PLATTE RIVER RECOVERY IMPLEMENTATION PROGRAM

Data Synthesis Compilation

Whooping Crane (*Grus americana*) Habitat Synthesis Chapters

PLATTE RIVER
RECOVERY IMPLEMENTATION PROGRAM

Prepared by staff of the Executive Director's Office for the Governance Committee of the Platte River Recovery Implementation Program

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PREFACE

This document was prepared by the Executive Director's Office (EDO) of the Platte River Recovery Implementation Program ("Program" or "PRRIP"). The information and analyses presented herein are focused solely on informing the use of Program land, water, and fiscal resources to achieve one of the Program's management objectives: contribute to the survival of whooping cranes by increasing habitat suitability and thus use of the Associated Habitat Reach (AHR) along the central Platte River in Nebraska. The Program has invested nine years in implementation of an adaptive management program to reduce uncertainties about proposed management strategies and learn about river and species responses to management actions. During that time, the Program has implemented management actions, collected a large body of physical and species response data, and developed modeling and analysis tools to aid in the interpretation and synthesis of data.

Implementation of the Program's AMP has proceeded with the understanding that management uncertainties, expressed as hypotheses and summarized as Big Questions, encompass complex physical and ecological responses to limited treatments that occur within a larger ecosystem that cannot be controlled by the Program. The lack of experimental control and complexity of response precludes the sort of controlled experimental setting necessary to cleanly follow the strong inference path of testing alternative hypotheses by devising crucial experiments (Platt 1964). Instead, adaptive management in the Platte River ecosystem must rely on a combination of monitoring of physical and biological response to management treatments, predictive modeling, and retrospective analyses (Walters 1997). The Program has pursued all three of these approaches, producing multiple lines of evidence across a range of spatial and temporal scales. These lines of evidence indicate implementation of the Program's Flow-Sediment-

Mechanical (FSM) management strategy, particularly the flow component, may not achieve the stated management objective and sub-objectives for whooping cranes; contribute to improved whooping crane survival during migration through increasing habitat suitability and use of the AHR.

This document is a compilation of four topical chapters with unique objectives and analyses that generally build on one another. Each of the chapters, which are intended to be useful as independent documents, include background information on the Program and thus may contain redundant content. Chapter 1 was developed to provide background and context to the discussions in the subsequent chapters. It provides a brief overview of whooping crane life history and occurrence within the AHR, a summary of previous investigations of habitat selection by whooping cranes along the Platte River, changes in river morphology that sparked regulatory intervention through the Endangered Species Act, and the competing management strategies the Program is implementing through an adaptive management framework. Chapters 2 and 3 focus specifically on whooping riverine habitat selection and suitability within the AHR and throughout the North-central Great Plains, respectively. Chapter 4 focuses on assumptions of priority hypotheses related to the beneficial effects of the FSM strategy on channel width measures and thus whooping crane habitat suitability, use of the Platte River, and survival during migration. Finally, a brief Summary of Key Findings has been added in order to combine and distill the most important conclusions of each chapter for Program decision makers.

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CHAPTER 1 – History and Context: The Path to Adaptive Management of Whooping Crane Habitat in the Central Platte River

Abstract

Observations of whooping crane use of the central Platte River is reviewed in relation to changes in hydrology and channel morphology over historical timeframes. The first observations of whooping cranes in the Associated Habitat Reach of the central Platte River date to the early 1800s. By the 1930s and 1940s river hydrology was altered by irrigation infrastructure and the channel actively narrowed in response to changing flow, sediment, and disturbance regimes. The loss of roosting habitat and whooping crane resources (forage) along the Platte River are hypothesized to be associated with the ongoing changes in the magnitude of channel forming flows and sediment transport. It is believed whooping crane survival during migration is negatively impacted by reductions in unobstructed channel width and unforested width along the Platte River. Adaptive management at a large scale is being used to test two management strategies to maintain suitable stopover habitat within the Associated Habitat Reach and thus to contribute to the survival of whooping cranes during migration.

Introduction

The Platte River Recovery Implementation Program (Program or PRRIP) is responsible for implementing certain aspects of the endangered whooping crane recovery plan. More specifically, the Program's Adaptive Management Plan (AMP) management objective is to improve survival of whooping cranes during migration through increased use of the Associated Habitat Reach (AHR) of the Platte River in central Nebraska (PRRIP 2006a). This ninety-mile reach extends from Lexington, NE downstream to Chapman, NE and includes the Platte River channel and off-channel habitats within three and one half miles of the river (Figure 1).

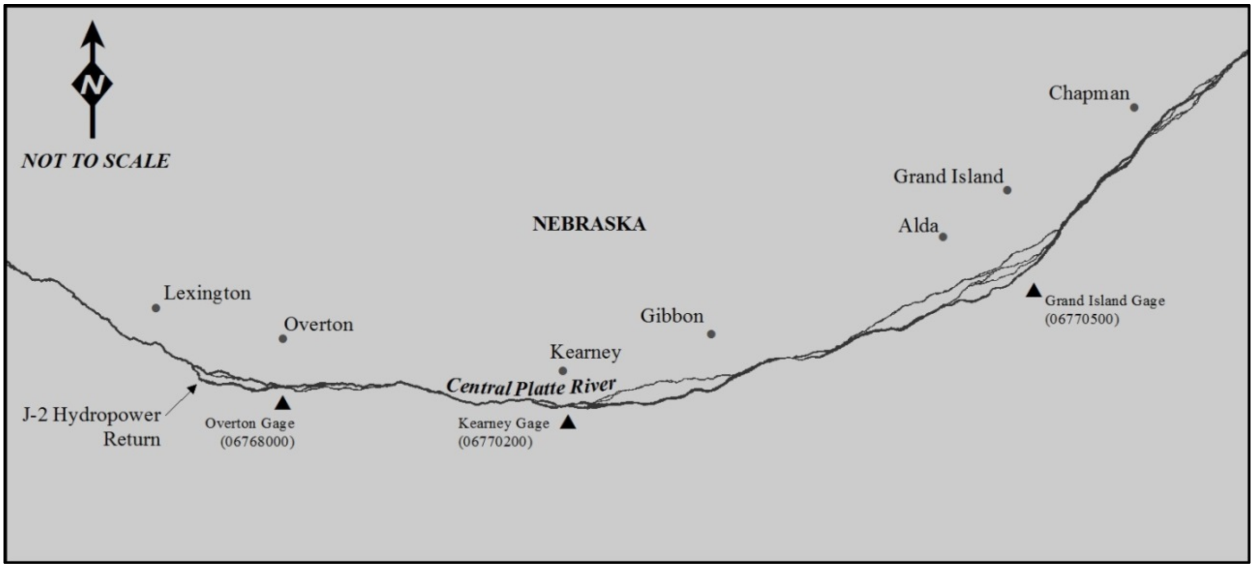

Figure 1. Associated Habitat Reach (AHR) of the central Platte River in Nebraska extending from Lexington downstream to Chapman.

The Program has invested nine years implementing an adaptive management program to test strategies for increasing whooping crane use of the AHR. Subsequent chapters of this document present analysis and interpretation of modeling, research, and monitoring efforts to date. The objective of this introductory chapter is to provide a brief overview of the large body of relevant Platte River literature and outline regulatory actions that led to the formulation of the Program. The chapter begins with a review of whooping crane monitoring and research in the AHR. Changes in hydrology and channel characteristics over historical timeframes are then explored. Finally, the rationale for regulatory intervention on behalf of the species is discussed and related to two management paradigms being evaluated by the Program.

Whooping Crane Life History

Whooping cranes are the tallest of North American birds and stand nearly five-feet tall. Their wingspan measures between seven and eight feet. Males weigh about 16 pounds and females about 14 pounds. Whooping cranes are a long-lived species that have been observed in the wild at an age >25 years. Adults are snowy white except for black primary feathers on the wings and a bare red face and crown. Immature cranes are a reddish cinnamon color that results in a mottled appearance as the white feather bases extend. The juvenile plumage is gradually replaced through the winter months and becomes predominantly white by the following spring as the dark red crown and face appear. Yearlings achieve the typical adult appearance by late in their second summer or fall. Whooping cranes are considered sub-adults and generally do not produce fertile eggs until they are 4 years old.

The whooping crane population, variously estimated at 500 to 1,400 individuals in 1870, declined to only 16 individuals in the migratory population by 1941 as a consequence of hunting and specimen collection, human disturbance, and conversion of the primary nesting habitat to hay, pastureland, and grain production (Canadian Wildlife Service and U.S. Fish and Wildlife Service 2007). The whooping crane was listed as endangered on March 11, 1967 (USFWS 1986). The historic range of the whooping crane once extended from the Arctic coast south to central Mexico, and from Utah east to New Jersey, into South Carolina, Georgia, and Florida. The historic breeding range once extended across the north-central United States and in the Canadian provinces, Manitoba, Saskatchewan, and Alberta. Currently the main threat to whooping cranes in the wild is the potential of a hurricane or contaminant spill destroying their wintering habitat on the Texas coast.

The Aransas – Wood Buffalo population of whooping cranes are long-distance migrants that breed in and around Wood Buffalo National Park located in Northwestern Canada and the Northern Territories and winter in and around Aransas National Wildlife Refuge (ANWR) located along the Gulf Coast of Texas. The migration route is well defined and a vast majority of all observations occur within a 200-mile wide corridor through Alberta, Saskatchewan, Montana, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas (Figure 2; Pearse et al. 2015). Whooping cranes are diurnal migrants, use traditional migration staging areas, and during migration utilize stopover sites to rest and build energy reserves to complete migration (Canadian Wildlife Service and U.S. Fish and Wildlife Service 2007). Although a variety of habitats are used during migration, a wetland is nearly always associated with a stopover site. At stopover sites, whooping cranes roost standing in shallow water associated with palustrine, lacustrine, or riverine wetlands. Whooping cranes are omnivorous feeders that forage on many items including mollusks, crustaceans, minnows, reptiles, amphibians, invertebrates, small mammals, small birds, berries, live oak, agricultural grains, and plant tubers located in wetlands, grasslands, and agricultural fields.

Whooping cranes migrate singly, in pairs, in family groups, or in small flocks and sometimes accompany sandhill cranes. Spring migration is preceded by mating behaviors such as dancing, unison calling, and frequent flying. Family groups and pairs are the first to leave the ANWR in late-March to mid-April. Whooping cranes are monogamous and form life-long pair bonds but will re-mate following the death of a mate (Canadian Wildlife Service and U.S. Fish and Wildlife Service 2007). Whooping cranes return to the same breeding territory in Wood Buffalo National Park in April and nest in the same general area each year (Whooping Crane

Tracking Partnership unpublished data). The nesting area in Wood Buffalo National Park is a poorly drained region interspersed with numerous potholes. Bulrush is the dominant emergent in the potholes used for nesting. Adult whooping cranes construct nests of bulrush and lay one to three eggs (usually two) in late April and early May. The incubation period is about 29 to 31 days. Whooping cranes will renest if the first clutch is lost or destroyed before mid-incubation. Both sexes share incubation and brood-rearing duties. Despite the fact that most pairs lay two eggs, sibling rivalry usually results in only one chick reaching fledging age. Only one-fourth of chicks that hatch survive to reach the wintering grounds.

Figure 2. Dotted line delineates the migration corridor of whooping cranes, including breeding areas in Wood Buffalo National Park and wintering areas near Aransas National Wildlife Refuge.

Autumn migration begins in mid-September and most birds arrive on the wintering grounds on the Texas Gulf Coast by early to mid-December. On the wintering grounds, pairs and family groups occupy and defend territories. Sub-adults and unpaired adult whooping cranes form loose flocks that use the same habitat, but remain outside of occupied territories where they first wintered (Stehn and Prieto). Sub-adults tend to winter in the area where they were raised their first year and paired cranes often locate their first winter territories near their parents' winter territory.

Whooping crane observations on or along the Platte River

Historical records of whooping occurrence on or along the Platte River from 1820–2014 were compiled or recorded by Swenk, Black, Brooking, Allen, USFWS, NGPC, Ross Lock, and Hastings Museum and have been summarized by Tom Pitts (1985), the Biological Work Group (1990), and the Executive Director's Office of the Program (Figure 3). It is important to note detection of whooping cranes along the central Platte River increased substantially beginning in 2001 with the implementation of systematic surveys of the AHR and that survey methodologies at Aransas National Wildlife Refuge were modified in 2011. Population estimates were obtained from the United States Fish and Wildlife Service (USFWS), the Whooping Crane Recovery Team, and the Whooping Crane Studbook and were compiled by Betsy Didrickson of the International Crane Foundation and the USFWS.

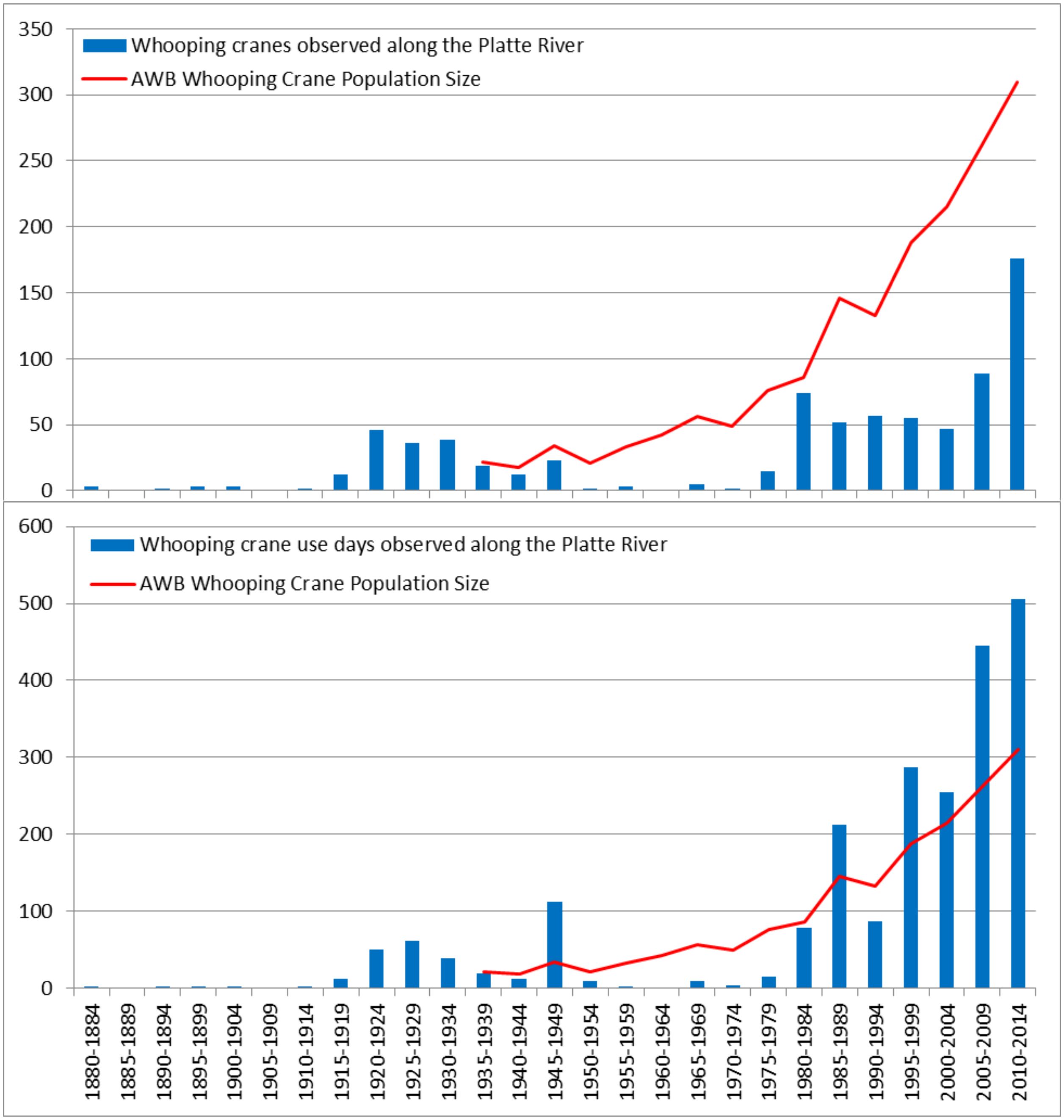

Figure 3. Numbers of whooping cranes (top bar plot) and whooping crane use days (bottom bar plot) reported on or near the Platte River in 5-year blocks of time, 1880-2014. The red line represents the numbers of whooping cranes counted in the Aransas-Wood Buffalo population at the end of each 5-year interval, 1939-2014. Monitoring effort on the Platte River changed substantially beginning in 2001 when systematic surveys of the Program Associated Habitat Area were initiated. It should also be noted that Allen (1952) and Pitts (1985) concluded the increase in observations along the Platte River during the 1920's was likely due to misidentification of whooping cranes.

Platte River habitat selection investigations

Characteristics of whooping crane roost habitat have been examined and described for the central Platte River in Nebraska (Johnson 1981; Lingle et al. 1984; Armbruster 1990; Faanes 1988; Faanes and Bowman 1992; Faanes et al. 1992). Several characteristics common to whooping crane riverine roost sites include shallow, wide, unvegetated channels and open visibility with the absence of tall trees or dense shrubs near the roost (Johnson and Temple 1980; U.S. Fish and Wildlife Service 1981; Johnson 1981; Armbruster 1990; Faanes et al. 1992; Austin and Richert 2001; National Research Council 2004). Ziewitz (1987) described whooping roosting habitat suitability using several parameters including unobstructed channel width. In this assessment, unobstructed channels ≤500 ft wide were assigned a minimum suitability value while unobstructed channel widths ≥1,150 ft were assigned a maximum suitability value. Table 1 of the Program's land plan infers whooping crane habitat suitability and use are maximized at UOCW of 1,150 ft (PRRIP 2006b). Shenk and Armbruster (1986) reported unobstructed channel widths 246 ft were unsuitable roosting habitat for whooping crane and roost habitat was optimized at unobstructed channel widths of 1,312 ft. Similarly, the USFWS (1986) reports whooping roosting habitat is optimized at unobstructed channel widths ≥1,158 ft and channels with unobstructed widths <500 ft were deemed unsuitable roosting habitat. Contrary to these reports, Austin and Richert (2005) found unobstructed channel widths at riverine roost sites averaged 764 ft and Johnson (1981) described optimal riverine roost habitat as being any channel with an unobstructed width ≥509 ft. Pitts (1985) even went so far as to report whooping crane selection of stopover habitat occurs at random. To date, however, roost characteristics and criteria have been developed based on a limited amount of quantitative information and most criteria have been derived from circumstantial roost locations that may not be representative of a typical stopover site (Armbruster 1990).

Changes in Associated Habitat Reach hydrology over historical timeframes

Water development in the Platte River basin began in the mid-1800s as settlers migrated to the region in search of gold and to homestead after the federal government opened the basin for settlement. The Platte River is now heavily developed with over seven thousand diversion rights and seven million acre-feet of storage (Figure 4; Simons & Associates Inc. 2000). Platte River discharge records begin in 1895, fifteen years before the completion of Pathfinder Dam, the first major agricultural storage project in the basin. Mean annual discharge and the magnitude of the mean annual peak discharge in the contemporary river are less than 40% of what was observed during the brief period of record prior to reservoir construction (Table 1; Stroup et al. 2006).

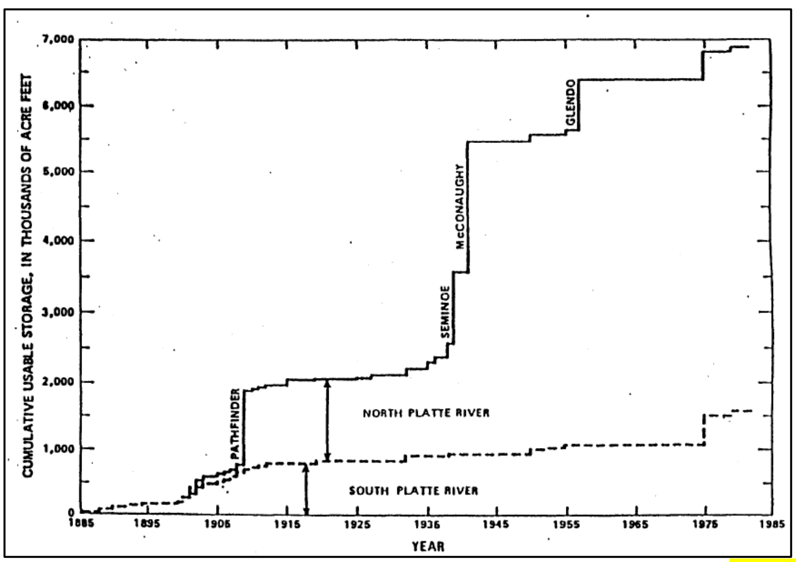

Figure 4. Cumulative usable storage in reservoirs in the Platte River basin (Simons and Associates Inc. 2000).

Table 1. Mean annual discharge and mean annual peak discharge at Overton gage adapted from Stroup et al. (2006).

	1895-1909	1910-1927	1928-1941	1942-1958	1959-1974	1975-1998	1999-2013
Mean Annual Discharge (cfs)	4,584	4,323	1,845	1,223	1,636	1,938	1,232
Mean Annual Peak Discharge (cfs)	20,725	18,218	11,548	6,685	7,301	7,176	5,056

Changes in Associated Habitat Reach sediment transport over historical timeframes

There is little bed material or sediment transport data available for the historical AHR. Simons and Associates Inc. (2000) generated a crude predevelopment sediment transport estimate of approximately 7.8 million tons per year based on a flow/sediment regression analysis and an estimate of sediment trapping in North Platte River reservoirs. Murphy et al. (2004) estimated much lower predevelopment sediment loads on the order of one to two million tons per year using a range of sediment discharge equations and discharge records from the period of 1895-1909. As indicated by the differences in these estimates, there is a high degree of uncertainty related to sediment loads in the historical AHR. Contemporary sediment load estimates are less variable and generally range from 400,000 – 1 million tons per year (Simons and Associates Inc. 2000, Murphy et al. 2004).

One of the most significant changes in sediment dynamics from predevelopment conditions is a sediment deficit in the upper half of the AHR due to clear water hydropower returns at the Johnson 2 (J-2) Return structure on the south channel downstream of Lexington, NE (Figure 5). An average of approximately 73% of Platte River flow is diverted at the Tri-County Diversion Dam downstream of North Platte and returns to the river at the J-2 Return where it constitutes approximately 47% of river flows (Murphy et al. 2004). Once diverted at North Platte, flow travels through several off-line reservoirs where almost all of the sediment is trapped. Accordingly, return flows at the J-2 Return structure are sediment-starved resulting in a sediment deficit (hungry water) below the return.

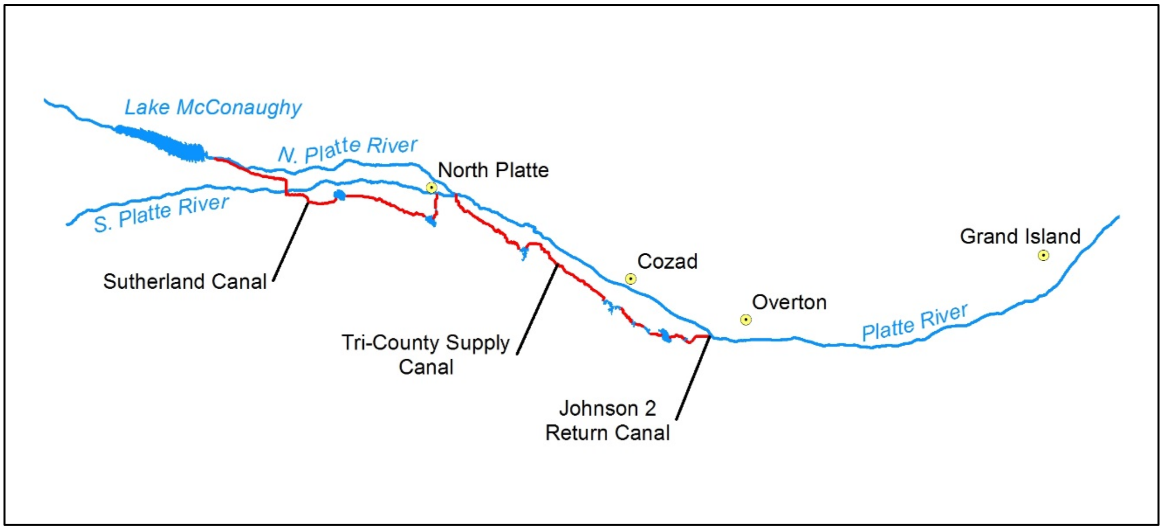

Figure 5. Map of Lake McConaughy, Tri-County Supply Canal and J-2 Return Canal. Figure reproduced from Murphy et al. (2004).

Changes in Associated Habitat Reach channel morphology over historical timeframes

The reduction in AHR active channel width (unvegetated width between permanently vegetated left and right banks) over historical timeframes through expansion of woody vegetation was first quantified by Williams (1978) and has been expanded upon in several subsequent analyses (Eschner et al. 1983, Currier et al. 1985, Peake et al. 1985, O'Brien and Currier 1987, Lyons and Randle 1988, Sidle et al. 1989, Johnson 1994, Simons and Associates 2000, Parsons 2003, Murphy et al. 2004, Schumm 2005, Horn et al. 2012). With the exception of Parsons (2003), which asserted no width change from 1930 to 1998, investigators have generally concluded the AHR experienced a significant width reduction as a result of the expansion of cottonwood forest into the channel. The change is evident in comparisons of aerial photography (Figure 6).

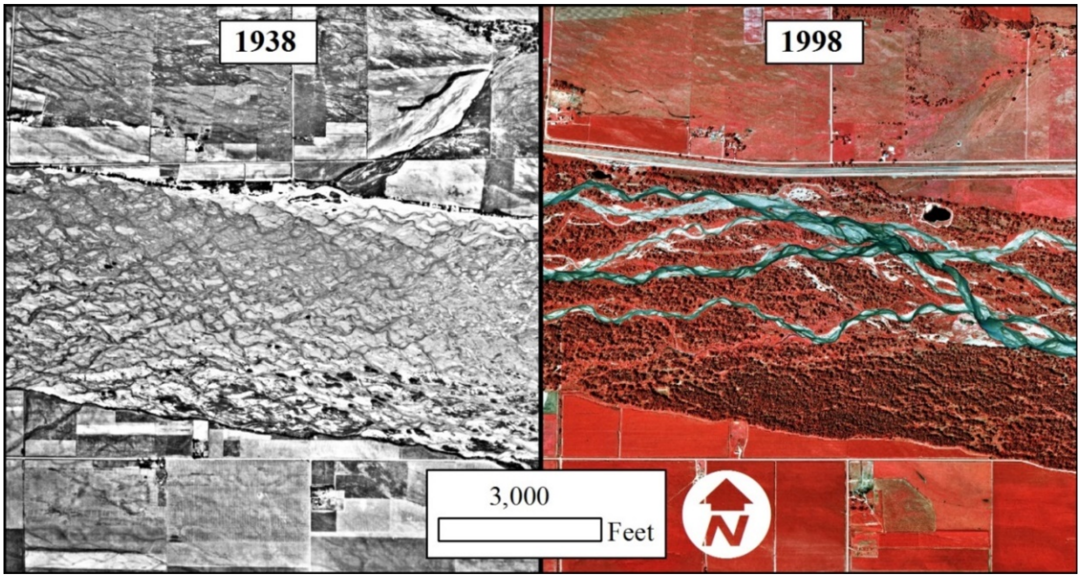

Figure 6. Comparison of 1938 and 1998 aerial photographs of the Associated Habitat Reach at River Mile 218 in the Odessa to Kearney bridge segment. Much of the 1998 channel area is occupied by riparian cottonwood forest.

The surveyed bank-to-bank or total width of the channel in the 1860s excluding large permanent islands was highly variable and averaged 3,800 ft (Figure 7). The proportion of the total width of the historical channel that was unvegetated is not known but has been estimated to be on the order of 90% (Johnson 1994). At the earliest aerial photography collection in 1938, unvegetated channel width averaged 2,600 ft. By 1998, average unvegetated width was 900 ft. Johnson (1994) evaluated the rate of change in active channel width in the AHR from 1938 to 1988 and found the majority of narrowing occurred during the 1940s and 1950s with channel area stabilizing by the 1980s (Figure 8).

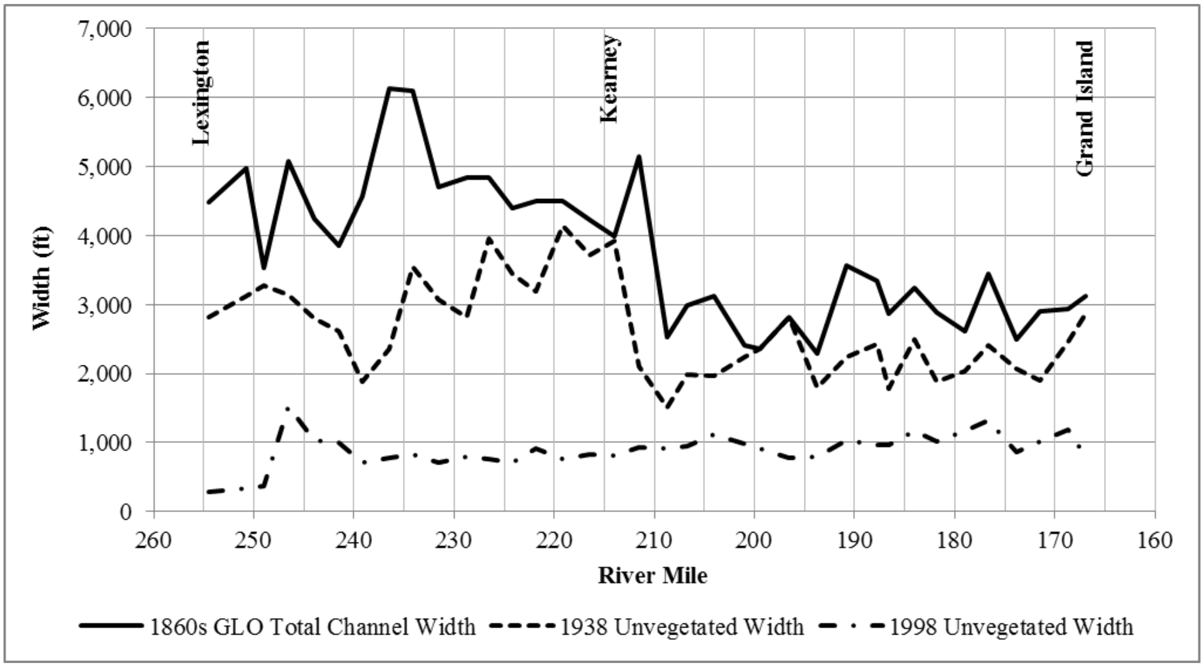

Figure 7. Total channel width in the Associated Habitat Reach from the 1860s General Land Office (GLO) survey, total unvegetated width in 1938 aerial photographs and total unvegetated width in 1998 aerial photographs.

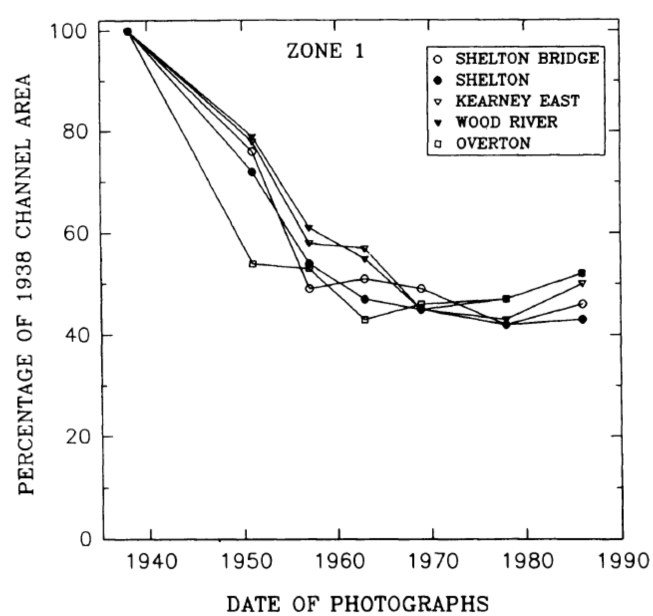

FIG. 8. Changes in active channel area in Zone 1 reaches from 1938 through 1986. Starting channel area in 1938 was set equal to 1.

Figure 8. Change in active channel area in the upper half of the Associated Habitat Reach 1938-1988 from aerial photography (Johnson 1994).

The drivers of woody vegetation expansion were explored in many of the channel width analyses with investigators generally concluding the change was due to alterations in hydrology caused by water development in the basin. Alternative hypotheses of the specific mechanisms of narrowing include:

1) a reduction of peak flow magnitude and associated ability to scour vegetation (Williams 1978, O'Brien and Currier 1987, Murphy et al. 2004),
2) a reduction in flow during the cottonwood germination period leading to increased recruitment (Johnson 1994, Simons and Associates 2000), and
3) a decrease in desiccation mortality of seedlings in summer as the river transitioned from ephemeral to perennial due to irrigation return flows (Schumm 2005).

Although changes in AHR channel width have been widely studied and debated, sandbar characteristics in the historical river are not well documented. Several investigations include brief descriptions of sandbars and islands recorded by travelers in the 19th Century (Eschner et al. 1983, Simons and Associates 2000, Murphy et al. 2004). The most descriptive observation of bedforms was contained in Mattes (1969) who reproduced a quote from a Mr. Evens in 1848 describing the Platte River near Kearney as "running over a vast level bed of sand and mica… continually changing into short offsets like the shingled roof of a house..." Other travelers generally characterized the bed of the river as being comprised of innumerable sandbars continually shifting and moving downstream (James 1823, Mattes 1969).

The first detailed characterization of AHR sandbar morphology was provided by Ore (1964) who classified Platte River bedforms as transverse bars. Further attempts to characterize sandbar morphology identified dominant bedforms as transverse/linguoid bars (Smith 1971, Blodgett and Stanley 1980), macroforms (Crowley 1981 and 1983), or a combination of both types (Horn et al. 2012). The historical accounts of Platte River bedforms appear to agree well with contemporary descriptions of transverse/linguoid bars.

Regulatory intervention in the Platte River Basin through the Endangered Species Act

In 1981, the USFWS deduced the most likely factors resulting in decreased whooping crane use of the Platte River between 1950 and 1980 were decreased unobstructed channel width, growth of woody vegetation along the bank lines, and increased human activity along the Platte River (USFWS 1981). The USFWS concluded additional diversions were likely to cause further habitat degradation and threaten the welfare of whooping cranes. As such, the USFWS determined whooping crane habitat along the central Platte River was threatened by upstream impoundments and diversions that reduce the magnitude of the annual spring runoff credited with historically creating and maintaining open-channel roosting habitat and for sustaining suitable bottomland (wet meadow) habitat deemed to be essential for foraging (USFWS 2006). The following excerpt from the Biological Opinion for the Platte River Recovery Implementation Program (USFWS 2006) provides the rationale for USFWS conclusions about the effects of upstream water development on whooping crane habitat in the AHR.

> "*Open Channel Roosting Habitat*
>
> *During the past century, channel habitat in the 170-mile long reach that lies within the whooping crane migration corridor has been transformed from a very wide and braided sandy channel to anabranched channels and heavily forested floodplain. Historical accounts of the Platte River place its width between 0.75- and 3 miles. Actual measurements by Bonneville in 1837 was a 1.25-mile width 25*

miles downstream of Fort Kearney, and a 1.0-mile width that was measured, by the explorer Fremont in 1845, downstream from the confluence of the North Platte and South Platte rivers (Currier et al. 1985).

Encroachment of woody vegetation into the former wide expanse of the river bed is described by Williams (1978), Eschner et al. (1983), Peake et al. (1985), Johnson (1990, 1994, and 1996), McDonald and Sidle (1992), Currier et al. (1985), and Currier (1995 and 1996a), Simons and Associates (2001), Murphy et al. (2004), and summarized by Sidle et al. (1989) and the EIS (Department of the Interior 2006). Within the Lexington to Chapman reach alone, Sidle et al. (1989) estimated that by the early 1980s the channel area had been reduced by 73 percent with the greatest reductions in the critical habitat reach from Lexington to Shelton (RM 196 to 250) (Figure VI-A6).

Currier et al. (1985) estimated that 70 percent of the open channel and 90 percent of the habitat value had been lost. Habitat loss and the threat of the Platte River whooping crane resources are related to the ongoing deterioration of forming processes (i.e., changes in the magnitude of channel forming flows and sediment transport) as described above. Further information on channel changes and loss of open channel discussed in 'Status of the Platte River Ecosystem' (Chapter VI, Section A) apply to the critical habitat reach.

Downstream of Lexington, the channel degradation described in the Status of the Platte River Ecosystem (Environment Baseline section, part A) of this biological opinion affects both channel roosting habitat and wet meadow foraging *habitat. No major tributary inflows or outflows occur below the J-2 Return and river flow patterns at Overton and Grand Island are generally similar, yet channel habitat losses are not uniform within the reach. Sediment-free J-2 Return discharges increase the downstream sediment transport to rates that are about twice the indicated amount supplied in to the habitat reach at Lexington (Randle and Samad 2003). Channel surveys indicate that much of the difference in the amount of sediment transported is from erosion of the channel bed.*

Channel bed degradation extends downstream from the J-2 Return near Lexington. The length of river reach undergoing degradation is not precisely determinable with existing data, but appears to be at least 20 miles and perhaps as much as 40 miles of a recent 15- year interval (Murphy et al. 1998, Holburn et al. 2006).

Channel bed erosion is a factor that adversely affects open channel roosting habitat by entrenching the channel and concentrating flow and increasing water depth and velocity. Channel downcutting has left high islands, banks, and benches at higher elevations and provide a surface for vegetation growth. Though the affects of this process on habitat vary somewhat among river reaches, the confining and down-cutting of the river channel between high banks has contributed to substantial decreases in horizontal visibility, open channel, and wetted channel area, and to changes from braided to anabranched river plan form.

The area of open, wide channels is not entirely eliminated in the critical habitat reach, but it is substantially reduced in amount and quality (Figure VI-B6).

Consequently, whooping crane use of the river channel for roosting is substantially limited from Lexington (RM 251) to the vicinity of Fort Kearny State Recreation Area (RM 210) (Fort Kearney lies in bridge segment 8 of Table IV-B2). Portions of the river in bridge segment 7 and 10 are maintained as open channel habitat by private non-government organizations.

Quantitatively, loss of whooping crane roosting habitat due to channel degradation is greatest in the upstream reaches. For example, between 1985 and 2000 near Overton, changes in channel morphology (i.e., channel downcutting and narrowing) virtually eliminated whooping crane roost habitat in a segment of the critical habitat reach near Overton (Figure VI-B7).

Changes in river morphology may have a controlling affect on the hydrologic relationship between the river and subirrigated meadows and wetland components of the adjoining bottomland grasslands. Platte River channel morphology must be improved and maintained in order to provide the wide channels suitable as roosting habitat and to restore and maintain wet meadows where cranes feed and rest.

Hydrocycling

Flows of the Platte River during spring and fall whooping crane migration seasons are composed in part of water diverted into CNPPID's system and returned at the upstream end of the central Platte River habitat area near Lexington. Returns at the J-2 Return and flows remaining in the south river depend in part on the *releases from Lake McConaughy and inflows from the South Platte River. Releases depend in turn on available water supplies in the basin.*

During low water supply conditions, discharges from the J-2 Return are variable. Based on operational descriptions, Hydrocycling may occur when flows reaching the Johnson No. 2 power station are less than 1.300 to 1.400 cfs, and must occur when flows reaching the Johnson No.2 power station are less than 1,050 cfs because of the risk of cavitation damage (CNPPID 2005). During low flow years, Hydrocycling may occur during whooping crane spring and fall migration periods.

The magnitude of the change in river stage attenuates downstream. Changes in river stage may range from imperceptible to a few inches (at RM 206 and 207) to more than 2 feet (RM 243-244) during Hydrocycling. The potential adverse effects of current Hydrocycling operations on whooping cranes may be occurring in a limited portion of the J-2 to Kearney reach of the river where wide channels occur, and most specifically in the segment of wide channels maintained as crane habitat.

Though migrating whooping cranes may use the Platte River at various times of day and are observed to retreat from fields to Platte River roosts during severe weather, the primary concern is the potential effects on nocturnal roosts. Whooping cranes stand in shallow (usually <0.7-foot) slow-moving water to roost. The current Hydrocycling operations may affect cranes in several ways, including the potential to flush the birds from their roosts at night, cause restless roosting behavior, and potentially increase exposure to predators (pers. comm., Gary Krapu

2006). Collision with utility lines is a principal known cause of direct injury and mortality to migrating whooping cranes (USFWS 1994g, Ward and Anderson 1992, Stehn and Wassenich 2006), and of sandhill crane injury and mortality along the Platte River (USFWS 1984g, Ward and Anderson 1992). Discussions are currently underway with CNPPID to develop and agreement on modified Hydrocycling operations to avoid or minimize effects to listed species and program benefits."

As indicated in the excerpt, a decline in AHR whooping crane habitat suitability has been inferred from the body of evidence documenting a significant change in Platte River hydrology and a morphological reduction in unvegetated AHR channel width over historical timeframes. Within this context, the USFWS began issuing jeopardy opinions for water projects that could further affect the hydrology of the AHR. These jeopardy opinions prompted the states of Wyoming, Colorado, and Nebraska and the Department of the Interior to enter into a Cooperative Agreement in 1997 for the purpose of negotiating a program to conserve threatened and endangered species habitat in the AHR while accommodating certain ongoing water development activities in the basin. Through the negotiation process, it became apparent that uncertainty and disagreements about species habitat requirements and appropriate management strategies were making it difficult to reach agreement on a program. Resolution was achieved through the development of an Adaptive Management Plan (PRRIP 2006a) that treats these disagreements as uncertainties related to two competing management strategies.

Competing Management Paradigms

The Program's two competing management strategies reflect different paths to achieving the objective of improving survival of whooping cranes during migration. The first strategy is the

Mechanical Creation and Maintenance (MCM) approach. This approach focuses on mechanical creation and maintenance of both in- and off-channel habitats for the whooping cranes including channel widening through management activities such as in-channel and bank line vegetation removal, the acquisition and restoration of off-channel wetland habitat, and the construction and preservation of wet meadow habitat. Various entities have created, maintained, and monitored whooping crane stopover habitat use in the AHR since 2001. Accordingly, there is little uncertainty about the ability to mechanically create and maintain wide open channels for whooping cranes. Instead, the uncertainties pertain to characteristics that influence selection of in- and off-channel habitats and the most economical means of creating and maintaining that habitat (PRRIP 2006a).

The second strategy is the Flow-Sediment-Mechanical (FSM) approach. This approach is water-centric with a focus on restoring channel width, improving sediment supply, and increasing annual peak flow magnitudes to increase the braided channel morphology and maintain unobstructed channel width. The FSM strategy is rooted in the view that, prior to the onset of water development and channel narrowing, the historical AHR once provided stopover habitat conditions critical for whooping crane survival and that the contemporary Platte River is insufficient to provide the population this critical resource. As discussed previously, there is a large body of evidence documenting AHR channel narrowing over historical timeframes with the most significant changes occurring during the period of 1940-1970 (Johnson 1994).

Chapters 2 and 3 provide an overview of whooping crane riverine habitat selection along the central Platte River and throughout the North-central Great Plains, respectively. Chapter 4 explores the validity of the assumption the FSM management strategy can create and maintain habitat conditions suitable for whooping crane use as identified in chapters 2 and 3 and preludes into a discussion on the potential implications for the Program's ability to create and maintain whooping crane roosting habitat using short-duration high flows.

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CHAPTER 2 – Whooping Crane Use of Riverine Stopover Sites along the Central Platte River, Nebraska

Abstract

The "Big Bend" reach of the central Platte River has been identified as critical habitat for the survival of the endangered whooping crane (*Grus americana*). Management intervention is now underway to rehabilitate habitat form and function on the central Platte River to increase use and thereby contribute to the survival of whooping cranes. The goal of our analysis was to develop habitat selection models that could be used to direct management activities along the central Platte River. As such, we focused our analysis on habitat metrics the Platte River Recovery Implementation Program (Program) has the ability influence to some degree. This includes channel characteristics such as total channel width, the width of channel unobstructed by dense vegetation, and distance of forest from the channel. Through the U.S. Fish and Wildlife Service's Environmental Account, the Program also has access to water that, through timed releases, can be used to influence flow-related metrics like wetted width and unit discharge (flow volume per linear foot of wetted channel). We developed *a priori* set of models to evaluate the influence these various metrics on the probability of whooping crane use and found the width of channel unobstructed by dense vegetation and distance to the nearest forest were the best predictors of whooping crane use. We were unable to establish evidence of a strong relationship between use and flow metrics, total channel width or unforested channel width. Our findings indicate the Program has the potential to influence whooping crane use of the central Platte River through removal of in-channel vegetation to increase unobstructed width in narrow (<450 ft) channels and through removal of trees within areas where the distance to nearest forest from the center of the channel is <500 ft.

Introduction

The Platte River Recovery Implementation Program (Program or PRRIP) is responsible for implementing certain aspects of the endangered whooping crane (*Grus americana*) recovery plan. More specifically, the Program's management objective is to contribute to the survival of the whooping crane during migration by increasing and maintaining migratory stopover habitat in the Associated Habitat Reach (AHR) of the Platte River in central Nebraska. This ninety-mile reach extends from Lexington, NE downstream to Chapman, NE and includes the Platte River channel and off-channel habitats within three and one half miles of the river (Figure 1).

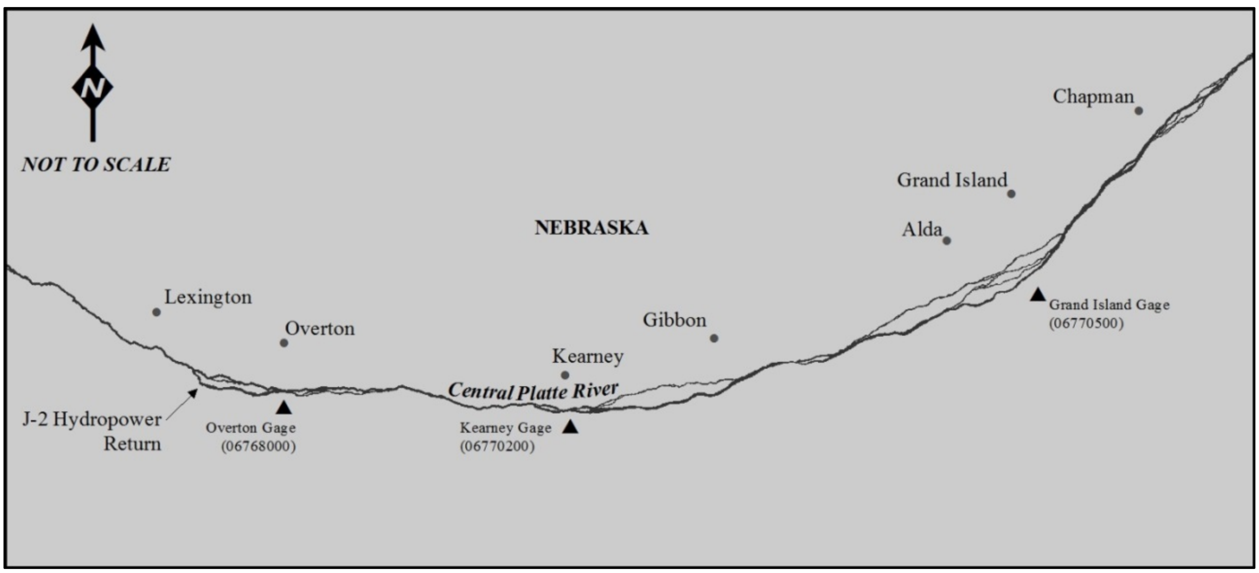

Figure 1. Associated Habitat Reach of the central Platte River extending from Lexington downstream to Chapman, NE.

During the First Increment of the Program (2007-2019), stakeholders committed to working toward this management objective by acquiring and managing 10,000 acres of land and 130,000-150,000 acre-feet of water to benefit whooping crane and other target species. However, there has been significant disagreement about species' habitat requirements and the appropriate strategy for managing the Program's land and water resources (Freeman 2010). In order to reach consensus for Program implementation, stakeholders agreed to treat disagreements as uncertainties to be evaluated within an adaptive management framework. The result is an Adaptive Management Plan (AMP) designed to test priority hypotheses including several associated with whooping crane responses to management actions designed to influence river form and improve habitat suitability (PRRIP 2006).

The whooping crane was listed as a federally endangered species in March 1967, and portions of the central Platte River were designated as critical habitat under the Endangered Species Act in May 1978 (U.S. Fish and Wildlife Service 1978). The National Research Council (2004) supported this critical habitat designation and concluded that current habitat conditions along the central Platte River adversely affect the likelihood of survival and recovery of the whooping crane population. Whooping crane stopovers occur throughout the migration corridor and last from one to several days during migrations that can last several weeks. Possible impacts of water and land development in the migration path has led to concern about the quality and quantity of stopover habitat for roosting and foraging. Along the central Platte River, flowing portions of riverine habitat have by far the highest incidence of stopover use for whooping cranes (Austin and Richert 2001; National Research Council 2004).

Evaluations of habitat characteristics at roost locations along the central Platte River date to the early 1980s (Johnson and Temple 1980; U.S. Fish and Wildlife Service 1981; Johnson 1981; Pitts 1985; Shenk and Armbruster 1986; U.S. Fish and Wildlife Service 1986; Ziewitz 1987; Armbruster 1990; Biology Workgroup 1990; Faanes et al. 1992; Austin and Richert 2001; National Research Council 2004; Canadian Wildlife Service and U.S. Fish and Wildlife Service 2005, Farmer et al. 2005). These analyses were focused on evaluations of hydrologic and geomorphic metrics assumed to be important for whooping crane habitat selection including unobstructed channel widths, distance to obstruction (i.e., nearest forest), view widths, flow, wetted width, suitable depth, etc. These analyses were typically developed based on a limited amount of quantitative information and most criteria were derived from circumstantial roost locations that may not be representative of a typical stopover site (Armbruster 1990). As a consequence, the results and conclusions 1) reflect the investigators assumptions about the habitat metrics that were important for whooping crane roost site selection and 2) may not be representative of typical stopover sites.

The objective of this analysis is to investigate riverine habitat selection by whooping cranes using methods that allow us to 1) identify habitat metrics that are both important for whooping crane use and that can be influenced through management activities and 2) do so in a manner that addresses changes in habitat through time and the biases associated with evaluation of circumstantial or opportunistic roost locations. This was accomplished through evaluation of channel and flow habitat characteristics at systematically detected whooping crane group stopover locations (fall 2001 – spring 2013) within a use-available resource selection function (RSF) estimation framework. A total of 16 *a priori* models were evaluated and ranked to identify the habitat metrics that appear to most strongly influence whooping crane roost location.

Methods

Our study area, the Associated Habitat Reach (AHR), encompasses the Platte River channel and a 3.5-mile buffer adjacent to the channel from the junction of US Highway 283 and Interstate 80 (near Lexington, Nebraska) downstream to Chapman, Nebraska (PRRIP 2011). Systematic whooping crane use data was collected during the spring and fall migration periods per the Program's whooping crane monitoring protocol (PRRIP 2011). Aerial surveys were flown daily during migration seasons, with the spring monitoring period spanning from March 21 to April 29, and the fall monitoring period spanning from October 9 to November 10. Flights followed the main river channel and took place at dawn to locate crane groups before they departed the river to begin foraging at off-channel sites. Return flights occurred after the river survey was completed and systematically surveyed upland areas and smaller side channels.

Whooping Crane Group Observation Data

Whooping crane habitat use within the AHR has been monitored since 2001. The basic sample unit for this analysis was a crane group (≥1 whooping crane). Per the Program's systematic monitoring protocol, crane groups were identified as being detected systematically during daily monitoring flights. Consequently, this dataset, and associated analyses, was unbiased with respect to the unequal monitoring effort associated with reports of observations by the public. The first observation of a crane group was identified as being unique with subsequent observations identified as repeat observations. For example, when crane groups were observed multiple days in a row, only the first observation was considered to be unique (independent).

The model selection process only utilized the unique (first) location for crane groups located systematically during implementation of the monitoring protocol (n=55). These observations are referred to as systematic unique observations. We also performed a supplementary analysis using the best model based on systematic unique observations using all systematically collected observations (n=176). This supplemental analysis substantially increased the number of observations in the analysis.

Parameterization of the A Priori Model Set

We quantified the characteristics of in-channel riverine habitat with two basic sources of information: aerial imagery and a HEC-RAS hydraulic model. We used aerial photographs and remote sensing data from LiDAR to determine the following metrics of channel openness for the analysis (Figure 2):

- Unobstructed Channel Width (UOCW) - Width of channel unobstructed by dense vegetation
- Nearest Forest (NF) - Distance to nearest riparian forest. Distance larger than 1,320 feet (1/4/ mile) were capped at 1,320 feet.
- Unforested Channel Width (UFCW) - Width of channel unobstructed by riparian forest

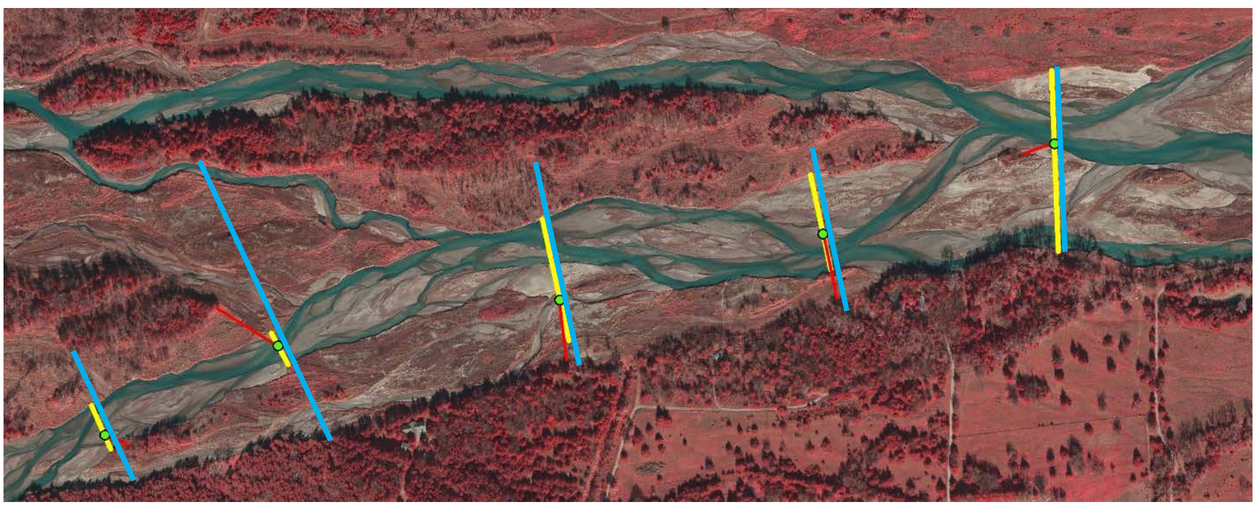

Figure 2. Example of how Unobstructed Channel Width (UOCW; yellow lines), Nearest Forest (NF; red lines) and Unforested Channel Width (UFCW; blue lines) were measured at whooping crane use and available locations.

We ran the Program's system scale HEC-RAS hydraulic model using the mean daily discharge at the nearest stream gage on the date of each whooping crane group observation to calculate following metrics that describe flow-related channel characteristics:

- Total Channel Width (TCW) - Total width of channel from left bank to right bank
- Unit Discharge (UD) - Flow (cfs) per linear foot of wetted channel width.
- Discharge divided by Total Channel Width (DIS) - Flow (cfs) per linear foot of total channel width (TCW).

HEC-RAS model geometry was developed primarily using 2009 LiDAR topography supplemented with 2009 surveyed channel transects and longitudinal profile surveys. Model roughness values were based on 2005 land use dataset. The model was calibrated based on gage rating curves, March 2009 inferred water surface elevation from LiDAR data, and 2009 surveyed water surface elevation. Each descriptor of habitat was tested for possible inclusion as a predictor variable in the habitat selection models.

Whooping Crane In-channel Riverine Habitat Selection

Habitat metrics were calculated for each whooping crane group use location and at the 20 corresponding randomly selected in-channel available points within 10 miles upstream and downstream of the use location. Sixteen a priori candidate models, including a null model, were developed based on the habitat variables described above (Table 1). No metrics were included together in a model if substantial correlation ($r \geq 0.50$) was present (Appendix I).

The habitat selection analysis was conducted within a resource selection function (RSF) estimation framework (Manly et al. 2002). In this model, characteristics of points used by whooping crane groups were contrasted to characteristics of points defined to be available for use by the whooping crane group. The relative difference in the distribution, or density, of these characteristics defines habitat selection. Multiple modelling paradigms were available for this estimation, with recent statistical advances demonstrating spatial point process models are underlying both the use-available approach and the presence-only approach (Johnson et al. 2006, Aarts et al. 2012, McDonald 2013, Warton and Aarts 2013). The use-available approach was chosen for this study because of the presence of existing literature for the handling of an important factor affecting whooping crane selection in AHR − changing availability.

Table 1. In-channel Riverine *a priori* model list evaluated for whooping crane roosting habitat use. The interpretation assumes an *a priori* direction (positive or negative) in the relationship between whooping crane habitat use and metrics, but actual model fit, based on data, could have been in the opposite direction.

Model	*A priori* Models	Interpretation
1	NULL	Habitat selection is random
2	UOCW	Select channels with views unobstructed by dense vegetation or wooded islands.
3	TCW	Select channels with increased distance from right to left bank including vegetated and wooded islands.
4	NF	Select channels with increased ‘openness’ which includes areas without trees located nearby in any direction.
5	UFCW	Select channels with wide unforested widths.
6	UOCW+NF	Select channels with views unobstructed by dense vegetation or wooded islands and with increased ‘openness’ which includes areas without trees located nearby in any direction.
7	TCW+UOCW	Select channels with views unobstructed by dense vegetation or wooded islands and increased distance from right to left bank that can include vegetated and wooded islands.
8	TCW+UD	Select channels with increased distance from right to left bank including vegetated and wooded islands during times when the amount of flow (cfs) per unit of wetted channel width (ft) provides suitable conditions for use.
9	TCW+DIS	Select channels with increased distance from right to left bank including vegetated and wooded islands during times when the amount of flow (cfs) per unit of total channel width (ft) provides suitable conditions for use.
10	TCW+UOCW+UD	Select channels with increased distance from right to left bank that can include vegetated and wooded islands and views unobstructed by dense vegetation or wooded islands during times when the amount of flow (cfs) per unit of channel wetted width (ft) provides suitable conditions for use.
11	TCW+UOCW+DIS	Select channels with increased distance from right to left bank that can include vegetated and wooded islands and views unobstructed by dense vegetation or wooded islands during times when the amount of flow (cfs) per unit of total channel width (ft) provides suitable conditions for use.

Model	*A priori* Models	Interpretation
12	TCW+NF+UOCW	Select channels with increased distance from right to left bank including vegetated and wooded islands, with increased ‘openness’ which includes areas without trees located nearby in any direction, and with views unobstructed by dense vegetation or wooded islands.
13	TCW+NF+UD	Select channels with increased distance from right to left bank including vegetated and wooded islands, with increased ‘openness’ which includes areas without trees located nearby in any direction during times when the amount of flow (cfs) per unit of channel wetted width (ft) provides suitable conditions for use.
14	TCW+NF+DIS	Select channels with increased distance from right to left bank including vegetated and wooded islands, with increased ‘openness’ which includes areas without trees located nearby in any direction during times when the amount of flow (cfs) per unit of total channel width (ft) provides suitable conditions for use.
15	TCW+UOCW+NF+UD	Select channels with increased distance from right to left bank including vegetated and wooded islands, with views unobstructed by dense vegetation or wooded islands, with increased ‘openness’ which includes areas without trees located nearby in any direction during times when the amount of flow (cfs) per unit of channel wetted width (ft) provides suitable conditions for use.
16	TCW+UOCW+NF+DIS	Select channels with increased distance from right to left bank including vegetated and wooded islands, with views unobstructed by dense vegetation or wooded islands, with increased ‘openness’ which includes areas without trees located nearby in any direction during times when the amount of flow (cfs) per unit of total channel width (ft) provides suitable conditions for use.

Wildlife habitat selection studies with changing availability has received much attention over the last few decades (Johnson 1980, Arthur et al. 1996, McCracken et al. 1998, Manly et al. 2002, McDonald et al. 2006). Whooping crane use of the Platte River represents a unique situation in that availability of resources change on both spatial and temporal scales. The spatial aspect of changing habitat conditions is chiefly due to the variability in channel morphology throughout the 90-mile AHR and the temporal component is associated with changes in channel form through time. We chose the discrete choice method of RSF estimation to incorporate changing availability at temporal and spatial scales. The discrete choice model accounts for changing habitat conditions in the study area, while modeling the underlying relationships between selection and predictor variables (McDonald et al. 2006). Non-linear changes in the RSF due to changing availability were handled with penalized regression splines to approximate the functional response (Aarts et al. 2013). With the exception of mixed linear models (Hebblewhite and Merrill 2008, Duchesne et al. 2010, Matthiopoulos et al. 2011), other methods of estimating RSF's using the inhomogeneous point process have not incorporated this facet of habitat selection into the statistical underpinnings of the method. It is possible that recent advances in space-time point process models proposed by (Johnson et al. 2013) may be appropriate for this type of data, but the incorporation of changing availability has not been addressed at this time.

Defining the Available Choice Set

The choice set represents a sample of points from an area the crane group could have selected for use. This distribution set is analogous to the background sample in Maxent (Phillips et al. 2006, Phillips and Dudik 2008) and the integration points in point process models (Hefley et al. 2015). In the discrete choice framework, the choice set is unique for each choice, or used location, and is linked to the choice through the likelihood terms in the model. In effect, the model allows the comparison between characteristics of each used location and the characteristics of the choice set. This pairing in the model is accomplished through the use of strata in the gam function (R Core Team, 2016).

As an aerially migrating whooping crane group approaches the river it cannot visually see the entire 90-mile AHR. Consequently, the choice set for each stopover location were necessarily limited to a subsection of the AHR. For the purposes of this analysis, we limited the choice set to a 20-mile reach of river centered on the use location and extending 10 miles upstream and downstream from that point. This decision was based on an aerial evaluation of viewsheds from 3,000 ft above ground level, which was a reported elevation for long distance flights by telemetry-marked whooping cranes in the 1980s (Kuyt 1992) as well as a commonly observed migration elevation during an ongoing telemetry study (PRRIP unpublished data). At 3,000 ft above ground, only large features like bridge crossings were readily discernable at distances >10 miles from the flight location without supplemental magnification.

Functional Response to Resource Selection

We used penalized regression spline methodology to evaluate a functional response in habitat use. Resource selection models evaluate functional responses (i.e., change in selection as a function of spatial or temporal changes in resource availability) and spline smoothers allow for non-linear effects. Smooth spline functions enabled a wide array of functional forms to be incorporated into the RSF, with the implementation of model selection determining the precise shape of the functional response. The smooth term in the habitat model likelihood is represented with a set of basic functions and associated penalties (Hastie and Tibshirani 1990, Wood 2006). The penalty is larger when the smoothing function is very "wiggly" and requires more degrees of freedom. The degrees of freedom for each smooth term is optimized for each iteration when the likelihood is maximized.

Statistical Modeling of Habitat Use/Resource Selection

Resource selection functions were developed to evaluate characteristics of whooping crane group habitat selection in the central Platte River. The basic premise of resource selection modeling is that resources (any quantifiable habitat characteristic) that are important to cranes will be "used" disproportionately to the availability of those resources in the environment (Manly et al. 2002). In our analyses, the characteristics at the used locations were contrasted to characteristics at randomly selected "available" locations in the study area.

To model habitat selection, a discrete choice model of resource selection was fit to the dataset. This model facilitates modeling habitat selection when the habitat that was available for use changes both temporally and spatially. The model evaluates a weighted relative selection ratio with a multinomial logit form expressed as:

$$w(X_{ij}) = \exp(s_1(X_{1ij}) + s_2(X_{2ij}) + \cdots + s_p(X_{pij}))$$

where X_1 to X_p are habitat metrics, j indexes the units in the choice set, and i indexes the unit selected, s_1 to s_p are the smooth functions of X_1 to X_p, respectively. Relative selection ratios were weighted against the maximum value of the upper confidence interval so that the highest value was one. The smooth terms are penalized regression splines, or smooth functions of the predictor variables describing the relationship between selection and the habitat metrics. The incorporation of penalized regression splines (i.e. smooth terms) into the linear predictor of the model is analogous to the parameterization of a generalized additive model (Wood 2006).

The use-availability likelihood was maximized using R statistical software (R Core Team 2016) through RStudio (RStudio Team 2016), specifically with the gam function of the mgcv package under a Restricted Maximum Likelihood Estimated Cox Proportional Hazards model. The mgcv package determines the smoothness of the spline, and associated degrees of freedom, through iteratively re-weighted least squares fitting of the penalized likelihood (Wood 2006). The penalty for the smoothing parameters is determined at each iteration using generalized cross validation. Final model determination among the set of candidate models was obtained using Akaike's Information Criterion (AIC).

Interpretation of the relationship between metrics in the model and habitat selection was through response functions and the degrees of freedom for the smooth terms. The estimated degrees of freedom indicate the amount of smoothness, with a value of 1 equivalent to a straight line. In cases where the estimated degrees of freedom were 1, we removed the smoothing component for that covariate and fit a parametric straight line. Due to a small sample size of systematic unique whooping crane group observations (n=55), we limited the potential degrees of freedom for regression splines to less than 4 for all variables.

Response Functions

After identifying the best fit models, we estimated the predicted relative selection ratio across the range of observed values of the metrics in the models. This analysis provided a graphical display of the modeled relationship between the predictor variables and the response, holding the effects of the other variables in the model constant at the mean.

Graphical displays of response functions were combined with rug plots to show the underlying data in model fitting. Rug plots display a tick mark for each data point in the model, with used points displayed at the top (use equals 1) and the choice set displayed at the bottom of the figure (available equals 0). Response functions were scaled to the largest predicted value (maximum equals 1) and predictor variables were displayed with 90% confidence intervals from the 10th to the 90th percentiles to limit the influence of extreme values on the interpretation of results.

Data Summary

We included the mean and standard deviation of each metric included in the *a priori* model set to provide basic summary statistics for each descriptor of whooping crane habitat. For each predictor variable in the top-ranked in-channel riverine habitat selection model, we developed mirrored histograms to graphically display the distribution of the values for each variable in order to contrast the distributions of the used set and available set of data. For each distributional density histogram, the area of the bars sums to one. Although these figures display the relationship between the predictor variables and the outcome (use by whooping crane groups), they simplify the assessment by combining data across the many choice sets. Despite this caveat, they are presented to provide a graphical precursor to understanding the statistical models of habitat use.

Results

Whooping Crane Habitat Selection based on Systematic Unique Observations

In-channel riverine habitat selection models were developed for the 55 spring and fall systematic and unique whooping crane group observations and the associated 1,100 available points. Mirrored histograms were provided to graphically display the data for each predictor variable in the top- ranked habitat selection model (Figures 3 and 4). These figures show the distribution of the values for each variable in order to contrast the distribution of use and available data. We also provided basic summary statistics for all metrics included in our *a priori* set of models in Table 2.

Statistical modeling of habitat use indicated UOCW and NF were the most important predictors of whooping selection of in-channel riverine habitat (Table 3). The relative selection ratio was maximized at an UOCW of 460 ft, but relative selection ratios were statistically similar for UOCW's ranging from 278 to 889 ft (Figure 5). The relative selection ratio was maximized at a distance of 512 ft from the nearest forest, but relative selection ratios were statistically similar for distances ranging from 257 to 684 ft from the nearest forest (Figure 6). The estimated degrees of freedom for the smoothed terms were 3.213 for UOCW and 3.178 for NF.

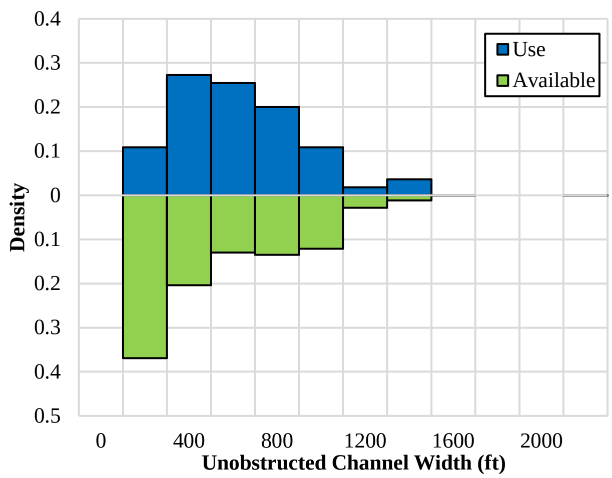

Figure 3. Mirrored histogram to graphically display the distribution of values for unobstructed channel width in order to contrast measurements collected at whooping crane roost locations (blue bars) and choice set or 'available' (green bars) locations. The area of the bars for stopover and available locations each sum to one.

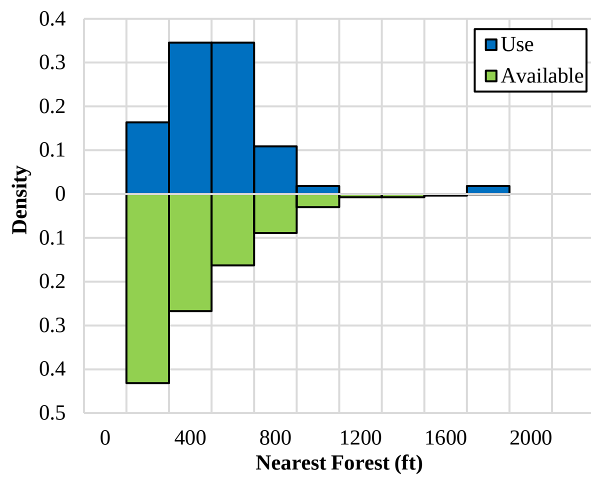

Figure 4. Mirrored histogram to graphically display the distribution of values for distance to nearest forest along a line running perpendicular to the channel in order to contrast measurements collected at whooping crane roost locations (blue bars) and choice set or 'available' (green bars) locations. The area of the bars for stopover and available locations each sum to one.

Table 2. Mean and standard deviation (in parenthesis) of metrics included in the *a priori* models for whooping crane group in-channel riverine roost location habitat selection analyses. The mean and standard deviation are provided for spring, fall, and a combination of the spring and fall systematic unique whooping crane use locations.

Covariate	Abbreviation	Units	Spring Mean (SD)	Fall Mean (SD)	Combined Mean (SD)
Unobstructed Channel Width	UOCW	Feet	485 (270)	579 (286)	523 (278)
Unforested Channel Width	UFCW	Feet	857 (370)	1,133 (374)	967 (393)
Total Channel Width	TCW	Feet	690 (350)	919 (407)	782 (387)
Nearest Forest	NF	Feet	386 (308)	470 (175)	419 (265)
Unit Discharge	UD	cfs/foot	2.64 (1.46)	1.75 (1.58)	2.28 (1.56)
Discharge/TCW	DIS	cfs/foot	1.77 (1.39)	1.22 (1.39)	1.55 (1.41)

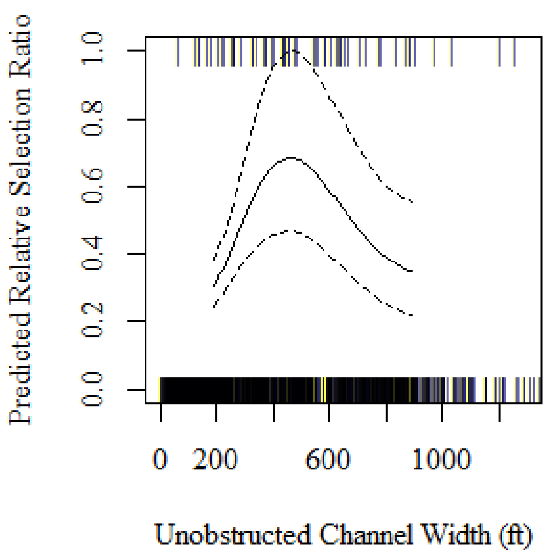

Figure 5. Predicted relative selection ratio for the top ranked RSF model, with 90% confidence intervals, of unobstructed channel widths (UOCW). Tick marks indicate actual data (use points are presented at y=1 and available points are presented at y=0). Data is displayed from the 10th to the 90th percentile of use locations.

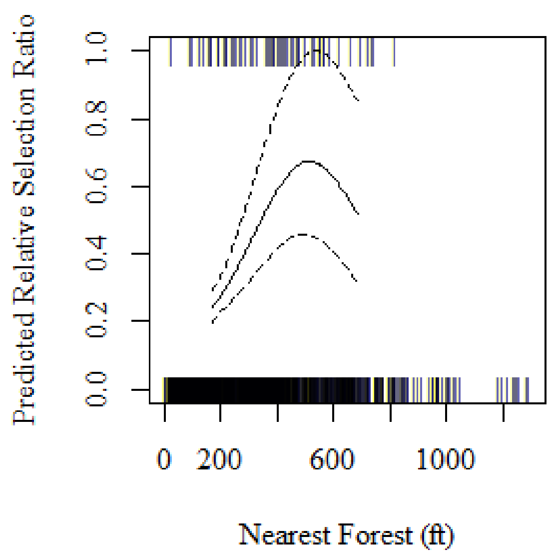

Figure 6. Predicted relative selection ratio for the top ranked RSF model, with 90% confidence intervals, of distances to nearest forest. Tick marks indicate actual data (use points are presented at y=1 and available points are presented at y=0). Data is displayed from the 10th to the 90th percentile of use locations.

Table 3. In-channel riverine habitat use model selection for whooping crane group stopover sites on the central Platte River.

Model	Metrics	df	AIC	ΔAIC	weight
6	UOCW+NF	61.35	859.25	0.00	0.49
12	TCW +UOCW+NF	62.33	861.12	1.87	0.19
15	TCW+UOCW+NF+UD	63.33	861.44	2.18	0.16
16	TCW+UOCW+NF+DIS	63.32	863.14	3.89	0.07
4	NF	57.73	864.85	5.60	0.03
2	UOCW	57.85	866.31	7.05	0.01
5	UFCW	57.78	866.98	7.73	0.01
13	TCW+NF+UD	59.72	867.03	7.77	0.01
7	TCW+UOCW	58.83	867.62	8.37	0.01
10	TCW+UOCW+UD	59.83	867.73	8.47	0.01
14	TCW+NF+DIS	59.71	868.56	9.31	0.00
11	TCW+UOCW+DIS	59.83	869.55	10.30	0.00
8	TCW+UD	56.00	881.35	22.10	0.00
3	TCW	55.00	881.93	22.68	0.00
9	TCW+DIS	56.00	882.63	23.38	0.00
1	NULL	54.00	883.70	24.45	0.00

Whooping Crane Group Habitat Selection based on all Systematic Observations

The top-ranked habitat selection model that included UOCW and NF, was used to analyze the 176 systematically collected whooping crane group observations identified during aerial surveys (2001 – 2013) as well as the associated 3,520 available points. The 176-systematic whooping crane group observations included the 55 unique locations in the Program's systematic monitoring data as well as 121 subsequent observations of the 55 whooping crane groups observed during aerial surveys. UOCW at use locations averaged 547 ft (SD = 290 ft; median = 547 ft) while UOCW at available locations averaged 310 ft (median = 246 ft). NF at use locations averaged 467 ft (SD = 262 ft; median = 445 ft) while NF at available locations averaged 391 ft (median = 294 ft). Model results indicate UOCW and NF relationships were similar to results of models derived from the systematic unique dataset. An increasing trend was observed from low to intermediate values of UOCW and NF, but relative selection ratios did not differ greatly from intermediate to high values because of the uncertainty in point estimates. The relative selection ratio was maximized at an UOCW of 618 ft, but relative selection ratios were statistically similar for UOCW's ranging from 239 to 901 ft. Similarly, the relative selection ratio was maximized at 595 ft from the nearest forest, but relative selection ratios were statistically similar for distances ranging from 368 to 779 ft.

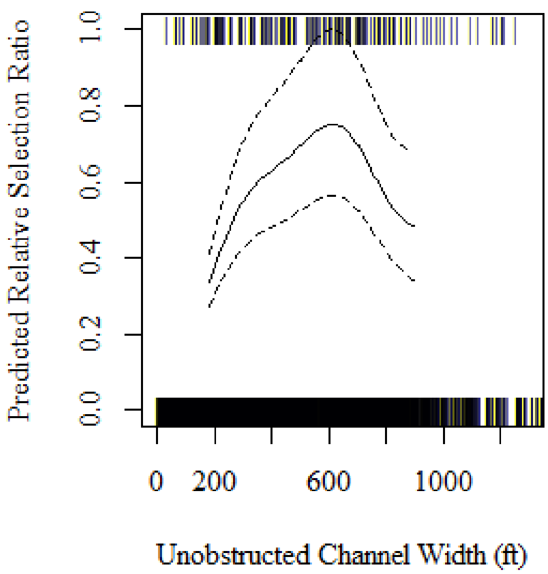

Figure 7. Predicted relative selection ratio for the top ranked RSF model evaluated with all systematic observations (n = 176), of unobstructed channel width (UOCW). Tick marks indicate actual data (use points are presented at y=1 and available points are presented at y=0). Data is displayed from the 10^{th} to the 90^{th} percentile of use locations with 90% confidence intervals.

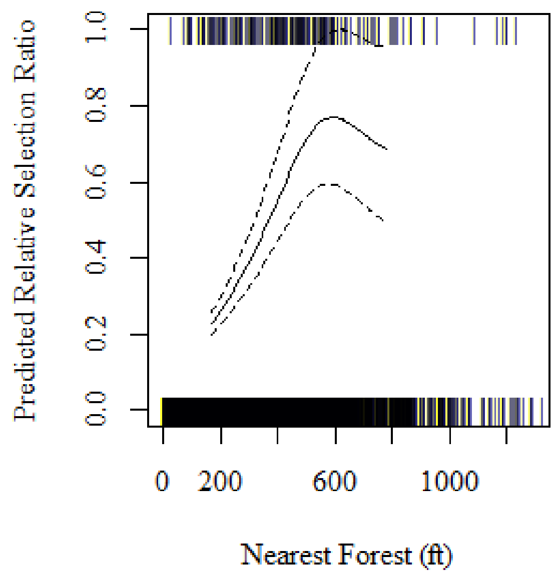

Figure 8. Predicted relative selection ratio for the top ranked RSF model evaluated with all systematic observations (n = 176), of nearest forest (NF). Tick marks indicate actual data (use points are presented at y=1 and available points are presented at y=0). Data is displayed from the 10^{th} to the 90^{th} percentile of use locations with 90% confidence intervals.

Discussion

The use of systematic aerial surveys to detect stopovers of whooping cranes over the course of 13 years provided 55 systematic unique locations and a total of 176 systematically collected stopover locations and allowed an evaluation of whooping crane use of riverine habitat throughout the AHR. Evaluations of riverine roost site habitat characteristics along the central Platte River have largely been focused on geomorphic and, more recently, hydrologic metrics including unobstructed channel width, distance to obstruction (e.g., nearest forest), wetted width, area of suitable depth, and flow (Biology Workgroup 1990; Farmer et al. 2005). Of these, wetted width and area of suitable depth are highly dependent on instantaneous flow and change continuously while, without intervention, other metrics generally change over longer periods of time (i.e., years). Given the relative stability of geomorphic features, we were able to obtain good estimates of UOCW, TCW, and NF remotely. However, the variability in hydrologic metrics such as area of suitable depth and wetted width required us to use hydraulic modeling to calculate the more stable and estimable metrics including unit discharge (UD) and discharge divided by total channel width (DIS).

Unit discharge (UD) is calculated as total discharge divided by the wetted width of the active channel. Selection for increasing UD would generally equate to an increase in wetted width and depth. We similarly evaluated discharge divided by total channel width (DIS), which related flow to total channel width. This covariate was included as total channel width can more readily be managed than the wetted width of the channel at a specific discharge. Given the Pearson correlation between these metrics ($r > 0.90$), including UD or DIS in our analysis was equivalent to testing both of these metrics at once.

Previous studies on the central Platte River assumed whooping cranes select roost locations based on flow-related habitat metrics similar to wetted width and proportion of the channel that is suitably shallow for roosting (Biology Workgroup 1990; Farmer et al. 2005). Our analysis did not identify a strong relationship between flow-related metrics and whooping crane use location. A model containing unit discharge was within 3 AIC units of the top model, but more parsimonious models had better explanatory ability and assumed the effect of unit discharge was negligible. Instead, we found the strongest relationship between metrics of channel openness (UOCW and NF) and roost location with crane groups generally selecting sites that were more "open" than narrowest channels that are present in the AHR. However, it should be noted that our analysis only addresses the influence of flow (on a given day) in roost location choice. It does not address the relationship between flow and a cranes' decision to use or not use riverine habitat. Such an analysis would need to include absence data which would require us to know flow conditions when whooping crane groups chose not to use the AHR. That data is not available.

The lack of a strong relationship between flow metrics and whooping crane selection of a specific roost location can be interpreted two ways: 1) flow is not important in whooping crane selection of roost locations, or 2) sufficient areas of suitable depth and wetted area were equally available and adequate at use and available locations on use days. Given water is almost always associated with whooping crane roost locations (Austin and Richert 2005), it is likely that sufficient areas of suitable depth and wetted area were available at use and available locations, reducing the importance of flow-habitat metrics in roost site selection. A crane group comprised of four to six adults will roost in an area that is generally less than 50 ft by 50 ft. Under most flow and channel configuration combination, there is much more suitably shallow water (<0.8 ft) roosting habitat than is required to accommodate the crane group sizes observed in the AHR.

Though increased UOCW and NF were important predictors of whooping crane group roost site selection, we were unable to establish a strong relationship between UFCW or TCW and whooping crane use. Though TCW and UFCW were included in models within 8 AIC units of the top model, our top model was more parsimonious and explained habitat selection as well as or better which indicates the effect of TCW and UFCW were negligible. Failure to find a strong relationship between TCW or UFCW and whooping crane use is likely related to the fact wider, unmanaged channels on the central Platte River are generally split by one or more densely vegetated or wooded islands which reduces their suitability as whooping crane roosting habitat.

Horizontal visibility has long been viewed as an important aspect for defining optimum and secure habitat for whooping crane roosts (Shenk and Armbruster 1986; Armbruster 1990; Farmer et al. 2005). Our results support that characterization as unobstructed channel width (UOCW) and distance to nearest forest (NF) were found to be important predictors of whooping crane group roost site selection. With regards to distance to nearest forest, we found whooping cranes were disproportionately using sites with distance to nearest forest between 500–550 ft. From a management perspective, our results indicate UOCWs ≥450 ft and unforested corridor widths ≥1,000 ft represent highly suitable habitat for roosting sites for whooping cranes along the central Platte River.

Characteristics of whooping crane roost habitat have been examined and described for the central Platte River in Nebraska (Johnson 1981; Lingle et al. 1984; Armbruster 1990; Faanes 1988; Faanes and Bowman 1992; Faanes et al. 1992). Several characteristics common to whooping crane riverine roost sites include shallow, wide, unvegetated channels and open visibility with the absence of tall trees or dense shrubs near the roost (Johnson and Temple 1980; U.S. Fish and Wildlife Service 1981; Johnson 1981; Armbruster 1990; Faanes et al. 1992; Austin and Richert 2001; National Research Council 2004). To date, however, roost characteristics and criteria have been developed based on a limited amount of quantitative information and most criteria have been derived from circumstantial roost locations that may not be representative of a typical stopover site (Armbruster 1990).

Shenk and Armbruster (1986) reported unobstructed channel widths 246 ft were unsuitable roosting habitat for whooping crane and roost habitat was optimized at unobstructed channel widths of 1,312 ft; however, these estimates were based on the opinion of participants of a workshop rather than an analysis of data. Similarly, the USFWS (1986) reports whooping roosting habitat is optimized at unobstructed channel widths ≥1,158 ft and channels with unobstructed widths <500 ft were deemed unsuitable roosting habitat; however, again these measures were not based on an analysis of data. Farmer et al. (2005) reported whooping cranes selected channels with wider unobstructed channel widths at both scales they evaluated. Our results corroborated their finding in that unobstructed channel width influenced stopover site selection by whooping cranes; however, we found the relationship was nonlinear and that habitat suitability was maximized when UOCW was ≥460 ft.

Johnson (1981) described optimal riverine roost habitat as being any channel with an unobstructed width ≥509 ft, which is similar to our findings. Austin and Richert (2001) found river widths at stopover roost locations distributed throughout the migration corridor ranged from 249 ft to 1,499 ft and averaged 764 ft. Though river widths reported by Austin and Richert (2001) are wider than unobstructed channel widths we observed within the AHR, discrepancies in these measures could simply be an artifact of biases in the observational data or how each metric was measured (i.e., river width may not be comparable to unobstructed channel width).

We used data collected systematically along the central Platte River during 2001-2013 to evaluate riverine habitat selection within the AHR. The goal of our analysis was to develop habitat models to be used to inform and direct management activities the Program is able to implement. We were unable to establish a relationship between whooping crane use and flow metrics or total channel width, but rather found unobstructed channel width and distance to the nearest forest were good predictors of whooping crane use. Our findings indicate the Program would have the potential to influence whooping crane use of the central Platte River through increasing unobstructed channel widths that are <450ft and mechanically removing trees within areas where the unforested corridor width is <1,000ft.

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Appendix I. Pearson correlation coefficients for whooping crane group in-channel riverine habitat selection in the central Platte River.

Habitat Metric	1	2	3	4	5	6
1- Unobstructed Channel Width	1.00	0.47	0.35	0.48	-0.11	-0.06
2- Unforested Channel Width		1.00	0.62	0.47	-0.16	-0.18
3- Total Channel Width			1.00	0.36	-0.24	-0.32
4- Nearest Forest				1.00	-0.12	-0.10
5- Unit Discharge					1.00	0.92
6- Discharge Divided by Total Channel Width						1.00

CHAPTER 3 – Whooping Crane Use of Riverine Stopover Sites within the North-central Great Plains, USA

Abstract

Although whooping cranes are known to use riverine roost sites throughout the migration corridor, few studies have attempted to evaluate habitat selection at riverine roost sites across multiple river systems. An important aspect of whooping crane roosts along their migration route is the amount of unobstructed visibility provided by stopover sites. Whooping cranes have been reported to select stopover locations based on the security offered by the site. One such form of security offered by riverine sites is the presence of water surrounding the roost. Another factor that is generally believed to enhance site security is wide open views not obstructed by dense, tall vegetation or wooded areas. The goal of our analysis was to develop habitat models that could be used to direct management activities along the central Platte River. As such, we focused our analysis on two metrics, unobstructed channel width (UOCW) and distance to nearest forest (NF), that the Platte River Recovery Implementation Program has the ability to influence. We used telemetry data obtained from a sample of 38 birds of all ages over the course of five years to provide an unbiased evaluation of whooping crane use of riverine habitat throughout the migration corridor. We evaluated the influence of UOCW and NF on whooping crane selection of riverine habitat throughout the North-central Great Plains in the United States. Our results indicate UOCW has the most influence on riverine habitat selection and the highest relative selection ratios occurred when UOCW was ≥668 ft; however, we found there is a fairly wide range of uncertainty in this estimate.

Introduction

Each year, the Aransas–Wood Buffalo (AWB) population of whooping cranes undertake a 5,000-mile round-trip migration from the breeding area in and near Wood Buffalo National Park in Northern Canada to the wintering area in and around Aransas National Wildlife Area on the gulf coast of Texas. The migration route is well defined and the vast majority of observations occur within a 200-mile wide corridor through Alberta, Saskatchewan, Montana, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas. During migration, whooping cranes utilize stopover sites to rest and build energy reserves to complete migration. Although a variety of habitats are used during migration, water is nearly always associated with a stopover site (Pearse et al. 2016). At stopover sites, whooping cranes typically roost standing in shallow water associated with palustrine or lacustrine wetlands and river channels.

Some stopover sites in the migration corridor are used consistently and receive relatively high annual use. One of these sites, the Big Bend reach of the central Platte River in Nebraska, is the only stretch of river designated as critical whooping crane habitat under the Endangered Species Act (Armbruster 1990; Biology Workgroup 1990). Characteristics of central Platte River roost habitat have been examined and described in detail (Johnson 1981; Lingle et al. 1984; Ziewitz 1987; Faanes 1988; Faanes and Bowman 1992; Faanes et al. 1992). Early examinations of roost sites in the central Platte River identified wide, unvegetated channels and open visibility with the absence of tall trees or dense shrubs near the roost as important habitat characteristics (Johnson and Temple 1980; U.S. Fish and Wildlife Service 1981; Johnson 1981; Ziewitz 1987; Armbruster 1990; Faanes et al. 1992; Austin and Richert 2001; National Research Council 2004). Recent Program analyses of central Platte River whooping crane use locations during the period of 2001-

2013 found the width of channel unobstructed by dense vegetation and the distance to nearest forest to be the best predictors of whooping crane use (Chapter 2). Ziewitz (1987) described whooping crane roosting habitat suitability using several parameters including unobstructed channel width. In this assessment, unobstructed channels ≤500 ft wide were assigned a minimum suitability value while unobstructed channel widths ≥1,150 ft were assigned a maximum suitability value. Table 1 of the Program's land plan infers whooping crane habitat suitability and use are maximized at 1,150 ft (PRRIP 2006). Contrary to Ziewitz (1987) and Table 1 of the Program's Land Plan (PRRIP 2006), Austin and Richert (2005) reported unobstructed channel widths at riverine roost sites averaged 764 ft and Johnson (1981) described optimal riverine roost habitat as being any channel with an unobstructed width ≥509 ft. Pitts (1985) even went so far as to report whooping crane selection of stopover habitat occurs at random.

Although whooping cranes are known to use riverine roost sites throughout the migration corridor, few studies have attempted to evaluate selection of riverine roost sites across multiple river systems (Stahlecker 1997; Austin and Richert 2005). The objective of this investigation is to assess if and how unobstructed channel width and distance to nearest forest influence whooping crane selection of riverine habitat throughout the North-central Great Plains in the United States. Results of this investigation provide a line of evidence regarding the importance of these habitat metrics in whooping crane roost site selection as well as an opportunity to compare habitat use along the central Platte River to riverine use throughout the migration corridor.

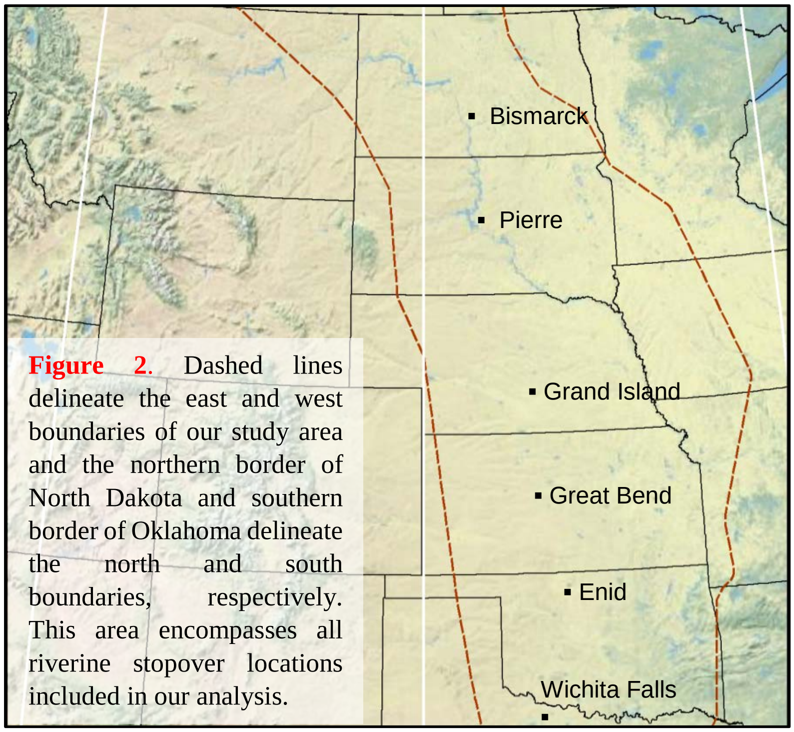

Figure 2. Dashed lines delineate the east and west boundaries of our study area and the northern border of North Dakota and southern border of Oklahoma delineate the north and south boundaries, respectively. This area encompasses all riverine stopover locations included in our analysis.

Methods

Our study area included the migration corridor for the Aransas-Wood Buffalo population within North Dakota, South Dakota, Nebraska, Kansas, and Oklahoma (Figure 2; Pearse et al. 2015). Locational data (henceforth, telemetry data) generated from 68 GPS-marked whooping cranes (2010-2014) was filtered to only include stopover (use) locations that occurred in riverine habitat (wetted channels) within the study area. The data was further filtered to only include a single location recorded during the first night of the stopover per whooping crane per stopover site (i.e., multi-day stopovers were only included in the analysis once). When >1 radio-marked whooping crane was present at a stopover at the same time, we included a use location for each bird present at the stopover site. We defined stopover sites as sites used as a roost for ≥1 night.

Defining the Choice Set

Habitat metrics were calculated for each whooping crane use location and at the 20 corresponding randomly selected in-channel available points within 10 miles upstream and downstream of the use location. It was assumed the cranes could reasonably evaluate this area based on an aerial evaluation of viewsheds from 3,000 ft above ground level by Program personnel, which was a reported elevation for long distance flights by telemetry-marked whooping cranes in the 1980s (Kuyt 1992) as well as a commonly observed migration elevation during an ongoing telemetry study (unpublished data). Hawth's Tools (Jenness 2011) was used to generate the 20 available locations per stopover location within each river segment. The points were stratified so each stopover location was paired with 20 available locations in the same river segment as the stopover location.

Parameterization of the A priori Model set

A GIS and USDA-NRCS Geospatial Imagery Data was used to delineate the unobstructed width of the channel along a line running perpendicular to the channel and through each stopover and available location. Unobstructed channel width (UOCW) was defined as the width of channel lacking dense vegetation as observed in USDA-NRCS Geospatial Imagery Data collected closest to the season use occurred. When channels were segmented by a densely-vegetated island, UOCW was delineated based on the channel segment nearest the stopover or available location. Distance to nearest forest (NF) was defined as the distance from the use or available location to the nearest forested area. Distance to nearest forest was truncated at 1,320 ft (1/4 mile) when no forested area was located within a quarter mile of the use or available location.

A list of 3 candidate models was developed, each containing a different combination of habitat metrics. This set of models, with the inclusion of a null model containing no habitat metrics, composed the complete set of *a priori* models evaluated (Table 1). The model selection process determined which *a priori* model was most parsimonious and useful in predicting habitat use with the Akaike Information Criterion statistic (AIC, Burnham and Anderson 2002). The most parsimonious *a priori* model with a ΔAIC <2.0 was considered the best model to infer conclusions about habitat selection (Burnham and Anderson 2002).

Mirrored histograms were prepared for each predictor to graphically display the data (Figures 4 and 5). These figures show the distribution of the values for each habitat metric in order to contrast this distribution for the stopover sites to the available sites. For each probability histogram, the area of the bars sums to one. Although these figures display the relationship between the predictor variables and the outcome (use by whooping cranes), they simplify the assessment by combining data across the many choice sets.

Statistical Modeling of Habitat Use/Selection

Methods and procedures used to model habitat selection throughout the North-central Great Plains were identical to those presented in Chapter 2.

Results

The use of telemetry data obtained from a sample of 38 birds of all ages over the course of five years provided 150 independent stopover locations. Measurements at these 150, riverine stopover (‘use’) locations and 3,000 available locations were obtained and incorporated into the habitat selection analysis. Though variable, mean UOCW and NF were wider at stopover locations than available locations for each metric (Table 3). Median UOCW was 548 ft at stopover and 462 ft at available locations. Median NF was 244 ft at stopover and 200 ft at available locations.

Table 1. *A priori* model set tested in the use-availability habitat selection analysis.

Covariate	Definition of Model Terms
Null	No covariates (habitat selection is random)
UOCW	Unobstructed channel width
NF	Distance to nearest forest maximized at 1,320 ft
UOCW+NF	Unobstructed channel width plus minimum distance to nearest forest maximized at 1,320 ft

Table 2. Models used in our habitat selection analysis ranked by AIC statistic. See Table 1 for a description of the metrics.

Rank	Covariates	AIC	ΔAIC
1	s(UOCW)	2685.3	0.0
2	s(UOCW) + s(NF)	2685.4	0.1
3	s(NF)	2704.8	19.5
4	NULL	2714.5	29.3

Table 3. Mean unobstructed channel widths (UOCW) and distance to nearest forest (NF) for all stopover and available locations. Standard deviations are provided in parentheses. See Table 1 for a description of metrics.

Metric	Mean Width (ft) at Stopover Locations (SD)	Mean Width (ft) at Available Locations (SD)
UOCW	663 (543)	639 (689)
NF	297 (222)	290 (339)

Statistical modeling of habitat selection indicated UOCW was an important predictor of whooping crane riverine habitat selection (Table 2). Predicted relative selection ratios increased with UOCW and was maximized at 668 ft (Figure 6); however, there is uncertainty in the point estimate and relative selection ratios were statistically similar for UOCW's ranging from 402 to 1,211 ft (Figure 6). Predicted relative selection ratios also increased with NF and was maximized at 492 ft when UOCW was maximized at 647 ft; however, NF was not included in the top, and more parsimonious model, and relative selection ratios were statistically similar for a wide range of values for NF (Figure 7).

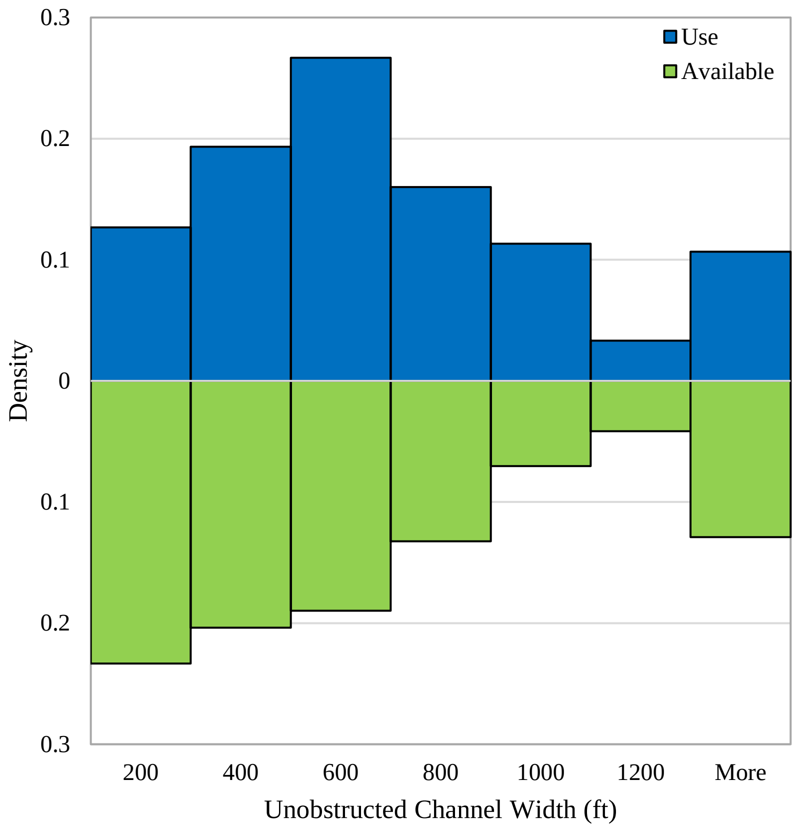

Figure 4. Mirrored histogram to graphically display the distribution of values for unobstructed channel width (UOCW) in order to contrast measurements collected at stopover (blue bars) and available (green bars) locations. The area of the bars for stopover and available locations each sum to one.

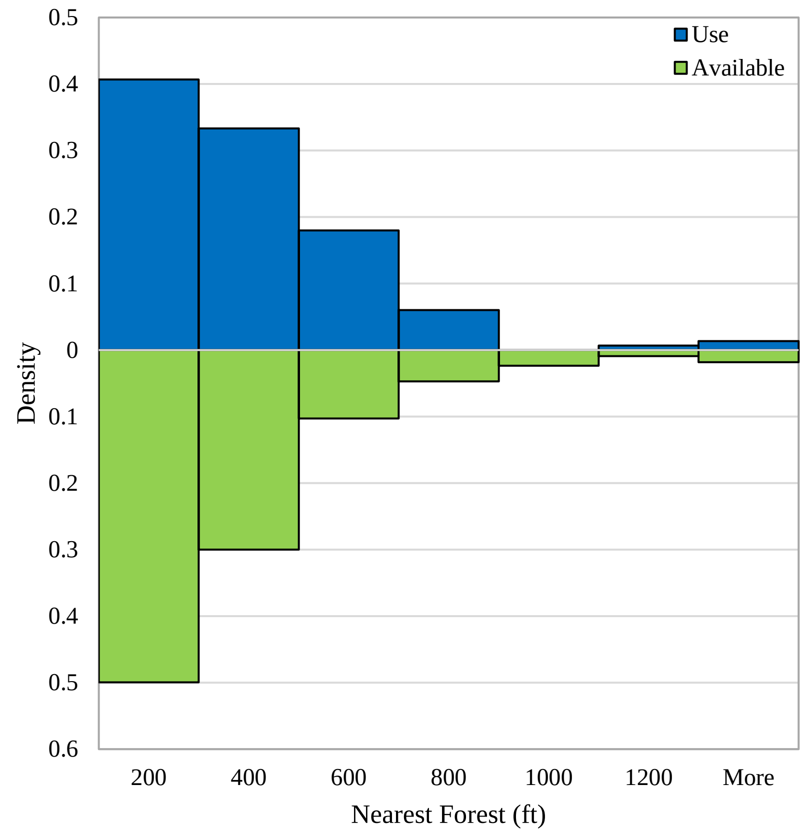

Figure 5. Mirrored histogram to graphically display the distribution of values for distance to nearest forest (NF) in order to contrast measurements collected at stopover (blue bars) and available (green bars) locations. The area of the bars for stopover and available locations each sum to one.

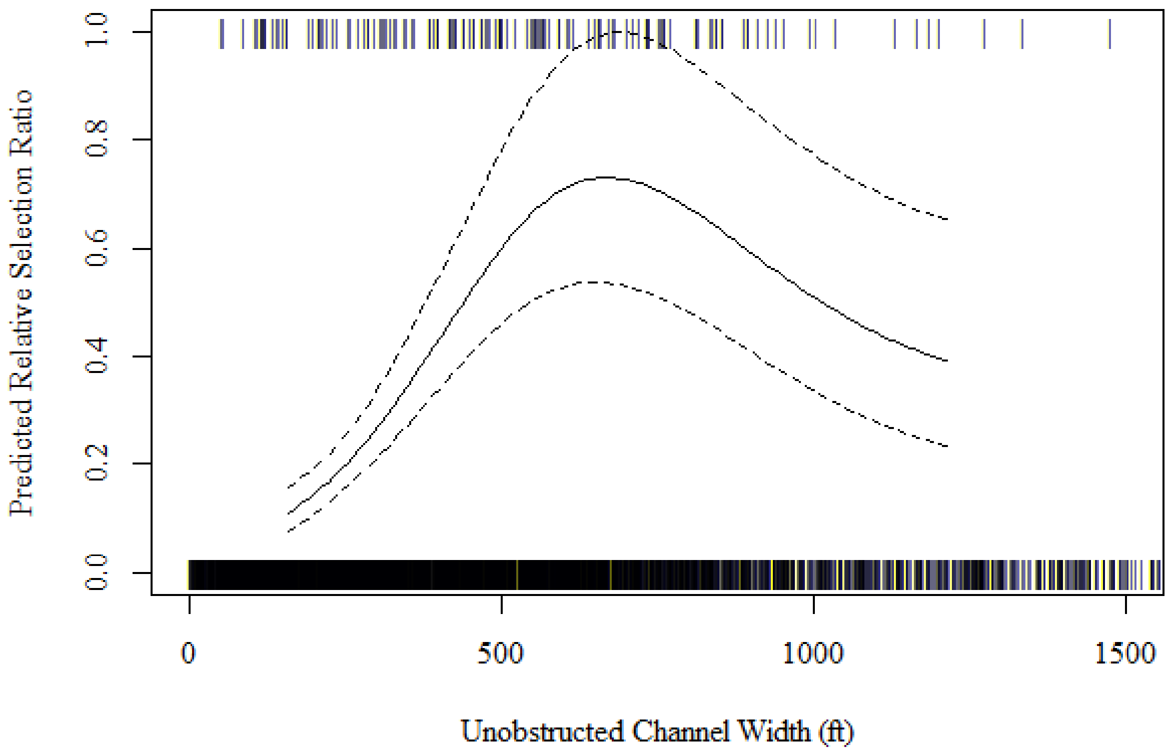

Figure 6. Predicted relative selection ratio, with 90% confidence intervals, across the range of unobstructed channel widths (UOCW). The response function was scaled to the largest predicted value was 1 and is only displayed between the 10th and 90th percentile of the stopover locations in order to limit the influence of values from the ***extreme*** ends of the distribution on the interpretation of the results. The selection ratio is maximized when unobstructed channel width is ≥668ft. Tick marks display actual data (use locations are plotted at y=1 available locations are plotted at y=0).

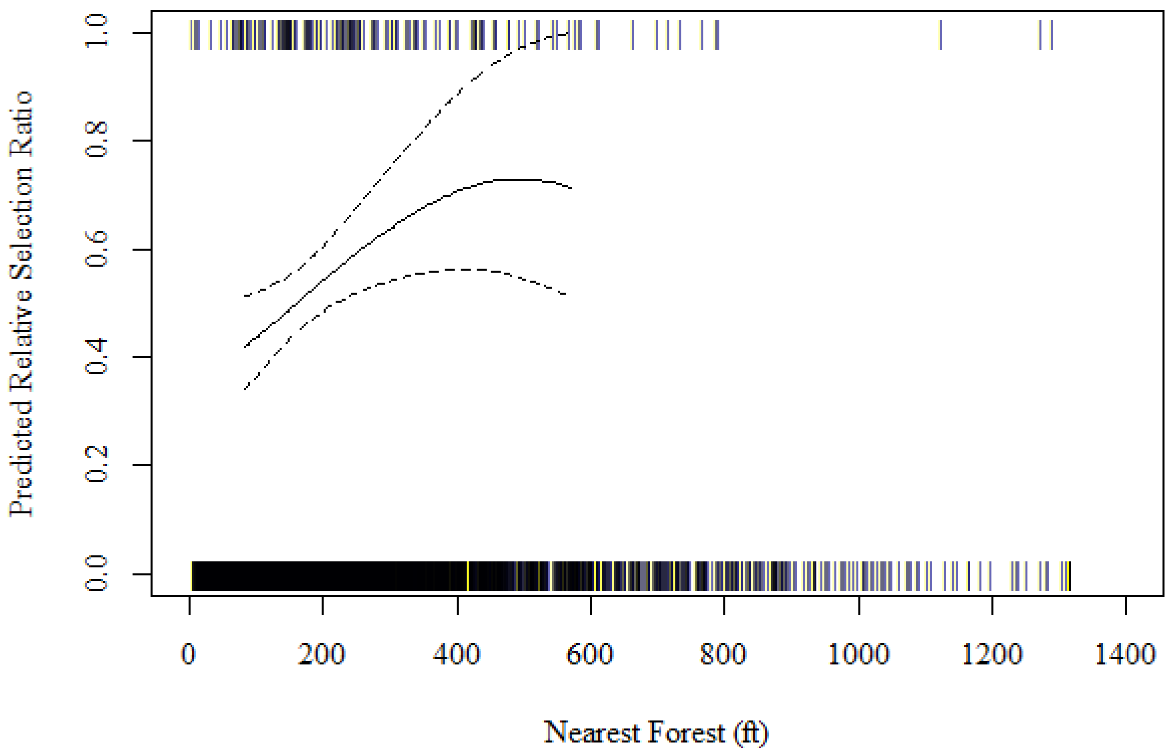

Figure 7. Predicted relative selection ratios with 90% confidence intervals from the second-ranked, and less parsimonious model, across the range of distances to nearest forest. The response function was scaled so the largest predicted value was 1 and is only displayed between the 10th and 90th percentile of the stopover locations in order to limit the influence of values from the ***extreme*** ends of the distribution on the interpretation of the results. The selection ratio is maximized when NF is ≥492ft and unobstructed channel width is ≥647ft. Tick marks indicate actual data (use locations are at y=1, available locations are at y=0).

Discussion

Several studies have characterized habitat use by whooping cranes using the U.S. Fish and Wildlife Service's opportunistic sightings database (Austin and Richert 2005; Faanes et al. 1992; Belaire et al. 2013; Hefley et al. 2015). These characterizations, however, are influenced by sampling bias, detection bias, and location error (Hefley et al. 2015). The use of telemetry data obtained from a sample of 38 birds of all ages over the course of five years provided 150 independent stopover locations and allowed access to a substantial set of unbiased data to evaluate whooping crane use of riverine habitat throughout the migration corridor.

An important aspect of the ecology of whooping cranes using roosts along their migration route is the amount of unobstructed visibility provided by stopover sites. Whooping cranes select stopover locations based on the security offered by the site (Ward and Anderson 1987). One such form of security offered by riverine sites is the presence of water surrounding the roost. Water provides a sense of security and enables whooping cranes to hear potential predators as they approach (Ward and Anderson 1987). While we did not examine presence of water at each use site, we assumed surface water was available during stopovers within riverine habitats. Another factor generally believed to enhance site security is wide open views not obstructed by dense, tall vegetation or wooded areas. Riverine habitat provides this security with the presence of wide unobstructed widths.

Whooping crane riverine roost sites and day-use sites tend to consistently lack tall vegetation in close proximity to the site (Austin and Richert 2005). Johnson and Temple (1980) reported that throughout the whooping crane's range, unobstructed bank to bank visibility at riverine roost sites was at least 656 ft. Lingle et al. (1984) reported that a Platte River roost site near Prosser, Nebraska, had an unobstructed bank to bank distance of 1,145 ft. Estimates derived by a Biology Ad Hoc Workgroup suggested habitat selection was optimized at unobstructed channel widths of 1,312 ft (Shenk and Armbruster 1986). Subsequent analyses of unobstructed channel width at whooping crane roosts through the spring 1987 migration period ranged from 699 ft to 1,207 ft (U.S. Fish & Wildlife Service, unpublished data). Although we did observe stopovers occurring in unobstructed channels of these widths, >50% of stopovers along the migration route were in channels with unobstructed widths that were <548 ft. Lingle et al. (1986) suggested whooping cranes choose the widest available sites. However, our results indicate whooping cranes use channels with moderately wide unobstructed channel widths at least as much as channels with very wide unobstructed channel widths, suggesting moderate unobstructed channel widths have a similar habitat value as very wide unobstructed channel widths.

Whooping crane stopover locations were located in channels with unobstructed widths ranging from 53 to 3,191 ft and averaged 663 ft (median = 548 ft). Johnson and Temple (1980) proposed a minimum suitability criterion for channel width of 180 ft. The narrowest observed unobstructed channel width at stopover locations within the migration corridor was 53 ft, which is much narrower than their recommendation. Similarly, Austin and Richert (2005) found river widths at stopover roost locations ranged from 249 ft to 1,499 ft and averaged 764 ft. Our telemetry data results are similar to the 712-foot mean unobstructed channel width observed at roost sites on the Platte River (Faanes et al. 1992) and corroborate findings of Johnson (1982) in that >60% of stopover locations were in channels with an unobstructed width >451 ft. However, results of our resource selection analysis suggest unobstructed channel widths as low as 400 ft statistically can be as favorable to whooping cranes as well.

Whooping cranes roosting in the Platte River have been noted to select sites with broad channels free of woody vegetation and with adequate horizontal and overhead visibility (U.S. Fish and Wildlife Service 1981). However, it has also been reported that banks and vegetation that form a visual obstruction may actually enhance their security, as long as they are not too close to the cranes (Faanes et al. 1992). Austin and Richert (2005) reported >70% of roost sites were adjacent to woodland habitat. To some degree the results of this study support both of these positions. For use locations, the median distance to nearest forest was 244 ft (range = 7 ft –1,292 ft), but we were not able to establish a strong relationship between whooping crane habitat selection and increased distance to nearest forest.

Relative selection ratios of whooping crane use along the central Platte River for systematic, unique observations of whooping cranes was highest in channels with unobstructed channel widths ≥450 ft and distances to nearest forest from the center of the channel ≥500 ft, but substantial uncertainty surrounds those estimates (Chapter 2). When considering whooping crane use of riverine habitat between the borders of Canada and Texas, relative selection ratios were statistically similar for unobstructed channel widths and distance to nearest forest as they were for the central Platte River; however, distance to nearest forest was not included in the most parsimonious, top-ranked model in this chapter and thus was not considered to have a substantial influence on selection. Both analyses had high amounts of uncertainty associated with modeling habitat use, leading to somewhat indistinguishable habitat use differences from intermediate to high values for each habitat metric. Accounting for uncertainties and use location information, it appears whooping cranes select channels that are moderately wide, but not necessarily the widest stretch of river available. Given results of analyses described in Chapters 2 and 3, it appears maintaining unobstructed channel widths of ≥600 ft and unforested corridor widths of ≥1,000 ft would result in highly favorable whooping crane riverine roosting habitat.

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CHAPTER 4 – Central Platte River Unvegetated Width Relations to Hydrology, Channel Morphology and Management Actions: Implications for a Water-centric Management Strategy

Abstract

The Flow-Sediment-Mechanical (FSM) approach is one of two management strategies presented in the Platte River Recovery Implementation Program's (Program) Adaptive Management Plan (AMP) to create and maintain suitable riverine habitat for whooping cranes. The Program's FSM management strategy consists of sediment augmentation, mechanical vegetation clearing and channel widening, and short duration high flow (SDHF) releases of 5,000 – 8,000 cfs for three days in two out of three years to increase the unvegetated width of the main channel and, by extension, 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 FSM management strategy. A strong positive relationship was identified between peak flows and TUCW and MUOCW in the AHR. However, peak discharge magnitude and durations that create highly favorable whooping crane roosting habitat are much greater than SDHF releases, as currently envisioned. Our analysis also indicates channel disking in combination with herbicide application would be effective in creating and maintaining highly favorable MUOCWs for whooping cranes in all but the very driest years.

Introduction

The Platte River Recovery Implementation Program's (Program or PRRIP) whooping crane management objective is to contribute to improved whooping crane survival during migration. The primary management sub-objective is to increase the availability of whooping crane migration habitat along the Associated Habitat Reach (AHR) of the central Platte River that extends approximately 90 miles from Lexington, NE downstream to Chapman, NE. Performance indicators include area of suitable roosting habitat, area of suitable foraging habitat, proportion of the population using the AHR during each migration season, and the number of days cranes use the AHR (crane use days) during each migration season (PRRIP 2006).

Whooping Crane Habitat Suitability and Use

The Program's whooping crane management objectives and indicators focus on habitat and use metrics (as opposed to population) due to the small proportion of the whooping crane population that uses the AHR in any given year and the limited amount of time individual birds spend in the area (~two to three days on average). Generally, 5–10% (range 0.9–7.4%) are detected during the Program's monitoring seasons annually; however, since 2011, an average of 16.7% of the population has been detected systematically or opportunistically within a 1-year timespan, with ~20% detected in the spring of 2017 alone (FWS 2017). Investigations of whooping habitat use along the central Platte River have been ongoing since the late 1970s and have focused on a range of hydrologic and geomorphic metrics including unobstructed channel widths, distance to obstruction (i.e., nearest forest), view widths, flow, wetted width, suitable depth, etc. (Johnson and Temple 1980; U.S. Fish and Wildlife Service 1981; Johnson 1981; Armbruster 1990; Biology Workgroup 1990; Faanes et al. 1992; Austin and Richert 2001; National Research Council 2004; Canadian Wildlife Service and U.S. Fish and Wildlife Service 2005, Farmer et al. 2005).

In 2015, Program monitoring and satellite telemetry data were used to perform whooping crane habitat selection analyses in the AHR (Chapter 2) and at riverine stopover sites throughout the migration corridor (Chapter 3). Those investigations, which included a variety of hydrologic and geomorphic habitat metrics, suggest riverine habitat use by whooping cranes increases with increasing width of channel unobstructed by dense vegetation (UOCW) and increasing distance to forest. Systematic AHR monitoring indicates the probability of whooping crane habitat selection of the central Platte River is greatest when UOCW exceeds approximately 450 ft and unforested corridor width exceeds 1,000 ft (Chapter 2). Migration corridor-wide telemetry data indicates the habitat selection of riverine habitat is greatest when UOCW exceeds approximately 650 ft and unforested corridor width exceeds 1,000 ft (Chapter 3).

It is important to note that many definitions for channel width have been used in past reports. For example, channel width has been defined as the width of channel from outer bank to outer bank (Faanes et al. 1992; Shenk and Armbruster 1986), water edge to water edge (Shenk and Armbruster 1986), unforested channel width (USFWS 1987; Ziewitz 1992), unobstructed channel width in 4 cardinal directions (Faanes 1992), unobstructed width of channel (Lingle et al. 1984 and 1986; Shenk and Armbruster 1986; Biology Workgroup 1990; Johnson and Temple 1980), and generically as river width (Austin and Richert 2005). The Program habitat selection analysis in Chapter 2 included metrics that described total bank-to-bank width, wetted width, width of channel unobstructed by dense vegetation (UOCW), and unforested width of the channel. However, only UOCW and distance to nearest forest (NF) were found to be important predictors of whooping crane use.

Program Management Actions to Improve Whooping Crane Habitat Suitability

The Flow-Sediment-Mechanical (FSM) approach is one of two management strategies presented in the Program's Adaptive Management Plan (AMP) to create and maintain suitable riverine habitat for whooping cranes. Proposed actions include: (1) vegetation clearing and channel widening (Mechanical), (2) partially offsetting the average annual sediment deficit of approximately 150,000 tons in the west half of the AHR through augmentation of sand (Sediment), and (3) implementation of short-duration high flows (SDHF) of 5,000 – 8,000 cfs for three days (Flow) in two out of three years to scour vegetation and maintain wide unobstructed channels.

These management actions are hypothesized to be sufficient to increase the unvegetated width of the main channel (Figure 1) and, by extension, increase channel suitability for whooping crane use. The mechanical component of the FSM management strategy has been employed in the AHR by various conservation organizations since the 1980s. Sand augmentation (sediment component) has been ongoing at varying levels since 2006. Implementation of SDHF releases has been limited by flow conveyance issues upstream of the AHR, but natural high flow events during the period of 2007–2014 have provided natural peak flows in excess of what the Program could produce at full FSM implementation. Each component of the FSM is discussed in greater detail in the following sections.

Mechanical

Overall, various organizations perform conservation on more than 30,000 acres for various species within the AHR, which encompasses all or a portion of approximately 47% of the channel within the ninety-mile reach. These organizations have been clearing in-channel vegetation and widening channels since the 1980s in an effort to increase channel width and prevent woody vegetation from establishing in the channel. Since Program inception in 2007, mechanical in-channel vegetation control efforts have included disking to clear islands and bank line disking and other mechanical actions to widen channels. These actions have been implemented by the USFWS Partners for Fish and Wildlife, The Crane Trust, The Nature Conservancy, Audubon Society, Nebraska Public Power District (NPPD), Central Nebraska Public Power and Irrigation District

(CNPPID), and the Program. Mechanical channel maintenance activities are ongoing in nine out of 12 bridge segments in the AHR (Table 1).

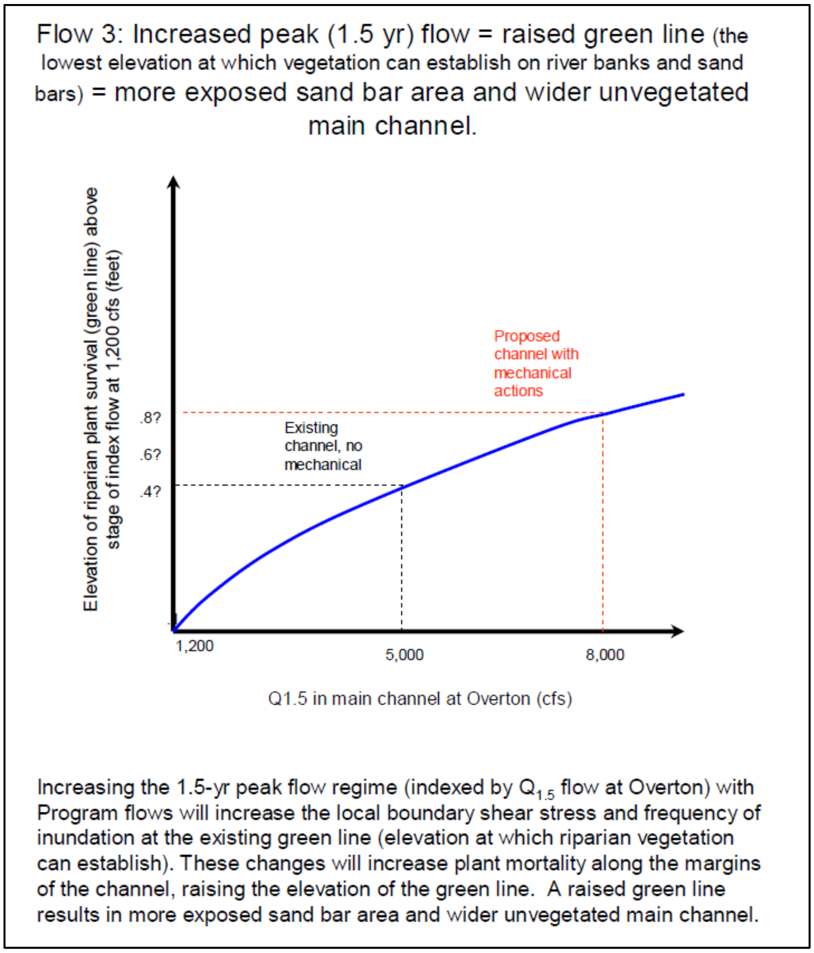

Figure 1. Program priority hypothesis Flow 3 which hypothesizes flows of 5,000 to 8,000 cfs (X-axis) will increase the green line (i.e., elevation at which riparian vegetation can establish; Y-axis) resulting in an increase the unvegetated width of the main channel.

Though not originally included in the FSM management strategy, reach-wide herbicide application has also become an important tool to eradicate and/or control the spread of common reed (*Phragmites australis)* during the period of 2008–2014. The spraying program has included aerial and ground application of herbicide to all common reed infestations detected in the channel

(Craig 2011). In excess of 15,000 acres have been sprayed in the AHR since the initiation of control efforts.

Table 1. Mechanical management actions undertaken by various entities since Program inception in 2007.

Bridge Segment	Length Managed (mi)	Mechanical Management Actions
Lexington to Overton	9.0	Vegetation removal from banks and islands, channel disking
Overton to Elm Creek	4.0	Vegetation removal from banks and islands, island leveling, channel widening, channel disking
Elm Creek to Odessa	4.0	Vegetation removal from banks and islands, island leveling, channel disking
Odessa to Kearney	0.0	
Kearney to Minden	4.7	Vegetation removal from banks and islands, channel disking
Minden to Gibbon	5.5	Vegetation removal from banks and islands, island leveling, channel disking
Gibbon to Shelton	1.7	Vegetation removal from banks and islands, channel disking
Shelton to Wood River	2.5	Vegetation removal from banks and islands, channel disking
Wood River to Alda	4.0	Vegetation removal from islands, island leveling, channel disking
Alda to Hwy 281	6.5	Vegetation removal from banks and islands, channel disking
Hwy 281 to Hwy 34	0.0	
Hwy 34 to Chapman	0.0	
TOTAL	41.9	

Sediment

The sediment component of the FSM strategy involves mechanical sand augmentation at the upstream end of the AHR to offset a sediment deficit from clear water hydropower returns at the J-2 return facility near Lexington, NE (Figure 2). The average annual sediment deficit is greatest in the south channel of the river immediately downstream of the J-2 Return. The deficit decreases in the downstream direction. There are no major tributary inputs of sediment in the AHR. Accordingly, the deficit is made up primarily through erosion of channel bed and bank materials in the south channel downstream of the return (Holburn et al. 2006; Murphy et al. 2006; HDR Engineering Inc. 2011).

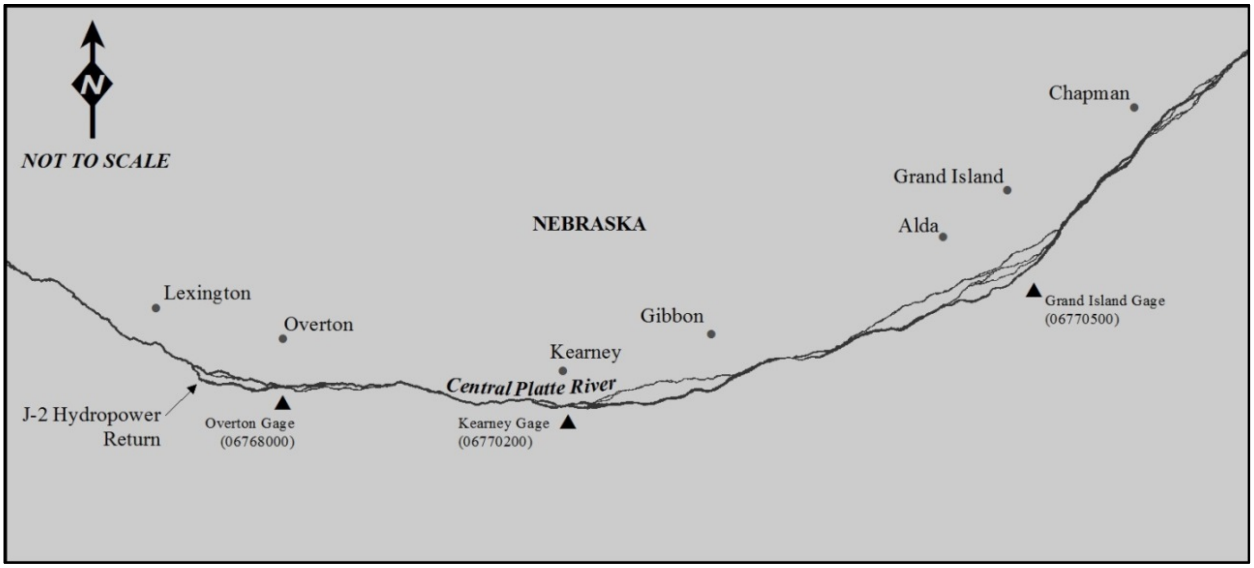

Figure 2. Associated Habitat Reach of the central Platte River extending from Lexington downstream to Chapman, NE. Locations of stream gages used in the analyses are included as well.

Sediment augmentation efforts began in 2006 as part of channel widening activities by NPPD at the Cottonwood Ranch property in the Overton to Elm Creek bridge segment. The Program has since expanded those efforts to include the addition of a second augmentation site upstream of the Overton Bridge (Table 2).

Table 2. Total annual discharge, sediment load, and sediment augmentation by water year. Sediment loads from Program system-scale geomorphology monitoring.

Water Year*	Total Annual Discharge at Overton (Acre-ft)	Sediment Augmented (tons)	Total Sediment Load at Overton (tons)	Total Sediment Load at Kearney (tons)	Total Sediment Load at Shelton (tons)	Total Sediment Load at Grand Island (tons)
2006	272,032	15,570	--	--	--	--
2007	569,912	21,875	--	--	--	--
2008	525,025	42,500	--	--	--	--
2009	585,994	50,000	200,000	207,300	214,900	281,500
2010	1,377,665	50,000	613,000	730,000	719,000	877,000
2011	2,691,194	50,000	1,424,000	1,728,000	1,467,000	2,011,000
2012	1,247,736	0	567,000	641,000	495,000	713,000
2013	638,733	182,000	255,200	268,700	165,700	209,700

* 2014 and 2015 data not available

The Program began conducting annual system-scale geomorphology and vegetation monitoring in 2009. Analysis of transect survey and sediment transport measurement data for the period of 2009–2013 strongly indicates the portion of the reach upstream from Kearney was degradational during that period, with an average annual sand deficit in the range of 100,000 tons (Tetra Tech Inc. 2014). Tetra Tech Inc. (2014) considered both survey and model results and concluded the portion of the reach downstream from Kearney was most likely aggradational. However, given potentially contradictory lines of evidence, Tetra Tech Inc. (2014) indicated this conclusion was only weakly supported by the data.

Flow

The primary physical process driver of the FSM management strategy is the implementation of short-duration high flows (SDHF) of 5,000 – 8,000 cfs for three days on a near annual basis. Implementation of SDHF is intended to increase the magnitude of peak flows (indexed by the $Q_{1.5}$ flow; the peak flow exceeded in two out of three years) from approximately 4,000 cfs to 5,000 – 8,000 cfs. Total release volumes on the order of 50,000 – 75,000 acre-ft are necessary to achieve full SDHF magnitude and duration due to reservoir release ramping constraints and flow attenuation.

Persistent channel conveyance constraints upstream of the AHR limit the Program's ability to generate flow release magnitudes in the 5,000 – 8,000 cfs range. As such, the Program has not had the ability to fully implement an SDHF magnitude release through the AHR. However, the easing of basin drought and subsequent river discharge recovery coincident with Program implementation since 2007 provided natural high flows of similar magnitude and greater duration than contemplated in the AMP. During the first nine years of Program implementation (2007–2015), mean annual discharge more than doubled, and the three-day mean annual peak discharge at Grand Island exceeded 5,000 cfs in seven out of nine years and 8,000 cfs in five out of nine years (Table 3; Figure 3). Overall, the shift in basin hydrology resulted in a nine-year period (2007–2015) with peak flow frequency, magnitude, and duration that substantially exceeded what could have been achieved under full FSM implementation during 2000–2006.

Table 3. 2007–2015 median discharge during the growing season (cfs) and annual peak flow event magnitudes (cfs), durations and volumes (acre-ft) at Grand Island (USGS Gage 06770500) in relation to the Short-Duration High Flow management action performance criteria.

Year	Median Discharge during Growing Season (cfs)	Average Daily Peak Discharge (cfs)	3-Day Mean Peak Discharge (cfs)	Days >5,000 cfs	Days >8,000 cfs	Total Event Volume (acre-feet)*
SDHF	NA	NA	5,000 – 8,000	3	0	50,000 – 75,000
2007	1,045	5,312	5,543	3	0	84,813
2008	903	12,472	10,900	13	5	253,012
2009	479	3,379	3,180	0	0	24,258
2010	2,243	8,498	8,540	17	6	535,319
2011	5,468	9,474	9,883	81	16	3,287,603
2012	238	3,300	3,183	0	0	332,310
2013	218	11,313	9,167	9	6	245,871
2014	943	7,342	7,263	6	0	181,269
2015	3,030	16,100	15,666	50	42	1,245,818

*Cumulative flow volume for consecutive days of discharge greater than 2,000 cfs.

Analysis Objectives

Overall, the scale of flow, sediment, and mechanical management actions and natural analogs during 2007–2015 have been sufficient to allow the Program to effectively explore vegetation response. The whooping crane resource selection analyses indicate the width of channel unobstructed by dense vegetation (UOCW) is an important predictor of whooping crane use. Accordingly, the maximum UOCW (MUOCW) at any given location within AHR channel is an important vegetation metric representing whooping crane habitat suitability. Another potentially important vegetation response metric is the total unvegetated width of the channel (TUCW). This is because the relationship between vegetation and physical processes and Program management actions will likely be more easily identified when evaluating all unvegetated segments across all channels as it eliminates the randomness associated with the spatial distribution of vegetated islands within the channel.

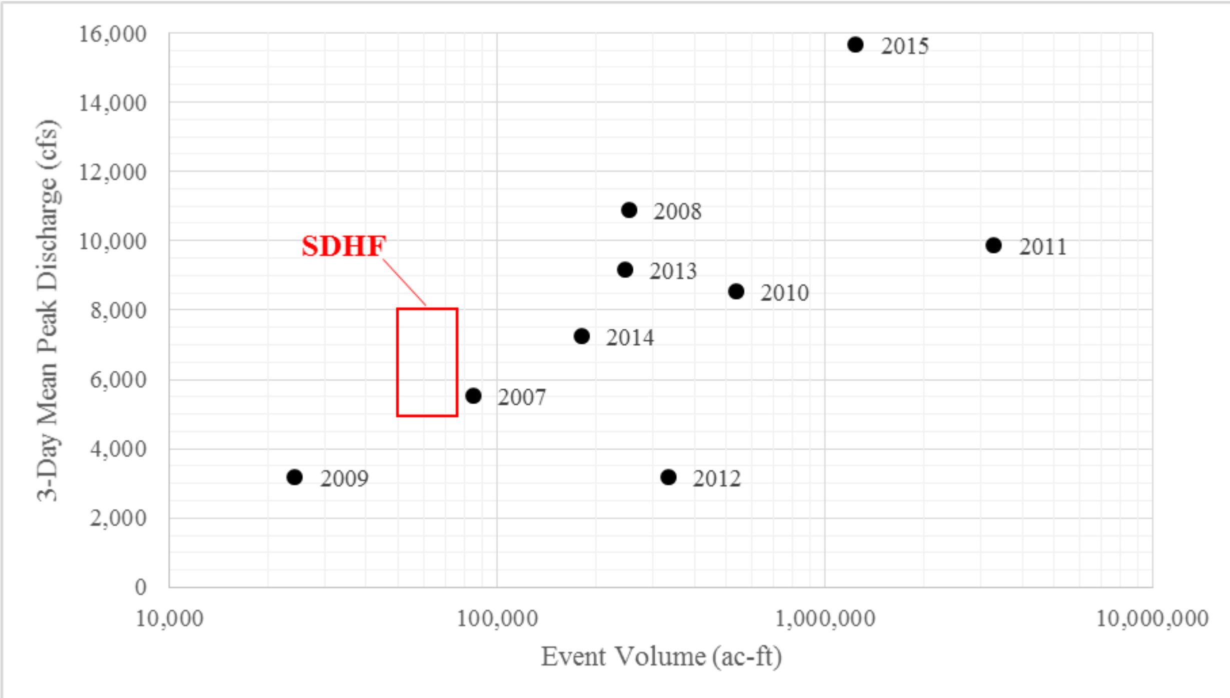

Figure 3. 2007–2015 three-day mean peak discharge (cfs) and event volume (acre-ft) at Grand Island (USGS Gage 06770500) in relation to the range of Short-Duration High Flow magnitudes and volumes. Event volumes are cumulative volumes from concurrent days during annual peak flow events when discharge exceeded 2,000 cfs.

Accordingly, the objectives of this analysis include 1) quantification of annual AHR TUCW and MUOCW through the First Increment of the Program (2007–2019), 2) evaluation of the relationship between TUCW and MUOCW in the AHR, 3) identification and quantification of management actions, hydrologic (flow) conditions, and physical conditions that influence annual TUCW and MUOCW in the AHR, and 4) application of analysis results to predict the ability of the FSM management strategy to create and maintain UOCWs that are highly suitable for whooping crane use.

Methods

Study Area

The AHR is a ninety-mile reach extending from Lexington, NE downstream to Chapman, NE and encompasses the Platte River channel and off-channel habitats within three and one half miles of the river (Figure 1). The study reach for this analysis focuses solely on the 84 miles of channel extending downstream from the Overton bridge to Chapman. The short reach between Lexington, NE and the Overton, NE was excluded due to the presence of the J-2 hydropower return. Natural river flows are largely confined to the north channel, and hydropower return flows are confined to the south channel in this reach, making it difficult to interpret relationships between hydrology and physical process relationships in this portion of the AHR.

Measurement of Total Unvegetated Width and Maximum Unobstructed Channel Width

We used summer or fall aerial imagery collected annually during periods of low flow to photo-interpret TUCW and MUOCW throughout the AHR during the period of 2007–2015. Unvegetated width metrics were delineated at a scale of 1” = 200’ along 436 pre-defined transects using ESRI ArcMAP Geographic Information System (GIS) software. Photo-interpretation of unvegetated width metrics was determined to provide acceptable measurement accuracy based on previous comparisons of field-measured and photo-interpreted unvegetated width measurements in the AHR (Werbylo et al. 2016). Transects were oriented perpendicular to flow and spaced at 1,000 ft intervals along the channel throughout the study area and encompassed all channels in split flow reaches. Figure 4 provides examples of TUCW and MUOCW width delineations.

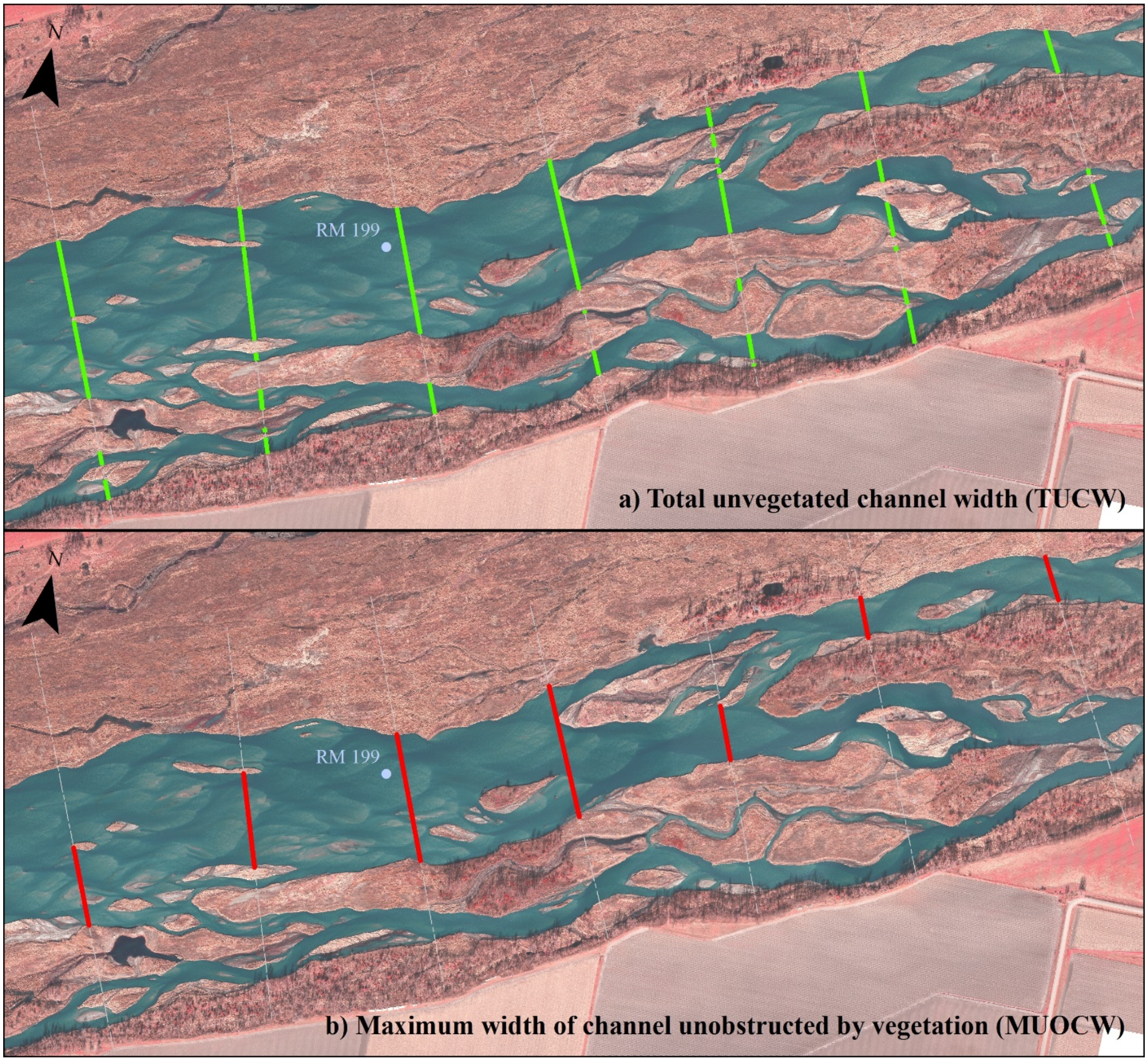

Figure 4. Examples of total unvegetated channel width (TUCW; a) and maximum width of channel unobstructed by vegetation (MUOCW; b) delineations near River Mile 199.

Model Metrics and Statistical Analyses

A number of investigators have attempted to identify the management, hydrologic, and geomorphic factors that influence channel width in the AHR. Most investigations evaluate those factors within the context of changes in unvegetated channel width during the period following water resources development in the basin (Williams 1978; O'Brien and Currier 1987; Johnson

1994; Simons and Associates Inc. 2000; Murphy et al. 2004; Schumm 2005). Several of the investigators identified peak flows as the controlling factor in channel width (Williams 1978; O'Brien and Currier 1987; Murphy et al. 2004). Although peak flow metrics of interest had varying return intervals and durations identified by different investigators, these differences were generally not discussed. Investigators also typically cited a secondary effect of reduction in sediment supply/transport. Others have identified mean June flows (Johnson 1994; Simons and Associates Inc. 2000), summer flows (Schumm 2005), slight differences in channel slope (Schumm 2005) and differences in bed material grain size (Murphy et al. 2004) as potentially controlling or at least influencing unvegetated channel width in the AHR. In addition, investigators have discussed the role of woody and/or scour resistant vegetation in limiting the ability of the AHR to widen in response to changes in hydrology (Tal et al. 2004). This phenomenon has been described as the vegetation ratchet effect because the channel is free to narrow through vegetation encroachment, but has limited ability to re-widen once bars and banks are stabilized by woody or other scour-resistant vegetation.

A total of 11 primary hydrologic, geomorphic, and management variables were identified based on our review of the literature, proposed FSM management actions, and our knowledge of ongoing activities in the AHR (Table 4). We performed 2 multiple quantile linear regression analyses to identify and quantify effect sizes of these variables on TUCW and MUOCW in the AHR during the period of 2007–2015.

Table 4. Hydrologic, geomorphic and management variables included in the robust regression analyses for total unvegetated channel width (TUCW) and unobstructed channel width (MUOCW) for the period of 2007–2015. Units of measurement (Units) and description of data acquisition (Description) are included for each metric.

Metric	Type	Units	Description
Peak Discharge	Hydrologic	Cubic feet per second (cfs)	Mean daily discharge records were obtained from www.water.usgs.gov for the three United States Geological Survey (USGS) stream gages located in the AHR (Figure 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	Cubic feet per second (cfs)	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	Cubic feet per second (cfs)	Mean annual minimum discharge events were identified for 10, 20, 30, and 40 day durations.
Mean June Discharge	Hydrologic	Cubic feet per second (cfs)	Mean daily discharge during the month of June.
Mean Growing Season Discharge	Hydrologic	Cubic feet per second (cfs)	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	Feet (ft)	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.
Median Grain Size	Geomorphic	Millimeter (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.
Channel Slope	Geomorphic	Dimensionles s	Mean channel slope for 1-mile reach centered on each transect. Slopes calculated from 2009 longitudinal profile of the AHR.
River Mile	Geomorphic	Mile (mi)	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 or not 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 a herbicide polygon, the transect was considered to be treated with herbicide.
Annual Herbicide	Management	Categorical	

Transects were subset spatially to utilize every fifth transect location to minimize autocorrelation. We used 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 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 (R^1) in a five-step model selection process. 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). A full description for the TUCW model selection process and tables for the MUOCW quantile linear regression processes are included in Appendices I and II. 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 hydrologic variables, 2) identify the duration of hydrologic variables that best explain each response, 3) identify the most important non-hydrologic variables, and 4) produce final models with both hydrologic and non-hydrologic variables that best explain and accurately predict TUCW and MUOCW at transect locations in the

AHR. 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 whooping crane habitat suitability described in the subsequent section.

Application of the Final MUOCW Model to Evaluate the FSM Management Strategy

The final MUOCW model was used to assess the potential performance of the FSM management strategy at a hypothetical habitat complex location given observed hydrology during the period of 1998–2015. The habitat complex was assumed to have a main channel bankfull width of 1,000 ft 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 SDHF events of 8,000 cfs for three days in approximately two out of three years. MUOCWs predicted under full SDHF implementation were compared to those predicted given observed hydrology to assess the ability of SDHF releases to increase MUOCW and maintain UOCWs that are highly suitable for whooping crane use.

Results

Total Unvegetated Channel Widths (TUCW) and Unobstructed Channel Widths (MUOCW)

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 5). From 2008–2014, MUOCW mean and median values were observed to have little variation, with the greatest yearly difference of 110 ft for mean and 89 ft for median observations. Likewise, from 2008–2014, TUCW mean and median values were observed to have little variation, with the greatest yearly difference of 219 ft for mean and 222 ft for median observations (Table 5).

Table 5. Observed total unvegetated channel widths (TUCW) and unobstructed channel widths (MUOCW) by river mile, 2007–2015.

Year	Mean TUCW(ft)	Median TUCW(ft)	Mean MUOCW(ft)	Median MUOCW(ft)
2007	572	558	300	260
2008	720	729	443	383
2009	650	642	373	341
2010	661	653	409	347
2011	869	864	481	430
2012	695	692	454	394
2013	722	720	483	421
2014	716	710	431	373
2015	1,054	1,027	625	575

Spatially, both TUCW and MUOCW were highly variable but generally increased with decreasing river mile (i.e., in a downstream direction). Both width metrics also increased from 2007–2015 at almost all locations within the AHR (Figure 6). However, the magnitude of width increases varied based on river segment. For example, the UOCW increase from river mile 170 to 180 was far less than what was observed from river mile 160 to 170 (Figure 6).

Relationship between TUCW and MUOCW

The relationship between TUCW and MUOCW for all transects in all analysis years is presented in Figure 7. In general, MUOCW increased with increasing TUCW, but there were few cases when the entire unvegetated width of the channel was consolidated into a single segment (MUOCW = TUCW). This indicates that under existing hydrologic, geomorphic, and management conditions, the channels of the AHR tend to contain either densely vegetated sandbars or be split by permanent islands. Accordingly, it is not appropriate to interpret MUOCW as being equivalent to TUCW or other metrics intended to describe the total width of AHR channels.

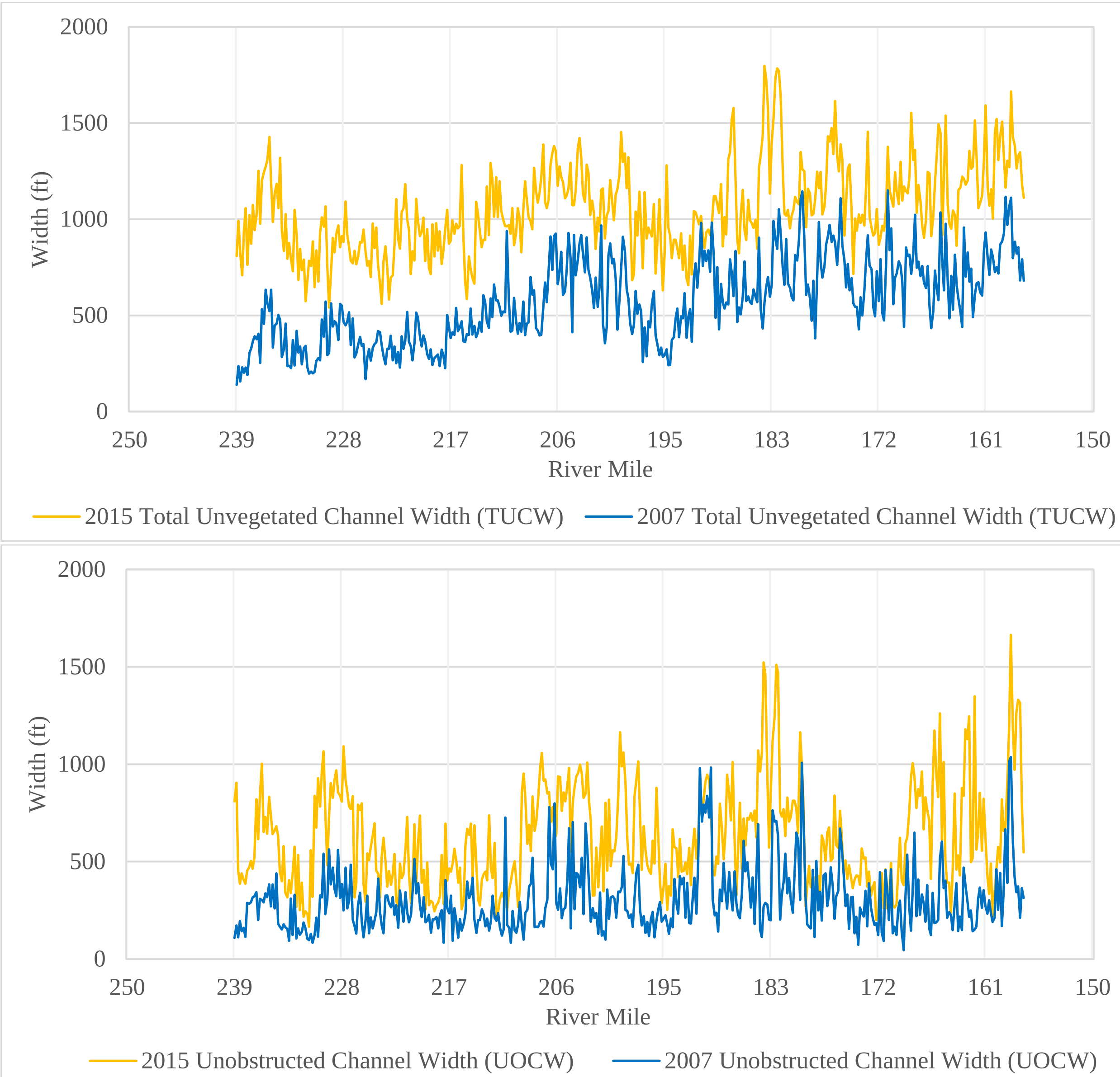

Figure 6. Observed total unvegetated channel widths (TUCW) and unobstructed channel widths (MUOCW) by river mile for analysis years 2007 and 2015.

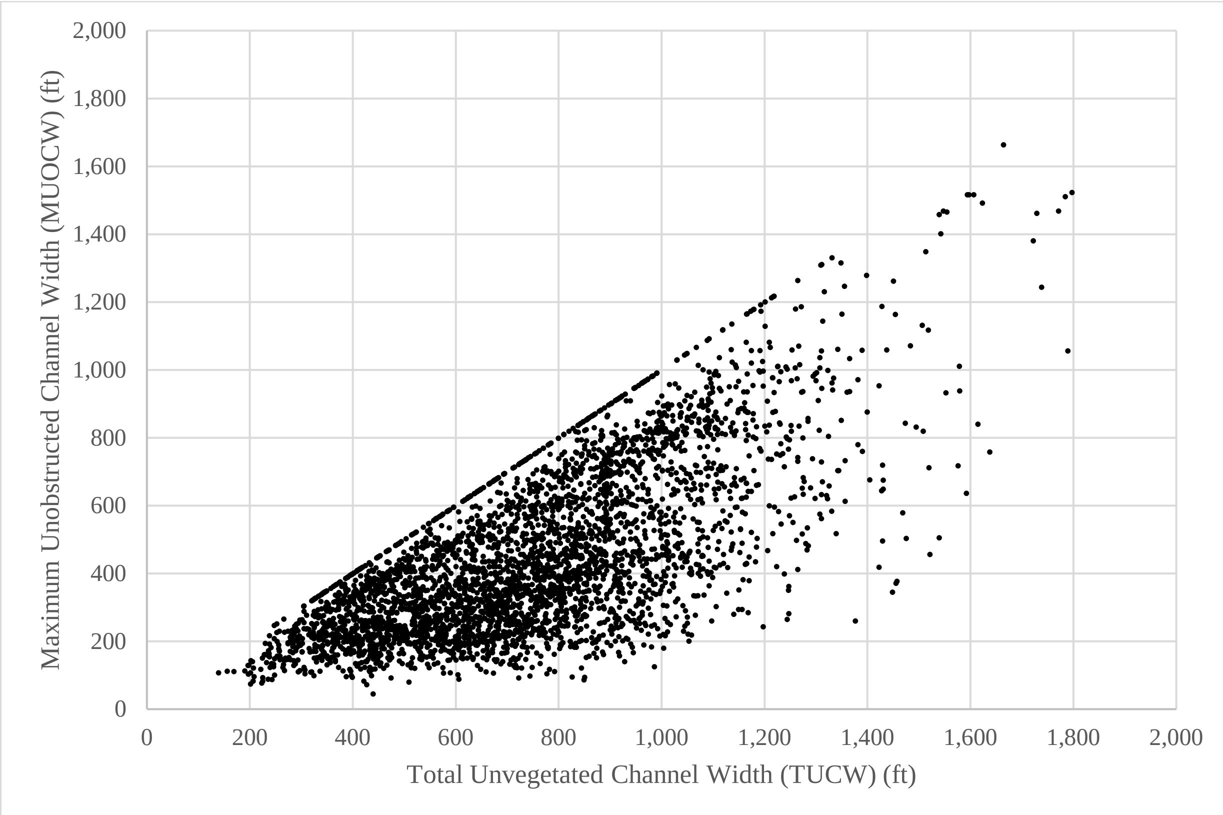

Figure 7. Relationship between total unvegetated channel width (TUCW) and maximum unobstructed channel width (MUOCW) for all transects, 2007–2015.

Quantile Regression Analysis – 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 6. Forty-day peak discharge ranged from 2,010 cfs to 12,486 cfs and generally occurred between early May and early July (Figure 8). Wetted width ranged from 603 ft to 1,717 ft. 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 2007 in the AHR. The proportion of transects sprayed was low in 2007 and 2008, prior to the commencement of large-scale phragmites spraying efforts. At full-scale implementation, up to 83% of transects were sprayed in a single year.

Table 6. Summary of important AHR flow, geomorphic and management metric values from 2007 to 2015 in relation to mean total unvegetated channel width (TUCW) and unobstructed channel width (MUOCW) from 2007 to 2015.

Year	40 Day Peak Discharge (cfs)	Bankfull Wetted Width (ft)[1]	Median Grain Size (mm)[2]	% of Transects Disked	% of Transects Sprayed	TUCW (ft)	MUOCW (ft)
2007	2,010			33%	0%	558	300
2008	3,825			41%	5%	729	443
2009	2,112			10%	13%	642	373
2010	5,171			5%	77%	653	409
2011	8,171	1,044	0.93	0%	44%	864	481
2012	2,922			9%	81%	692	454
2013	3,661			11%	71%	720	483
2014	2,943			18%	74%	710	431
2015	12,486			0%	83%	1,027	625

[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.

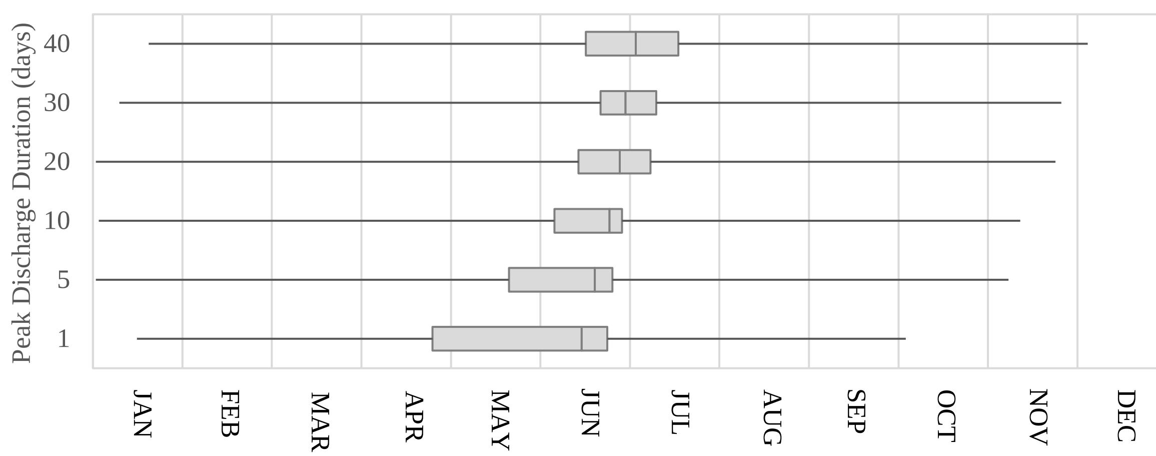

Figure 8. Distribution of peak discharge dates from the Overton, Kearney, Grand Island and Duncan gauges from 2007 to 2015. Median values are presented, along with the lower and upper quartiles. Minimum and maximum values are presented as bars.

We found TUCW was best explained by 40-day duration peak discharge, disking, herbicide application, and wetted width of the channel at bankfull discharge (Appendix I Table I-5; Table 7); 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 ~436 AIC units lower than a model only including 40-day peak discharge and wetted width and ~850 AIC unit lower than the null model. All variables had a positive effect on TUCW from 2007–2015. The formula of the top model to explain TUCW at the 0.5 quantile (τ = 0.5) was noted as:

$$TUCW = 199.41 + 0.04 * 40\ Day\ Peak + 136.14 * Disking + 33.52 * Herbicide + 0.32 * Wetted\ Width \quad 1.1$$

where "40 Day Peak" refers to mean 40-day duration peak discharge, "Herbicide" and "Disking" were categorical variables based on whether or not herbicide or disking were applied within the previous year, and "Wetted Width" 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, disking increased TUCW by 53 ft and herbicide increased TUCW by 19 ft on average. At the 0.95 quantile, disking increased TUCW by 201 ft and herbicide increased TUCW by 81 ft on average (Table 7).

Table 7. Multiple quantile regression beta estimates of the top model from the total unobstructed channel width (TUCW) model selection process.

Quantile	Intercept	40-Day Peak	Disking	Herbicide	Wetted Width
0.05	-23.75	0.04	52.82	18.91	0.29
0.10	50.20	0.04	90.89	23.51	0.26
0.25	119.41	0.04	111.09	31.66	0.28
0.50	199.11	0.04	136.14	33.52	0.32
0.75	298.30	0.04	122.13	22.46	0.37
0.90	364.56	0.03	127.74	69.97	0.44
0.95	379.53	0.03	201.28	81.17	0.49

Based on the results of our top quantile regression model at the 0.5 quantile, for each 1,000 cfs increase in 40-day peak discharge, on average, we would expect a 38 ft (95% CI = 10 – 59 ft) increase in TUCW annually, when no disking or herbicide treatment was applied and wetted width at bankfull discharge was held at its median value (Figure 9). When transects were disked, on average, TUCW was 136 ft (95% CI = 103 – 164 ft) wider than at transects where no disking occurred within the previous year. When transects were disked and herbicide was applied, on average, TUCW was 170 ft (95% CI = 113 – 223 ft) wider than transects where no other management actions occurred in the previous year. For each 100 ft increase in wetted width at bankfull discharge, on average, we would expect a 32 ft (95% CI = 29 – 36 ft) increase in TUCW annually (Figure 10).

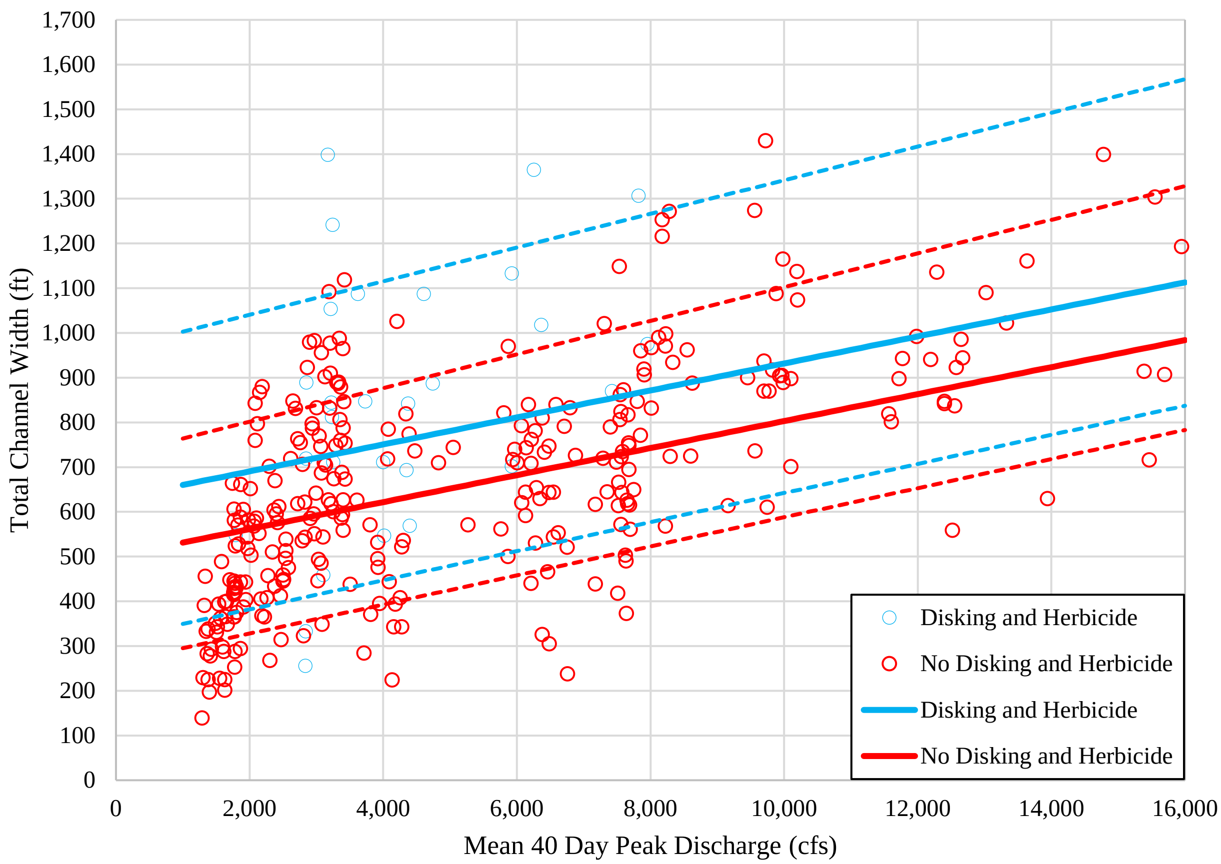

Figure 9. Predicted relationships of total unvegetated channel width (TUCW) to 40-day peak discharge at transects in the AHR with (blue) or without (red) management actions from 2007–2015. Dashed lines represent 90% quantile regression prediction intervals and points display the subset of measured TUCWs at transects used in quantile regression analyses. Points represent

transects where no management actions (red), disking only (dark blue), or disking and herbicide (blue) occurred.

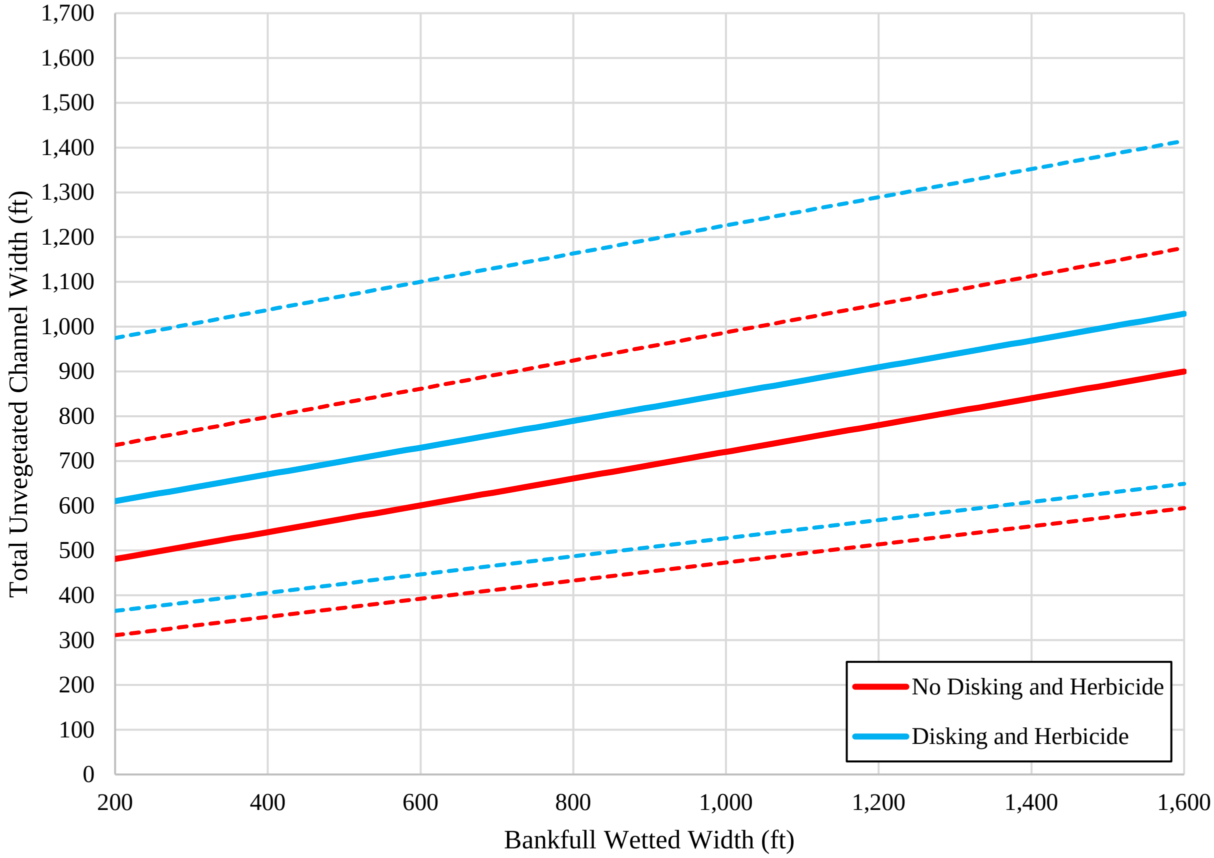

Figure 10. Predicted relationships of total unvegetated channel width to wetted width at transects in the AHR with (blue) or without (red) management actions from 2007–2015. Dashed lines represent 90% quantile regression prediction intervals.

We used several methods to assess the accuracy of the top model we identified through AIC model selection. First, we compared observed and predicted TUCW at each transect for each year. Utilizing the TUCW linear model and betas previously stated at the 0.5 quantile, 45% of TUCW predictions were within 100 ft and 76% of predictions were within 200 ft of actual values observed from 2007–2015. Overestimating TUCW was of special concern since narrower than predicted TUCW potentially have more negative consequences for whooping crane habitat suitability than underestimations. Twenty-nine percent of TUCW predictions were overestimated by more than 100 ft and only 11% were overestimated by more than 200 ft.

We also compared mean observed and predicted TUCW for all transects in each year (Table 8) and compared observed and predicted widths for each AHR bridge segment across all years (Table 9). Only two years, 2007 and 2010, were found to contain mean errors >10% of actual values. When observing errors by bridge segment, four of the eleven bridge segments contain mean errors >10% of actual values, but no mean errors exceeded 17% (Table 8).

Table 8. Comparison of mean observed and predicted total unvegetated channel width (TUCW) in AHR for the period of 2007-2015 using a 0.5 quantile regression. Parentheses indicated 90% quantile regression prediction intervals.

Year	Observed Mean TUCW (ft)	Predicted Mean TUCW (ft)	Mean Error (ft)	Mean Error as % of Observed TUCW
2007	572	670 (401 - 947)	99 (-171 - 375)	17 (-30 - 66)
2008	720	777 (495 - 1059)	56 (-225 - 339)	8 (-31 - 47)
2009	650	608 (365 - 870)	-42 (-285 - 221)	-6 (-44 - 34)
2010	661	740 (502 - 1029)	79 (-159 - 367)	12 (-24 - 56)
2011	869	811 (570 - 1071)	-58 (-299 - 202)	-7 (-34 - 23)
2012	695	640 (404 - 941)	-55 (-291 - 246)	-8 (-42 - 35)
2013	722	751 (506 - 1041)	29 (-216 - 319)	4 (-30 - 44)
2014	716	716 (467 - 1017)	-1 (-249 - 301)	0 (-35 - 42)
2015	1054	991 (746 - 1266)	-63 (-309 - 211)	-6 (-29 - 20)

Table 9. Comparison of mean observed and predicted total unvegetated channel width (TUCW) by bridge segment for the period of 2007–2015 using a 0.5 quantile regression. Parentheses indicated 90% quantile regression prediction intervals.

Bridge Segment	Observed TUCW (ft)	Predicted TUCW (ft)	Error (ft)	Error as % of Observed TUCW
Overton - Elm Creek	590	575 (362 - 826)	-15 (-229 - 236)	3 (-39 - 40)
Elm Creek - Odessa	572	550 (334 - 815)	-22 (-238 - 242)	4 (-42 - 42)
Odessa - Kearney	500	525 (334 - 767)	24 (-167 - 266)	5 (-33 - 53)
Kearney - Minden	638	583 (374 - 837)	-56 (-264 - 198)	9 (-41 - 31)
Minden - Gibbon	864	732 (469 - 1033)	-132 (-395 - 169)	15 (-46 - 20)
Gibbon - Shelton	880	775 (506 - 1078)	-105 (-373 - 198)	12 (-42 - 23)
Shelton - Wood River	620	723 (485 - 988)	103 (-135 - 367)	17 (-22 - 59)
Wood River - Alda	780	835 (557 - 1142)	54 (-223 - 362)	7 (-29 - 46)
Alda - Hwy 281	972	939 (631 - 1266)	-33 (-341 - 294)	3 (-35 - 30)
Hwy 281 - Hwy 34	872	911 (632 - 1208)	39 (-240 - 335)	4 (-28 - 38)
Hwy 34 - Chapman	834	926 (650 - 1221)	92 (-185 - 387)	11 (-22 - 46)

Quantile Regression Analysis – Metrics Found to Influence Maximum Unobstructed Channel Width

We found MUOCW was best explained by 40-day duration peak discharge and wetted width of the main channel (Appendix II Table II-4) and were incorporated in the only model with a model weight >0.10 (w_i = 0.83). Disking, herbicide application, and median grain size were also included in the top model explaining MUOCW. AIC values indicated our top model which included disking, herbicide application and median grain size was ~45 AIC units lower than a model that only included 40-day peak discharge and wetted width and ~451 AIC unit lower than the null model. All variables had a positive effect on MUOCW from 2007–2015 except median grain size, which exhibited a negative relationship. The formula of the top model used to explain MUOCW at the 0.5 quantile (τ = 0.5) was noted as:

$$UOCW = 191.64 + 0.02 * 40\ Day\ Peak + 122.22 * Disked + 24.11 * Herbicide + 0.18 * Main\ Channel\ Wetted\ Width - 95.09 * Median\ Grain\ Size \quad 2.1$$

where "40 Day Peak" refers to mean 40-day duration peak discharge, "Herbicide" and "Disking" were categorical variables based on whether or not herbicide or disking were applied within the previous year, "Main Channel Wetted Width" refers only to the main channel and not the total wetted width of all channels at bankfull discharge, and "Median Grain Size" refers to the median size of the substrate.

Besides the effects of 40-day peak discharge and median grain size, other beta values generally increased from low to high quantiles. For example, at the 0.05 quantile, disking increased MUOCW by 23 ft and herbicide increased MUOCW by 18 ft on average. At the 0.95 quantile, on average, disking increased TUCW by 172 ft and herbicide increased TUCW by 43 ft (Table 10).

Table 10. Multiple quantile regression beta estimates of the top model from the unobstructed channel width (MUOCW) model selection process.

Quantile	Intercept	40 Day Peak	Disking	Herbicide	Main Channel Wetted Width	Median Grain Size
0.05	58.48	0.01	22.86	18.16	0.04	14.09
0.10	145.96	0.01	28.12	22.76	0.04	-37.61
0.25	205.11	0.01	116.65	31.90	0.09	-92.59
0.50	191.64	0.02	122.22	24.11	0.18	-95.09
0.75	226.44	0.02	165.15	50.55	0.37	-132.01
0.90	67.08	0.02	142.63	35.26	0.64	-10.75
0.95	360.90	0.01	171.76	43.07	0.66	-212.90

Based on the results of our top quantile regression model at the 0.5 quantile, for each 1,000 cfs increase in 40-day peak discharge, on average, we would expect a 20 ft (95% CI = 16 – 24 ft) annual increase in MUOCW, when no disking or herbicide treatment was applied and other variables were held at their median values (Figure 12). For each 100 ft increase in bankfull wetted width of the main channel, on average, we would expect an 18 ft (95% CI = 14 – 23 ft) increase in MUOCW (Figure 13). When transects were disked, on average, MUOCW was 122 ft (95% CI

= 85 – 163 ft) wider than transects where no disking occurred within the previous year. When both disking and herbicide were applied, on average, we found transects were 146 ft (95% CI = 91 – 217 ft) wider than transects where no management actions occurred in the previous year. We also found as median grain size decreased, MUOCW increased (Figure 14). For each 0.1 mm decrease in median grain size, on average, MUOCW increased by 10 ft (95% CI = 2 – 19 ft).

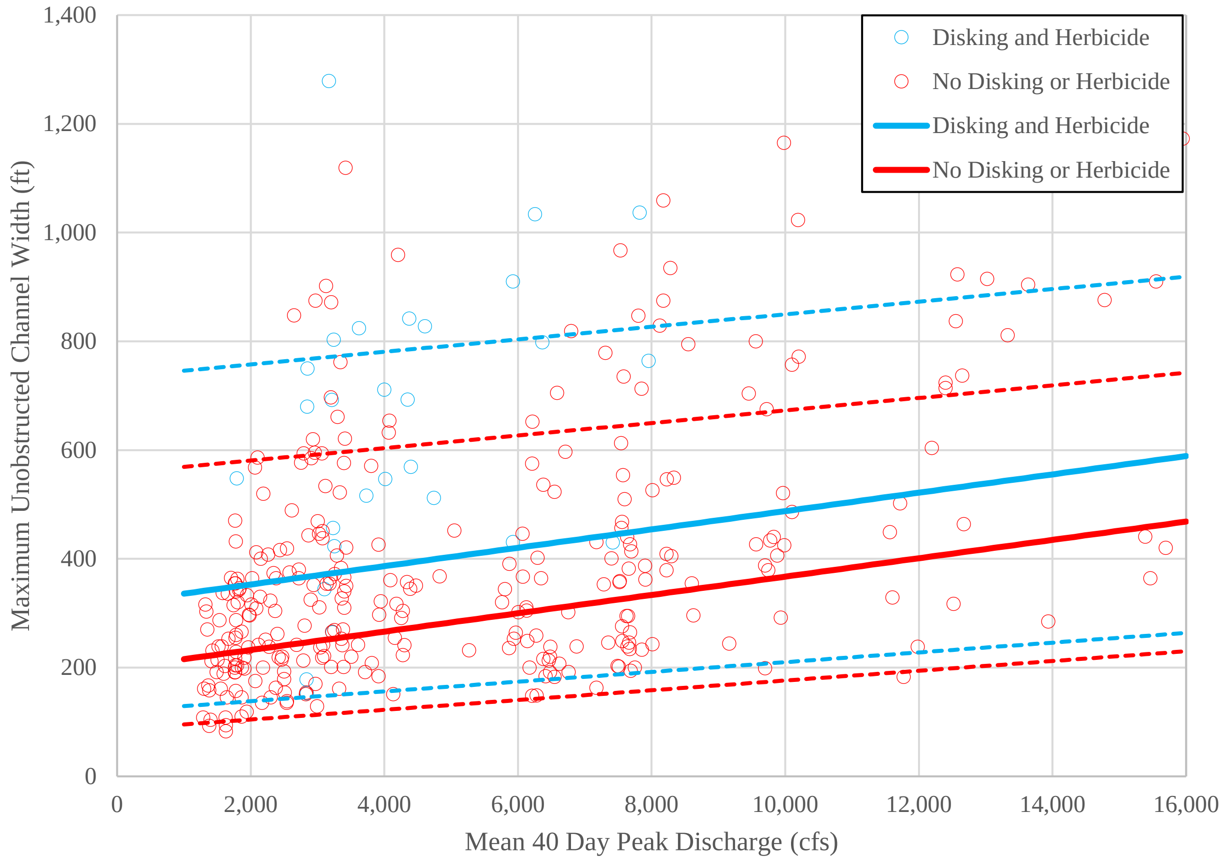

Figure 12. Predicted relationships of maximum unobstructed channel width (MUOCW) to 40-day peak discharge at transects with (blue) or without (red) management actions in the AHR from 2007–2015. Dashed lines represent 90% quantile regression prediction intervals and points display the subset of measured UOCWs at transects used in robust regression analyses. Points represent transects where no management actions (red), disking only (dark blue), or disking and herbicide (blue) occurred.

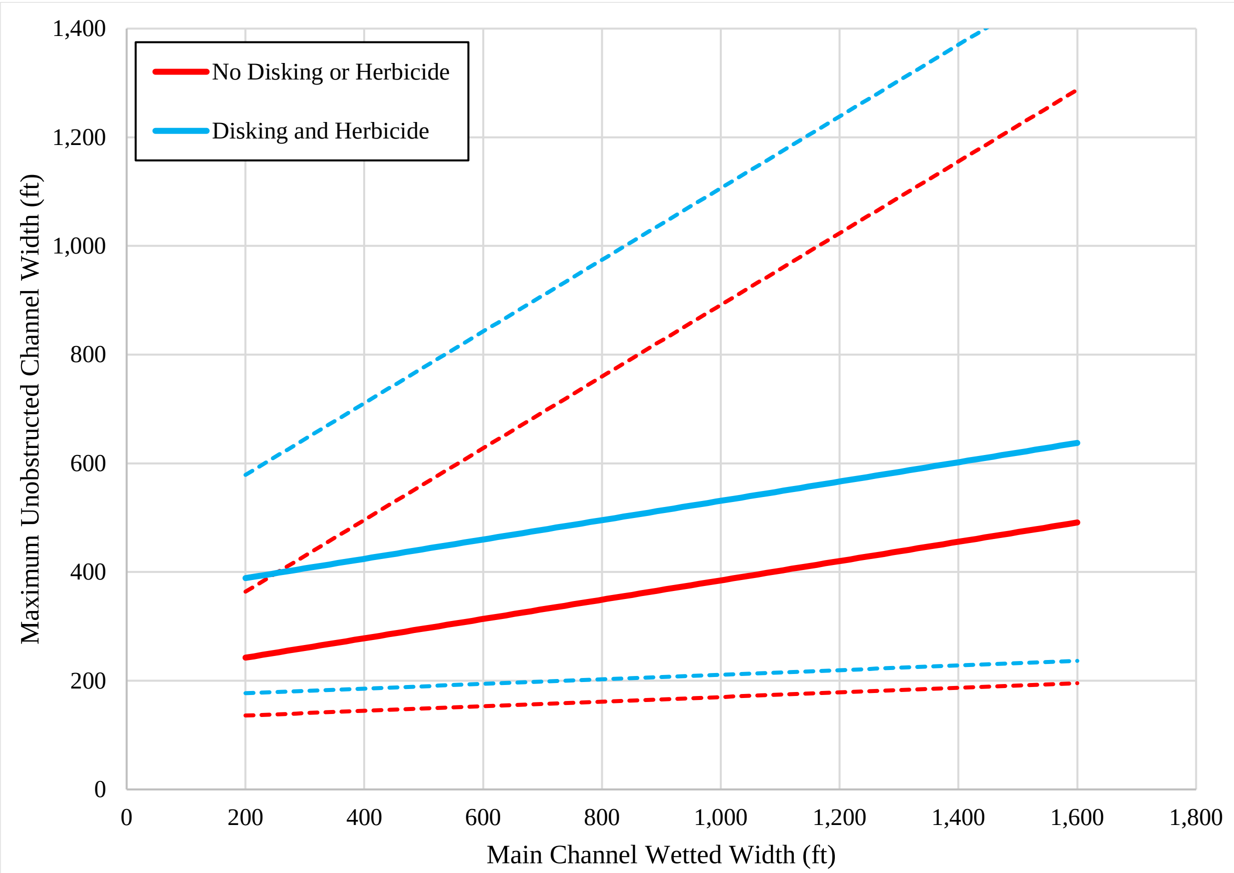

Figure 13. Predicted relationship between maximum unobstructed channel width and main channel wetted width at transects with (blue) or without (red) management actions in the AHR from 2007–2015. Dashed lines represent 90% quantile regression prediction intervals.

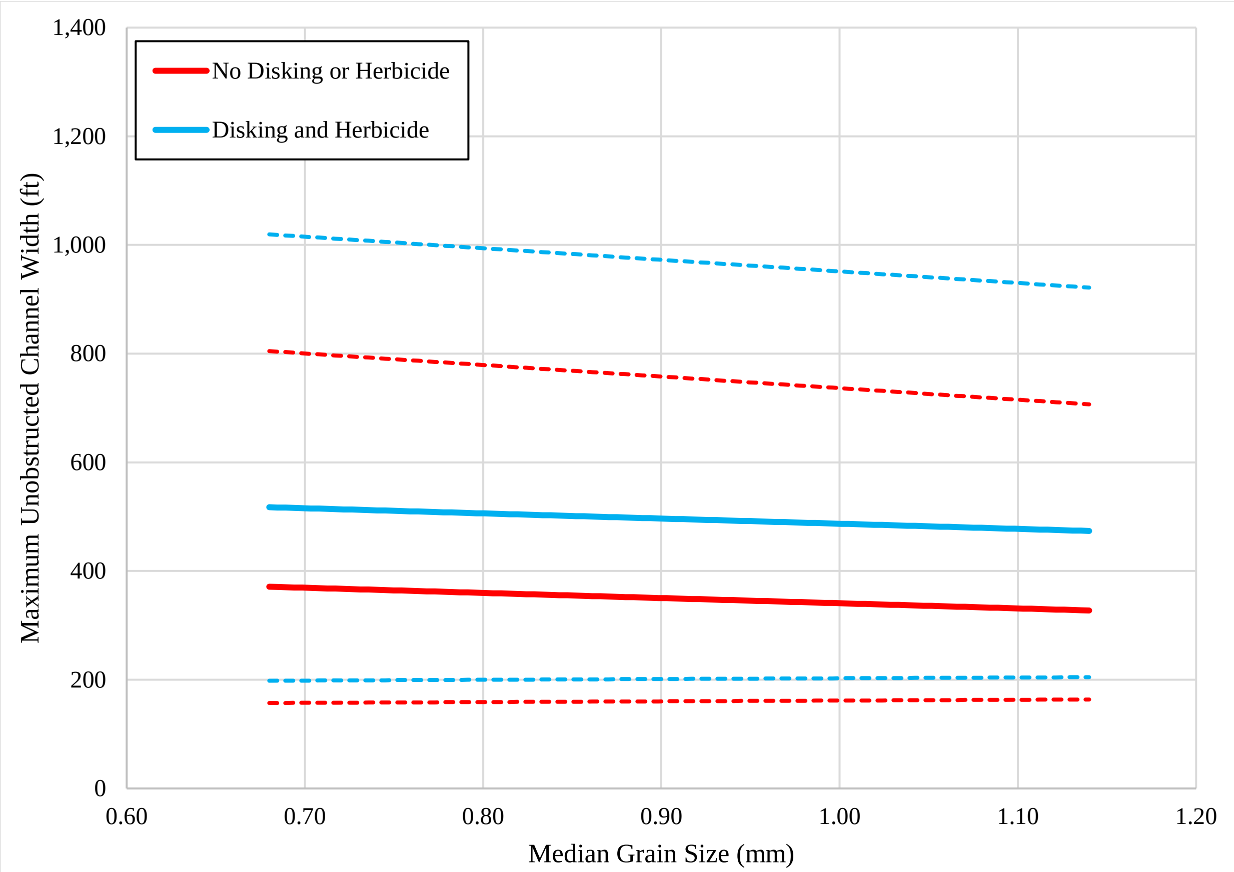

Figure 14. Predicted relationship between maximum unobstructed channel width and median grain size at transects with (blue) or without (red) management actions in the AHR from 2007–2015. Dashed lines represent 90% quantile regression prediction intervals.

We incorporated several measurements 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, 39% of MUOCW predictions were within 100 ft and 69% were within 200 ft of actual values observed from 2007–2015. Once again, overestimating MUOCW was of special concern since narrower than predicted MUOCW potentially have more negative consequences for whooping crane habitat suitability than underestimations. Only 37% percent of MUOCW predictions were overestimated by more than 100 ft and 10% were overestimated by more than 200 ft.

We also compared mean observed and predicted MUOCW for all transects within the AHR in each year (Table 9) and compared observed and predicted widths for each bridge segment across all years (Table 10). Eight of the nine years assessed were found to contain mean prediction errors <20% of actual values (Table 9). Seven of the eleven bridge segments in the AHR were found to contain mean prediction errors <20% of actual values (Table 10).

In addition, we performed a Monte Carlo analysis using Oracle Crystal Ball software to assess the sensitivity of predicted MUOCW to the observed distributions of the variables contained in the top model. Appropriate distributional assumptions were determined by Oracle Crystal Ball and fit to observed data for each model variable and a total of 100,000 random simulations were run to calculate sensitivity associated with each variable based on contribution to variance. Overall, 40-day mean peak had the greatest impact on MUOCW and contributed 42.7% of the variance in predicted MUOCWs, disking contributed 32.8%, bankfull wetted width contributed 22.0%, median bed material grain size contributed -1.3% and herbicide contributed 1.1% (Appendix III).

Table 11. Comparison of mean observed and predicted maximum unobstructed channel width (MUOCW) in the AHR for the period of 2007–2015 using a 0.5 quantile regression. Values in parentheses represent 90% quantile regression prediction intervals.

Year	Observed MUOCW (ft)	Predicted MUOCW (ft)	Error (ft)	Error as % of Observed MUOCW
2007	300	354 (152 - 802)	54 (-148 - 501)	18 (-49 - 167)
2008	443	426 (183 - 883)	-17 (-260 - 440)	4 (-59 - 99)
2009	373	305 (140 - 747)	-68 (-234 - 374)	18 (-63 - 100)
2010	409	397 (189 - 854)	-12 (-220 - 445)	3 (-54 - 109)
2011	481	432 (206 - 894)	-49 (-275 - 413)	10 (-57 - 86)
2012	454	338 (159 - 786)	-116 (-295 - 332)	26 (-65 - 73)
2013	483	406 (190 - 864)	-77 (-293 - 380)	16 (-61 - 79)
2014	431	389 (179 - 843)	-42 (-252 - 412)	10 (-59 - 96)
2015	625	552 (265 - 1033)	-73 (-360 - 408)	12 (-58-65)

Table 12. Comparison of mean observed and predicted unobstructed channel width (UOCW) by bridge segment for the period of 2007-2015 using a 0.5 quantile regression. Values in parentheses represent 90% quantile regression prediction intervals.

Bridge Segment	Observed MUOCW (ft)	Predicted MUOCW (ft)	Error (ft)	Error as % of Observed
Overton - Elm Creek	324	156 (397 - 711)	-73 (-241 - 314)	18 (-61 - 79)
Elm Creek - Odessa	338	158 (444 - 697)	-106 (-286 - 253)	24 (-64 - 57)
Odessa - Kearney	307	155 (334 - 666)	-26 (-179 - 332)	8 (-54 - 99)
Kearney - Minden	328	161 (312 - 717)	15 (-152 - 405)	5 (-49 - 130)
Minden - Gibbon	400	178 (583 - 857)	-183 (-405 - 274)	31 (-69 - 47)
Gibbon - Shelton	414	185 (528 - 891)	-114 (-343 - 363)	22 (-65 - 69)
Shelton - Wood River	385	182 (415 - 831)	-30 (-233 - 416)	7 (-56 - 100)
Wood River - Alda	449	200 (502 - 938)	-52 (-302 - 436)	10 (-60 - 87)
Alda - Hwy 281	489	211 (604 - 1029)	-115 (-393 - 425)	19 (-65 - 70)
Hwy 281 - Hwy 34	466	212 (360 - 991)	106 (-148 - 631)	30 (-41 - 175)
Hwy 34 - Chapman	468	215 (457 - 1002)	11 (-242 - 545)	2 (-53 - 119)

Analysis of SDHF Performance

Simulated SDHF releases were added to observed mean daily flows for the period of 1998–2015 (Figure 18) to evaluate the predicted increase in channel width under full SDHF implementation. The modified flow series included ten SDHF releases. Simulated SDHF releases were added to the flow record during the month of April in two out of three years during dry periods. SDHF releases were not added in wet years or the years immediately following the two highest discharge years (1999 and 2011). Specifically, SDHF implementation was added in the years of 1998, 2001, 2002, 2004, 2005, and 2007. The SDHF hydrograph in all cases included two to three days of up-ramping flows, three days at a discharge of 8,000 cfs 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. SDHF volumes ranged from 26,000 to 68,000 acre-ft. Predicted increases of TUCW and MUOCW values at the 0.05, 0.50, and 0.95

response quantiles with and without SDHF releases (assuming a main channel bankfull wetted width of 1,000 ft, herbicide treatment, and no disking) are presented in Table 13. Implementation of an SDHF release in a given year is predicted to increase TUCW by 0 – 26 ft and MUOCW by 0 – 14 ft depending on baseline river discharge at the time of the release. The greatest increases in TUCW and MUOCW are predicted to occur when baseline river discharge is low.

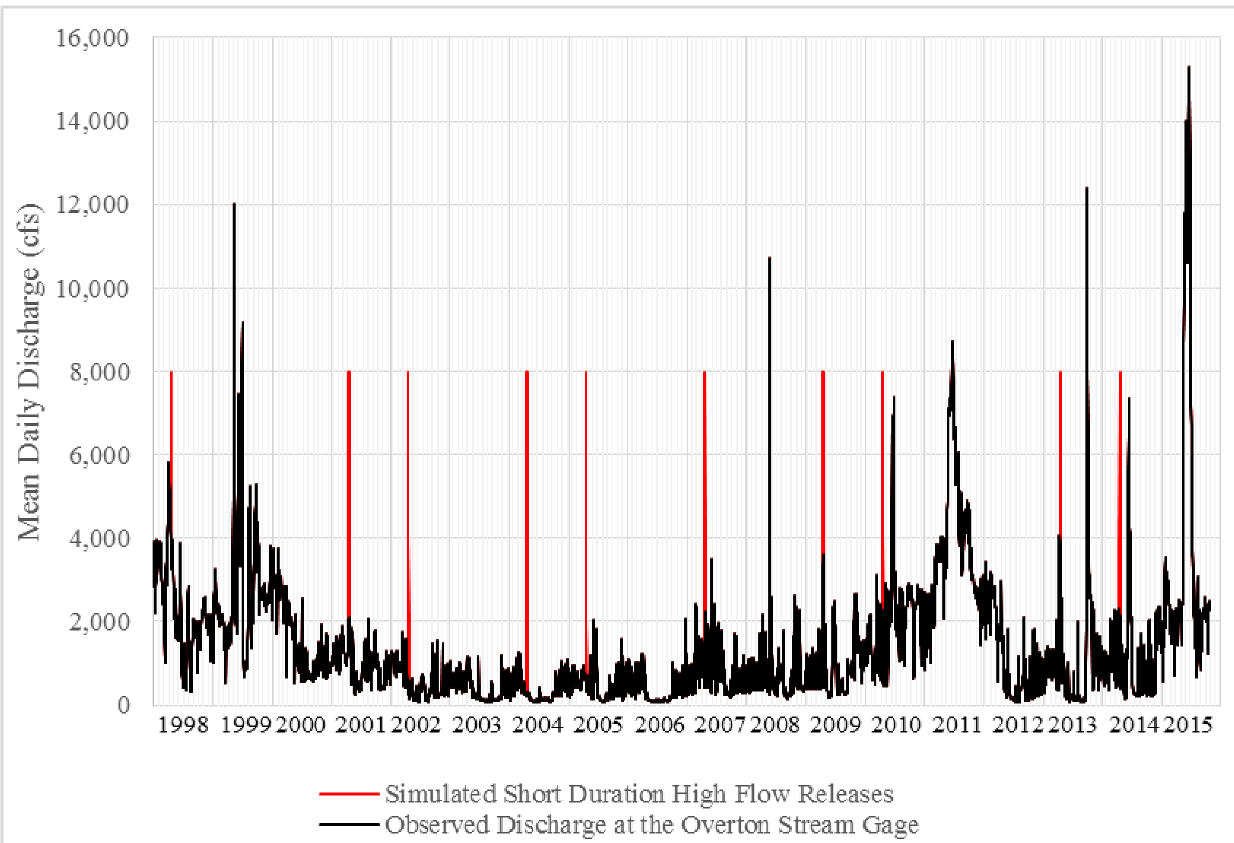

Figure 18. Observed hydrology at the USGS Overton Stream Gage (06768000) and simulated short duration high flow events of 8,000 cfs for three days in approximately two out of three years.

Table 13. Predicted increases in maximum unobstructed channel width (MUOCW) and total unvegetated channel width (TUCW) at specified quantiles (τ) with implementing a short duration high flow (SDHF) during 1998, 2001, 2002, 2004, 2005, and 2007 on the central Platte River, Nebraska.

	Δ MUOCW (ft)			Δ TUCW (ft)		
Year	τ (0.05)	τ (0.50)	τ (0.95)	τ (0.05)	τ (0.50)	τ (0.95)
1998	4	7	5	13	13	11
1999	0	0	0	0	0	0
2000	0	0	0	0	0	0
2001	7	13	9	24	23	20
2002	7	13	9	24	23	21
2003	0	0	0	0	0	0
2004	5	9	6	17	17	15
2005	7	12	9	24	23	20
2006	0	0	0	0	0	0
2007	7	14	9	26	25	22
2008	0	0	0	0	0	0
2009	0	0	0	0	0	0
2010	0	0	0	0	0	0
2011	0	0	0	0	0	0
2012	0	0	0	0	0	0
2013	0	0	0	0	0	0
2014	0	0	0	0	0	0
2015	0	0	0	0	0	0

Discussion

The Program's FSM management strategy consists of sediment augmentation to offset the sediment deficit due to clear water hydropower returns, mechanical vegetation clearing and channel widening, and SDHF releases in approximately two out of three years to increase and maintain the width of channel free from vegetation. This investigation provides insights about the beneficial effects of each of these management actions in maintaining TUCW and more specifically, MUOCWs that are highly suitable for whooping crane roosting habitat.

This investigation included an indirect evaluation of sediment through inclusion of median grain size. Differences in median grain size through the AHR may be an indicator of sediment balance with coarser grain sizes in deficit reaches due to winnowing of bed material. However, differences in grain size may also be attributable to differences in local sediment transport capacity as a result of variability in channel width. Overall, median grain size was found to be correlated with maximum unobstructed channel width, with a predicted 10-foot increase in MUOCW for every 0.1 mm decrease in median bed material grain size. However, it is difficult to assess whether sediment supply is influencing width or width is influencing grain size. Overall, uncertainty in causation versus correlation may not be that important, as MUOCW appears to be somewhat insensitive to median grain size which only accounted for 1.3% of the variance in predicted MUOCWs (Appendix IV).

Program priority hypothesis Flow 3 postulates peak flow magnitude is a major driver in maximum unobstructed channel width. Specifically, increasing peak flow magnitude (metric is $Q_{1.5}$) is hypothesized to increase the vegetation-free width of the main channel in the AHR (Figure 13). Quantile regression analyses in this investigation strongly support the assertion of a positive relationship between peak flow magnitude and TUCW and MUOCW in the AHR. Overall, 40-day mean peak discharge accounted for 42.7% of the variance in predicted MUOCWs. The analyses, however, do not support the assertion that increasing peak flow magnitude through SDHF releases of 5,000 – 8,000 cfs for three days in two out of three years will produce substantive increases in the vegetation-free width of the channel. Maximum increases in TUCW of 26 ft and MUOCW of 14 ft are predicted. This is due to the very short duration and low volume of SDHF releases in relation to the 40-day peak discharge duration that is the best hydrologic predictor of TUCW and

MUOCW in the AHR. The difference in peak-volume relationships between observed natural peak flow events and SDHF is apparent in Figure 3.

Overall, these analyses strongly indicate peak flows significantly influence TUCW and MUOCW in the AHR, but SDHF releases, as currently envisioned, would likely not be effective in managing MUOCW to create and/or maintain suitable whooping crane habitat. SDHF is predicted to produce maximum increases in MUOCW of approximately 14 ft, which is a minimal effect during very dry periods when mean MUOCW is on the order of 100 ft narrower than the low end of the 500 – 700 ft range of highly-favorable UOCWs for whooping crane use (Chapters 2 and 3). During wetter years when baseline MUOCW is closer to the lower end of the suitable range, the much greater duration of the natural peak flow events appears to eclipse the limited effect of an SDHF.

Although it appears unlikely that SDHF releases will prove to be a viable management tool capable of achieving the hypothesized results envisioned within the FSM strategy, disking in combination with herbicide application is likely to become an effective management tool under any strategy. The predicted effect of channel disking and spraying is an increase of well over 100 ft in MUOCW across most of its distribution. The major limitation of disking, however, is the lack of a system-scale beneficial effect. The Program can utilize disking to effectively manage MUOCW at Program habitat complexes, but cannot utilize disking on other conservation or private lands without landowner agreements.

This investigation also highlights the uncertainties that are introduced when exploring the relationship between physical process and species habitat metrics. The quantile regression analysis results indicated 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. 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. Uncertainty around predicted maximum unobstructed channel widths is evident in the 95% prediction intervals displayed in Figures 11 to 13. This loss of predictive ability occurs because the spatial distribution of vegetated bars and/or islands within the channel exerts a strong control on MUOCW. This is evident in Figure 4, where TUCW is somewhat consistent across all transects but MUOCW is highly variable depending on the location of vegetated bars within the channel.

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Appendix I. Total Unvegetated Channel Width (TUCW) robust linear regression model selection results from a 5-step process, including a full description of procedures, which were also utilized for both MUOCW modeling efforts.

In the first step, we determined the duration of peak discharge that best explained total unvegetated channel width by comparing AIC values of univariate robust regression models of 1, 3, 5, 10, 20, 30, 40, 50, and 60-day mean peak discharge durations. Three and 5 day durations coincide with SDHF flow duration management strategies. Duration covariates in models with a ΔAIC value ≤2.0 were passed along to the second modeling step. Based on AIC values, 40-day peak discharge duration was passed along to the second modeling step (Table I-1).

Table I-1. Akaike's Information Criterion (AIC), quantile regression ($\tau = 0.5$) model selection of peak discharge duration influence on total unvegetated channel width in the Associated Habitat Reach (AHR), 2007–2015. Results correspond to model selection step 1.

Peak Discharge Duration	AIC	ΔAIC	Likelihood	AICw	R^1
40 Days	10617.94	0.00	1.00	1.00	0.23
20 Days	10802.49	184.56	0.00	0.00	0.14
30 Days	10805.79	187.86	0.00	0.00	0.14
10 Days	10814.78	196.84	0.00	0.00	0.13
5 Days	10815.04	197.10	0.00	0.00	0.13
50 Days	10816.53	198.59	0.00	0.00	0.13
60 Days	10827.03	209.09	0.00	0.00	0.12
3 Days	10834.24	216.31	0.00	0.00	0.12
1 Day	10856.39	238.46	0.00	0.00	0.11
Null	11032.35	414.42	0.00	0.00	0.00

Second, we combined the best annual duration model covariates and mean peak flows from the previous year over the same duration. Forty-day duration peak discharge was combined previous the previous year's peak discharge. Combinations were made with 0 to 100% of peak flow from the previous year at intervals of 20%. We hypothesized a lag effect of peak flows would carry over to the current year and this step would help us determine how important previous year peak flow was to total unvegetated channel width. Important combined previous and current year duration variables, in models with a ΔAIC value ≤2.0, were passed along to the fourth modeling step, which, in part, compared all hydrologic variables for ability to explain total unvegetated channel width (Tables I-2, I-4a). Based on AIC values, 40 Day peak discharge with 0% discharge from the previous year was passed along to the fourth modeling step.

Table I-2. Akaike's Information Criterion (AIC), quantile regression (τ = 0.5) model selection of current and previous year 40-day peak discharge influence on total unvegetated channel width in the Associated Habitat Reach (AHR), 2007–2015. Results correspond to model selection step 2.

Current and Previous Year Peak Discharge	AIC	ΔAIC	Likelihood	AICw	R^1
40 days with 0% Last Year	10617.94	0.00	1.00	1.00	0.23
40 days with 40% Last Year	10791.17	173.23	0.00	0.00	0.14
40 days with 60% Last Year	10792.17	174.23	0.00	0.00	0.14
40 days with 20% Last Year	10796.25	178.31	0.00	0.00	0.14
40 days with 80% Last Year	10796.78	178.84	0.00	0.00	0.14
40 days with 100% Last Year	10803.70	185.76	0.00	0.00	0.14
Null	10937.86	371.44	0.00	0.00	0.00

Third, we performed the same procedure from step 2 for mean minimum discharge for 10, 20, 30, and 40 day durations. A step to add a lag effect of minimum discharge was not included due to little influence of low flows from previous year compared to high flows on total unvegetated channel width. Important minimum duration variables, in models with a ΔAIC value ≤2.0, were passed along to the fourth modeling step (Table I-3).

Table I-3. Akaike's Information Criterion (AIC), quantile regression (τ = 0.5) model selection of mean minimum discharge 40-day peak discharge influence on total unvegetated channel width in the Associated Habitat Reach (AHR), 2007–2015. Results correspond to model selection step 3.

Mean Minimum Discharge Duration	AIC	ΔAIC	Likelihood	AICw	R^1
40 Days	10971.39	0.00	1.00	0.96	0.04
20 Days	10978.07	6.68	0.04	0.03	0.04
30 Days	10982.23	10.84	0.00	0.00	0.03
50 Days	11006.31	34.92	0.00	0.00	0.02
Null	11032.35	60.96	0.00	0.00	0.00

In our fourth model selection step, we tried to identify to best hydrological and non-hydrological variables. All hydrological variables, including those from the best peak and minimum flow models, were compared by modeling total unvegetated channel width in univariate models (Table I-4a). We then performed the same procedure for all non-hydrological variables (Table I-4b). Covariates in important univariate models (ΔAIC≤2.0) were then passed to the final modeling step. We also included several other non-hydrological variables which have been hypothesized to have an importance in explaining total unvegetated channel width when utilized as an additive effect with 40-day duration peak discharge. For example, we hypothesize disked transects would have wider total unvegetated channel widths than non-disked transects given the same peak discharge duration and flow.

Table I-4a. Akaike's Information Criterion (AIC), quantile regression (τ = 0.5) model selection of hydrologic variables on total unvegetated channel width in the Associated Habitat Reach (AHR), 2007–2015. Results correspond to model selection step 4.

Hydrological AIC table	AIC	ΔAIC	Likelihoo	AICw	R^1
40-Day Peak Discharge	10617.9	0.00	1.00	1.00	0.23
Mean June Discharge	10847.4	229.53	0.00	0.00	0.11
Mean Growing Season	10864.1	246.23	0.00	0.00	0.10
Null	10937.8	319.92	0.00	0.00	0.00
30-Day Minimum Discharge	10971.3	353.45	0.00	0.00	0.04

Table I-4b: Akaike's Information Criterion (AIC), quantile regression (τ = 0.5) model selection of non-hydrologic variables on total unvegetated channel width in the Associated Habitat Reach (AHR), 2007–2015. Results correspond to model selection step 4.

Non-Hydrological AIC table	AIC	ΔAIC	Likelihood	AICw	R^1
Wetted Width	10618.72	0.00	1.00	1.00	0.23
Mile	10772.12	153.40	0.00	0.00	0.15
Median Grain Size	10817.11	198.39	0.00	0.00	0.13
Herbicide	11006.73	388.00	0.00	0.00	0.02
Channel Consolidation	11016.53	397.80	0.00	0.00	0.01
Disking	11023.32	404.60	0.00	0.00	0.01
Channel Slope	11025.99	407.26	0.00	0.00	0.01
Null	11032.35	413.63	0.00	0.00	0.00

Finally, we used the best identified hydrologic and non-hydrologic variables, 40-day peak discharge with 0% of last year's flow and wetted width, along with other geomorphic and management variables to develop a suite of models to explain total unvegetated channel width observed from 2007 to 2015 (Table I-5). We included variables in final models with seemingly little explanatory power based on AIC values reported in step four. These included variables that were hypothesized to explain trends in total unvegetated channel width not captured by wetted width and 40-day peak discharge. For example, disking was included in the final modeling step due to the hypothesis disked transects generally had wider total unvegetated channel width than non-disked channels regardless of wetted width or 40-day peak discharge value.

Table I-5. Akaike's Information Criterion (AIC), quantile regression (τ = 0.5) model selection results of annual total unvegetated channel width in the Associated Habitat Reach (AHR), 2007–2015.

Non-Hydrological AIC table	AIC	ΔAIC	Likelihood	AICw	R[1]
40-Day Peak + Disking + Herbicide + Wetted Width	10181.85	0.00	1.00	0.56	0.42
40-Day Peak + Disking + Wetted Width	10182.35	0.50	0.78	0.44	0.42
40-Day Peak + Disking + Herbicide + Median Grain Size	10441.50	259.65	0.00	0.00	0.32
40-Day Peak + Disking + Median Grain Size	10445.46	263.61	0.00	0.00	0.32
40-Day Peak + Disking + Herbicide + River Mile	10446.75	264.89	0.00	0.00	0.32
40-Day Peak + Disking + Mile	10454.41	272.56	0.00	0.00	0.31
40-Day Peak	10617.94	436.08	0.00	0.00	0.23
Null	11032.35	850.50	0.00	0.00	0.00

[1]Null model tests the hypothesis that unobstructed channel width remained constant from 2007-2015.

Appendix II. Maximum Unobstructed Channel Width (MUOCW) robust linear regression model selection results from multi-step process.

Table II-1. Akaike's Information Criterion (AIC), quantile regression ($\tau = 0.5$) model selection of peak discharge duration influence on unobstructed channel width in the Associated Habitat Reach (AHR), 2007–2015. Results correspond to unobstructed channel width model selection step 1.

Peak Discharge Duration	AIC	ΔAIC	Likelihood	AICw	R[1]
40 Days	10694.6	0.00	1.00	1.00	0.08
20 Days	10723.8	29.20	0.00	0.00	0.06
30 Days	10724.8	30.15	0.00	0.00	0.06
10 Days	10726.9	32.27	0.00	0.00	0.06
5 Days	10734.8	40.21	0.00	0.00	0.06
50 Days	10735.6	41.01	0.00	0.00	0.06
60 Days	10738.4	43.73	0.00	0.00	0.06
3 Days	10743.2	48.56	0.00	0.00	0.05
1 Day	10759.4	64.77	0.00	0.00	0.04
Null	10825.1	130.51	0.00	0.00	0.00

Table II-2. Akaike's Information Criterion (AIC), quantile regression ($\tau = 0.5$) model selection of current and previous year 40-day peak discharge influence on unobstructed channel width (UOCW) in the Associated Habitat Reach (AHR), 2007–2015. Results correspond to UOCW model selection step 2.

Previous Year Discharge	AIC	ΔAIC	Likelihood	AICw	R[1]
40-Day Peak with 0% Last Year	10694.64	0.00	1.00	1.00	0.08
40-Day Peak with 60% Last Year	10720.06	25.42	0.00	0.00	0.07
40-Day Peak with 40% Last Year	10720.16	25.52	0.00	0.00	0.07
40-Day Peak with 80% Last Year	10722.88	28.24	0.00	0.00	0.06
40-Day Peak with 20% Last Year	10723.58	28.94	0.00	0.00	0.06
40-Day Peak with 100% Last Year	10727.13	32.49	0.00	0.00	0.06
Null	10825.15	130.51	0.00	0.00	0.00

Table II-3. Akaike's Information Criterion (AIC), quantile regression (τ = 0.5) model selection of mean minimum discharge 40-day peak discharge influence on unobstructed channel width (MUOCW) in the Associated Habitat Reach (AHR), 2007–2015. Results correspond to MUOCW model selection step 3.

Mean Minimum Discharge Duration	AIC	ΔAIC	Likelihood	AICw	R^1
30 Days	10805.11	0.00	1.00	0.38	0.01
20 Days	10805.24	0.12	0.94	0.36	0.01
10 Days	10805.91	0.80	0.67	0.25	0.01
40 Days	10812.55	7.44	0.02	0.01	0.01
Null	10825.15	20.03	0.00	0.00	0.00

Table II-4a. Akaike's Information Criterion (AIC), quantile regression (τ = 0.5) model selection of hydrologic variables on unobstructed channel width (UOCW) width in the Associated Habitat Reach (AHR), 2007–2015. Results correspond to UOCW model selection step 4a.

Hydrological AIC table	AIC	ΔAIC	Likelihood	AICw	R^1
40-Day Peak Discharge	10694.64	0.00	1.00	1.00	0.08
Mean June Discharge	10766.91	72.27	0.00	0.00	0.04
Mean Growing Season Discharge	10780.44	85.80	0.00	0.00	0.03
30-Day Minimum Discharge	10805.11	110.47	0.00	0.00	0.01
Null	10825.15	130.51	0.00	0.00	0.00

Table II-4b. Akaike's Information Criterion (AIC), quantile regression (τ = 0.5) model selection of non-hydrologic variables on unobstructed channel width (UOCW) width in the Associated Habitat Reach (AHR), 2007–2015. Results correspond to UOCW model selection step 4b.

Non-Hydrological AIC table	AIC	ΔAIC	Likelihood	AICw	R^1
Main Channel Wetted Width	10738.56	0.00	1.00	1.00	0.05
Median Grain Size	10755.30	16.74	0.00	0.00	0.04
MILE	10771.16	32.60	0.00	0.00	0.04
Disking	10789.43	50.86	0.00	0.00	0.02
Herbicide	10809.12	70.56	0.00	0.00	0.01
Channel Slope	10820.28	81.72	0.00	0.00	0.00
Channel Consolidation	10825.67	87.11	0.00	0.00	0.00
Null	10825.15	86.58	0.00	0.00	0.00

Table II-5. Akaike's Information Criterion (AIC), quantile regression (τ = 0.5) model selection results of annual maximum unobstructed channel width (MUOCW) in the Associated Habitat Reach (AHR), 2007–2015. Results correspond to MUOCW model selection step 5.

Combined Models	AIC	ΔAIC	Likelihood	AICw	R^1
40-Day Peak + Main Channel Wetted Width + Disking + Herbicide + Median Grain Size	10581.75	0.00	1.00	0.69	0.15
40-Day Peak + Main Channel Wetted Width + Disking + Median Grain Size	10584.56	2.81	0.25	0.17	0.15
40-Day Peak + Main Channel Wetted Width + Disking + River Mile + Herbicide	10585.73	3.99	0.14	0.09	0.15
40-Day Peak + Main Channel Wetted Width + Disking + River Mile	10588.51	6.76	0.03	0.02	0.14
40-Day Peak + Main Channel Wetted Width + Disking	10588.73	6.98	0.03	0.02	0.14
40-Day Peak + Main Channel Wetted Width	10627.11	45.36	0.00	0.00	0.12
Null	11032.35	450.60	0.00	0.00	0.00

Appendix III. Oracle Crystal Ball Monte Carlo simulation results for top MUOCW Quantile regression model at the 0.5 quantile. Variable distributions are presented in figures III-1:5 and figure III-6 displays the sensitivity analysis results.

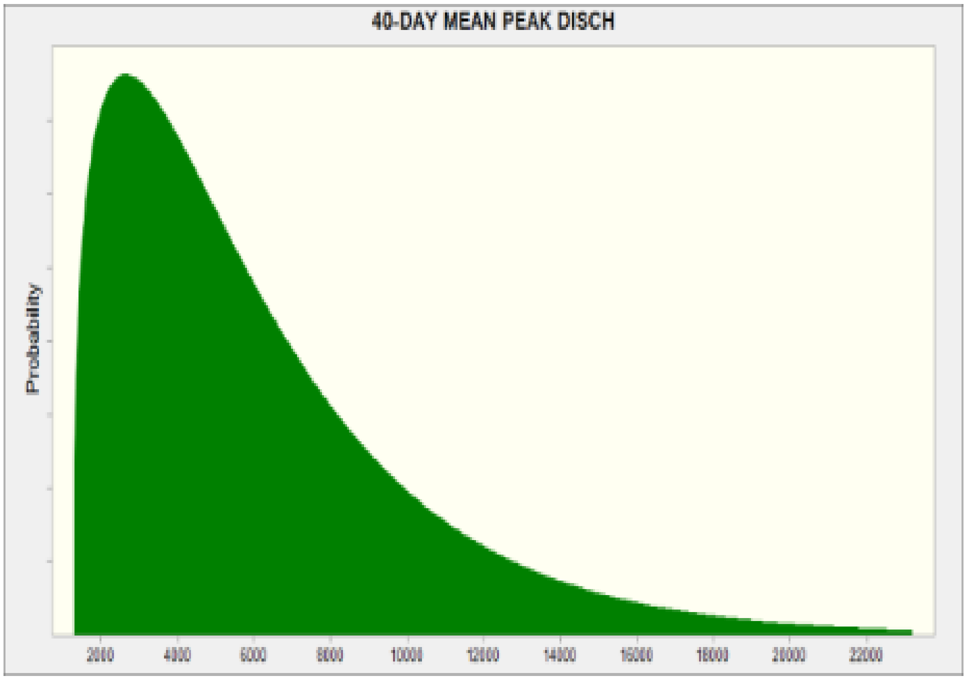

Figure III-1. Gamma distribution fitted to the predictor variable "40-day peak" for use in a sensitivity analysis through Monte Carlo simulation.

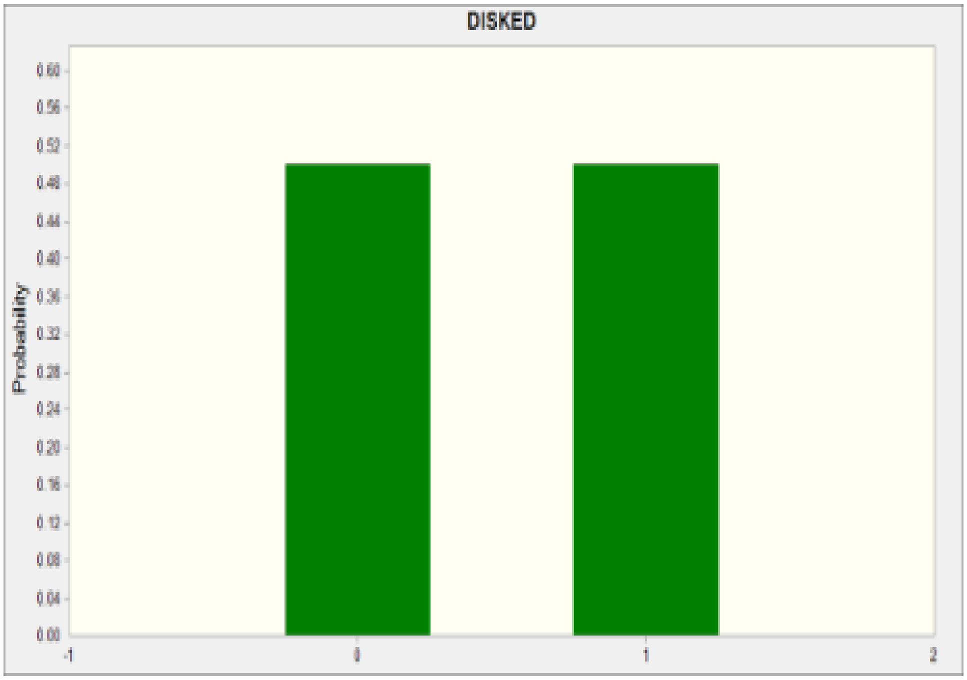

Figure III-2. Uniform distribution fitted to the binary predictor variable "Disking" for use in a sensitivity analysis through Monte Carlo simulation.

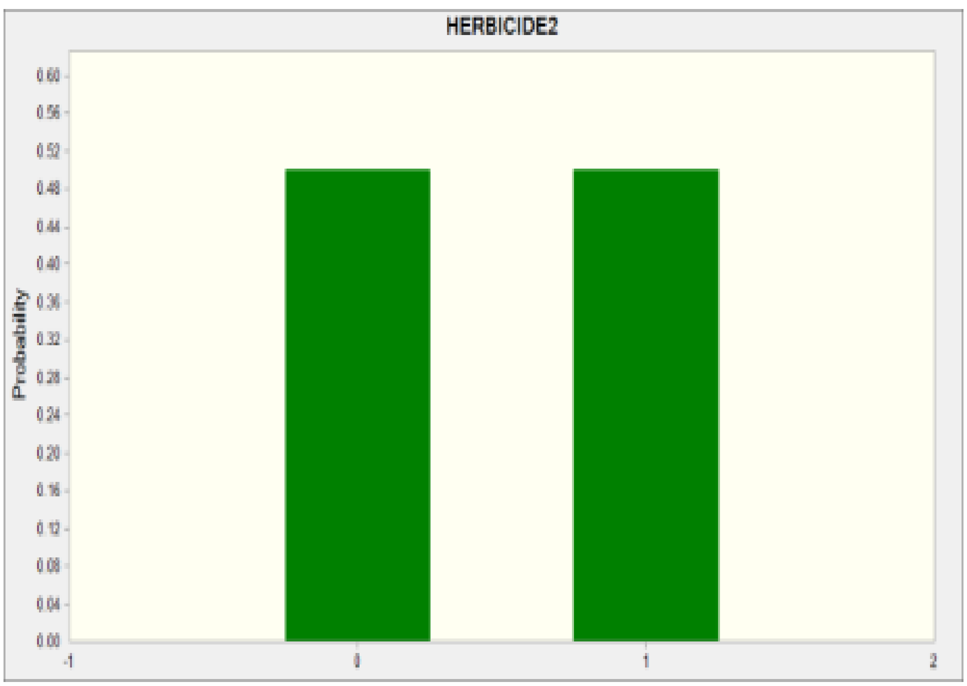

Figure III-3. Uniform distribution fitted to the binary predictor variable "Herbicide" for use in a sensitivity analysis through Monte Carlo simulation.

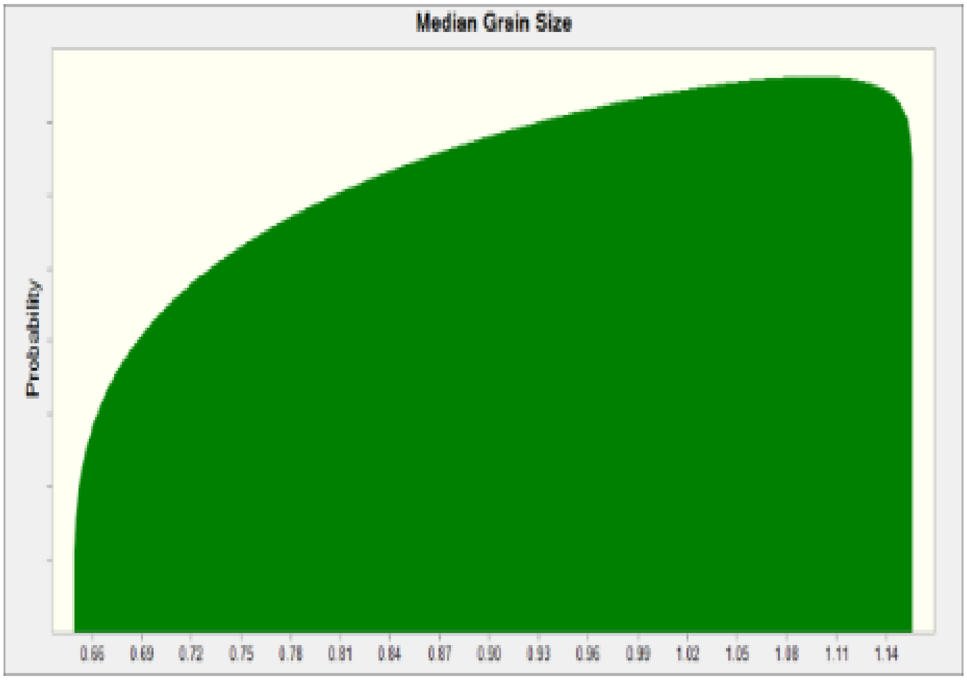

Figure III-4. Beta distribution fitted to the binary predictor variable “Median Grain Size” for use in a sensitivity analysis through Monte Carlo simulation.

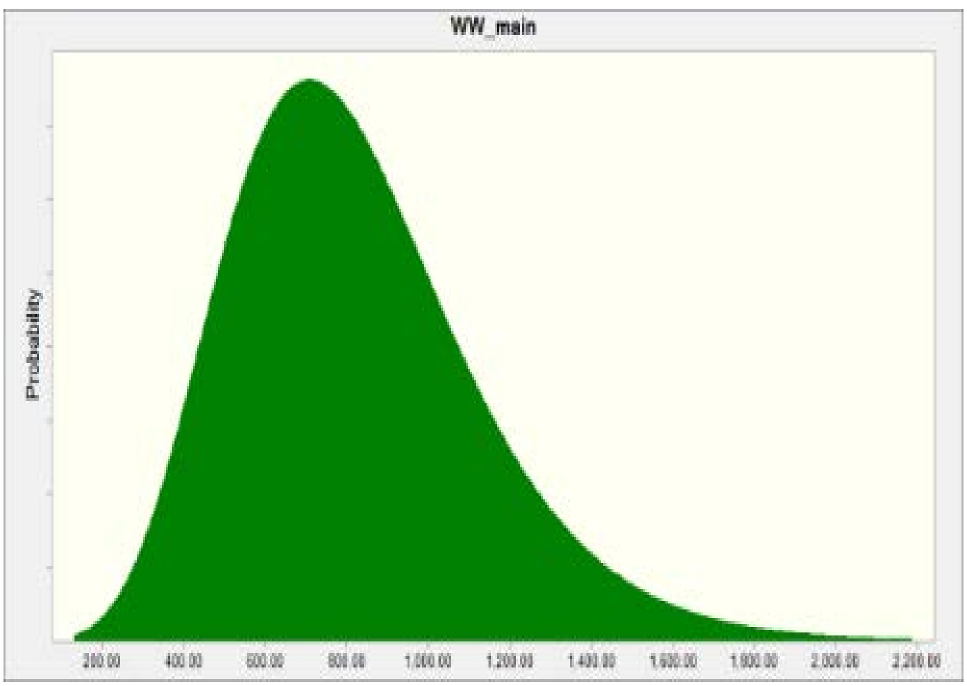

Figure III-5. Lognormal distribution fitted to the binary predictor variable “Main Channel Wetted Width” for use in a sensitivity analysis through Monte Carlo simulation.

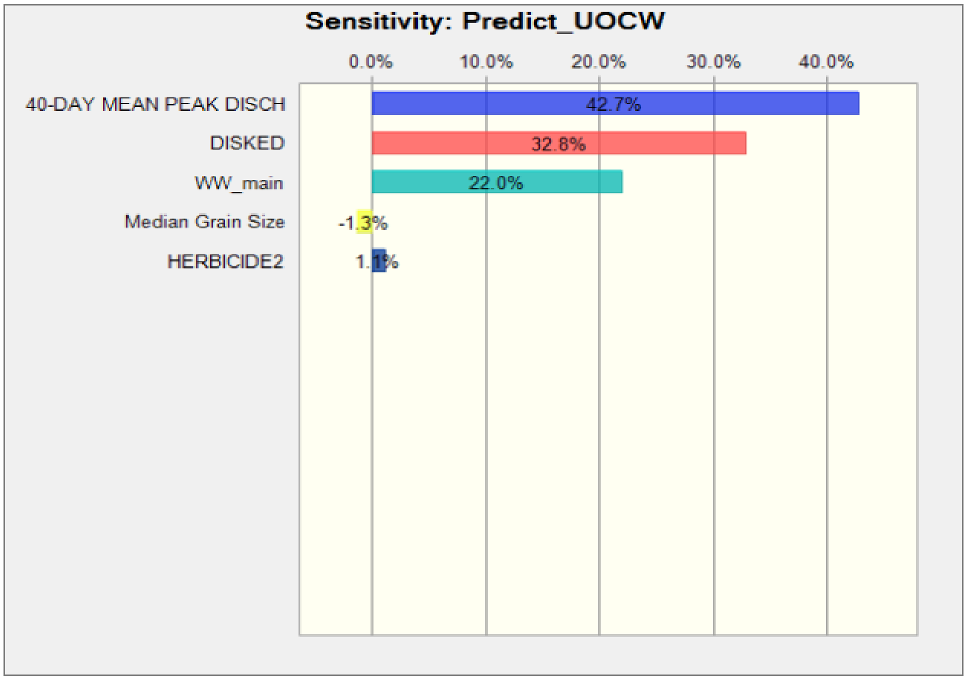

Figure III-6. Monte Carlo simulation sensitivity results for the response variable "Maximum Unobstructed Channel Width".

SUMMARY OF KEY FINDINGS

To date, the Platte River Recovery Implementation Program (Program) has invested nine years implementing an Adaptive Management Plan (AMP) to evaluate, in part, the Program's ability to contribute to the survival of whooping cranes during migration through increased habitat suitability and use of the Associated Habitat Reach (AHR). During this time, enough progress has been made to allow us to address critical uncertainties and assess the performance of the Flow-Sediment-Mechanical (FSM) management strategy. In short, given the results of our weight of evidence approach outlined in Chapters 1-4, the Executive Director's Office (EDO) of the Program concludes implementation of the FSM strategy will not create or maintain suitable in-channel roosting habitat for whooping cranes. A narrative of key findings follows.

We used data collected systematically along the central Platte River during 2001-2013 to evaluate riverine habitat selection within the AHR. The goal of our analysis was to develop habitat models to be used to inform and direct management activities the Program is able to implement. We were unable to establish a relationship between whooping crane use and flow metrics or total channel width, but rather found unobstructed channel width and distance to the nearest forest were good predictors of whooping crane use. Our findings indicate the Program would have the potential to influence whooping crane use of the central Platte River through increasing unobstructed channel widths that are <500ft and mechanically removing trees within areas where the unforested corridor width is <1,000ft.

We also used telemetry data obtained over the course of five years, 2010-2014, to provide an unbiased evaluation of whooping crane use of riverine habitat throughout the migration corridor. Based on findings in Chapter 2, we evaluated the influence of unobstructed channel width and distance to nearest forest on whooping crane selection of riverine habitat throughout the North-central Great Plains in the United States. Our results indicate probability of selection for unobstructed channel width was maximized around 650 ft and unforested corridor width was maximized around 1,000ft. Based on results of Chapters 2 and 3, the Program informally accepted unobstructed channel widths of at least 600 ft and unforested corridor widths of at least 1,000 ft as highly favorable whooping crane riverine roosting habitat and as management objectives for whooping crane habitat at the Program's Pawnee complex between Odessa and Kearney, Nebraska.

As a final step, we used annual delineations of total channel width and maximum unobstructed channel width throughout the AHR to evaluate several flow and mechanical management alternatives hypothesized to create and maintain whooping crane roosting habitat. Results of our quantile regression analyses indicate a positive relationship between unobstructed channel width and disking and peak discharge. Our results also indicate disking and flows substantially exceeding the magnitude and duration of a Short-Duration High Flow (SDHF) release are the only management activities able to create and maintain 600 ft unobstructed channel widths believed to be favorable for whooping crane roosting habitat.

Implementation of SDHF releases, the physical process driver of the FSM management strategy, is hypothesized to produce suitable riverine roosting habitat for whooping cranes within the AHR. However, natural high flow events in 2007, 2008, 2010, 2011, 2013, and 2014 all exceeded minimum SDHF magnitude and duration and only with the extreme high flow event occurring in 2015 did average unobstructed channel width exceed 600 ft. As such, our weight of evidence approach leads us to conclude implementation of the FSM management strategy will not create or maintain favorable whooping crane riverine roosting habitat. Mechanical creation and maintenance of in-channel roosting habitat in the AHR, however, is ongoing and evaluations of use of these habitats are forthcoming.