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Investigating whooping crane habitat in relation to hydrology, channel morphology and a water-centric management strategy on the central Platte River, Nebraska



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Abstract

The Flow-Sediment-Mechanical approach is one of two management strategies presented in the Platte River Recovery Implementation Program's (Program) Adaptive Management Plan to create and maintain suitable riverine habitat (≥ 200 m wide unobstructed channels) for whooping cranes (*Grus americana*). The Program's Flow-Sediment-Mechanical management strategy consists of sediment augmentation, mechanical vegetation clearing and channel widening, channel consolidation, and short duration high flow releases of 142–227 m³/s for three to five days in two out of three years in order to increase the unvegetated width of the main channel and, by extension, create and maintain suitable habitat for whooping crane use. We examined the influence of a range of hydrologic and physical metrics on total unvegetated channel width (TUCW) and maximum unobstructed channel width (MUOCW) during the period of

2007–2015 and applied those findings to assess the performance of the Flow-Sediment-Mechanical management strategy for creating and maintaining whooping crane roosting habitat. Our investigation highlights uncertainties that are introduced when exploring the relationship between physical process drivers and species habitat metrics. We identified a strong positive relationship between peak flows and TUCW and MUOCW within the Associated Habitat Reach of the central Platte River. However, the peak discharge magnitude and duration needed to create highly favorable whooping crane roosting habitat within our study area are much greater than short duration high flow releases, as currently envisioned. We also found disking in combination with herbicide application to vegetated portions of the channel are effective for creating and maintaining highly favorable unobstructed channel widths for whooping cranes in all but the very driest years. As such, resource managers could prioritize the treatment of mid-channel islands that are vegetated to increase the suitability of roosting habitat for whooping cranes.

Keywords: Ecology, Environmental science, Hydrology

1. Introduction

Historically, the central Platte River in Nebraska, USA, exhibited a braided planform defined by very wide and sandy channels (Eschner et al., 1983). Mature woody vegetation was established mostly on islands of different sizes and maybe on the banks (Simmons and Associates, 2000). Significant upstream water extractions due to development began in the mid-19th Century and accelerated into the 20th Century. These extractions reduced flow through the central Platte, disturbed numerous geomorphic processes (Williams, 1978; O'Brien and Currier, 1987; Simons and Associates, 2000; Murphy et al., 2004; Tal et al., 2004; Schumm, 2005), and resulted in significant narrowing of the active channel area, evidenced by the encroachment of woody vegetation (Johnson, 1994). Consequently, the contemporary Platte River exhibits a braided to anastomosed planform defined by narrow sandy channels that are bound by large stands of mature woody vegetation.

The reduction in channel width of the central Platte River over time and the mechanisms driving this reduction have been studied extensively (Williams, 1978; O'Brien and Currier, 1987; Johnson, 1994; Simons and Associates Inc. 2000; Murphy et al., 2004; Schumm, 2005), often in the context of acknowledging a link between reach-wide reductions in channel width and reductions in habitat available for threatened or endangered species that use the channel, like the whooping crane (*Grus americana*). These linkages were first realized during many of the early whooping crane habitat selection studies performed on the central Platte River (Johnson, 1982; Lingle et al., 1984; Ziewitz, 1987;

Faanes and Bowman, 1992; Faanes, 1992; Faanes et al., 1992). During this time, the United States Fish and Wildlife Service (USFWS) and several conservation organizations became concerned that the widespread reductions in channel width (i.e., narrowing) were causing a decline in the availability and suitability of roosting habitat for the whooping crane (USFWS, 1978; PRRIP, 2006). This led the USFWS to issue jeopardy opinions for any basin water project that could reduce flow through the central Platte River and contribute to the ongoing narrowing of the channel.

In response, the Platte River Recovery Implementation Program (Program or PRRIP) was formed in 2006 and tasked, in part, with contributing to improved whooping crane survival by increasing the availability and suitability of whooping crane habitat along the central Platte River (i.e., creating and maintaining suitably-wide channel widths). The Program's Adaptive Management Plan, which was developed by experts, outlines two management strategies to create and maintain suitably-wide channel widths. The first is known as the Mechanical Creation and Maintenance strategy (PRRIP, 2006). It consists only of sustained mechanical interventions like in-channel vegetation removal via disking and herbicide application. The second management strategy is known as the Flow-Sediment-Mechanical strategy (PRRIP, 2006). As developed, it consists of: limited mechanical interventions to remove in-channel vegetation, flow consolidation into a single channel (which was eventually deemed unfeasible due to permitting and property rights constraints), sediment augmentation, and flow augmentation and management via prescribed releases. The mechanical interventions and sediment augmentation pieces of the FSM strategy have been implemented on the central Platte River since Program implementation in 2007 and, despite upstream channel capacity constraints and other factors preventing the Program from making specific releases prescribed in the Adaptive Management Plan, the natural hydrology in has provided a range of flow conditions including some that resemble the prescribed releases. Overall, the information gathered has been sufficient to begin to explore the effectiveness of the Flow-Sediment-Mechanical strategy at maintaining suitable channel widths for whooping cranes.

The objective of our study was to use the data collected by the Program to identify and quantify relationships between mechanical interventions, flow, and physical channel conditions on in-channel vegetation in the central Platte River. Here, we begin with a description of the methods, including a characterization of the study area, a description of the channel width metrics and a description of the statistical analyses. We then present the results and conclude with a discussion of the results as they relate to channel processes, the Flow-Sediment-Mechanical management strategy and ultimately roosting habitat for an iconic endangered species, the whooping crane.

2. Methods

2.1. Study area

The study area for this analysis was a 135-km reach of the central Platte River extending from Overton to Chapman, Nebraska (Fig. 1). This reach includes the critical habitat area for the whooping crane (USFWS, 1978). As is the case with the central Platte River as a whole, this reach is comprised of braided to anastomosed channels that have narrowed substantially over time. The historically active channels are now dominated by large stands of woody vegetation (Johnson, 1994), while the currently active channels tend to be slightly incised with many sandbars that are both unvegetated and covered with vegetation. These active channel bars are generally submerged by flows greater than about 35 m³/s. Flows through the study reach can change by more than 50 m³/s per day as they are heavily influenced by a hydropower return directly upstream of Overton and a diversion near Elm Creek (Fig. 1). The shallow nature of the channels produce width to depth ratios that range from approximately 50:1 to 300:1, depending on flow. The mean bed slope of the channel in the study area is approximately 0.12 cm/m, and the total drainage area at the Kearney stream gage is 136,077 km² (06770200).

2.2. Measurement of total unvegetated width and maximum unobstructed channel width

Our analysis focused on two channel width metrics: the maximum unobstructed channel width (MUOCW) and the total unvegetated channel width (TUCW). The MUOCW is an important predictor of whooping crane use (PRRIP, 2017) and is measured as the widest unvegetated width of the channel, including all bare-sand islands and water area between patches of dense vegetation. The TUCW includes all water and bare-sand area within the outer bank (i.e., historically active area) of

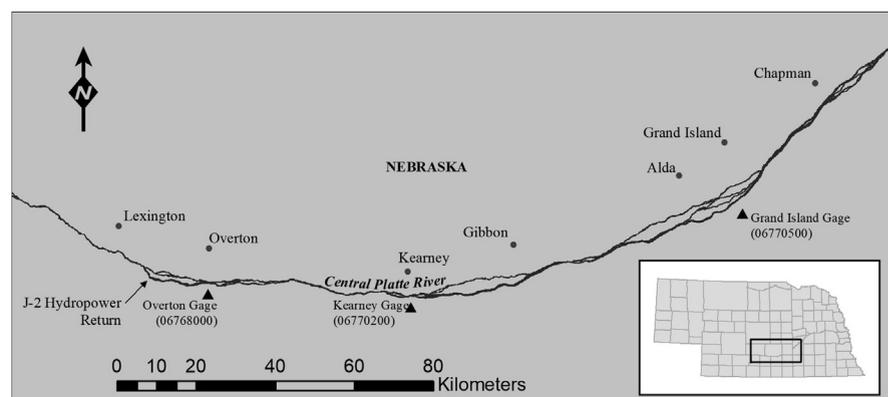


Fig. 1. Associated Habitat Reach of the central Platte River extending from Lexington downstream to Chapman, Nebraska. Locations of stream gages (triangles) used in our analyses are included as well.

the channel. In fully-consolidated channels free of in-channel vegetation, MUOCW and TUCW are equal. In channels with vegetated islands, MUOCW is smaller than TUCW and is highly dependent upon spatial location of vegetated islands (Fig. 2) and, consequently, the TUCW is not always representative of general channel width conditions. For example, if a wide portion of the channel is split by a very small island, the MUOCW would be approximately half of the TUCW. Including TUCW in the analysis eliminated this randomness in channel width measures associated with the MUOCW metric, allowing us to more easily evaluate the relationship between vegetation, physical processes, and Program management actions.

We used summer or fall aerial imagery collected annually during periods of low flow to photo-interpret TUCW and MUOCW throughout the study area during the period of 2007–2015. Unvegetated width metrics were delineated at a scale of 1 cm = 2,400 cm along 436 predefined transects using ESRI ArcMap Geographic Information System (GIS) software. Transects were oriented perpendicular to flow, were spaced at 305-m intervals along the channel throughout the study area and encompassed all channels in split-flow reaches (Fig. 2). Photo-interpretation of unvegetated width metrics was determined to provide generally acceptable measurement

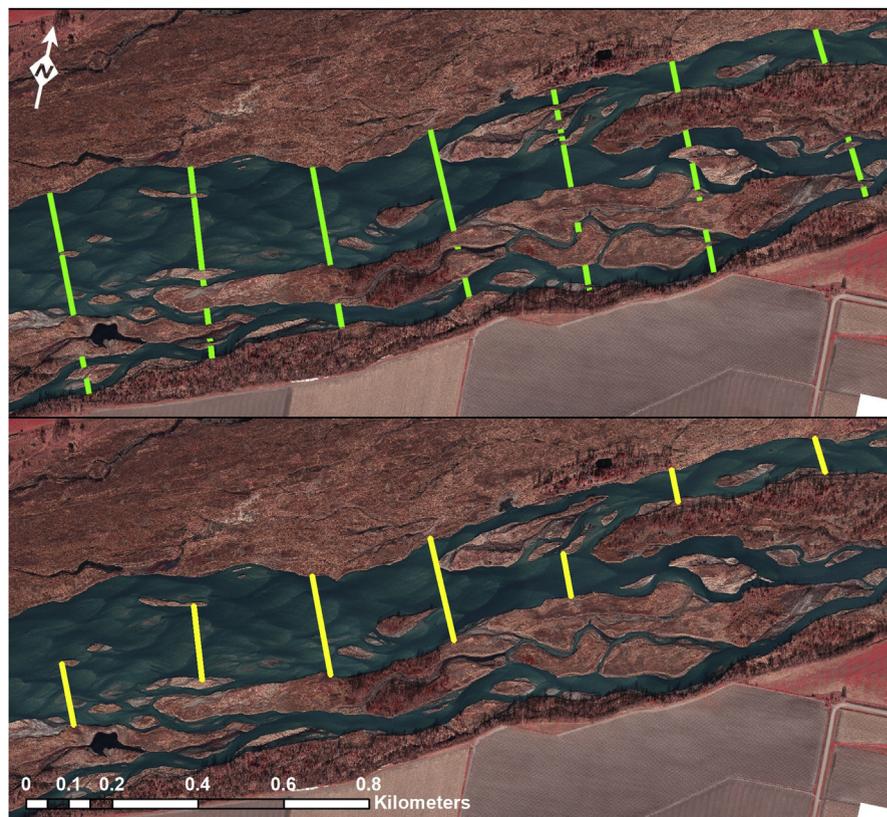


Fig. 2. Examples of total unvegetated channel width (TUCW; top) and maximum width of channel unobstructed by vegetation (MUOCW; bottom) delineations.

accuracy based on previous comparisons of field-measured and photo-interpreted unvegetated width measurements in the study area (i.e., average differences of less than plus or minus 10 m, when evaluating average widths of about 160–240 m; Werbylo et al., 2016).

2.3. Model metrics and statistical analyses

A total of 11 primary hydrologic, geomorphic, and management variables were identified based on our review of the literature, proposed Flow-Sediment-Mechanical management actions, and our knowledge of ongoing activities in the study area (Table 1; Supplementary Data). We performed 2 multiple quantile linear regression analyses to identify and quantify size effects of these variables on TUCW and MUOCW within the study area during the period of 2007–2015.

Transects were subset spatially to utilize every fifth transect location to minimize auto-correlation and provide enough information for a robust statistical analysis. We used a quantile regression analysis because our dataset contained heterogeneous variances and obvious bias due to unmeasured variables, which made traditional least squares linear regression inappropriate (Rosenbaum, 1995; Terrell et al., 1996; Cade et al., 1999; Cade, 2003). Quantile regression provides a more comprehensive view of variable relationships by estimating multiple rates of change (i.e., slopes) throughout the distribution of the response variable (Koenker and Bassett, 1978).

Due to the high number of possible covariate combinations, especially due to uncertainty of the best peak and minimum flow durations to predict TUCW and MUOCW, we utilized Akaike's Information Criterion (AIC) and quantile regression goodness of fit for a given quantile in a five-step model selection process (PRRIP, 2017). Local Interpretation of quantile regression goodness of fit was developed to be analogous to interpretation of least squares regression coefficient of determination (Koenker and Machado, 1999). Similar multi-step AIC model selection efforts have been observed in ecological modeling efforts (Baasch et al., 2010; McGowan et al., 2011; Catlin et al., 2015). The model selection steps and goodness of fit measurements were analyzed where the quantile value (τ) was 0.5 and no covariates were included together in models if absolute Spearman correlation was ≥ 0.5 . We utilized this multi-step selection process to: 1) identify the most important peak discharge duration; 2) identify the influence of previous year's peak discharge; 3) identify the most important minimum discharge duration; 4) identify best overall hydrologic variable; and 5) produce and evaluate final models with the best hydrologic variable and *a priori* non-hydrologic variables. Within each model selection step, the best model was identified as the most parsimonious model with a delta AIC ≤ 2.0 . Model coefficient confidence intervals were produced with an inverted rank test (Koenker, 1994) and the 0.05 and 0.95 response quantiles were used to produce 90% prediction intervals to evaluate the suitability of habitat for whooping cranes.

Table 1. Hydrologic, geomorphic and management variables included in our regression analyses for total unvegetated channel width (TUCW) and maximum unobstructed channel width (MUOCW) for the period of 2007–2015. Type, units of measurement and a description of data acquisition are included for each metric.

Metric	Type	Units	Description
Peak Discharge	Hydrologic	m ³ /s	Mean daily discharge records were obtained from www.water.usgs.gov for the three United States Geological Survey (USGS) stream gages located in the study area (Fig. 1). Annual hydrologic metrics were calculated for each transect by linear interpolation from the nearest gage. Mean annual peak discharges were identified for 1, 3, 5, 10, 20, 30, 40, 50, and 60-day durations.
Peak Discharge + Previous Year Peak Effect	Hydrologic	m ³ /s	Mean annual peak discharge + a percentage of peak discharge from previous year. Metric intended to identify peak discharge effects across multiple years. Previous year peak effects included 0%, 20%, 40%, 60%, 80%, and 100% of previous year peak discharge.
Minimum Discharge	Hydrologic	m ³ /s	Mean annual minimum discharge events were identified for 10, 20, 30, and 40-day durations.
Mean June Discharge	Hydrologic	m ³ /s	Mean daily discharge during the month of June.
Mean Growing Season Discharge	Hydrologic	m ³ /s	Mean daily discharge during the portion of the year when vegetation is actively germinating and growing in the channel. Growing season is defined as 15-April through 15-August.
Wetted Width at Bankfull Discharge	Geomorphic	m	Wetted width of the channel at bankfull discharge. Metric included to represent “vegetation ratchet” control on width adjustment potential. Widths were delineated from June 2011 aerial imagery, which was flown at near bankfull discharge. Areas of shallow overbank flow were omitted.
Main Channel Wetted Width	Geomorphic	m	Wetted width of the main channel at bankfull discharge. Metric included to represent “vegetation ratchet” control on width adjustment potential. Widths were delineated from June 2011 aerial imagery, which was flown at near bankfull discharge. Areas of shallow overbank flow were omitted.
Median Grain Size	Geomorphic	mm	Average of median bed and bar material grain size during the period of 2009–2014 at Program pure panel anchor point locations. Transect grain size was identified based on nearest anchor point.

(continued on next page)

Table 1. (Continued)

Metric	Type	Units	Description
Channel Slope	Geomorphic	Dimensionless	Mean channel slope for 1.61-kilometer reach centered on each transect. Slopes calculated from 2009 longitudinal profile of the study area.
River Kilometer	Geomorphic	km	General metric included to represent general effect of declining sediment deficit from west to east.
Annual Disking	Management	Categorical	Annual delineations of disking and herbicide application were used to classify transects in GIS as to whether these management actions were applied. If any portion of a transect was intersected by the disking polygon, the transect was considered disked. If any portion of a transect was intersected by an herbicide polygon, the transect was considered to be treated with herbicide.
Annual Herbicide	Management	Categorical	

2.4. Application of the final MUOCW model to evaluate the flow-sediment-mechanical management strategy

The final MUOCW model was used to assess the potential performance of the Flow-Sediment-Mechanical management strategy at maintaining suitable channel widths at a hypothetical channel reach location given observed hydrology during the period of 1998–2015. The hypothetical reach was assumed to have a main channel bankfull width of 305 m and a median bed material grain size of 0.9 mm. Annual MUOCW was first calculated given observed hydrology during the period of 1998–2015 at the Overton stream gage (06768000). Observed hydrology was then altered to add a series of flow prescriptions described in the Program's Adaptive Management Plan (PRRIP, 2006). These flows are referred to as short duration high flows and are events of 227 m³/s for three days in approximately two out of three years. Short duration high flow releases were not added in wet years or the years immediately following the two highest discharge years (1999 and 2011). Specifically, short duration high flow implementation was added in 1998, 2001, 2002, 2004, 2005, and 2007. In all cases the short duration high flow hydrograph included two to three days of up-ramping flows, three days at a discharge of 227 m³/s and two to three days of down-ramping flows following the peak. Ramping duration depended on observed discharge with longer ramping duration under low discharge conditions. MUOCWs predicted under full short duration high flow implementation were compared to those predicted given observed hydrology to assess the ability of short duration high flow releases to increase MUOCW and maintain unobstructed channel widths that were found to be highly suitable for whooping crane use (PRRIP, 2017).

3. Results

3.1. Total unvegetated channel width and maximum unobstructed channel width

TUCW and MUOCW followed similar trend patterns from 2007–2015. The lowest average values for each width measurement were observed in 2007 and the highest was in 2015 (Table 2). From 2008–2014, mean and median MUOCW values were observed to have little variation where the difference between the maximum and minimum value was 33 m for mean and 27 m for median observations. Likewise, from 2008–2014, mean and median TUCW values were observed to have little variation, where the difference between the maximum and minimum value was 67 m for mean and median observations (Table 2).

3.2. Metrics found to influence total unvegetated channel width

A summary of important annual flow, geomorphic and management variable values in relation to mean TUCW and MUOCW are presented in Table 2. Forty-day peak discharge ranged from 36.48 m³/s to 453.07 m³/s and generally occurred between early May and early July. Wetted width ranged from 149 m to 595 m. Disking was somewhat variable during the analysis period, ranging from a low of 0% of transects being disked in 2011 to a high of 41% of transects in 2008 in the study area. The proportion of transects sprayed was low in 2007 and 2008, prior to the commencement of reach-wide phragmites spraying efforts. At full-scale implementation, up to 83% of transects were sprayed in a single year.

We found TUCW was best explained by 40-day duration peak discharge, diskings, herbicide application, and wetted width of the channel at bankfull discharge (Table 3); all of which were incorporated in one of two models that carried substantial model weight ($w > 0.40$). AIC values indicate our top model was ~437 AIC units lower than a model that only included 40-day peak discharge and ~850 AIC unit lower than the null model. All variables had a positive effect on TUCW from 2007–2015 (Table 4). The formula of the top model to explain TUCW at the 0.5 quantile ($\tau = 0.5$) was noted as:

$$TUCW = -19.10 + 0.36\beta_1 + 35.49\beta_2 + 5.52\beta_3 + 0.55\beta_4 \quad (1)$$

where β_1 was the mean 40-day duration peak discharge, β_2 and β_3 were categorical variables based on whether or not herbicide or diskings were applied within the previous year respectively, and β_4 was a measure of the wetted width of all channel segments at bankfull discharge.

Besides the effects of 40-day peak discharge, beta values generally increased from low to high quantiles of TUCW. For instance, at the 0.05 quantile, diskings increased TUCW by 6.2 m and herbicide increased TUCW by 9.0 m on average. At the 0.95

Table 2. Summary of important flow, geomorphic and management metric values from 2007 to 2015 in relation to mean and median total unvegetated channel width (TUCW) and mean and median unobstructed channel width (MUOCW) by 1.61-km reach of river within the Associated Habitat Reach (study area), 2007–2015. 40-day peak discharge was calculated as the maximum 40-day running average of mean daily discharge during the year.

Year	40 Day Peak Discharge (m ³ /s)	Bankfull Wetted Width (m) ¹	Median Grain Size (mm) ²	% of Transects Disked	% of Transects Sprayed	Mean TUCW (m)	Median TUCW (m)	Mean MUOCW (m)	Median MUOCW (m)
2007	57	318	0.93	33%	0%	174	170	92	79
2008	108			41%	5%	219	222	135	117
2009	60			10%	13%	198	196	114	104
2010	146			5%	77%	201	199	125	106
2011	231			0%	44%	265	263	147	131
2012	83			9%	81%	212	211	138	120
2013	104			11%	71%	220	219	147	128
2014	83			18%	74%	218	216	131	114
2015	354			0%	83%	321	313	191	175

¹ Bankfull width measurements were derived from 2011 aerial imagery.

² Median grain size was calculated as the average of measurements from 2009–2014. We assumed bankfull width and median grain size were relatively stable at individual transects from 2007–2015.

Table 3. Akaike's Information Criterion (AIC) model selection results of annual total unvegetated channel width (TUCW) in the Associated Habitat Reach (study area), 2007–2015. Δ AIC represents the change in AIC value from the top-ranked model, AIC_w represents the probability each model is the best given the models tested, and R^1 equals the goodness of fit for the given quantile ($\tau = 0.5$).

Metrics	AIC	Δ AIC	AIC _w	R^1
40-Day Peak + Disking + Herbicide + Wetted Width	8321.29	0.00	1.00	0.42
40-Day Peak + Disking + Herbicide + Median Grain Size	8580.94	259.65	0.00	0.32
40-Day Peak + Disking + Herbicide + River Km	8586.18	264.89	0.00	0.32
40-Day Peak + Disking + Herbicide	8704.14	382.85	0.00	0.26
40-Day Peak	8757.37	436.08	0.00	0.23
Wetted Width	8758.16	436.87	0.00	0.23
River Kilometer	8911.56	590.27	0.00	0.15
Median Grain Size	8956.55	635.26	0.00	0.13
Disking + Herbicide	9122.29	801.00	0.00	0.03
Null	9171.79	850.50	0.00	0.13

¹Null model was used to test the hypothesis that unobstructed channel width remained constant from 2007–2015.

Table 4. Multiple quantile regression beta estimates in the top model from the total unobstructed channel width (TUCW) model selection process.

Quantile	Intercept	40-Day Peak Discharge	Disking	Herbicide	Wetted Width
0.05	−39.33	0.340	6.18	8.95	0.39
0.10	−39.61	0.387	17.53	9.80	0.42
0.25	−30.14	0.389	32.94	7.91	0.47
0.50	−19.10	0.359	35.49	5.52	0.55
0.75	−7.24	0.364	31.31	7.17	0.61
0.90	5.55	0.339	39.39	11.82	0.67
0.95	21.03	0.340	67.03	23.54	0.66

quantile, disking increased TUCW by 67.0 m and herbicide increased TUCW by 23.5 m on average (Table 4).

Based on the results of our top quantile regression model at the 0.5 quantile, for each 5-m³/s increase in 40-day peak discharge, on average, we would expect a 1.8 m (95% CI = 1.7–2.0 m) increase in TUCW annually when no disking or herbicide treatment was applied and wetted width at bankfull discharge was held at its median value (Fig. 3). When transects were disked, on average, TUCW was 35.5 m (95% CI = 26.2–42.9 m) wider than at transects where no disking occurred within the previous year. When transects were disked and herbicide was applied, on average,

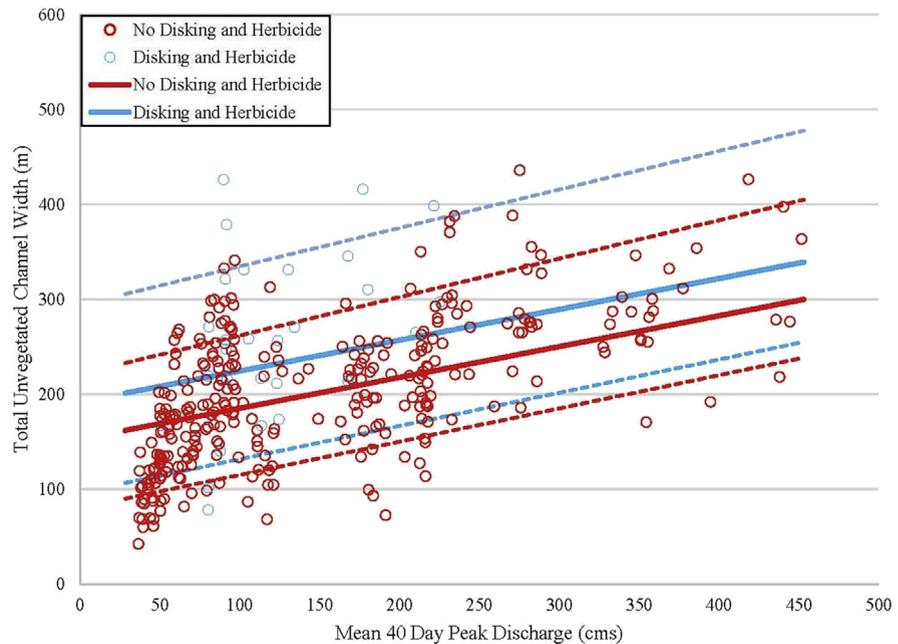


Fig. 3. Predicted relationships of total unvegetated channel width (TUCW) to 40-day peak discharge at transects in the Associated Habitat Reach (study area) without (red) or with (blue) management actions from 2007–2015. Dashed lines represent 90% quantile regression prediction intervals and points display the subset of measured TUCWs at transects used in quantile regression analyses. Points represent transects where no management actions (red) or disking and herbicide (blue) occurred.

TUCW was 41.0 m (95% CI = 24.0–55.3 m) wider than transects where no other management actions occurred in the previous year. For each 30-m increase in wetted width at bankfull discharge, on average, we would expect a 19.9 m (95% CI = 16.57–22.20 m) increase in TUCW annually.

We compared observed and predicted TUCW at each transect for each year. Utilizing the linear model and betas previously stated at the 0.5 quantile, 45% of TUCW predictions were within 30 m and 76% of predictions were within 60 m of actual values observed from 2007–2015. Only two years, 2007 and 2010, were found to contain mean errors >10% of observed values (Table 5).

3.3. Metrics found to influence maximum unvegetated channel width

We found MUOCW was best explained by 40-day duration peak discharge and wetted width of the main channel (Table 6). Disking and herbicide application were also included in the top MUOCW model. AIC values indicated our top model was ~109 AIC units lower than a model that only included 40-day peak discharge and ~240 AIC unit lower than the null model. All variables had a positive effect on

Table 5. Comparison of mean observed and predicted total unvegetated channel width (TUCW) in Associated Habitat Reach (study area) for the period of 2007–2015 using a 0.5 quantile regression. Parentheses indicated 90% quantile regression prediction intervals.

Year	Observed Mean TUCW (m)	Predicted Mean TUCW (m)	Mean Error (m)	Mean Error as % of Observed TUCW
2007	174	204 (122–289)	30 (–52–114)	17 (–30–66)
2008	219	237 (151–323)	17 (–69–103)	8 (–31–47)
2009	198	185 (111–265)	–13 (–87–67)	–6 (–44–34)
2010	201	225 (153–314)	24 (–48–112)	12 (–24–56)
2011	265	247 (174–326)	–18 (–91–62)	–7 (–34–23)
2012	212	195 (123–287)	–17 (–89–75)	–8 (–42–35)
2013	220	229 (154–317)	9 (–66–97)	4 (–30–44)
2014	218	218 (142–310)	0 (–76–92)	0 (–35–42)
2015	321	302 (227–386)	–19 (–94–64)	–6 (–29–20)

Table 6. Akaike’s Information Criterion (AIC) model selection results of annual maximum unobstructed channel width (MUOCW) in the Associated Habitat Reach (study area), 2007–2015. R^1 equals the goodness of fit for the given quantile ($\tau = 0.5$).

Combined Models	AIC	Δ AIC	Likelihood	AICw	R^1
40-Day Peak + Disking + Herbicide + Main Channel Wetted Width	8724.67	0.00	1.00	1.00	0.15
40-Day Peak + Disking + Herbicide + Median Grain Size	8776.88	52.21	0.00	0.00	0.12
40-Day Peak + Disking + Herbicide	8781.04	56.37	0.00	0.00	0.11
40-Day Peak + Disking + Herbicide + River Kilometer	8781.53	56.86	0.00	0.00	0.11
40-Day Peak	8834.08	109.40	0.00	0.00	0.08
Main Channel Wetted Width	8878.00	153.33	0.00	0.00	0.05
Median Grain Size	8894.74	170.07	0.00	0.00	0.04
Disking + Herbicide	8904.45	179.78	0.00	0.00	0.04
River Kilometer	8910.60	185.92	0.00	0.00	0.04
Null	8964.58	239.91	0.00	0.00	0.00

MUOCW from 2007–2015. The formula of the top model used to explain MUOCW at the 0.5 quantile ($\tau = 0.5$) was noted as:

$$UOCW = 27.96 + 0.24\beta_1 + 39.31\beta_2 + 8.48\beta_3 + 0.18\beta_4 \quad (2)$$

where β_1 was the mean 40-day duration peak discharge, β_2 and β_3 were categorical variables based on whether or not herbicide or disking were applied within the previous year, respectively, and β_4 referred only to the main channel and not the total wetted width of all channels at bankfull discharge.

Besides the effects of 40-day peak discharge, other beta values generally increased from low to high quantiles. For example, at the 0.05 quantile, disking increased MUOCW by 6.3 m and herbicide increased MUOCW by 5.0 m on average. At the 0.95 quantile, on average, disking increased MUCW by 61.9 m and herbicide increased MUCW by 14.5 m (Table 7). Based on the results of our top quantile regression model at the 0.5 quantile, for each $30\text{-m}^3/\text{s}$ increase in 40-day peak discharge, on average, we would expect a 7.3 m (95% CI = 5.8–8.3 m) annual increase in MUOCW, when no disking or herbicide treatment was applied and bankfull wetted width was held at its median value (Fig. 4). For each 30-m increase in bankfull wetted width of the main channel, on average, we would expect a 5.3 m (95% CI = 4.0–7.2 m) increase in MUOCW. When transects were disked, on average, MUOCW was 39.3 m (95% CI = 28.3–52.1 m) wider than transects where no disking occurred within the previous year. When both disking and herbicide were applied, on average, we found transects were 47.8 m (95% CI = 30.0–68.2 m) wider than transects where no management actions occurred in the previous year.

We used several analyses to validate the accuracy of the top MUOCW model we identified through the AIC model selection process. Utilizing the MUOCW linear model and betas previously stated for the 0.5 quantile, 36% of MUOCW predictions were within 30 m and 66% were within 60 m of actual values observed from 2007–2015. Once again, overestimating MUOCW was of special concern since narrower than predicted MUOCWs would potentially have more negative consequences for habitat suitability for whooping cranes than underestimations. Only 36% percent of MUOCW predictions were overestimated by more than 30 m and 17% were overestimated by more than 60 m. We also compared mean observed

Table 7. Beta estimates for the maximum unobstructed channel width (MUOCW), multiple quantile regression model selection process.

Quantile	Intercept	40-Day Peak Discharge	Disking	Herbicide	Main Channel Wetted Width
0.05	22.176	0.113	6.326	5.030	0.045
0.10	33.819	0.092	8.077	6.603	0.039
0.25	32.477	0.143	36.560	8.443	0.092
0.50	27.959	0.244	39.310	8.484	0.175
0.75	24.612	0.227	53.733	18.315	0.391
0.90	16.774	0.214	43.221	10.453	0.647
0.95	31.619	0.175	61.892	14.512	0.700

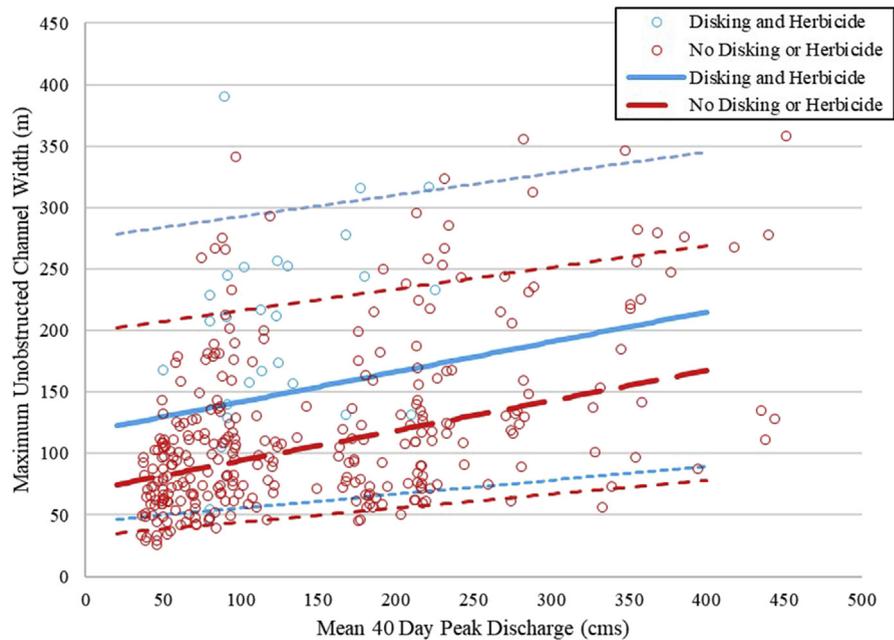


Fig. 4. Predicted relationships of maximum unobstructed channel width (MUOCW) to 40-day peak discharge at transects with (blue) or without (red) management actions in the Associated Habitat Reach (study area) from 2007–2015. Dashed lines represent 90% quantile regression prediction intervals and points display the subset of measured MUOCWs at transects used in regression analyses. Points represent transects where no management actions (red) or disking and herbicide (blue) occurred.

and predicted MUOCW for all transects within the study area in each year and found eight of the nine years assessed contained mean prediction errors that were <20% of observed values (Table 8).

3.4. Analysis of short duration high flow performance

Based on simulated releases, short duration high flow volumes ranged from 32.6 million to 83.6 million m³. Implementation of a short duration high flow release in a given year was predicted to increase TUCW by 0.0–6.7 m and MUOCW by 0.0–4.6 m depending on baseline river discharge at the time of the release. The greatest increase in TUCW and MUOCW were predicted to occur when baseline river discharge was low.

4. Discussion

We found 40-day mean peak discharge, wetted width of the channel, disking and herbicide application to be the best predictors of TUCW in the study area. The strong influence of peak discharge is consistent with previous investigations which identified peak flows as an important driver of unvegetated width within the study area (Williams, 1978; O'Brien and Currier, 1987; Murphy et al., 2004). Williams

Table 8. Comparison of mean observed and predicted maximum unobstructed channel width (MUOCW) in the Associated Habitat Reach (study area) for the period of 2007–2015 using a 0.5 quantile regression. Values in parentheses represent 90% quantile regression prediction intervals.

Year	Observed MUOCW (m)	Predicted MUOCW (m)	Error (m)	Error as % of Observed MUOCW
2007	92	121 (50–292)	29 (–42–200)	32 (–46–217)
2008	135	145 (60–312)	10 (–75–177)	7 (–56–131)
2009	114	106 (45–274)	–8 (–69–160)	–7 (–61–140)
2010	125	135 (61–299)	10 (–64–174)	8 (–51–139)
2011	147	148 (67–304)	1 (–80–157)	1 (–54–107)
2012	138	115 (51–287)	–23 (–87–149)	–17 (–63–108)
2013	147	138 (61–303)	–9 (–86–156)	–6 (–59–106)
2014	131	132 (57–301)	1 (–74–170)	1 (–56–130)
2015	190	187 (85–335)	–3 (–105–145)	–2 (–55–76)

(1978) was the first investigator to assert that declines in study area channel width were likely due to systematic reductions in peak flow magnitude. O'Brien and Currier (1987) expanded upon Williams' work by postulating that peak flow magnitudes of 226–453 m³/s were necessary to maintain the channel. Murphy et al. (2004) further refined the peak flow hypothesis by narrowing it to the 1.5-year flood and hypothesizing that mechanical channel widening in combination with an average 1.5-year flood magnitude of 170–227 m³/s would allow for sustained unvegetated channel widths exceeding 300 m. Notably, none of these investigations assessed peak flow event duration and associated flow volume. The short duration high flow (i.e., flow prescription) component of the Program's Flow-Sediment-Mechanical management strategy grew out of the work by Murphy et al. (2004), reflecting both the frequency and magnitude postulated by the authors. The short duration high flow duration of 3–5 days was borne out of necessity, reflecting the volume of water that the Program could reasonably store and release on a near-annual basis.

Our investigation strongly supports the assertion of a positive relationship between peak flow magnitude and both TUCW and MUOCW in the study area. The analyses, however, do not support the assertion that increasing the frequency of peak flow of 227 m³/s magnitude through short duration high flow releases for 3–5 days in two out of three years will produce substantive increases in the vegetation-free width of the channel. The minimal effect of short duration high flow releases is likely due to the very short duration and low volume in relation to the 40-day peak discharge duration that was the best hydrologic predictor of unvegetated width in the study area. The disparity between short duration high flow and natural peak flow event volume is apparent in Fig. 5.

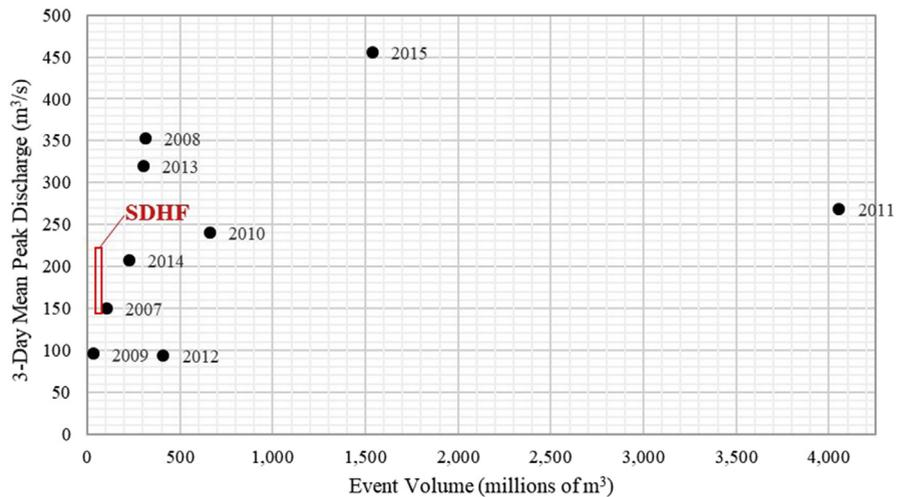


Fig. 5. 2007–2015 three-day mean peak discharge (m³/s) and total event volume (millions of m³) at Grand Island (USGS Gage 06770500) in relation to the range of Short-Duration High Flow (SDHF) magnitudes and volumes. Event volumes are cumulative volumes from concurrent days during annual peak flow events when discharge exceeded 57 m³/s.

Other investigators have identified mean June flows (Johnson, 1994) as a key predictor of channel narrowing as specifically related to the establishment of cottonwood seedlings in the channel. Johnson (1994) suggested that mean June flows ranging from 75–85 m³/s would prevent seedling establishment during the cottonwood germination period and maintain existing channel widths. We did not find mean June flow to be effective at maintaining or increasing the unvegetated width of channel. This may be due to the broader focus of our analysis, which was not limited to woody vegetation. Other factors such as summer flow (Schumm, 2005), slight differences in channel slope (Schumm, 2005) and differences in bed material grain size (Murphy et al., 2004) have been hypothesized as potentially controlling or at least influencing unvegetated channel width in the study area. Some or all of these metrics might influence unvegetated channel width to some degree but were not found to be strong predictors of channel response in our analyses.

Wetted width of the channel and application of management in the form of diking and herbicide application were found to have the strongest influence on in-channel vegetation. We attribute the inclusion of wetted width in the top model to the influence of the vegetation ratchet effect (Tal et al., 2004). The historical proliferation of scour-resistant vegetation such as cottonwood trees and the more recent establishment of phragmites limits the ability of the channel to adjust laterally in response to peak flows. The two remaining metrics, diking and herbicide, reflect the intensive management of in-channel vegetation by the Program and other conservation organizations and the degree to which those activities influence the presence and

distribution of in-channel vegetation. The importance of herbicide application is underscored by research indicating that phragmites is resistant to erosion due to drag and local scour associated 100-year recurrence interval discharge in the study area (Bankhead et al., 2016).

4.1. Management implications

Our research indicates that attempts to increase the magnitude of the 1.5-year recurrence interval flow magnitude through implementation of short duration high flow releases would have a minimal effect on TUCW and MUOCW with predicted increases on the order of 5–7 m. Accordingly, short duration high flow releases as presented in the Program's Adaptive Management Plan do not appear to be a viable management action for maintenance of highly-suitable whooping crane roosting habitat. In contrast, disking in combination with herbicide application does appear to be effective in managing unvegetated channel width in the study area. The predicted effect of channel disking and spraying was an increase of well over 30 m in MUOCW across most of its distribution. The major limitation of disking, however, is the lack of a system-scale beneficial effect. In general, disking can be utilized to effectively manage MUOCW at owned habitat complexes but cannot be done elsewhere without landowner agreements. It is also important to note that long duration, natural high-flow events such as those occurring in 2011 and 2015 do substantially increase TUCW. Activities that reduce the magnitude and/or duration of large natural peak flow events would likely necessitate an increase in the frequency and scale of mechanical management.

Our investigation also highlights uncertainties that are introduced when exploring the relationship between physical process and species habitat metrics. The quantile regression analysis results indicate a strong relationship between TUCW and hydrologic, geomorphic, and management variables with the top model explaining on the order of 42% of the variability in the data at the 0.5 quantile of the response. However, when evaluating the relationship for MUOCW, which is primarily a habitat suitability metric for whooping cranes, the top model only explained 15% of the variability in the data at the 0.5 quantile of the response. This loss of predictive ability occurs because the random spatial distribution of vegetated bars and/or islands within the channel exerts a strong control on MUOCW. Mechanical interventions like disking and herbicide applications can have a disproportionately large effect on habitat metrics like MUOCW as they allow for targeted application to maximize effectiveness. Specifically, conservation organizations could prioritize treatment of vegetated, mid-channel sandbars and islands that have a substantial effect on unobstructed channel width, which is a primary driver of whooping crane habitat suitability.

Declarations

Author contribution statement

Jason Farnsworth, David Baasch, Patrick D. Farrel, Chadwin Smith, Kevin Werbylo: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

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