 1951 (Table 2). Despite this order of magnitude difference in river flow, the area of inundation at the Wild Rose slough declined by 0.8 acres between 1951 and 1999 (Fig. 12, Table 2). Similarly, for Mormon Island where we have overlapping imagery coverage between years (Fig. 13), the total area of inundated sloughs was less in 1999 (23.05 acres) compared to 1951 (31.85 acres), with most loss of inundated sloughs occurring at the upper reaches of the sloughs (western portion of the island) and in a large slough on the southern end of the island (Fig. 13).

Table 2. Total inundation extent of Wild Rose slough delineated from aerial imagery shown with corresponding river flows and precipitation totals prior to imagery acquisition over the time series.

Year	Day	Slough area inundated (acres)	River flow (cfs)	Precipitation 2 weeks prior (in)	Precipitation 1 week prior (in)
1951	8-May	5.0	1080	1.5	0.01
1999	13-May	4.2	10800	1.32	0.15
2003	12-Sep	0.9	0	2.22	2.21
2004	31-Mar	3.6	449	0.76	0.76
2004	21-Aug	0.4	0	0.43	0.08
2006	23-Jul	1.3	0	1.04	0.78
2010	28-Oct	3.7	1220	0.14	0.14

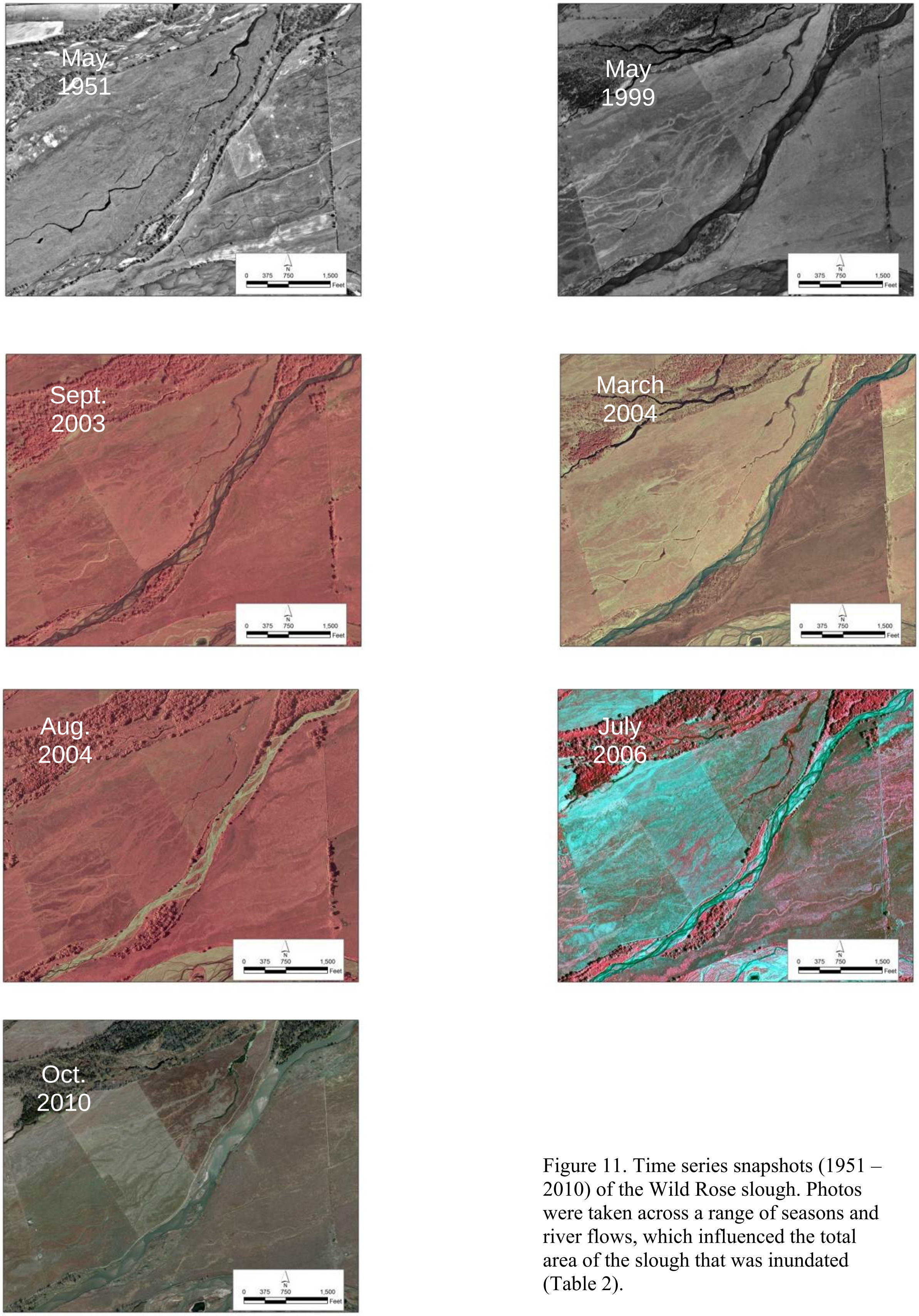


Figure 11. Time series snapshots (1951 – 2010) of the Wild Rose slough. Photos were taken across a range of seasons and river flows, which influenced the total area of the slough that was inundated (Table 2).

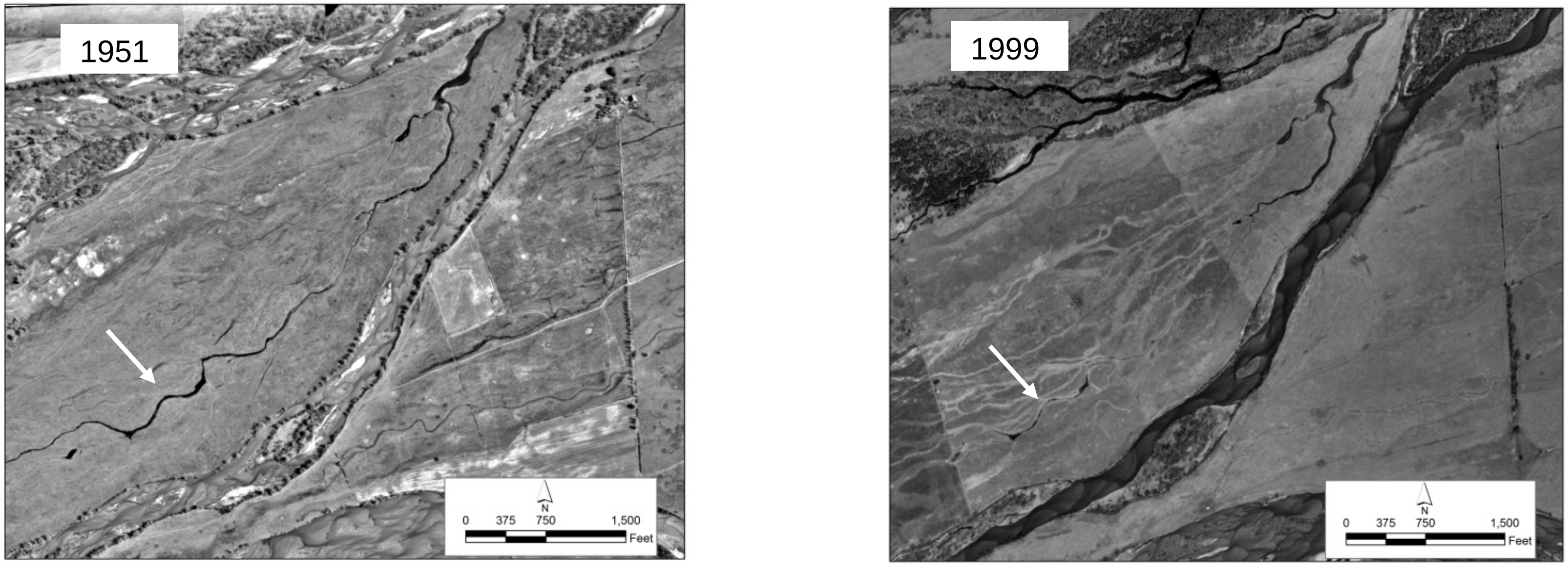


Figure 12. Comparison of Wild Rose slough inundation on Shoemaker Island between May 1951 and May 1999. The area of slough inundated declined by 0.8 acres between photos, despite river flows being ten times higher in 1999; white arrows denote the portion of the slough with most pronounced drying. The amount of precipitation preceding image capture was similar between photos, so this variation is not due to a rapid response to rain in 1999. Note also how much water is present in the south river channel in 1999 and the sloughs. This pattern suggests that the connection between groundwater and surface water has been altered between photos. In addition, the amount of slough visible is obscured in 1951 due to dense grass cover (likely ungrazed when image captured), so there may actually be even greater inundation than we could detect from the imagery. In contrast, the surrounding pastures lacked dense vegetation in 1999, so plant growth was not obstructing the view of the sloughs. Therefore, the extent of slough decline between photos is likely an underestimate, as less of the slough network is visible beneath the grass in 1951.

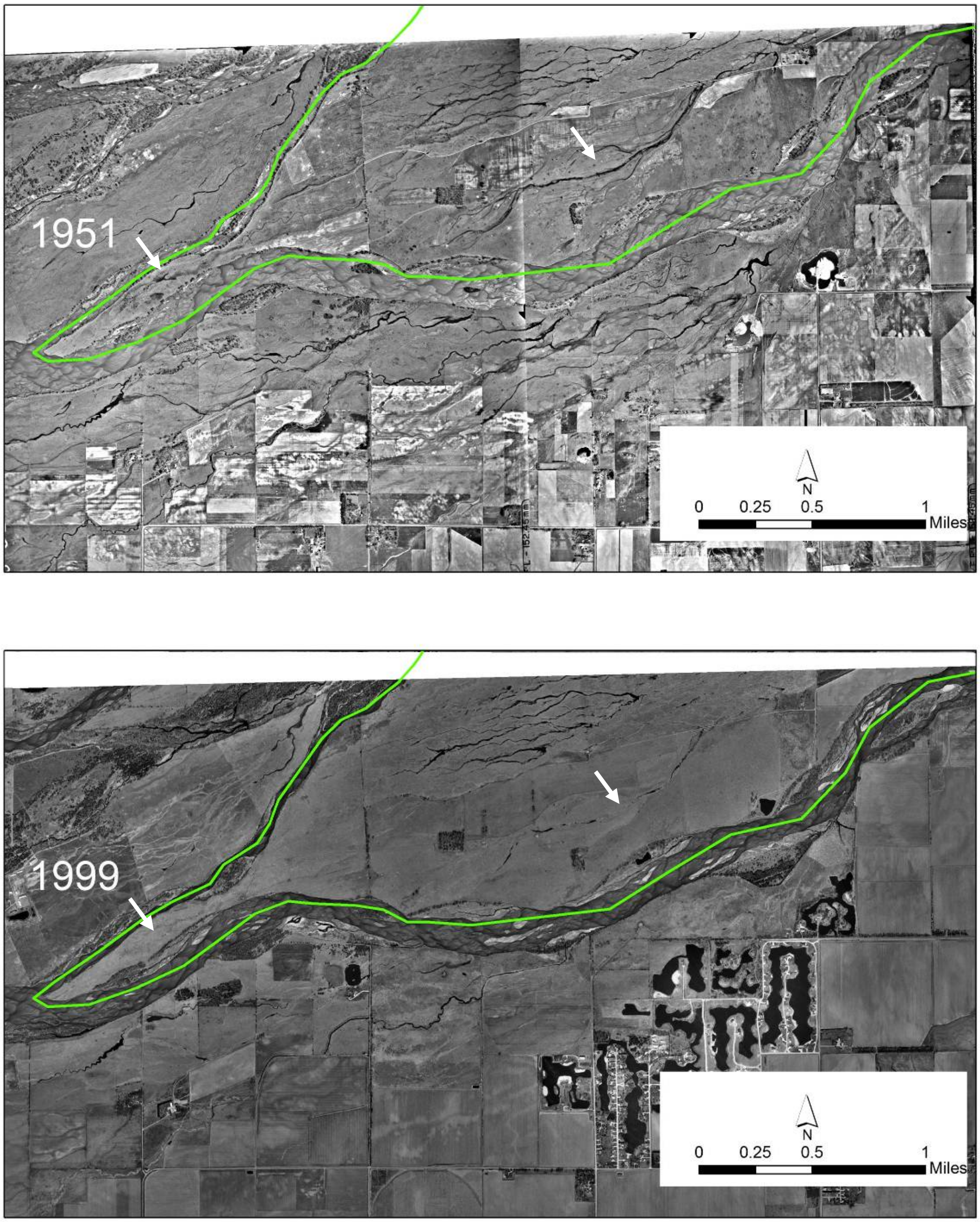


Figure 13. Comparison of Mormon Island slough inundation between May 1951 and May 1999. The area of slough inundated declined by 28% where overlapping coverage exists between photos, despite river flows being ten times higher in 1999. The amount of precipitation preceding image capture was similar between photos, so this variation is not due to a rapid response to rain in 1999. Note the almost entire loss of the large slough on the southern side of the island and loss of upstream slough segments (denoted by arrows).

Slough inundation under changing groundwater elevations

Modeled inundation patterns varied dramatically between Mormon and Shoemaker Islands. The portion of Shoemaker Island we modeled (Fig. 14) was characterized by deep, entrenched slough channels that held water for long periods, while a majority of Mormon Island was characterized by an extensive network of shallower, wider sloughs that occupied the central portion of the Island (Fig. 15). As the modeled water table elevation rose on Shoemaker Island, most exposed water remained in the slough channels (Fig. 14). Conversely, rising groundwater combined with the shallow channel morphology of the Mormon Island sloughs resulted in exposed water extending beyond the slough banks (Fig. 15). These Mormon Island sloughs may expand their areal extent rapidly with a small rise in water table at higher groundwater stages. The Mormon Island sloughs are considered a wet meadow environment (Nagel 1981).

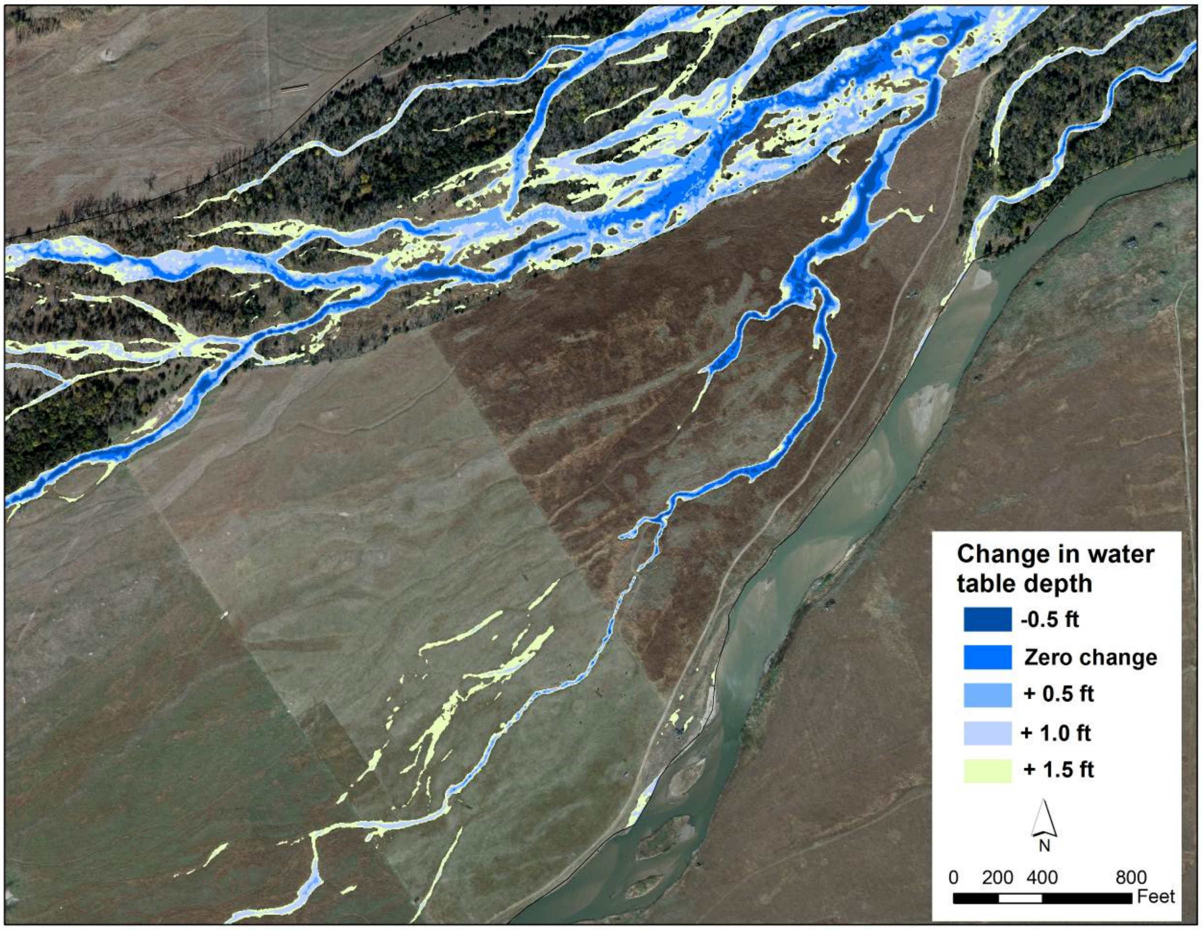


Figure 14. Modeled inundation pattern predicted for Shoemaker Island. Zero change (medium blue) is the extent of visible water in the base photo (taken on 28 October 2010). A -0.5 ft change (i.e., dropping of water table 0.5 ft) results in slough drying and reduced inundation, denoted by dark blue. An increase in groundwater of 0.5 ft or more fills more upstream portions of the slough. Large increases in groundwater (i.e., raising it 1.5 ft; yellow shading) rarely produce overbank flow from the slough, indicative of the deep channel morphology of the slough.

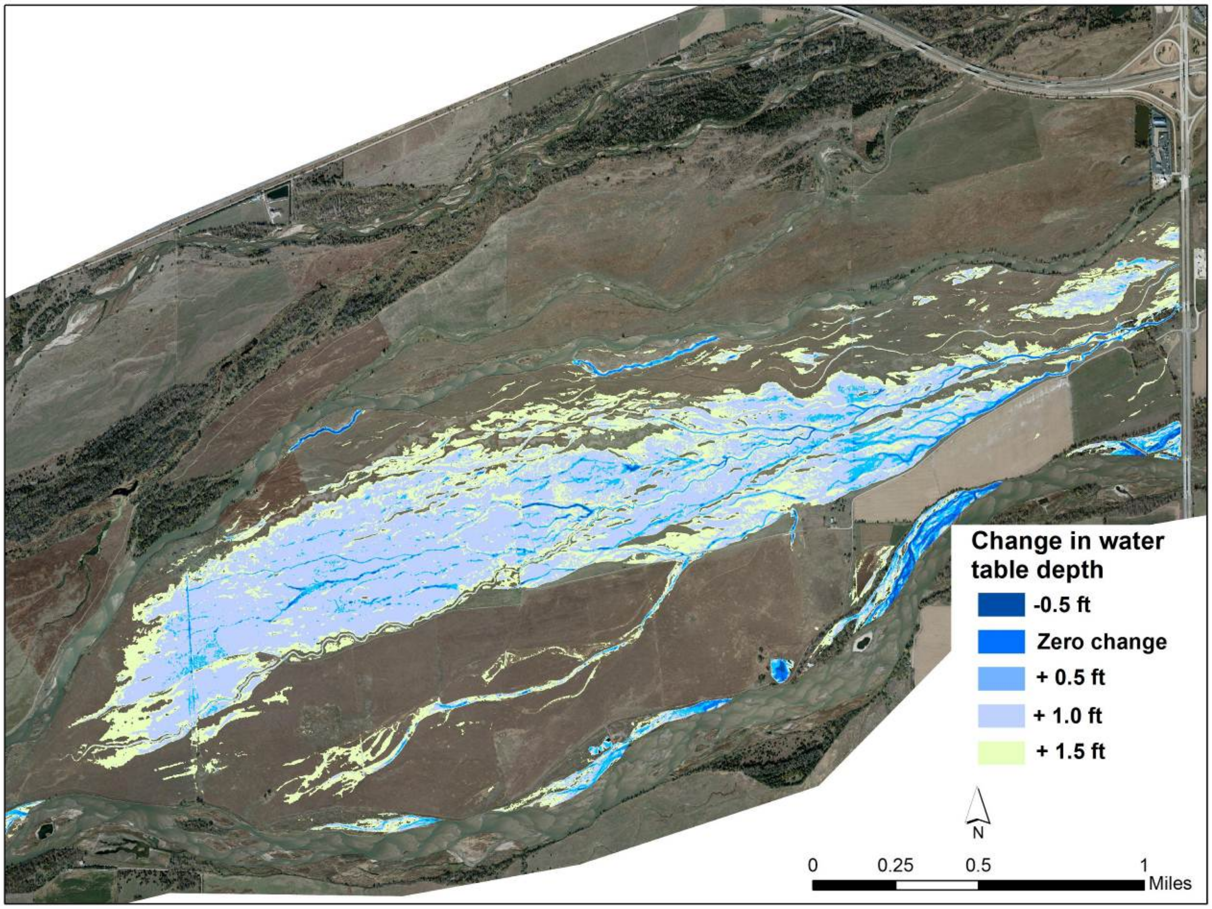


Figure 15. Modeled inundation pattern predicted for Mormon Island. Zero change (medium blue) is the extent of visible water in the base photo (taken on 28 October 2010). A -0.5 ft change (i.e. dropping of water table 0.5 ft) results in drying of sloughs and reduced inundation, denoted by dark blue. An increase in groundwater of 1.0 ft more (denoted by light blue and yellow shading) results in water overtopping the slough banks and inundating the floodplain, thus creating a wet meadow environment.

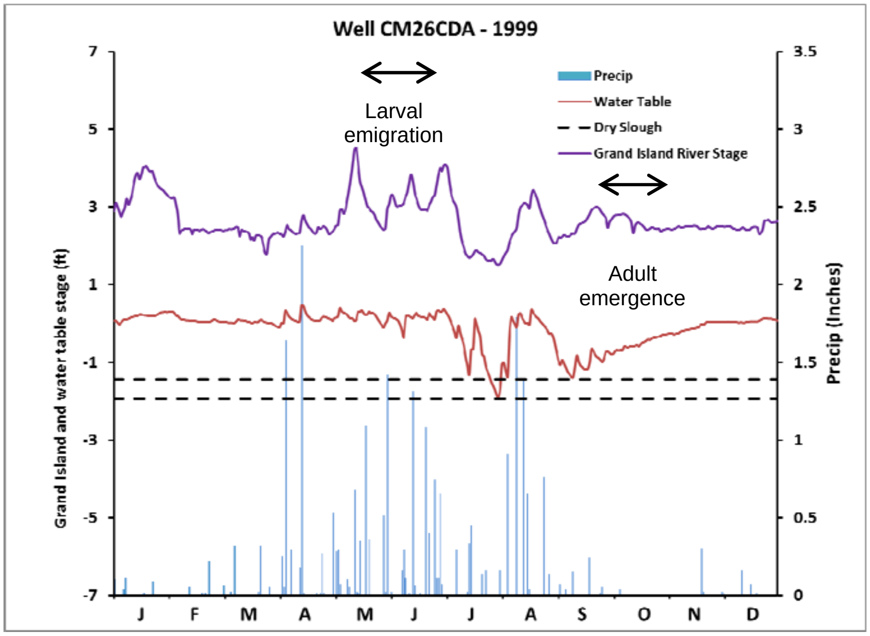
Duration of slough inundation (hydroperiod) in wet and dry years

Models of slough inundation for Mormon Island were used to estimate hydroperiods for the type locality and to provide a reasonable estimate of drying for most sloughs on Mormon Island. To reiterate, we modeled inundation pattern and duration for a subset of years where continuous water table data were available and that encompassed both wet (1997-1999) and dry (2000-2003) periods. We had no way to account for whether water in the slough was frozen during winter months, so inundation estimates reflected the presence of water, in either the liquid or solid state. During wet years the average duration of inundation for the type locality was 340 days, ranging from 304 to 365 days inundated (Table 3; Fig. 16). During the dry period, the average inundation duration was 249 days, ranging from 200 to 290 days inundated (Table 3; Fig. 16); the majority of the drying occurred in summer and fall. In one of the driest years (2002), the majority of the sloughs were dry by late May and not re-hydrated until late October. Although we modeled slough inundation for Shoemaker Island, no historical well data were available nearby to reasonably predict hydroperiods for sloughs on Shoemaker Island.

Our estimates of inundation duration for Mormon Island corresponded well to what Whiles and Goldowitz (2001) observed from field measurements of slough hydroperiods. For the type locality in 1997, they measured a hydroperiod of 331 days, while our model estimate was 330 days. Whiles and Goldowitz (2001) measured two other sloughs with shorter hydroperiods on Mormon Island; they observed 296 days of inundation duration for slough MI2, while we estimated the range of inundation between 285 and 317 days, with a mean of 301 days. Similarly, their driest slough (MI3) only held water for 94 days; our estimated mean inundation duration at that site was 117 days.

Table 3. Summary of modeled hydroperiods for the type locality from 1997 to 2003. Hydroperiods were estimated by calculating the number of days the water table was above 1.44 or 1.94 ft (see methods).

	1997	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Number of inundated days water table above 1.44 ft	317	304	359	234	273	235	200
Number of inundated days water table above 1.94 ft	337	347	365	268	290	255	218
Mean number of inundated days	330	330	363	255	284	248	211



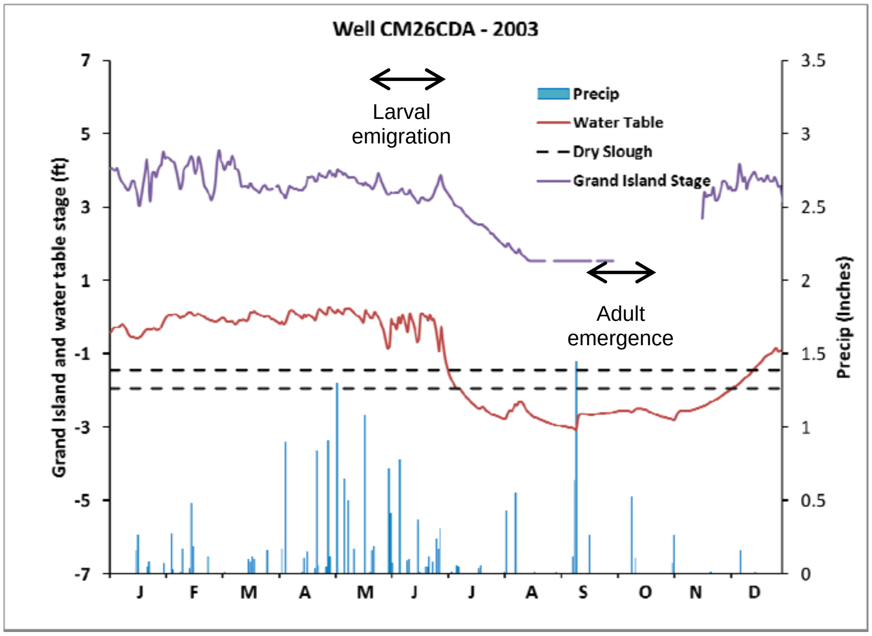


Figure 16. Change in river stage (purple line), precipitation (blue bars), and water table stage (red line) for the type locality on Mormon Island for a wet (1999) and dry (2003) year. The dashed line denotes the water table elevation in this well (CM26CDA) where the slough would go dry (see methods for explanation). In the wet (1999) year, the water table barely crosses the dashed line, indicating that the slough was wet nearly all year, and that there was water in the slough during the aquatic phase of the PRCF lifecycle (~September-May). In constrast, in the dry year (2003), the water table declines below the dashed line in June, and remains low the rest of the year, indicating a drying of the type locality from June onward. The dry year would result in a slough without water in the autumn when adults emerge and return to the slough to lay eggs.

Discussion

We focused our slough hydrology studies on Mormon and Shoemaker Islands because of their relatively unaltered topography (i.e., little leveling for agriculture), long-term groundwater data (Hurr 1993, Wesche et al. 1994, R. Henszey *unpublished data*), and known populations of the PRCF (Whiles et al. 1999, Vivian 2010, Geluso et al. 2011). This potentially is a best-case scenario for PRCF habitat availability, and patterns observed on these islands may not apply to other portions of the river. This area historically had such high water tables that little of it was plowed prior to its establishment as a preserve in 1980 (Nagel 1981). Therefore, sloughs were not leveled for agriculture as they were in other parts of the Platte River valley (Sidle et al. 1989). Visual examination of the aerial photographs in 1938 confirmed the continued presence of sloughs over the period of record; most of the sloughs that were present in 1938 still were present on current photos. Remnant networks of such natural sloughs are rare in the Platte River valley (Sidle et al. 1989). However, the physical presence of a linear depression does not necessarily mean that inundation patterns of the sloughs are constant through time.

For our first research objective—to quantify changes in the area of inundated sloughs over the photographic record—comparison of 1951 and 1999 imagery indicated that the area of sloughs inundated declined on both Shoemaker and Mormon Islands. These photos were an ideal comparison because they were both taken in May, thus reducing variability in hydrology associated with seasonality and evapotranspiration (e.g., Wesche et al. 1994). Both years also had similar precipitation levels preceding the photos, which is important because a single rainfall event can elevate water levels for up to a week (Henszey 2000). Other analyses have found significant correlations between river stage/flow and groundwater stage on Mormon Island (Hurr 1993, Wesche et al. 1994, Sanders 2001). Therefore, we expected that groundwater elevations, and hence slough inundation, would have been higher in 1999 because river flows were ten times higher. This, however, was not the case, and suggested that other factors altered inundation patterns of the sloughs.

Determining a mechanism behind the drying of sloughs between 1951 and 1999 is beyond the scope of this study, and a number of factors potentially affected the groundwater elevation. The Platte River channel bed may have incised between 1951 and 1999, thus lowering the gradient from the river into the adjacent wet meadows. One could test this by analyzing cross-sectional elevation data through time along the south channel. Alternatively, changes in regional groundwater dynamics may have affected the water table. Groundwater level changes in counties south of our study site (Adams and Clay counties) indicate declines of 5-20 ft relative to pre-development conditions (*see* Fig. 1 in Sanders 2001 of data from Nebraska Department of Natural Resources). Perhaps some of these declines extend farther north than reported/measured into our study region. Local landuse practices also may have influenced groundwater dynamics on the islands. Evapotranspiration leads to declining water tables (e.g., Wesche et al. 1994), so greater vegetation growth could deplete groundwater and lead to a reduction in surface water in sloughs. Greater plant vigor in recent decades, due to better grazing practices and/or climatic factors, could have depressed the water table via high rates of transpirational losses. An analysis of grazing intensity through the photographic record would help determine if this is a factor. However, for Shoemaker Island in our analysis, the pastures had little grass cover in 1999 compared to 1951, suggesting that transpiration was not the primary driver of reduced surface water. In general, analyses of aerial photographs between 1951 and 1999, coupled with more detailed analyses of wells and channel cross-sections (if available) and grazing records, are needed to help understand causes behind these changing inundation patterns.

Our second research objective was to model the duration of slough inundation under different hydrological scenarios to determine potential changes in suitable habitat for the Platte River caddisfly. Our models of slough inundation in wet (1997-1999) and dry (2000-2003) periods showed that slough hydroperiods on Mormon Island, such as at the type locality, were ~91 days shorter during the dry period. The PRCF was discovered during this wet period (Whiles et al. 1999, Alexander and Whiles 2000), when hydroperiods were long enough to support the aquatic phase of the PRCF through spring and provide moisture in autumn when adults emerged. Subsequent surveys for the PRCF during and after the drought (Goldowitz 2004) observed reduced densities of the insect. Our model, when coupled with timing of larval emergence from the slough (spring) and adult emergence/egg laying (autumn) (Whiles et al. 1999, Geluso et al. 2011), suggested that declines in the PRCF in the early 2000s could have resulted from sloughs drying too early in the spring and/or being too dry in autumn when adults returned to lay eggs. In a wet year (1999), the slough went dry after larvae emigrated and was inundated again by the time adults emerged. Conversely, in a dry year (2003), the slough dried early, possibly before the insects could complete the aquatic phase of their life cycle or forcing them to emigrate at a smaller, less fit size, and remained dry during the period when adults typically would return to lay eggs (Whiles et al. 1999, Geluso et al. 2011). It is unknown whether PRCF eggs can survive for a period without moisture, like other species of *Ironoquia* (Williams and Williams 1975), but it is likely that dry autumnal conditions are not ideal for the PRCF. Future studies could investigate whether eggs can survive with moist soil from capillary action when sloughs lack surface water. In addition, indirect effects of extremely dry conditions in the slough environment that affect vegetation composition and productivity, and hence the food base for the PRCF are unknown, and also could influence densities of the PRCF in wet and dry periods (e.g., Geluso and Harner *in review*).

Combined, results suggested that hydrological alterations that diminish groundwater levels, and consequently, slough inundation, reduce the available habitat required for the Platte River caddisfly to complete the aquatic phase of its life cycle from September to May. Mormon and Shoemaker Islands have large areas of natural sloughs remaining, unlike many other regions of the Platte River. Even when ample, inundated slough habitat is available, it is not guaranteed that the PRCF will be present (Vivian 2010). Additional controls on their presence also need to be evaluated. For example, modifications of thermal regimes by inflowing groundwater in sloughs may modulate water temperatures relative to river water (slough water warmer in winter and cooler in summer), thus making groundwater fed sloughs more suitable to the PRCF. Furthermore, inundation of relatively intact, natural sloughs is variable within and among years. For example, from the historical precipitation record, it is clear that the region has cycled through wet and dry periods since 1938, and the caddisfly likely has persisted through this time frame. Perhaps deep, consistently inundated sloughs like Wild Rose slough that maintain water in dry years help protect the species by serving as source populations after stressful climatic periods. Alternatively, maybe this species can enter a dormant stage and persist through prolonged stressful periods. Future studies should locate the remaining sloughs in the central

Platte River valley that have the potential for adequate, predictable autumn-spring inundation, survey them for the Platte River caddisfly, and consider their future protection for the PRCF and other species that require these dynamic, off-channel habitats.

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