PLATTE RIVER HYDROLOGY AND SANDBAR DYNAMICS: IMPLICATIONS FOR TERN AND PLOVER REPRODUCTIVE ECOLOGY

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ABSTRACT

John William Hardy's (1957) concept of the physiological adaptation of interior least tern (*Sternula antillarum athalassos)* to begin nesting concurrent with recession of the spring rise has been embraced in Platte River literature and expanded to include piping plover (*Charadrius melodus*). The distributions of central Platte River tern and plover nest initiation dates were examined in relation to the annual hydrograph of the historical central Platte River and contemporary central and lower Platte River. An emergent sandbar habitat model was developed to evaluate the potential for reproductive success given observed hydrology, stage-discharge relationships, and sandbar height distributions. No evidence was found to suggest these species are physiologically adapted to begin nesting concurrent with the recession of the late spring rise on the Platte River. Model results indicate a limited potential for piping plover reproductive success due to the timing and length of the nesting and brood rearing period in relation to the timing of the late spring rise. Least tern success potential is higher due to the shorter nesting and brood rearing duration which increases the likelihood of successful renesting following nest loss during the late spring rise. Sensitivity analyses indicate the potential for reproductive success was most sensitive to sandbar height. Past species habitat suitability and productivity assessments based on the assumption that sandbars build to the water surface during peak flow events should be re-evaluated.

SHORT TITLE: Sandbar dynamics and tern and plover reproduction

KEY WORDS: central Platte River, hydrology, interior least tern, lower Platte River, piping plover, reproductive success, sandbar height distributions, stage-discharge relationships.

INTRODUCTION

Interior least tern (*Sterna antillarum athalassos*; hereafter, least tern) and piping plover (*Charadrius melodus*) are two species of endangered and threatened shore birds that nest on barren to sparsely vegetated riverine sandbars, sand and gravel pits, and along lake shorelines

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(USFWS, 1990). The Platte River Recovery Implementation Program (Program) has been tasked with improving tern and plover use and productivity along 145 km of the big bend reach of the Platte River in central Nebraska, USA. Program activities in this reach, known as the Associated Habitat Reach (AHR), are intended to mitigate declines in species habitat suitability due to water development in the Platte River basin (Department of the Interior, 2006).

The decline in AHR habitat suitability has been inferred from 1) the body of evidence documenting a substantial change in central Platte River hydrology and associated reduction in unvegetated channel width over historical timeframes, 2) the presence of species nesting on off-channel habitat, but lack of suitable sandbar nesting habitat and on-channel productivity in the contemporary central Platte River, and 3) species use of riverine habitat in the contemporary lower Platte River which experiences higher peak flow magnitudes. Implicit in this inference are the assumptions that on-channel productivity in the lower Platte is sufficient to maintain stable subpopulations and the lower Platte River is an analog for the historical central Platte prior to water development.

The hydrology of the central and lower Platte River is characterized by two spring rises, one in early spring due to localized snowmelt and one in the late spring due to snowmelt and precipitation runoff from basin headwaters in the high plains and Rocky Mountains (Murphy *et al.,* 2004). Investigations of breeding ecology of least tern and piping plover in the Platte basin have embraced Hardy's (1957) suggestion of a relationship between nesting and cessation of spring floods, stating that these species are adapted to begin nesting in the central Platte River after water levels recede in the spring and sandbars are exposed (Faanes, 1983; Sidle *et al.,* 1988; Kirsch, 1996). Thus, the lack of use and productivity in the central Platte River has been attributed to the reduction in the magnitude of the spring rise resulting in unsuitably-low sandbar habitat likely to be inundated as a result of rainfall events during the nesting season (USFWS, 2006).

The relationship between the annual hydrograph, sandbar habitat and species ecology has been explored and debated in other river systems (Dugger *et al.,* 2002; Jorgensen, 2009; Catlin *et al.,* 2010). These relationships and statements about the similarities of the contemporary lower Platte River and the historical central Platte River have been debated, but not evaluated through comparative analyses. The objectives of this investigation were to: 1) examine the timing of the late spring rise in relation to least tern and piping plover nesting ecology on the historical and contemporary central Platte River and the contemporary lower Platte River and 2) compare and contrast the potential for on-channel species productivity in the central and lower Platte River segments given our current understanding of channel hydraulics and sandbar height relationships.

METHODS

Study Areas

Two segments of the Platte River in Nebraska were included in this study (Figure 1). The AHR in central Nebraska USA is a 145 km stretch of river extending from Lexington downstream to Chapman, Nebraska. The lower Platte River (LPR) study area is a 53 km stretch of river extending from the confluence of the Elkhorn River to the Missouri River near Plattsmouth, Nebraska. This segment has the highest incidence of on-channel nesting in the Platte River basin.

Nest and Brood Exposure Data

The specific dates least tern and piping plover initiate nests, hereafter referred to as nest initiation dates, were compiled from all on- and off-channel central Platte River monitoring data for the period of 2001– 2013 (Baasch, 2014). Standardized Program nest exposure periods (nest initiation to chick fledging) were used to establish the nesting and brood rearing period for each species (Baasch *et al*., 2015). To eliminate the disproportionate effect of early and late nests on the length of the nest initiation season, the 5th and 95th percentile of the nest initiation dates were used to define the nest initiation window. A direct analysis of on-channel only nest initiation dates in relation to peak discharge dates was not possible given the paucity of on-channel nesting in the central Platte River and lack of season-long systematic monitoring data for the LPR.

Historical Central Platte River Flow Record Extension

Mean daily flow observations in the historical AHR (1895–1938) were of specific interest in this study. However, with the exception of a five-year period from 1902–1906, they were unavailable prior to 1915 (Stroup *et al.*, 2006). Mean daily flows were, however, available upstream on the North Platte River near North Platte in all years but 1910 and on the North Platte River above Lake McConaughy in all years except 1913–1914 (Stroup *et al.*, 2006). A flow record extension technique, Maintenance of Variance Extension Type 1 (MOVE.1; Hirsch, 1982), was used to estimate mean daily flows on the Platte River near Overton, Nebraska from 1895–1914 using upstream flow observations. The North Platte River data near North Platte, Nebraska was used to develop flow estimates for the period of 1895–1914 with the exception of 1910 which used the North Platte River data above Lake McConaughy. Model performance was assessed by comparing MOVE.1 estimated and observed Platte River flows near Overton, Nebraska, 1902–1906 using Nash Sutcliffe Coefficient of Efficiency (NSCE; Nash and Sutcliffe, 1970). The NSCE values for the application of the MOVE.1 method for the North Platte River at North Platte and above Lake McConaughy were deemed acceptable with NSCE values of 0.75 and 0.70, respectively. The historical central Platte River daily discharge records from the flow record extension exercise (1895–1914) were combined with records from USGS Gage 06768000 at Overton (1915–1938) to produce a 44 year historical AHR data series.

Contemporary Central and Lower Platte Discharge

Daily discharge records for the contemporary central and lower Platte River reaches were retrieved from the U.S. Geological Survey (USGS, 2001) National Water Information System (NWIS) for 1954–2012, which was the longest concurrent period of record for both the central and lower Platte River gages. Gage 06770500 at Grand Island, Nebraska was used for AHR hydrology and gage 06805500 at Louisville, Nebraska was used for the LPR hydrology.

Species Nest Initiation in Relation to Platte River Hydrology

The annual hydrograph was computed for the historical AHR and contemporary AHR and LPR reaches from mean daily discharge records. The hydrographs were plotted against the distribution of AHR least tern and piping plover nest initiation dates to evaluate the relative timing of the species nest initiations period in relation to annual peaks. A more detailed within-year analysis of nesting in relation to peak flows was not possible due to the lack of systematically collected season-long monitoring data in the historical AHR and contemporary LPR reaches.

Modeling the Availability of Emergent Sandbars

<u>Stage-Discharge Relationships</u>

Stream gage stage-discharge rating curves were used to characterize river hydraulics in the contemporary reaches in an effort to be consistent with previous analyses (Parham, 2007; Jorgensen, 2009). However, critiques of similar analyses in other systems caution that use of hydraulic data at gage locations may not be representative of the geomorphic variability of a river system, specifically in reaches with least tern and piping plover nesting (Jorgensen, 2009; Catlin *et al.*, 2010). To address this concern, stage-discharge relationships at gage locations were compared to best-available hydraulic data at nest sites. In the contemporary AHR, limited nesting has occurred on sandbars at river kilometers 320 and 370 (Baasch, 2014). Modeled HEC-RAS stage-discharge relationships at these locations were compared to USGS stage-discharge rating curves for the Kearney and Grand Island, Nebraska gages (HDR Inc. *et al.*, 2011). No stream gage stage-discharge relationships exist for the historical AHR. As such, the stage-discharge relationship for the historical AHR was generated from a HEC-RAS hydraulic model of the historical channel near Odessa, Nebraska (Simons & Associates Inc., 2012).

In the LPR, a Federal Emergency Management Agency HEC-2 hydraulic model was used to make a similar comparison (HDR Inc. *et al.*, 2009). Stage-discharge relationships at the Louisville and Ashland, Nebraska gages were compared to modeled stage-discharge relationships in the Cedar Creek and Gun Club reaches, which have consistently supported nesting (Brown and Jorgensen, 2008, 2009, 2010; Brown *et al.*, 2011, 2012, 2013).

<u>Sandbar Heights</u>

A combination of remote-sensing data and hydraulic modeling data were used to develop a distribution of sandbar heights relative to peak stage in the contemporary AHR following a natural high-flow event that occurred in 2010. The USGS conducted field surveys of sandbar topography in the LPR following the 2010 event and generated a similar sandbar height distribution (Alexander *et al.*, 2013). Sandbar data was not available for the historical AHR.

<u>Emergent Sandbar Availability Model</u>

A spreadsheet model was developed to estimate the annual availability of emergent sandbar habitat during the nesting season using discharge records, stage-discharge relationships, and observed sandbar heights in the AHR and LPR segments. Model input and output variables are listed in Table 1.

Model operations/calculations for each analysis year included:

1. Identify maximum daily discharge for the period from 1 January the year prior to each analysis year and ending 1 July of the analysis year. Maximum flow during this period was considered to be the habitat-forming discharge ($DISCH_{HAB}$) controlling the height of sandbars in the analysis year. The 1.5 year period for identification of $DISCH_{HAB}$ allowed for sandbar persistence through two nesting seasons.
2. Calculate stage ($STAGE_{HAB}$) of the habitat-forming discharge for each nesting season from gage stage-discharge relationship.
3. Calculate the stage associated with sandbars ($STAGE_{BAR}$) for each nesting season by subtracting sandbar height (BAR HEIGHT) relative to peak stage from $STAGE_{HAB}$.
4. Calculate daily stage ($STAGE_{DAILY}$) during the least tern and piping plover nesting and brood rearing seasons of each year.
5. Compare daily river stage ($STAGE_{DAILY}$) to sandbar stage ($STAGE_{BAR}$) to determine if bar height exceeded river stage (i.e., were emergent).
6. Calculate the maximum number of contiguous days during each nesting and brood rearing seasons when bar height exceeded stage.
7. Subtract period for successful nesting and brood rearing (64 days for piping plovers and 49 for least terns; Table 2) from maximum contiguous days with emergent sandbars to determine the number of days during each nesting season when a nest could have been initiated and successfully fledge chicks without being inundated (SUCCESS WINDOW).

Model Sensitivity to Stage-Discharge Relationships and Sandbar Height

The contemporary AHR and LPR reach models were run for the period of 1954–2012 and the historical AHR model was run for the period of 1895–1938. The median SUCCESS WINDOWs were calculated for each species as well as the percent of years when there was no SUCCESS WINDOW (0 days) and the percent of years when the SUCCESS WINDOW encompassed the entire nesting seasons. The sensitivity of SUCCESS WINDOW to stage-discharge relationships and sandbar heights was assessed using Oracle® Crystal Ball software. Monte Carlo simulations were run with triangular distribution of stage per unit discharge ranging from 70% – 130% of the default model value, approximating the range of observed stage-discharge relationships in the reaches. Sandbar heights were varied by ±0.46 meters from the default model value to represent bar height potential ranging from at peak stage to approximately 1 m below peak stage. Each input variable's contribution to variance in species SUCCESS WINDOW output was used to assess sensitivity.

RESULTS

Species Nest Initiation in Relation to Platte River Hydrology

The contemporary AHR nest initiation window for piping plovers was 1 May – 23 June and was 28 May – 16 July for least terns (Table 2). Approximately 90% of on-channel least tern and piping plover nest initiation dates reported on the lower Platte River during the period of 2008–2013 also fell within the same timeframes (Brown and Jorgensen, 2008, 2009, 2010; Brown *et al.*, 2011, 2012, 2013). The entire nesting and brood rearing season for piping plovers encompassed the period from 1 May – 26 August and 28 May – 30 August for least terns (Table 2).

Two spring rises were evident in the annual hydrographs of the historical AHR, contemporary AHR and contemporary LPR (Figure 2). The first occurred in the February–March period and the second peak occurred in mid-June. The peaks were less defined in the contemporary AHR due to the flow damping influence of storage reservoirs (Simons & Associates Inc. and URS Greiner Woodward Clyde, 2000). The beginning of the piping plover nest initiation window coincided with the end of the early-spring rise, but peaked a month prior to the late-spring rise in June (Figure 2). The nest initiation window for least tern coincided more closely with the late-spring rise, although the peak of initiation still preceded the mid-June peak (Figure 2).

Modeling the Availability of Emergent Sandbars

<u>Stage-Discharge Relationships</u>

Stage-discharge relationships for the Grand Island (06770500) and Ashland gages (06801000) were most representative of nesting colony locations within the AHR and LPR, respectively (Figures 3 and 4). It was not possible to directly assess the representativeness of the stage-discharge relationship for the historical AHR. However, channel width in the modeled reach near Odessa, Nebraska (1,300 m) was similar to that of the channel near Lexington, Nebraska, (1,220 m) where the earliest on-channel nesting in the AHR was observed (Wyoff, 1960) providing some confidence that the relationship was reasonable.

<u>Sandbar Heights</u>

Median bed material grain size in the contemporary AHR is approximately 0.96 mm and in the LPR is 0.22 mm. The median sandbar height in the AHR in 2010 was 0.46 m below peak stage and the median height in the LPR was 0.61 m below peak stage (Program unpublished report; Figure 5). The slightly lower sandbar heights relative to peak stage observed in the lower Platte River were consistent with published bedform height relationships in which bedform height potential decreases as bed material grain size decreases (Ikeda, 1984; Van Rijn, 1984; Julien and Klaassen, 1995). The median bed material grain size of the historical AHR of approximately 0.4 mm (USACE, 1931) was finer than the contemporary AHR (0.96 mm) and coarser than the LPR (0.22 mm). Consequently, median sandbar heights would be expected to range between 0.46 m and 0.61 m below peak stage. A median sandbar height of 0.46 m was used in the historical AHR model to provide a conservatively high estimate of sandbar heights.

Emergent Sandbar Availability Model

We found the median annual windows that species could have initiated a nest and successfully fledged chicks (SUCCESS WINDOW) to be highest in the LPR Reach and lowest in the Historical AHR (Table 3). However, the median SUCCESS WINDOW for piping plover was minimal in all reaches (<5 days). The SUCCESS WINDOW for least terns was somewhat higher in the LPR and Contemporary AHR reaches. However, the potential for season-long successful nesting was less than 30% for both species in all reaches. Overall, the model predicted limited potential for successful fledging either species in the Historical AHR and piping plover in the contemporary reaches. The potential for successful fledging of least tern chicks was somewhat higher in the contemporary reaches, although the median window was only three weeks in the LPR and two weeks in the contemporary AHR.

Model Sensitivity to Stage-discharge Relationships and Sandbar Height

The emergent sandbar model sensitivity analysis indicated that the median SUCCESS WINDOW for all reaches was insensitive to stage-discharge and quite sensitive to sandbar height input variables. In all cases, over 90% of the variance in SUCCESS WINDOW was attributable to sandbar height (Table 4).

DISCUSSION

Timing of Annual Hydrograph in Relation to Tern and Plover Nesting Ecology

The late-spring rise on the Platte River typically occurs during mid-June and recedes in late-June or July. Least tern and piping plover nest initiation dates within the AHR peak 2–4 weeks prior to the late spring rise. The nesting ecology of the piping plover appears to be especially problematic because the late-spring rise often occurs after most nests have been initiated and, given the length of the nesting and brood rearing season, there is little potential for renesting. The peak of least tern nest initiation also often occurs prior to the late-spring rise, but the later overall nest initiation window and shorter nesting and brood rearing periods provide more potential for renesting following a late-spring rise.

Potential for Successful Nesting

Previous AHR and LPR analyses predicted the potential for successful nesting in most years (Parham, 2007; USFWS, 2006). In contrast, the emergent sandbar habitat model predicts limited potential for successful nesting in the contemporary AHR and LPR Reaches and extremely limited potential in the historical AHR. The widely differing predictions are the result of the prior assumption that sandbars build to the peak flow stage during the annual peak flow. This assumption is challenged by the empirical analyses of sandbar heights discussed herein. It is also challenged by observations of nest loss due to flood events.

Wycoff (1960) provided the earliest least tern nest records in the historical AHR. His observations in the 1940s occurred slightly after the historical AHR model period, but before substantial changes in AHR channel width occurred. In 1947, a mean daily peak discharge of 394 cms occurred on 23 June. On-channel nests observed in 1948 were inundated twice even though the highest mean daily peak discharge during the 1948 nesting season was 127 cms which is well below the hypothesize habitat-forming discharge of 394 cms.

In 1978, discharge in the AHR peaked at 297 cms. Faanes (1983) reported all on-channel least tern and piping plover nests in 1979 were inundated by flows of 85 cms. In 2014, two least tern nests were initiated within the AHR following the 2013 high flow event that had a peak mean daily discharge of 286 cms (Baasch, 2014); those nests were inundated at 82 cms. The contemporary AHR model predicted that the 1979 nests would have been inundated at 123 cms and 2014 nests inundated at 116 cms.

Similarly, a discharge of 2,379 cms within the LPR at Louisville in 2008 produced sandbar habitat inundated by a discharge of 595 cms in 2009, flooding 50 least tern and 14 piping plover nests (Brown and Jorgensen, 2009). In 2010, a mean daily peak discharge of 3,398 cms at Louisville produced sandbar habitat inundated in 2011 at a peak discharge of 940 cms flooding all 56 least tern and 7 piping plover nests observed on the river (Brown *et al.*, 2011). The contemporary LPR model predicted that the 2009 nests would have been inundated at 968 cms and 2011 nests inundated at 1,489 cms.

These comparisons indicate the sandbar model slightly over-predicts the discharge necessary to inundate sandbars used by the species. Consequently, sandbar heights of 0.45 m below peak stage in the AHR and 0.61 m in the LPR appear to be conservatively high and previous analyses assuming sandbars build to the water surface seriously underestimated the potential for nest loss due to inundation.

Nest loss to flooding is a natural event to which least terns, and to some extent piping plovers, have adapted to through renesting and other reproductive strategies (Sidle *et al.*, 1992; Kirsch and Sidle, 1999). The potential for success of late season renesting is a model uncertainty linked to the viability of on-channel nesting following the late spring rise. A considerable level of tern renesting has been reported in the LPR following flooding but chicks resulting from renesting events were not monitored to fledging age so it is unknown they fledged (Brown and Jorgensen, 2009; Brown *et al.*, 2011). Support of LPR monitoring of renesting events through fledging would allow for a better understanding of least tern population dynamics.

Decline in Central Platte River Habitat Suitability for Least Tern and Piping Plover

The decline of on-channel species habitat in the AHR has been inferred from the reduction in AHR channel width from the pre-development period, lack of on-channel nesting in the contemporary AHR, and species use of the LPR. This inference assumes the LPR currently supports reproductive levels sufficient to maintain species populations and that the LPR is a functional analog for the historical AHR. The assumption that the LPR is a functional analog for the historical AHR is not supported by this analysis. Channel width in the historical AHR was much wider than the contemporary LPR and flows were approximately 50% lower. Consequently, stage increase and the associated ability to build suitably-high sandbars was likely very limited. The late-spring rise also consistently occurred during mid-June, seriously limiting the potential for successful plover renesting.

An Alternative Hypothesis for the Persistence of Species Populations in the Platte Basin

Why then, do these species occur along the Platte River? An alternative view is suggested by historical and contemporary species use of both in- and off-channel habitats. The earliest species observations in the AHR include documentation of nesting on natural sandbars, artificially created on-channel islands comprised of spoil from a sandpit operation, and at an off-channel sandpits (Wycoff, 1960). In the lower portion of the basin, records in the late 1800s include off-channel nesting at rainwater basins and along lake shorelines (Pitts, 1988; Ducey, 2000).

In the contemporary LPR and AHR, these species routinely make use of off-channel habitats regardless of whether on-channel habitat is available or not (Baasch, 2014; Brown and Jorgensen, 2008, 2009, 2010; Brown *et al.*, 2011, 2012, 2013). These off-channel habitats have been viewed as an inferior alternative to on-channel nesting habitat that became necessary as on-channel habitat suitability declined over historical timeframes (Sidle *et al.*, 1993; National Research Council, 2005). However, the limited potential for success of on-channel nesting in the central and lower Platte and the consistent use of off-channel habitat, off-channel habitats may have allowed the species to expand into and persist in a basin where the hydrology is not ideally suited to their reproductive ecology.

Implications for Species Management in the Contemporary AHR

The results of these analyses and other ongoing least tern and piping plover research and monitoring efforts have led the Program to re-examine the benefits of management strategies that place a heavy emphasis on flow-created on-channel habitat. The Program has instead shifted towards species management activities focused primarily on maintaining a substantial supply of suitable off-channel habitat while providing a limited amount of on-channel habitat. Program decision-makers are currently engaged in a structured decision-making process to determine how much and what kinds of off- and on-channel habitat the Program will manage in the future.

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Table 1. Input and output variables for the emergent sandbar habitat model.

Model Input Variables	
$DISCH_{HAB}$	Maximum of mean daily flow (cms) from 1 January of the previous year through 1 July of analysis year. Considered to be the discharge that controlled sandbar height in analysis year
$STAGE_{HAB}$	River stage (m) associated with $DISCH_{HAB}$
BAR HEIGHT	Sandbar height (m) below peak stage.
$STAGE_{BAR}$	Stage (m) of sandbars
$DISCH_{DAILY}$	Daily river discharge (cms)
$STAGE_{DAILY}$	Daily river stage (m)
Model Output Variables	
SUCCESS $WINDOW_{PLOVER}$	Number of days when piping plover nests could be initiated, incubated, and hatch and the chicks successfully fledged without being inundated.
SUCCESS $WINDOW_{TERN}$	Number of days when least tern nests could be initiated, incubated, and hatch and the chicks successfully fledged without inundation.

Table 2. Ninetieth percentile of least tern and piping plover nesting and brood rearing dates within the Associated Habitat Reach (AHR), 2001–2013.

Nest Exposure Metric	Piping Plover	Interior Least Tern
Nest Count (Number of Nests)	287	770
Nest Initiation and Egg Laying Period (Days)[1]	8	3
Incubation Period (Days)	28	21
Brooding Period (Days)	28	21
Period for Successful Nesting (Days)[2]	64	45
First Nest Initiation Date (Day-Month)	1-May	28-May
First Hatch Date (Day-Month)[3]	6-Jun	21-Jun
First Fledge Date (Day-Month)[4]	4-Jul	12-Jul
Median Nest Initiation Date (Day-Month)	15-May	10-Jun
Median Hatch Date (Day-Month)	20-Jun	8-Jul
Median Fledge Date (Day-Month)	18-Jul	29-Jul
Last Nest Initiation Date (Day-Month)	23-Jun	16-Jul
Last Hatch Date (Day-Month)	29-Jul	9-Aug
Last Fledge Date (Day-Month)	26-Aug	30-Aug
Nesting Initiation Window (Days)	118	95

[1] Nest initiation date was determined by the date a nest (scrape with ≥1 egg) was first observed or by egg floating techniques.

[2] Nest initiation and egg-laying period + incubation period + brooding period

[3] Hatch date was determined by observations of ≥1 chick or was estimated based on chick age.

[4] Fledge date was determined by the earlier date between first observing sustained flight and a predefined fledging age for each species.

Table 3. Emergent sandbar habitat model output by reach.

		Median SUCCESS WINDOW (days)		*No SUCCESS WINDOW (% of years)*		*Season-Long SUCCESS WINDOW (% of years)*	
Reach	*Model Period*	*Piping Plover*	*Least Tern*	*Piping Plover*	*Least Tern*	*Piping Plover*	*Least Tern*
LPR Reach	*1954 -2012*	*4*	*21*	*42%*	*17%*	*22%*	*25%*
Contemporary AHR	*1895 -1938*	*0*	*14*	*53%*	*29%*	*25%*	*29%*
Historical AHR	*1954 -2012*	*0*	*0*	*84%*	*68%*	*5%*	*7%*

Table 4. Emergent sandbar habitat model median SUCCESS WINDOW sensitivity to stage-discharge and sandbar height input variable values. Monte Carlo sensitivity analysis utilized stage-increase per unit discharge range from 70% to 130% of default model value. Sandbar height range for AHR reaches ranged from 0 to 0.91 m below formative stage. Sandbar height range for LPR Reach ranged from 0.15 to 1.07 m below formative stage.

	Stage-Discharge (% of Variance)		*Sandbar Height (% of Variance)*	
Reach	*Piping Plover*	*Least Tern*	*Piping Plover*	*Least Tern*
LPR Reach	*6.0%*	*6.1%*	*94.0%*	*93.9%*
Contemporary AHR	*3.6%*	*5.3%*	*96.4%*	*94.7%*
Historical AHR	*2.0%*	*3.9%*	*98.0%*	*96.1%*

Lead Author: J. M. Farnsworth

Figure 1

Top of Figure

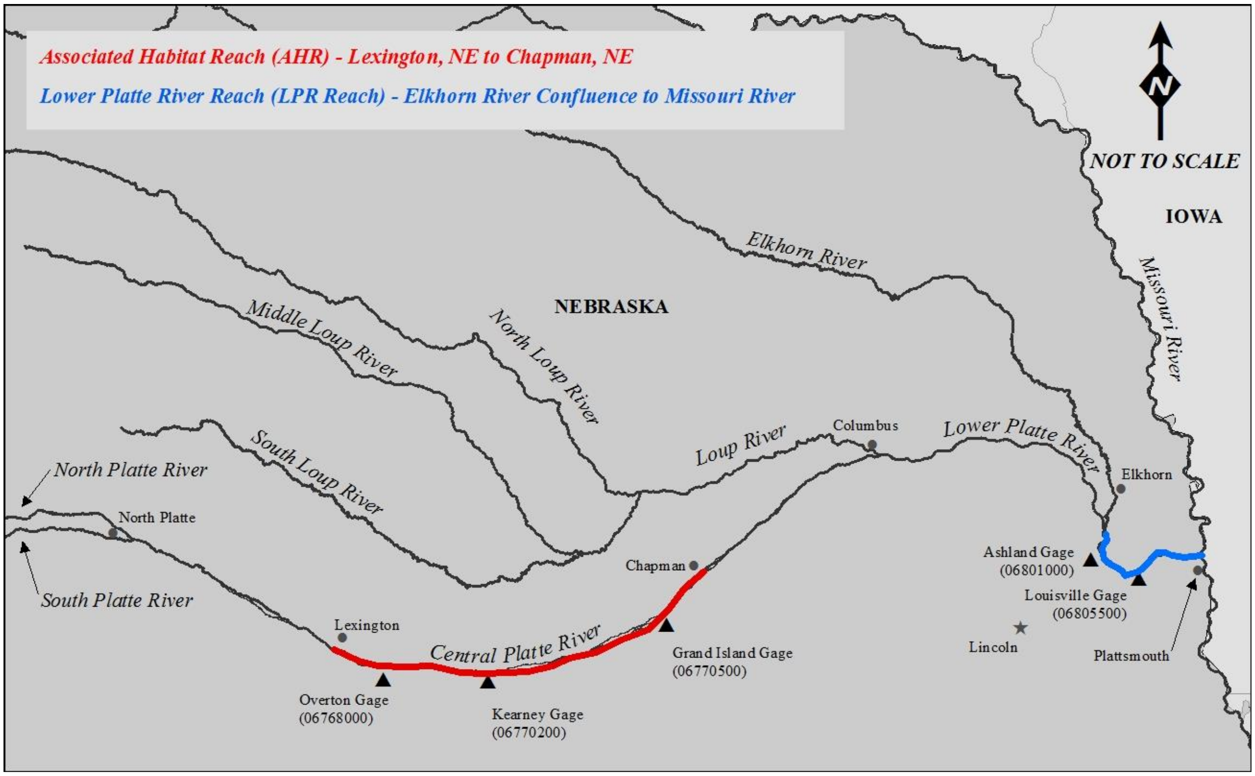

Figure 1. Location of AHR and LPR study areas and stream gages.

Lead Author: J. M. Farnsworth

Figure 2

Top of Figure

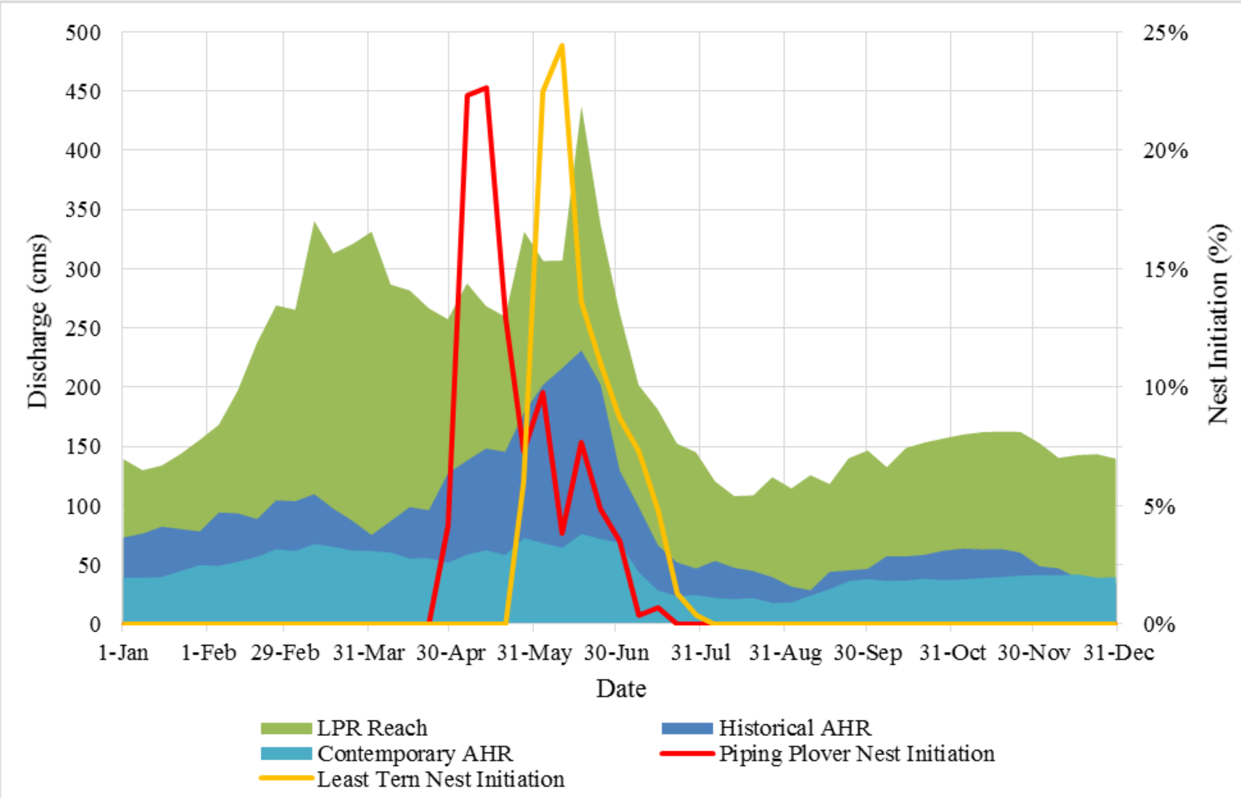

Figure 2. Distribution of AHR piping plover nest initiation dates (2001–2013) in relation to the annual hydrographs of the LPR (1954–2012), contemporary AHR (1954–2012) and historical AHR (1895–1938).

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Figure 3

Top of Figure

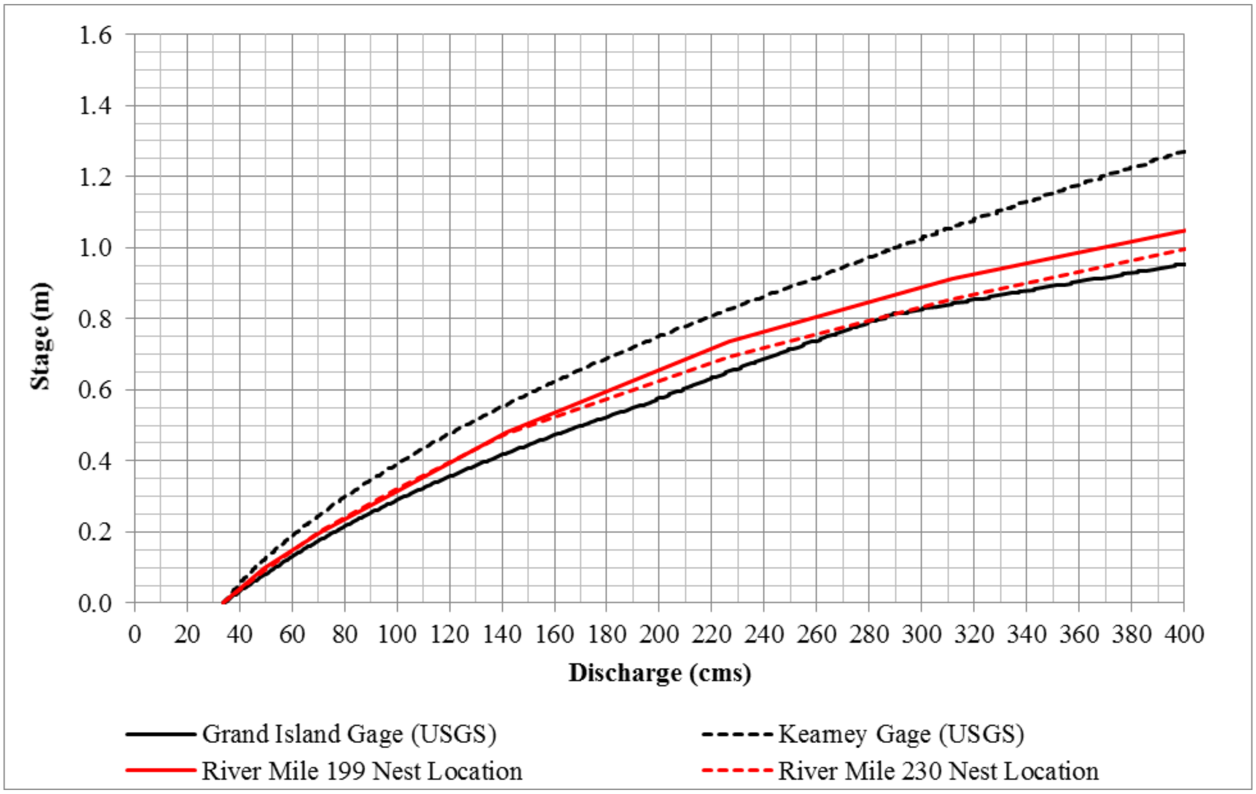

Figure 3. Comparison of contemporary Grand Island (06770500) and Kearney (06770200) stream gage stage-discharge relationships and HEC-RAS model stage-discharge relationships at river kilometer 515 and 595 in the AHR. All relationships were normalized to a stage of 0.0 m at 34 cms for comparison. The stage-discharge relationship at the Grand Island gage was within 0.09 m of the relationships at the nest locations throughout the discharge range and the shape of the curves was very similar.

Lead Author: J. M. Farnsworth

Figure 4

Top of Figure

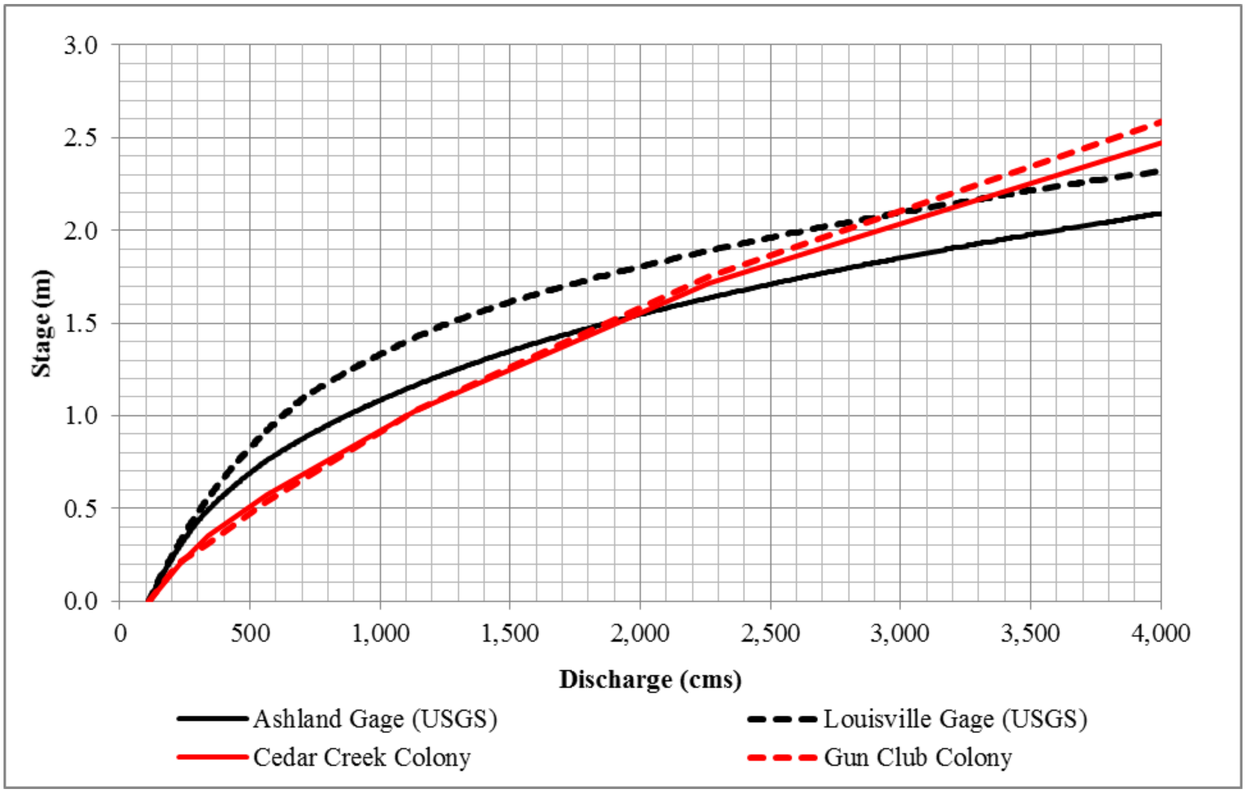

Figure 4. Comparison of Louisville (06805500) and Ashland (06801000) stream gage stage-discharge relationships and FEMA HEC-2 model stage-discharge relationships at Cedar Creek and Gun Club colony locations in the LPR. All relationships were normalized to a stage of 0.0 m at 113 cms for comparison.

Lead Author: J. M. Farnsworth

Figure 5

Top of Figure

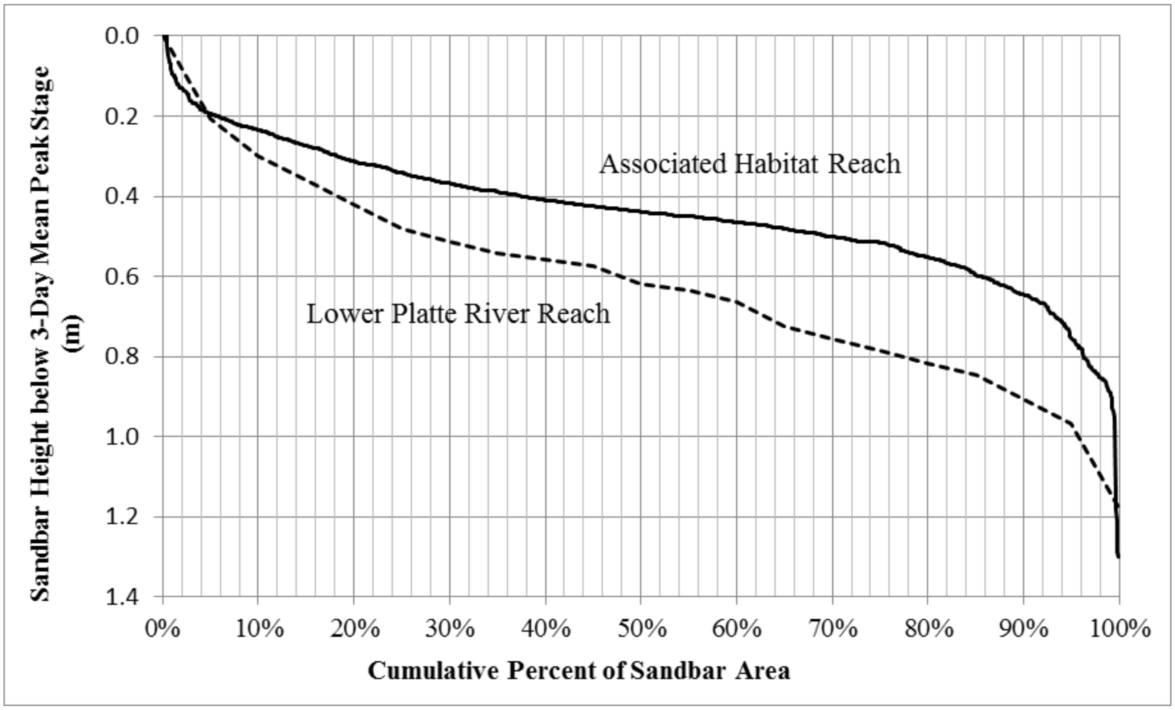

Figure 5. Cumulative distribution of heights of sandbars formed during the 2010 natural high-flow event.