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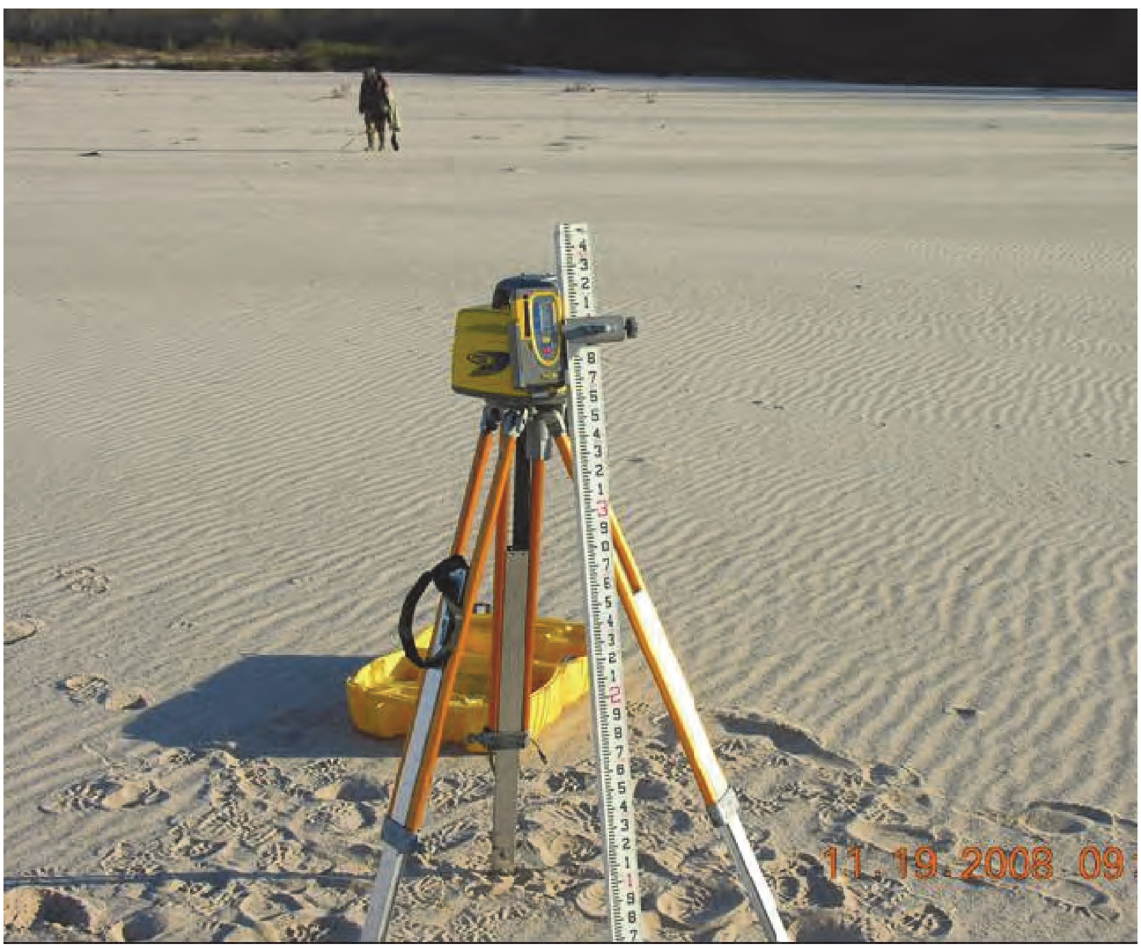
Effects of Dam Operations on Least Tern Nesting Habitat and Reproductive Success Below Keystone Dam on the Arkansas River

Casey A. Lott and Robert L. Wiley

December 2012



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Abstract

This report describes Least Tern (*Sternula antillarum*) sandbar nesting habitat (SNH) on the Arkansas River below Keystone Dam from field and GIS measurements after the 2008 nesting season. This season was preceded by 2 years with high-magnitude, long-duration dam releases (>50,000 cfs for >3 weeks), which resulted in major habitat renewal; replacing small, low-elevation sandbars that were mostly covered with vegetation with large, completely bare, high-elevation sandbars. Habitat measurements are reported relative to hydrographs that describe Keystone Dam operations for hydropower production and flood control (based on a post-dam era of 1977-2008). Habitat measurements for 2008-2009 were compared to a degraded habitat dataset that was simulated in ArcGIS based on descriptions in the most recent USFWS biological opinion for the Arkansas River. TernCOLONY, an individual-based model of Least Tern reproduction, was then used to evaluate how dam operations affect ILT reproduction, given these two sets of habitat conditions, across the range of dam operations. In simulations, infrequent nest flooding mortality was observed when habitat conditions were outstanding (e.g., after the high flows of 2007-2008). Conversely, regular nest mortality due to flooding, as well as higher predation rates, resulted in low reproductive success when habitat conditions were degraded. Given this baseline understanding, three different management alternatives were simulated that were designed to reduce flooding and/or predator mortality when habitat conditions are degraded (e.g., mechanical sandbar habitat restoration, predator control, and a combination of the two). Only management treatments that included predator control components were effective at increasing regional reproductive output. Since ILT populations experience periods with excellent habitat conditions and degraded habitat conditions at the decadal scales that affect population trajectories, widespread application of this type of evaluation would be helpful to assess the persistence of regional ILT populations considered important to the ILT metapopulation.

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Preface

The habitat measurement portion of this study was coordinated by American Bird Conservancy (ABC) under contract with the U.S. Army Engineer District, Tulsa. Point of Contact at the Tulsa District is Stephen A. Nolen. ABC subcontracted with David Miller & Associates, Incorporated, to lead field habitat measurements. This project was closely related to a larger effort, in collaboration with the U.S. Army Engineer Research and Development Center (ERDC), Penn State University, and Lang, Railsback & Associates to develop an individual-based model of Least Tern reproduction that can be used to assess the effects of river management on tern populations (Lott et al., in preparation a, b, c). Point of contact at the ERDC Environmental Laboratory is Dr. Richard A. Fischer.

Habitat measurements for this report were funded by the Tulsa District, as part of compliance with a Biological Opinion (U.S. Fish and Wildlife Service (USFWS) 2005a). Additional funds to support incorporation of these results into the individual-based modeling program were provided by the Dredging Operations and Environmental Research (DOER) Program. The program manager for DOER at the ERDC is Dr. Todd Bridges.

The authors would like to thank the following for their support regarding this project: Steve Nolen, Everett Laney, Jerry Sturdy, Tonya Dunn, Bill Chatron, Mary Ann Duke, and John Daylor at the Tulsa District; Steven Gebhardt of David Miller & Associates; Kevin Stubbs of USFWS; Steve Railsback, Colin Sheppard, and Michael Koohafken of Lang, Railsback, & Associates; Ed Laurent, Merrie Morrison, and David Pashley of American Bird Conservancy, and seasonal field workers Jeff Dacey and Hunter Wiley.

Commander of ERDC was COL Kevin J. Wilson. Director of ERDC was Dr. Jeffery P. Holland.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
inches	0.0254	meters
miles (U.S. statute)	1,609.347	meters
miles per hour	0.44704	meters per second
square feet	0.09290304	square meters
square miles	2.589998 E+06	square meters

1 Introduction

Background

Least Terns (*Sternula antillarum*) are fish-eating birds that nest on bare substrates in a variety of open habitats on rivers and coasts (Thompson et al. 1997). The interior population of the Least Tern (ILT) is defined as all Least Terns nesting >50 miles from the Gulf of Mexico on rivers of the Great Plains and in the Lower Mississippi Valley (U.S. Fish and Wildlife Service (USFWS) 1985, 1990). Most individuals of this population nest on bare sandbars on large rivers, primarily the Mississippi, Red, Arkansas, Canadian, Missouri, and Platte (Lott 2006).

ILT were added to the USFWS list of endangered and threatened wildlife in 1985 due to concerns about breeding habitat loss and degradation associated with water resource development projects, which affect a large proportion of this population (USFWS 1985). Large multi-purpose dams, engineered navigation systems, bank stabilization projects, and wells or canals that remove water for irrigated agriculture affect ILT nesting habitat across much of their range (USFWS 1990). Many of the large dams and navigation systems in the range of ILT are operated by the U.S. Army Corps of Engineers (USACE) 1999, 2002, 2003, 2004a, 2004b, 2005) and operations are constrained by incidental take statements in USFWS Biological Opinions that have been negotiated through Section 7 consultations under the Endangered Species Act (ESA) (USFWS 2003, 2005a, 2005b, 2006).

Historically, sandbar nesting habitat on many rivers throughout the range of ILT has been lost or strongly degraded due to channel responses to large dam placement or channelization for navigation (see Friedman et al. (1998) for an overview, Funk and Robinson (1974) for the Missouri River, Williams (1978) for the Platte River, Stinnett et al. (1988) for the upper Canadian River, Tommelleri (1984) for the upper Arkansas River, and Knoll (2006) for the lower Arkansas River). In addition to this initial (and in some cases, ongoing) pulse of habitat loss during channel adjustment to large-scale river engineering, multi-purpose dam operations continue to have direct effects on ILT reproductive success (e.g., nest or chick mortality due to flooding). The effects of dam operations are strongest directly below eight large, multi-purpose dams on the Arkansas, Red, Canadian, and Missouri Rivers (USFWS 2003, 2005a).

The Arkansas River below Keystone Dam supports one of the largest Least Tern breeding populations across the range of the federally listed interior population, and the second-largest breeding population below a major multi-purpose dam (Figure 1, Table 1, adapted from Lott (2006)). The Red River below Denison Dam has the largest below-dam interior Least Tern population. Only two other populations with >150 terns occur immediately below large, multi-purpose dams across the range of ILT.Both of these populations are on the Missouri River, below Gavins Point Dam and below Garrison Dam (Table 1, USFWS (2003)). Four additional river reaches support small nesting populations of ILT directly below large, multi-purpose dams: the Arkansas River below Kaw Dam, the Canadian River below Eufaula Dam, and the Missouri River below Fort Peck and Fort Randall Dams (Figure 1, Table 1, USFWS (2003, 2005a); Lott 2006).

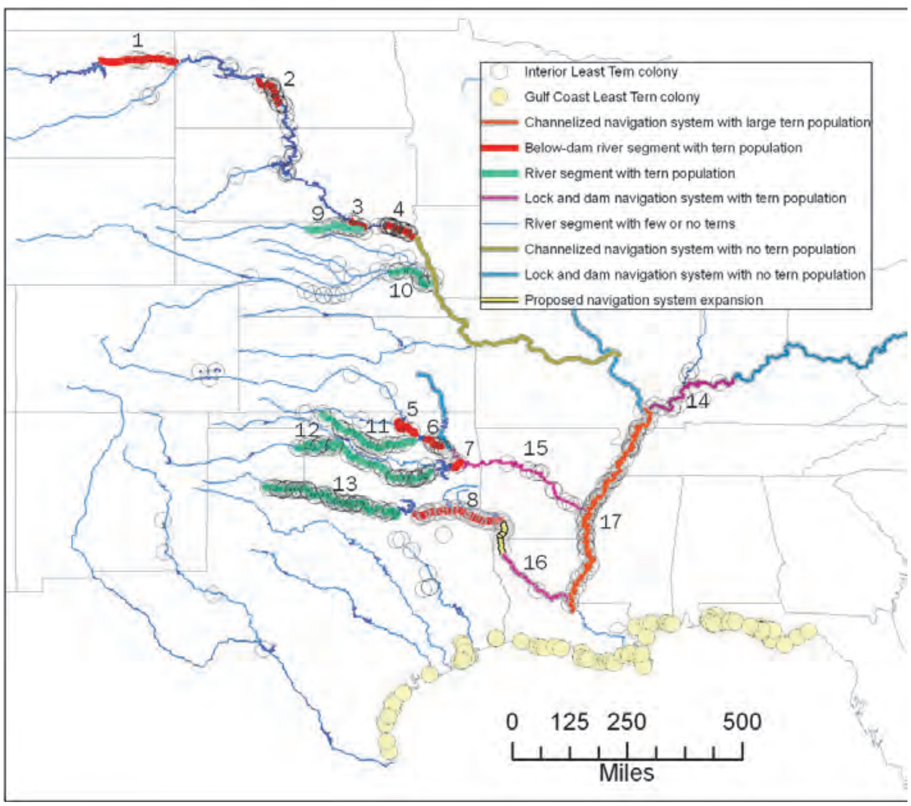

Figure 1. Geographic range of the Interior Least Tern population, with nearby Least Tern colonies on the Gulf of Mexico (adapted from Lott (2006). River segments were classified into four types where tern populations are present and three types where terns are lacking or small populations are present (e.g., <50 terns at <3 on-river sites). River segment types are represented by line colors (see figure legend). Numbers indicate river segments listed in Table 1. Note that ILT colonies also occur on reservoirs, sandpits, salt flats, and rooftops (Lott 2006). The 17 numbered segments represent all river segments where counts of >100 terns have occurred at least once during the breeding season within the last 10 years.

Table 1. The 17 major river segments with nesting populations across the range of the Interior Least Tern. Numbers match Figure 1.

Number	Segment name	Type	ESA reference	Adult terns (2005)	% of ILT	% of ILT-Mississippi[1]
1	Missouri River below Fort Peck Dam	Below-dam	USFWS 2003	34	0.2%	0.5%
2	Missouri River below Garrison Dam	Below-dam	USFWS 2003	199	1.1%	3.0%
3	Missouri River below Fort Randall Dam	Below-dam	USFWS 2003	76	0.4%	1.1%
4	Missouri River below Gavins Point Dam	Below-dam	USFWS 2003	476	2.7%	7.2%
5	Arkansas River below Kaw Dam	Below-dam	USFWS 2005a	104	0.6%	1.6%
6	Arkansas River below Keystone Dam	Below-dam	USFWS 2005a	550	3.1%	8.3%
7	Canadian River below Eufaula Dam	Below-dam	USFWS 2005a	118	0.7%	1.8%
8	Red River below Denison Dam	Below-dam	USFWS 2005a	1376	7.8%	20.8%
9	Niobrara River	Periodic flooding/habitat renewal	na	289	1.6%	4.4%
10	Lower Platte River	Periodic flooding/habitat renewal	na	53	0.3%	0.8%
11	Cimarron River	Periodic flooding/habitat renewal	na	186	1.1%	2.8%
12	Canadian River above Eufaula Dam	Periodic flooding/habitat renewal	na	342	1.9%	5.2%
13	Red River above Denison Dam	Periodic flooding/habitat renewal	na	394	2.2%	5.9%
14	Ohio River	Lock and dam navigation system	na	132	0.8%	2.0%
15	Arkansas River (McClellan-Kerr) Navigation System	Lock and dam navigation system	USFWS 2005a	319	1.8%	4.8%
16	Red River (J.Bennett Johnston) Navigation System	Lock and dam navigation system	USFWS 2005b	51	0.3%	0.8%
17	Lower Mississippi River Navigation System	Channelized navigation system	USACE 1999	10960	62.3%	na

The Tulsa District of the USACE (The District) has administrative authority for several dams that provide water supply, hydro-electric power generation, flood control, and target flows for downstream navigation on large

[1] The percentage of the total ILT population that DOES NOT INCLUDE ILT nesting on the Lower Mississippi River.

rivers in Oklahoma (USACE 2002, 2003). A component of operational authority for these dams is compliance with the ESA. Specifically, in a Biological Opinion regarding the operations of several USACE reservoirs in the Tulsa District, the USFWS defined four Reasonable and Prudent Measures (RPMs) that USACE must follow to be in compliance with the ESA. The list below comes directly from USFWS (2005a):

1. RPM 1. Maintain suitable habitat for nesting Least Terns in the Action Area.
2. RPM 2. Monitor, evaluate, and adjust operations to minimize take of Least Terns.
3. RMP 3. Monitor and evaluate Least Tern habitat conditions.
4. RPM 4. Reduce predation and human disturbance of Least Terns.

This report addresses many of the terms and conditions that were listed under RPMs 1-3. Specifically, the report addresses an inventory of Least Tern nesting habitat conducted after the 2008 breeding season. This inventory was undertaken to comply directly with one of the terms of RPM 3, which directs the USACE to periodically measure all potential nesting habitat below Keystone Dam on the Arkansas River. In order to evaluate how operations affect take of Least Terns (RPM 2), a simulated set of habitat conditions was created that reflects the degraded habitat conditions that prevailed on the Arkansas River below Keystone Dam prior to high flows in 2007-2008.

In accordance with RPM 1, suitable nesting habitat is defined explicitly and suitable nesting habitat is summarized at flow magnitude benchmarks suggested in USFWS (2005a)- e.g., peak hydro-power releases and flood control releases of 20,000 cfs. To understand how operations may be adjusted to minimize take of nesting Least Terns (RPM2), habitat measurements are first framed relative to operational hydrographs of Keystone Dam and an individual-based model of Least Tern reproduction is then used (Lott et al., in preparation a, b) to simulate nest and chick mortality due to flooding with model inputs representing both the high-quality habitat conditions measured after the high flows of 2007-2008 and the simulated degraded habitat conditions that existed prior to these flows (as described in USFWS (2005a)).

Objectives

The objectives of this study are to:

1. Quantify the amount and seasonal availability of Least Tern sandbar nesting habitat (SNH) below Keystone Dam as it existed after the high, habitat-forming flows of 2007-2008.
2. Create a simulated set of sandbars representative of the degraded habitat conditions that existed in 2006, prior to the high flows of 2007-2008.
3. Describe the effects of dam operations on the seasonal availability of SNH, flooding-related mortality of ILT nests and chicks, and overall ILT reproductive success, under both sets of habitat conditions, across the whole range of operations that have occurred during the post-dam era.
4. Discuss the potential for various management treatments (e.g., mechanical creation of nesting sandbars or predator management) to reduce ILT nest or chick mortality and/or increase ILT reproductive success.

Approach

The objectives of this study present the methodological challenge of illustrating temporal patterns of SNH inundation/exposure across the entire range of flows that typify reservoir operations. This requires completing three sequential steps to estimate sandbar exposure at different flows. Once these challenges have been met, results must be presented within a framework that clarifies how reservoir operations directly affect the reproductive success of sandbar nesting birds. The following three steps are used to estimate sandbar amounts at different flows; this process is described in greater detail in Chapter 3 of this report, “Methods.”

1. Topographic data are collected to create digital elevation models for each sandbar. [1]
2. Sandbar-specific models of the relationship between flow and elevation are created so that sandbar water lines (and consequently, exposed areas) can be displayed/summarized at any flow.
3. Models are used to demonstrate how dam releases and downstream flow conditions (e.g., base flow, runoff, antecedent flow conditions) result in different flows at variable distances from dams.

Habitat area estimates will only be meaningful to river managers if results are presented relative to both reservoir operations and Least Tern biology. Therefore, to introduce summaries of habitat area estimates at different flows, the following information was also presented:

[1] If topographic surfaces generated from LIDAR had been available, these could have been used for this step.

1. The ecological and historical context for observations (below).
2. A resource-based definition of sandbar nesting habitat (SNH) that accounts for the breeding biology of Least Terns (below).
3. An exploration of hydrographs that typify the operations of Keystone Dam (Chapter 2).

Least Tern population ecology on regulated rivers

ILT population dynamics have rarely been described relative to the ecological processes that affect the distribution, abundance, and quality of nesting habitat at the temporal scales most likely to affect tern population trajectories (e.g., across several generations of tern reproduction) (see U.S. Department of Interior (USDOI) 2006 and Appendix B of USACE 2011). This approach appears to be critical to assessing interactions among river management, ecological processes, and tern population persistence.

This report addresses how existing system operations (e.g., dam releases for hydropower generation, flood control, and the provision of navigation flows) affect the distribution and abundance of Least Tern nesting habitat given current dominant hydrogeomorphic and biological processes. Results are framed relative to the USFWS Biological Opinion (BiOp) covering the study area (USFWS 2005a) and historic, post-alteration hydrographs spanning the 32-year period from 1977-2008 on the Arkansas River. This period represents the full range of years after major dam closures (Kaw and Keystone Dams).

As noted in USFWS (2005a), previous quantitative habitat measurements for this river are not available. Therefore, this initial inventory of ILT nesting habitat conditions is reported in a format that will allow for both quantitative and qualitative comparisons with future investigations. A context is provided for the presentation and interpretation of ILT nesting habitat measurements that should be useful for rivers across the range of ILT. This approach relies heavily on framing results relative to the interacting contexts of reproductive ecology and current system operations (Chapter 2).

To understand how habitat-related factors affect ILT reproductive success and/or population trajectories, ***ILT nesting habitat must be defined and measured relative to the current ecological setting of regulated rivers***. This requires clearly linking habitat assessments to system operations; in particular, the ways in which operations control the regional and seasonal availability of suitable nesting habitat. Without a detailed understanding of how operations affect tern habitat conditions, it is difficult to understand how river management might affect population process or how to develop management strategies that will be effective in promoting ILT recovery.

It should be emphasized that it is critical to focus on the ecological processes that ***currently*** occur on managed rivers, with their altered flow regimes and channels, since it is these conditions that directly affect tern population trajectories. Although the natural flow regime paradigm (Poff et al. 1997) may help to understand some system behaviors, it may not be particularly useful for developing effective management strategies for systems that have been severely altered for many years. These river segments may have reached post-alteration equilibriums with controlling processes that differ from pre-alteration states (Friedman et al. 1998). Of equal importance, most highly altered rivers have a low probability of returning to their original state, even with considerable investment in ecosystem restoration (Jacobson and Galat 2006).

A general definition of ILT sandbar nesting habitat (SNH)

The term “sandbar” defines a transitional landform on rivers; specifically, a sandbar is a raised portion of a river bed that represents an “in-channel accumulation of sediments” with substrates ranging in size from silt to boulders (Charlton 2008). Sandbars can be completely inundated, partially inundated/exposed, or completely exposed (if the river is dry). The authors propose a resource-based definition (Gaillard et al. 2010) of “nesting habitat” as the sum of physical and biological resources necessary to sustain ILT reproduction. These definitions are combined in this report to describe the seasonal availability and quantity of “sandbar nesting habitat” (SNH) for Least Terns. The term “sandbar nesting habitat” is preferred over the commonly used term “emergent sandbar habitat” (ESH) (USFWS 2003, 2005a, 2006; USACE 2011), since all of the exposed portions of a sandbar are not necessarily suitable for nesting.

The definition of SNH described above focuses habitat description on Least Tern life history and nesting behavior, which allows habitat management to focus on specific elements that affect fitness. For example, within the study area, terns do not successfully nest on the low-elevation portions of the river bed that are regularly exposed and then inundated at near-daily intervals by fluctuating hydropower releases that occur throughout the breeding season.

Therefore, the current discussion of SNH is restricted to only the portions of sandbars that are exposed above regularly occurring two-unit peak hydropower releases (e.g., 11-12,000 cfs from Keystone Dam). Since downstream runoff or base flow frequently adds ~1,000 cfs to peak hydropower releases during the Least Tern breeding season, only the bare portions of sandbars that are exposed at flows above 13,000 cfs are considered as suitable SNH. Note: the term "flow" combines dam releases with base flow and runoff in contributing drainage areas downstream of dams.

The authors prefer the specificity of this approach to more general habitat classification based on recognizable land cover types from aerial photography; e.g., exposed dry sand, wet sand, or sparsely vegetated sand (USACE 1999, 2011; USFWS 2003; Sherfy et al. 2008). Amounts of these cover types depend directly on river stage, which varies (often severely) across the breeding season and hourly on rivers with hydropower operations (see Chapter 2). Due to this variation, there is no such thing as a static 10-acre sandbar. Rather, a sandbar may be 18 acres at 12,000 cfs, 7 acres at 15,000 cfs, 2 acres at 20,000 cfs, and inundated at 22,500 cfs. For this reason, sandbar acreages are always presented relative to specified flows, and this is recommended as a standard approach for habitat summaries across the breeding range of ILT. Because of the critical dependence of habitat area on flow, as it translates to stage, direct comparison of habitat amounts (e.g., between two different time periods) should only occur at the same flow. *The more obviously that benchmark flows for habitat comparison can be related to system operations, the more useful habitat quantification will be for management.*

Drawing inferences from SNH measurements

This report presents summaries of SNH availability relative to seasonal dam releases/flows that drive the timing of sandbar exposure or inundation, which has consequences for the timing and magnitude of Least Tern breeding effort (nest initiation) and reproductive success (the combined survival of eggs to hatch and chicks until first flight). SNH acreage summaries are also presented at several management-relevant benchmark flows. However, simply presenting the area of exposed sandbar at a single point in time or at a single flow, without accounting for the critical elements of timing and duration of exposure, provides little insight on the effects of reservoir operations on ILT reproduction. To better understand how the timing, magnitude, and duration of high-flow events affect nesting habitat availability, Chapter 4 includes graphs with complete time-series of sandbar exposure across Least Tern breeding seasons.

This report also examines how reservoir operations might affect Least Tern reproduction (e.g., by causing nest or chick flooding mortality or by limiting the availability of suitable habitat during the breeding season).The consequences of seasonal trends in habitat availability on Least Tern mortality and reproductive success are examined by simulating numerous Least Tern breeding seasons (in daily time-steps) in TernCOLONY. TernCOLONY is an individual-based model of Least Tern reproduction that uses the habitat measurements and time-series of sandbar-specific peak daily flows as documented in this report as inputs (Chapter 5).

TernCOLONY simulates the behavioral processes of ILT arrival from spring migration, colony site selection, mate selection, nest site selection, site abandonment, and re-nesting after nest or young chick mortality (Lott et al., in preparation (a)). TernCOLONY simulations reproduce spatial and temporal patterns of regional ILT distribution, abundance, and mortality events during the breeding season that have been documented in empirical studies (Lott et al., in preparation (b)). Model nests are placed at elevations typical of nest placement on real world sandbars and chicks can walk to the top of sandbars to avoid rising water. Consequently, nest and chick mortality during model simulations reflects regional variation in site elevations (and site use by terns) and spatial and temporal variation in how tern nesting intersects with flooding events. While the hydrographs of Chapter 2 and the seasonal habitat graphs of Chapter 4 can hint at site- or year-based flooding risk, TernCOLONY simulates the behavior of the tern population realistically enough to estimate where and when actual flooding mortality events are likely to occur.

A specific definition of SNH

SNH is described in terms of five physical and biological characteristics that are necessary for Least Tern nest initiation and successful reproduction. It is possible that successful reproduction occurs in the absence of some of these conditions in some years, but it is doubtful that this represents a consistently large portion of regional reproductive output at the multi-year time frames that control population trajectories.

Since Least Tern eggs cannot survive deep or prolonged inundation, the first physical habitat resource that is necessary for successful reproduction is a nest site that is not inundated during egg laying and incubation. In contrast to immobile eggs, Least Tern chicks can walk away from nests 1-2 days after they hatch to higher elevations on sandbars. However, tern chicks swim poorly and few survive sandbar inundation. Therefore, a second requirement for successful reproduction, which combines physical habitat characteristics with flow regimes, is that nesting sandbars should not be inundated until chicks are able to fly. These two requirements can only be addressed by relating measurements of sandbar elevations to dam releases and downstream flows and then linking the exposure of different sandbar elevations with the timing of events (e.g., incubation, chick rearing) during the Least Tern breeding season.

Third, Least Terns place their nests in bare and open areas and will not nest on portions of sandbars that are covered by vegetation. Based on previous research, all portions of a sandbar with >30% ground cover (regardless of vegetation type) were considered to be unsuitable for nesting (Thompson et al. 1997). The distribution and abundance of sandbar vegetation is controlled by the interaction between the physical template of soils and hydrology.Therefore, the impact of reservoir releases on the ecological processes of vegetation establishment has a strong effect on this habitat-limiting feature (Wiley and Lott, in preparation). When plant establishment occurs, previously suitable SNH is lost. When vegetation succession advances so much that higher flows do not suppress sandbar vegetation, this loss can be irreversible (USFWS 1990, Friedman et al. 1998, Johnson 2000).

Similarly, while terns will nest within 50 ft of low vegetation (USACE 2011), they tend not to nest on sandbars (or portions of sandbars) that are <250 ft from large trees or mature forest, either on the river's banks or on forested islands that are near or connected to sandbars (Knoll 2006, USACE 2011, Appendix B). Similarly, Least Terns tend not to nest within 200 ft of riverbanks, regardless of bank-side vegetation characteristics (USACE 2011). Therefore, a fourth minimum physical/biological requirement for habitat suitability is that an otherwise suitable sandbar (high enough to avoid inundation and bare enough to provide nesting sites) is also not immediately adjacent to large trees or the riverbank. This study characterizes all sandbar areas within 50 ft of sandbar vegetation, within 250 ft of large trees, or within 200 ft of riverbanks as "unsuitable." These portions of bare sandbars are not included in acreage summaries for SNH. The distance from trees that was used to establish this threshold was shorter than the distance that might be suggested from observational data on the Missouri River (USACE 2011).This is because some birds nest within 250 ft of large trees on the slightly narrower channel of the Arkansas below Keystone Dam (e.g., Zink Island; Hill 1993) and on the Lower Red River between Texarkana and Shreveport (M.P. Guilfoyle and R.A. Fischer, U.S. Army Engineer Research and Development Center, Environmental Laboratory, unpublished data).

Finally, ILT eat mostly small fishes (Thompson et al. 1997). Chicks must be fed by their parents before they can fly and acquire food on their own. Therefore, a fifth minimum biological resource for successful reproduction is the availability of enough prey fishes to support chick growth until fledging. A large variety of foraging micro-habitats are available in close proximity to most nesting sites on the Arkansas and Red Rivers, where ILT can acquire a diverse assortment of native and non-native prey fish (Tibbs 1995). It is therefore unlikely that food resources limit tern reproduction within the study area. Consequently, this study does not attempt to directly quantify foraging habitat, prey availability, food delivery rates, or chick growth rates, which would be very costly. Rather, in assessing SNH, it was assumed that prey availability does not limit tern reproduction in the study area and the study focused exclusively on the first four physical/biological criteria above to describe SNH.

Contexts for the interpretation of habitat measurements

All field studies occur within administrative, historical, and biological contexts and this document provides information to place the interpretation of results from this study in such contexts. Future studies that measure sandbar nesting habitat for Least Terns should be presented within such contexts.

1. This set of habitat measurements (fall/winter 2008-2009) was completed to partially satisfy the requirements of a USFWS Biological Opinion regarding a number of Corps of Engineers projects on the Arkansas and Red Rivers (USFWS 2005a).
2. Both field and analytical methods, especially the framework for the interpretation of results (Chapter 2), were designed to help understand how reservoir operations affect Least Tern nesting habitat use and reproductive success.
3. Despite an extensive search of both peer-reviewed and grey literature for Least Terns, no previously published studies were located that provided

methodological guidelines to achieve the specific objective of linking dam operations to SNH amount or seasonal availability. This was surprising given the prominent discussion of the potential for reservoir operations to limit nesting habitat availability in the original listing document for ILT (USFWS 1985), the Recovery Plan (USFWS 1990), and BiOps resulting from Section 7 consultations for nearly all of the rivers where ILT occur (USFWS 2003, 2005a, 2005b, 2006).

4. 2008-2009 habitat measurements occurred 32 years after closure of the last large, main-stem dam to be completed on the Arkansas River (Kaw Dam, which is ~115 miles upstream of Keystone Dam, in 1976). Therefore, current habitat conditions reflect considerable adjustment of the river channel to the post-alteration hydrograph and hydrogeomorphic setting. For example, the channel has been scoured to bedrock for several miles below the dam due to the absence of new sediment inputs.Deltaic sediments and vegetation communities (Johnson 2002) are present where faster river currents meet the backwater pool behind Webbers Falls Dam.
5. The 2008-2009 habitat measurements were completed immediately following relatively high-flow events in 2007 and 2008 on the Arkansas River. Such high-flow events have been rare during the post-alteration era. Consequently, the 2008-2009 habitat measurements are viewed as representing relatively “high-quality” nesting habitat conditions for terns, compared with the more “degraded” habitat conditions that would occur many years after a habitat-forming flow, when habitat conditions would be expected to be poor due to erosion and vegetation succession (e.g., see the qualitative description of 2004 habitat conditions on the Arkansas River, excerpted from USFWS [2005a], in number 8 below).
6. The 2008-2009 measurements represent a snapshot of habitat conditions after the 2008 breeding season. Habitat conditions will change after any snapshot measurement (sometimes rapidly, sometimes slowly, depending on the interaction between initial habitat conditions, subsequent flows, and their effects on erosion and vegetation establishment). This report provides a framework for direct comparison of one snapshot measurement with another. It also provides a framework for understanding how SNH conditions that prevail during any one sampling period may limit tern habitat use or reproduction across the full range of reservoir operations that have occurred in the post-alteration era (see Chapters 2, 4, and 5).
7. In the absence of a time series of similar habitat measurements, inference from this single set of measurements is most appropriate for this one set of conditions. This snapshot attempts to answer the question: “When habitat conditions are good, how do reservoir operations affect ILT reproductive

success?"). Given number 5 above, it seems unlikely that 2008-2009 habitat conditions are representative of the full range of past habitat conditions for ILT.

8. The following two quotes (from p. 32 of USFWS 2005a) describe the degraded SNH conditions that prevailed on the Arkansas River below Keystone Dam during the 2004 breeding season, the excellent habitat conditions that had occurred for several years after the high dam releases of 1993, and the degraded conditions that had existed prior to 1993. These quotes inspired the creation of a set of simulated sandbars representative of the degraded habitat conditions that prevailed prior to the high flows of 2007-2008 (Chapter 3).

> Least Tern nesting habitat quality and quantity have declined on most of the Arkansas River and the current conditions are probably the worst known since Least Tern monitoring began in the 1980s. The degree of habitat degradation cannot be accurately quantified due to the Corps' failure to fully implement some of the reasonable and prudent measures in the 1998 opinion that required monitoring of habitat on the Oklahoma reach. Nonetheless, differences in Arkansas River habitat quality relative to 1994 are apparent. Flows of >30,000 cfs in 1994 did not flood many of the Least Tern nesting sites (Leslie et al. 2000), but flows of only 15,000 cfs would flood most of the suitable habitat and nests in 2004 and 2005. Most of the higher islands and sandbars are now vegetated to a degree that precludes Least Tern nesting.

> After scouring flows in 1993 that elevated existing sandbars and created new sandbars, the number of breeding colonies, adults observed, number of nests, chicks, and eggs observed, and number of terns fledged all increased the following year. In addition, loss of nests due to flooding declined the following year (Leslie et al. 2000). Leslie et al. (2000) reiterated the need for periodic (>7 years) scouring flows to maintain the quality of nesting habitat available to terns. However, habitat quality has declined since 1993 due to a lack of scouring flows. No major high-flow events have occurred in recent years and habitat has declined in quantity and quality. In 2004, frequent flooding events and poor habitat conditions reduced or eliminated reproductive success on most of the Least Tern nesting areas within the Action Area.

2 Defining Sandbar Nesting Habitat Relative to Operational Hydrographs

This chapter presents a number of different hydrographs that provide context for the development of field and analytical methods for habitat measurements (Chapter 3). It also presents the results of habitat measurements (Chapter 4), and evaluates the effects of reservoir operations on tern populations (Chapters 5 and 6).

The series of hydrographs presented here was designed to increase understanding of how reservoir operations affect SNH, and consequently, Least Tern breeding populations. This chapter was written for all stakeholders in river management, not just endangered species biologists, planning and regulatory biologists, or any others involved with the conservation of ILT, compliance with ESA, and implementation of ecosystem restoration projects that have been proposed to benefit ILT. The authors believe that management and conservation strategies will be more effective when all stakeholders understand how system operations affect endangered species.

Defining the ILT breeding season

To define the temporal extent of the ILT breeding season, 6 years of data on nest initiation dates (2001-2006; 2,325 nests) are summarized for a census of nests on the four below-dam river segments of the Missouri River (Gavins Point, Fort Randall, Garrison, and Fort Peck) (unpublished USACE data, summarized in USACE (2011)). This dataset provided a series of benchmark dates that helped to define the Least Tern breeding season temporally during a time period where flooding mortality was rare and nesting very likely occurred as early as possible (Table 2). Similar complete time series of nest initiation dates, based on a census of nests across the entire breeding season, were not available for other regions. However, many publications have reported first, peak, and last nesting dates for Least Terns on the Missouri, Platte, Niobrara, Arkansas, Mississippi, and Canadian Rivers (reviewed in Lott et al. (in preparation (a)), Appendix A). This summary clearly showed that nest initiation dates are similar across the breeding range of ILT, including the Arkansas River below Keystone Dam. Consequently, many of the graphs in this report include reference lines on the x (date) axis to illustrate how time series of flows or habitat availability relate to tern nesting phenology.

Table 2. Standard nest initiation dates for Least Terns from a census of 2,325 nests on the Missouri River between 2001 and 2006.

Benchmark date	Julian date	Short date
First arrival	124	5/3
First nest	138[1]	5/17
10% of all nests	150	5/29
25% of all nests	155	6/3
50% of all nests	161	6/9
75% of all nests	173	6/21
90% of all nests	183	7/1
100% of all nests	203	7/21
Last fledging date	244	8/31

Classifying breeding seasons to water year types

Three different seasonal flow patterns have been common during the Least Tern breeding season below Keystone Dam on the Arkansas River in the post-dam era: low-water years, high-water years, and years with mid-season floods (Figures 2 and 3). Within the high-water years and years with mid-season floods, considerable variation has been present in the timing, duration, and magnitude of high-flow events. The specificity of these high-flow events may have strong influences on Least Tern reproduction in any given year. For example, the ***timing*** of high flow events relates to whether or not nests or chicks are flooded. The ***magnitude*** of events (and also the elevation of existing sandbars) relates to how many nests or chicks get flooded. Finally, the ***duration*** of high-flow events may relate to whether or not enough time remains in the breeding season for re-nesting after a flood event.

These three different water year types were used to group many of the summaries of SNH in this report. The three water year types (and their frequency in the post-dam era) are also used to: 1) draw inferences about the potential long-term effects of reservoir operations on Least Tern reproduction, and 2) illustrate how effective management strategies may differ among water year types. The three major water year types below Keystone Dam are defined as follows:

[1] A single nest initiation on 7 May, 10 days earlier than all other nests over this 6-year period, was removed from this summary as an outlier.

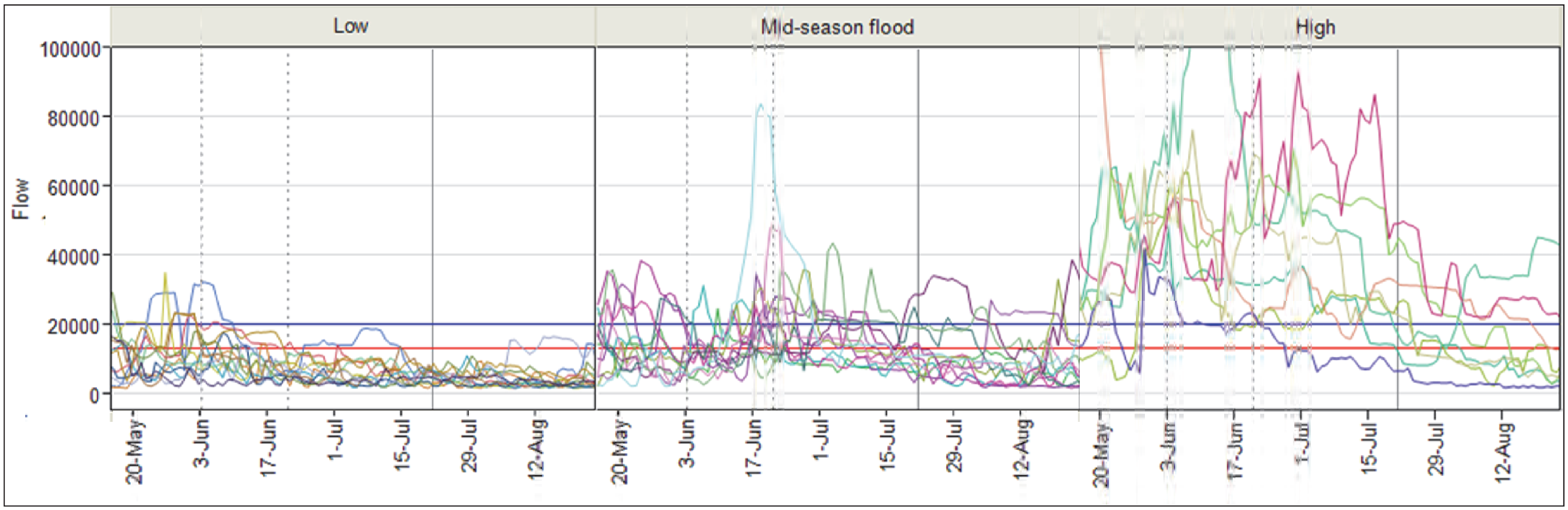

Figure 2. Panels represent the three common breeding season water year types below Keystone Dam during the post-dam era (1977-2008): low-water years (37.5% of years), mid-season flooding years (37.5% of years), and high-water years (25% of years). Lines within each panel represent variation in time series of peak daily flows for individual years within each type. See text on previous page for criteria used to classify each year to a specific water year type. Red horizontal line indicates peak hydropower flows of 13,000 cfs that regularly occur during the breeding season. Blue horizontal line indicates moderate flood control releases of 20,000 cfs. Dashed vertical lines indicate the dates by which 25% (3 June) and 75% (21 June) of all nests are typically initiated during years with no major floods. The solid vertical line at 21 July indicates the typical last date for nest initiation in a year without major floods. These same vertical reference lines will be used to indicate important dates within the ILT breeding season on other graphs throughout this document.

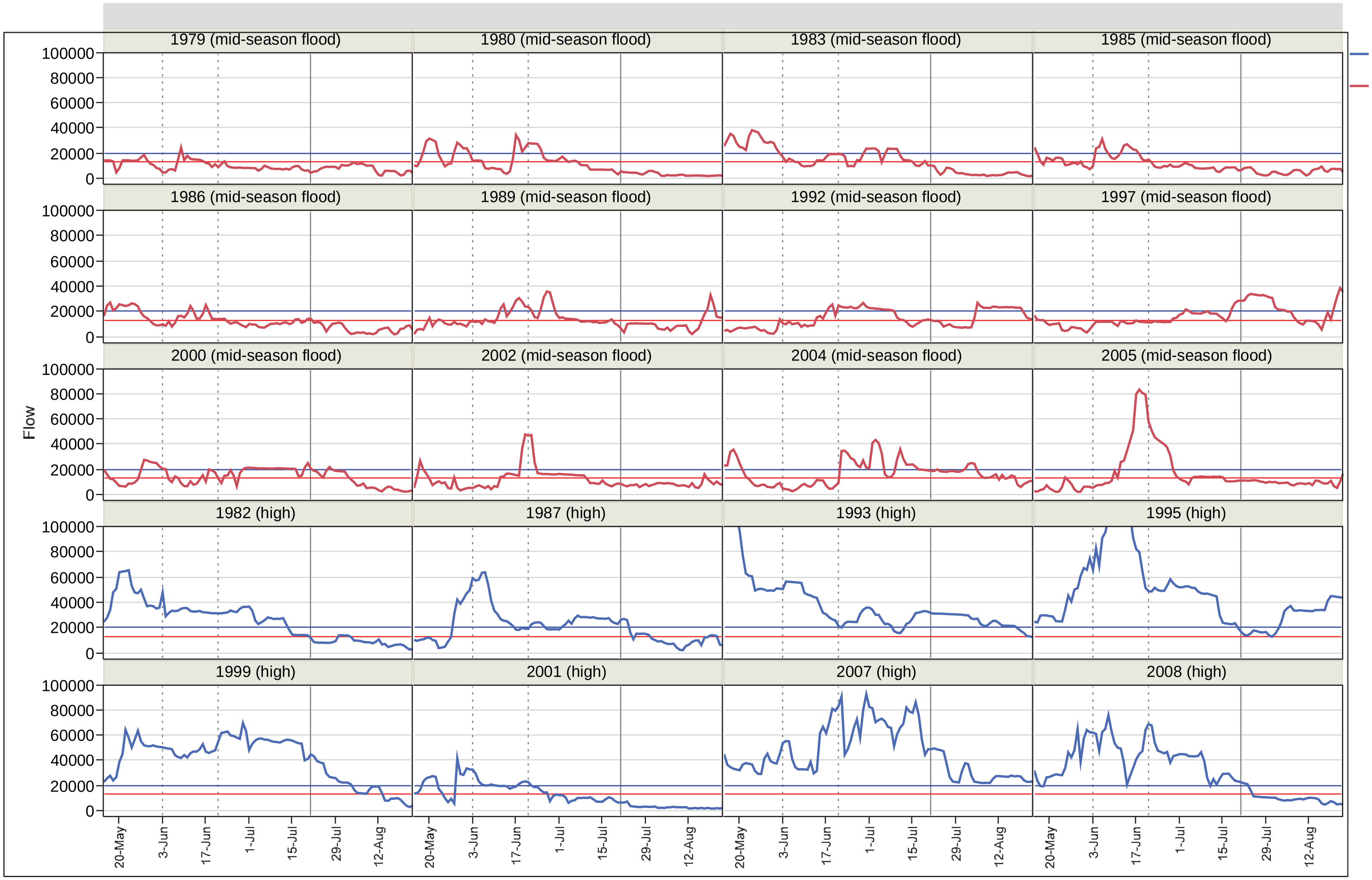

Figure 3. Peak daily flows at the Haskell Gauge for 20 of 32 ILT breeding seasons during the post-dam era (1977-2008) where flows >20,000 cfs occurred after 9 June, the median nest initiation date for Least Terns in a typical dry year. Years are labeled by water year type. Note variation in the timing, duration, and magnitude of high flows within the Least Tern breeding season. Compare this with low water years (in Figure 2), where flows >20,000 cfs typically did not occur beyond the first few days of the breeding season, when small numbers of nests have been initiated. X and y-axis references are the same as in Figure 2.

1. Low-water years (12 of 32 [37.5% of all years]): Breeding seasons where peak daily flows were consistently near or below peak hydropower releases for much of the breeding season, presenting little flooding risk for nests or chicks. If higher flows occurred, they were usually <20,000 cfs and happened early in the breeding season. In these years, flows >20,000 cfs did not occur after 9 June, the date by which 50% of nests are typically initiated (Table 2). Flows after the last possible nest initiation date, during the chick period, were generally lower than 13,000 cfs.
2. Mid- to late-season flooding (12 of 32 [37.5% of all years]): Breeding seasons where flows <20,000 cfs occurred for at least 5 days prior to 9 June, the date by which 50% of nests are typically initiated (Table 2), allowing for nest initiation. These low flows were then followed by flows >20,000 cfs any time after 9 June, during the second half of nest initiation or during the chick period. These years have the potential for large amounts of nest or chick mortality.
3. High-water years (8 of 32 [25% of all years]): Sustained high flows (>20,000 cfs) covering a large part of the breeding season (at least 14 of the 19 days between 3 June and 21 June, when the central 50% of Least Tern nests are typically initiated, Table 2) may have precluded nesting (due to the inundation of all sandbars) or caused extensive mortality to nests or chicks (if flooding occurred after nest initiation).

This classification of annual breeding season flows into three different water year types reflects common interactions between reservoir storage at the beginning of a breeding season, precipitation events within a breeding season, and rule curves that govern dam releases during the breeding season (USACE 2003). Rule curves are numeric protocols that guide dam operations under a wide range of reservoir inflow and predicted meteorological scenarios (USACE 2002). Rule curves reflect negotiated compromises to meet multiple congressionally authorized purposes for major dams (e.g., flood control, storage for water supply, recreation, wildlife). While water control may have limited flexibility to alter dam releases for endangered species within the constraints of existing rule curves (USACE 2002), major changes that would significantly alter the types of flow regimes reported here (which have typified the post-dam era) seem unlikely. During a recent revision of the Missouri River Master Manual, the inability to alter rule curves to support regular ILT (and Great Plains Piping Plover) habitat renewal, or to avoid dam-related flooding during the breeding season, resulted in the creation of an extensive program for mechanical habitat creation to mitigate for these losses (USFWS 2003, USACE 2011).

Relating annual hydrographs to long-term habitat change

This report focuses primarily on hydrographs that relate to ILT nesting habitat use and reproductive success during any one breeding season. However, other hydrographs provide more insight towards understanding the processes that create and destroy sandbar nesting habitat at the multi-year scales that control Least Tern population trajectories (Sidle et al. 1992, Johnson 1994, Leslie et al. 2000, USACE 2011 [Appendix B]). For example, periodic high releases/flows at any time of year, or prevailing intra-annual flow patterns, may create new SNH or maintain/improve existing SNH by promoting or discouraging vegetation establishment and survival on sandbars. This report discusses hydrographs that relate to long-term habitat change with less detail than those that may directly influence reproduction in any one year due to the absence of a time series of SNH measurements that would help to understand mechanisms of long-term habitat change (e.g., Johnson 1994). For context, however, annual hydrographs with mean daily flows are presented for the 20 years prior to the 2008-2009 data collection (Figure 4). See Wiley and Lott (in preparation) for more details on interactions between reservoir releases/flows and vegetation succession.

Choosing appropriate flow metrics for data summary

The preparation of hydrographs related to ILT habitat conditions, or the effects of flows on reproduction, requires careful consideration of which flow metric to summarize, which will vary given the objective of each analysis. This report discusses the different types of daily flow metrics that can be summarized from hourly flow data (e.g., peak daily flows, mean daily flows, minimum daily flows).This discussion illustrates the importance of evaluating more than just mean daily flows (the standard metric of many long-term USGS gage data sets) to understand the effects of reservoir operations on ILT habitat and population dynamics.

Sub-daily fluctuations in dam releases sometimes result in large differences between mean daily flows, peak daily flows, and minimum daily flows (calculated from 24 hourly flow values) (Figure 5). These three different summary statistics are each useful for understanding different components of the effects of reservoir operations on nesting terns. Use of the wrong metric in the wrong context could lead to erroneous conclusions.

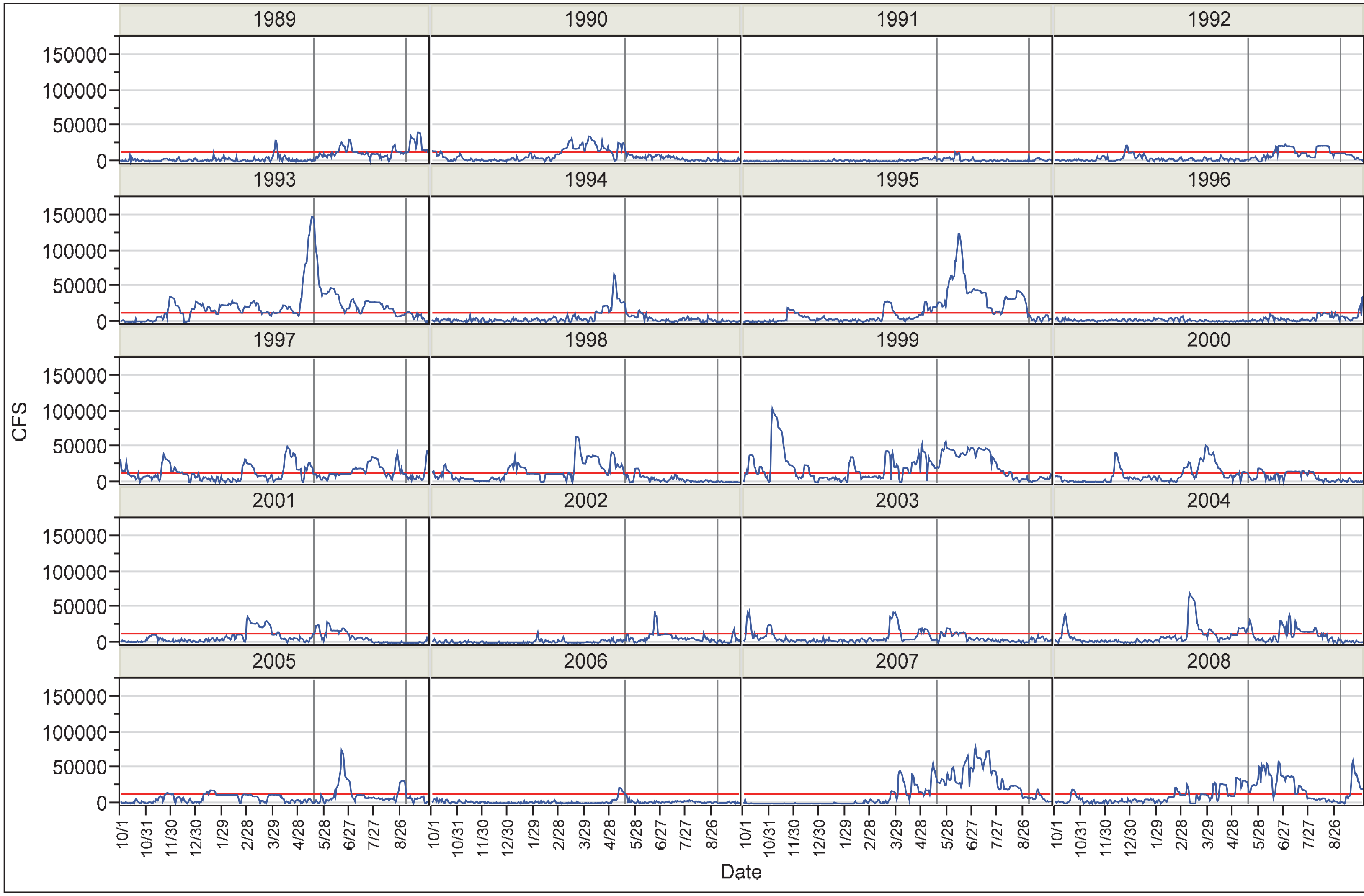

Figure 4. Mean daily flows at the Tulsa gage for the 20 USGS water years prior to the 2008-2009 habitat measurements. USGS water years span the 12-month period from 1 October of one year to 30 September of the following year and are named by the calendar year that they end in (e.g., 1 October 1998 to 30 September 1999 is called the "1999" water year). The y-axis reference line is at the minimum suitable habitat flow of 13,000 cfs. The solid grey x-axis reference lines indicate the complete Least Tern breeding season (see Table 2).

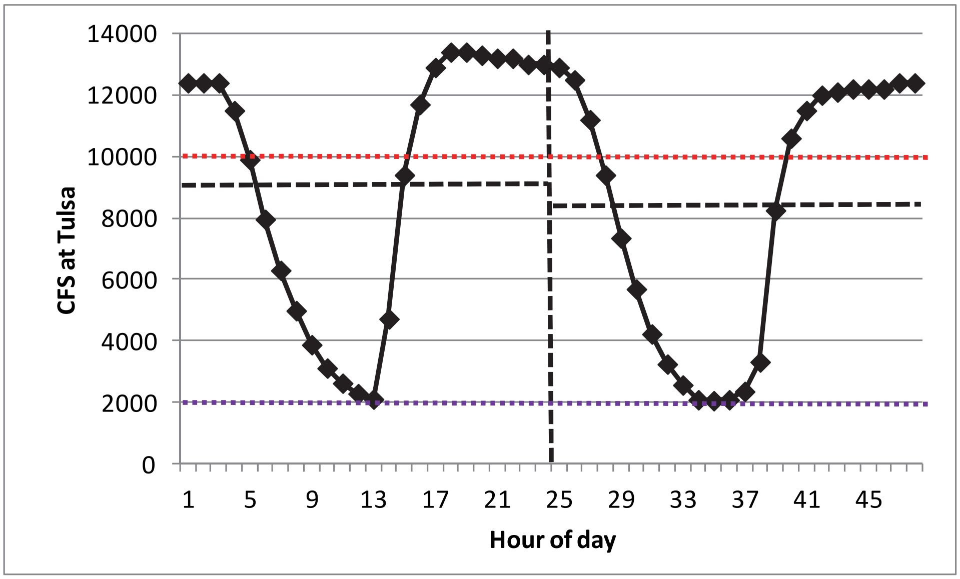

Figure 5. Hourly flows at the Tulsa gage on the Arkansas River from 21-22 June 1991, illustrating a typical 24- to 48-hr period of reservoir operations during peak hydropower generation. The dashed vertical line is midnight on 21 June. Points, connected by the black line, represent hourly flow values. The black, dashed horizontal lines represent 24-hr mean daily flows. The dashed, red horizontal line indicates a theoretical Least Tern nest at an elevation that would be inundated at 10,000 cfs. Mean daily flows would predict that this nest would remain dry, while peak daily flows show that this nest would be inundated on both days. Similarly, mean daily flows mask the fact that flows of 2,000 cfs occur on both days (the dashed, purple line). These flows may be low enough for a sandbar to become connected to the shoreline, improving access for predators or humans, which may lead to ILT mortality.[1]

For example, since nests and chicks rarely survive inundation for >1 hr, peak daily flows most accurately represent the risk of flooding mortality for terns. If a nest were placed on part of a sandbar that is inundated at a flow of 10,000 cfs, mean daily flows during a peak hydropower generation cycle, where hourly flows vary considerably, might predict that this nest would survive to hatch (since several hours of low flows might pull the daily mean down to <8-9,000 cfs). However, inspection of peak daily flows would reveal that this nest would be unlikely to survive 2 days (Figure 5). For this reason, peak daily flows are used to evaluate flooding risk.

Similarly, a few hours of high flows during peak hydropower production can produce daily means that mask lower flows that frequently connect sandbars to the shoreline for several hours of each day, which may increase disturbance or mortality from people or predators (Figure 5). For this reason, hourly data should be used to prepare low-flow hydrographs related to disturbance or predation risk.

[1] Personal Communication. 2008 Kevin Stubbs, Biologist, U.S. Fish and Wildlife Service, Tulsa, OK.

In contrast to flooding mortality, which can happen instantaneously when water levels rise to inundate nests or whole sandbars, sandbar deposition during habitat-forming flows (and the resulting sandbar elevation and geometry) is related to both the magnitude and duration of high flows that almost always last more than one day. Therefore, hydrographs related to sandbar formation should probably be constructed from mean daily flow data, rather than peak daily flow data (e.g., Figure 4). Finally, vegetation establishment and mortality may be affected by peak, mean, or minimum daily flows due to species differences in daily water requirements, tolerance durations for inundation or desiccation, and the removal of propagules and substrates via erosion (Wiley and Lott, in preparation).

Fundamental hydrograph types for evaluating the effects of dams on Least Tern reproduction

Although there has been widespread recognition that reservoir operations affect both the amount and quality of nesting habitat, there has been little effort to quantify habitat conditions in direct relation to operational hydrographs (Parham 2007, Tracy-Smith et al. 2011). This section describes two categories of hydrographs that are critical to performing and reporting on habitat measurements, determining the amount of SNH that is seasonally available for ILT nesting, and understanding how system operations affect reproductive success. These are:

1. Within-day flow variation due to hydropower releases, which can affect natural processes like erosion and plant succession, many details of how habitat is measured, and how hydrologic datasets are summarized to evaluate effects of reservoir operations on terns.
2. High releases/flows during the breeding season that may flood nests or chicks.

Within-day flow variation due to hydropower releases

Patterns of within-day flow variability related to hydropower generation

Dams that generate hydroelectric power have release schedules designed to generate power during periods of high demand and conserve water (for future power generation or other purposes) during periods of low demand (USACE 2003). This results in characteristic dam release hydrographs (Figure 6) with peak releases for several hours interspersed with lower flows (or no releases) during periods of low electricity demand (weeknights, early

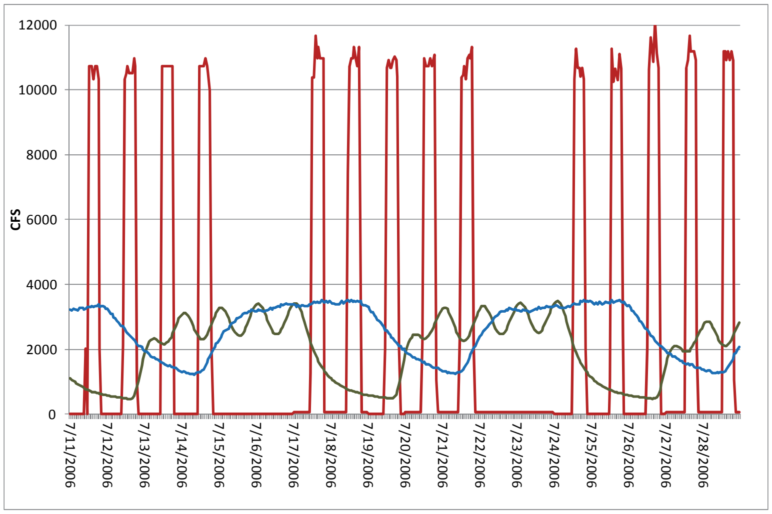

Figure 6. Downstream attenuation of Denison Dam (on the Red River) peak hydropower releases (red line) during a period with no runoff and minor tributary inputs (hourly data are shown here). Dark green line represents attenuation of dam releases at the Arthur City gage, 93 miles downstream. It takes dam releases ~60-80 hr to arrive at Arthur City. Note the reduced magnitude of peak flows, higher minimum flows, and less severe amplitudes of peaks at Arthur City. Blue line represents hourly flows at the DeKalb gage, 170 miles downstream. Dam releases take ~110-130 hr to reach DeKalb. This far downstream, hourly variation in dam releases becomes imperceptible and the 5-day peak hydropower generation cycle translates as a consistent 5-day flow (~3,600cfs), followed by a flow reduction of several days caused by a lack of weekend releases from Denison Dam. This promotes the growth of waterline vegetation that can tolerate regular desiccation during the growing season (e.g., Yellow-Nut Sedge, Figure 10).

mornings, and weekends). This characteristic hydrograph attenuates, but is still recognizable, far downstream from dams that generate hydroelectric power (Figure 6). During dry periods with low tributary base flow and no runoff, peak flows are lower at downstream gages than near dams (Figure 6). During periods with higher base flow (e.g., early spring) or during runoff events, peak flows are higher at downstream gages (Figure 7). In either case, minimum daily flows are higher downstream due to retention of water in the channel, whereas the channel directly below the dam may be dry after releases are terminated (Figures 6 and 7).

How daily stage variation affects sandbar exposure

Large variation in hourly dam releases during hydropower generation may translate into large stage variations, which can result in highly variable sandbar exposure throughout the course of one day. For example, the sandbar measured at Arkansas River Mile (RM) 479 had 47.2 exposed acres

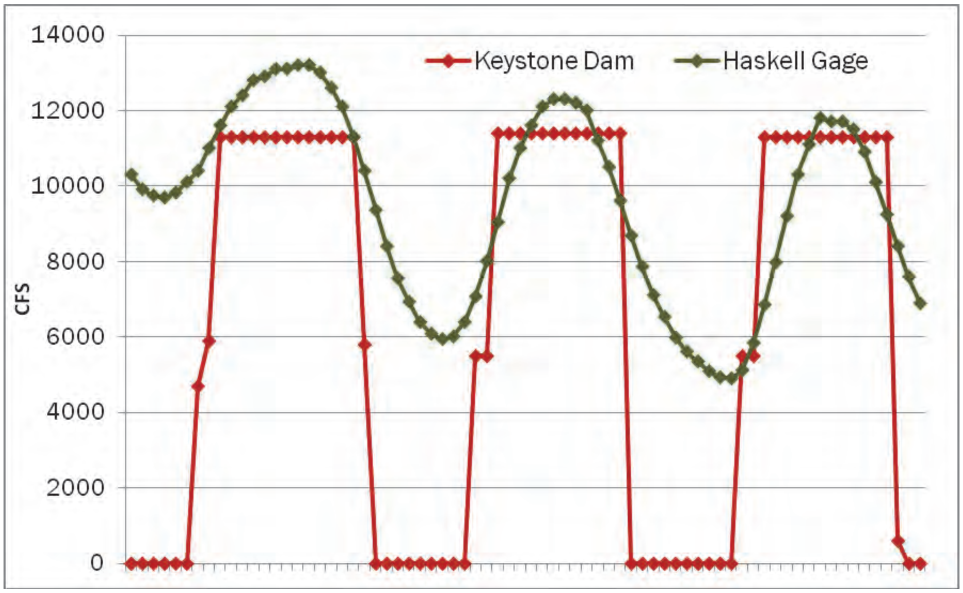

Figure 7. Hourly Keystone Dam releases during a 3-day peak hydropower generation cycle (red line), with hourly gage readings at Haskell, ~56.5 miles downstream (green line) during a typical period of declining runoff in contributing areas below the dam (25 May-27 May 1990). Peak flows at Haskell are higher due to runoff. Minimum flows at Haskell are also higher due to retention of water in the channel and base-flow contributions.

at daily low flows of around 2,000 cfs and only 17.2 exposed acres at daily peak hydropower flows of 13,000 cfs (Figure 8). In other words, 30 of the 47.2 acres exposed at low flows (63.5%) were not suitable habitat. This same sandbar had only 1.8 exposed acres at 16,000 cfs and was inundated at 21,000 cfs. Since this range of acreage estimates is large (and directly influenced by operations that vary considerably both hourly and across the course of the breeding season), it does not seem useful to have only a single point estimate of the exposed sandbar amount; particularly if this estimate reflects a flow that is not representative of how reservoir operations affect ILT reproduction. The fact that 47 acres of this sandbar are exposed at frequent low flows, which may be documented from an aerial photograph, may be misleading when this is compared with the full data summary of acres by flow, which clarifies that this sandbar has very little nesting habitat exposed at 16,000 cfs and that all nests and chicks will be inundated at the relatively minor flood control releases of 21,000 cfs.

Figure 8 shows variation in acreage estimates for four sandbars within the range of flows that occur several days per week due to peak hydropower generation on the Arkansas River. Note the rather large acreage estimates at 2,000 cfs. Although these acres are regularly exposed for several hours throughout the week, they are also inundated at least five times a week. As

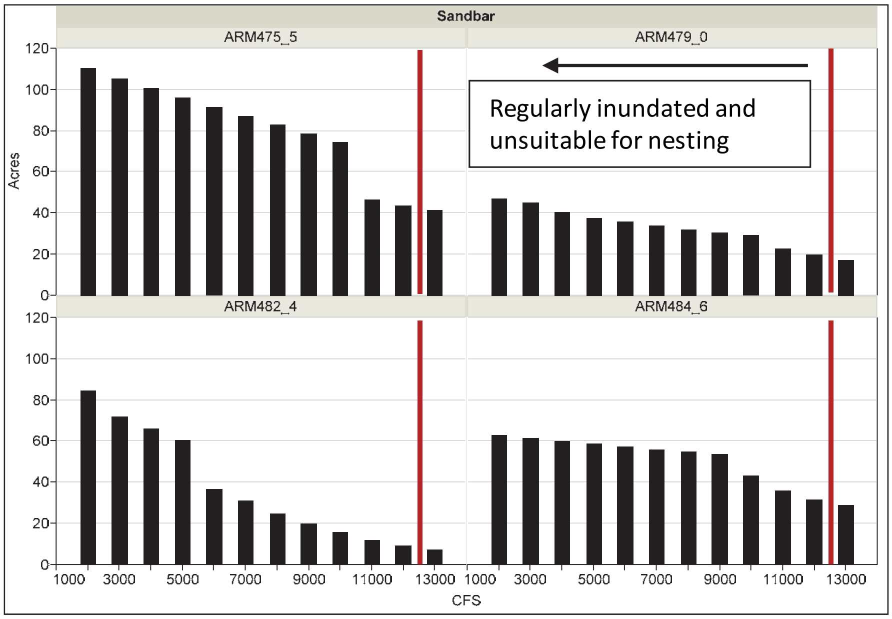

Figure 8. Exposed acres by flow for four sandbars on the Arkansas River below Keystone Dam within the range of flows that occurs near-daily during peak hydropower operations (2,000-13,000 cfs). Note: at 2,000 cfs, 305 acres are exposed on these four sandbars. However, at 13,000 cfs, the cutoff for habitat suitability (red line), only 95 acres are exposed.

such, they do not represent suitable nesting habitat, since all nests placed on these portions of sandbars would be destroyed. Low flow data are prevalent in many publically available aerial photography datasets due to the high frequency of low flows late in the growing season. However, habitat measurements based on these data would vastly overestimate the amount of SNH for ILT. For this reason, "suitable" habitat is described in this report as only the higher-elevation portions of sandbars that are not regularly inundated by peak hydropower releases.

Daily stage variations also produce significant within-day variation in: 1) the depth and availability of different shallow-water habitats for fish, 2) the extent of saturated portions of sandbars that provide shorebird and wading bird foraging habitat (Tracy-Smith et al. 2011), 3) the elevation and extent of potential plant germination surfaces (e.g., wet sand with new propagules delivered to it), 4) the exposure or presence of various types of wetland vegetation), and 5) connections between sandbars and shorelines at low water, which provide easier access for terrestrial predators or off-road vehicles. In sum, releases that typify periods of peak hydropower generation result in large daily variation in exposed sandbar acreage, as well as several other ecologically important landform/land cover types that affect tern habitat and reproductive success.

Effects of daily stage variation on sandbar erosion and plant establishment

Sub-daily variation in sandbar exposure contributes to ecological processes in ways that are novel for many of the rivers where ILT nest. For example, erosion is exacerbated on the banks of newly formed sandbars that are repeatedly saturated for several hours each day and then exposed to rapidly falling water levels, which results in intensified rates of undercutting and slab failure (Knighton 1998). This process reduces the size and persistence of sandbars. It also leads to particularly steep banks on the high-energy thalweg margin of sandbars, or the banks of active back channels (chutes) (Figure 9). This process precludes vegetation establishment on many sandbar shorelines, since plants either have their substrate eroded from beneath them, their seeds resuspended and transported prior to germination, or their young roots removed by flow forces. Similarly, many propagules cannot tolerate the regular desiccation that occurs for several hours each day when water levels fall on shorelines with less vertical relief.

Figure 9. Lateral sandbar erosion due to regular slab failure on the banks of sandbars (both on thalweg and back channel margins) is increased by large sub-daily stage variation in river reaches with peak hydropower releases (see Figure 6 for the type of hydrograph that can exacerbate this kind of erosion).

The nature of how peak hydropower releases affect plant establishment changes downstream from dams. At increasing distances, the effects of hourly flow variation are attenuated. Many miles downstream from dams, regular, short-term high releases for hydropower translate into relatively consistent waterline elevations for the 5 days of the week during hydropower operations, followed by a short-term decrease in stage, reflecting the absence of hydropower releases on the weekend, with a return to consistent waterlines for another 5 days (Figure 6). This pattern translates into sandbar shoreline conditions (on hydropower reaches) that strongly favor the growth of vegetation that can tolerate periodic desiccation. In the study area, this is represented by the vegetation habitat type dominated by Yellow-Nut Sedge (Figure 10). The characteristic pattern of weekly hydropower dam releases promotes a vegetation response far downstream from dams that stabilizes the shoreline of sandbars with persistent herbaceous vegetation, which may prolong the persistence of sandbars.

Figure 10. Vegetation community dominated by Yellow-Nut Sedge, indicative of the sandbar shoreline associated with peak hydropower flows during the growing season.

Downstream travel of hydropower releases and waterline flow interpolation

Short-term high releases during peak hydropower generation translate downstream as recognizable peaks at downstream gages, and result in characteristic "valleys" after the pulse of a peak release passes a gage (Figures 6 and 7). Time differences between these characteristic peaks and valleys in hydrographs at dams and downstream gages can be used to estimate the velocity that water travels downstream. This velocity can be used to estimate flows corresponding to waterlines at specific times for sandbars downstream from gages, given a distance measurement from the gage to a sandbar. This process is often called "flow interpolation." In reality, the velocity at which water travels downstream varies in complex fashion throughout the year due to: 1) the magnitude of dam releases; 2) previous dam releases that affect antecedent conditions in the channel; and 3) other conditions that affect antecedent channel conditions (e.g., amount of vegetation in the channel, sediment characteristics, and water extraction). Rather than modeling all of these factors, for which data were lacking, flow travel rates were visually estimated from hourly hydrographs for flow interpolation (Chapter 3).

The variable timing and magnitude of downstream attenuation of fluctuating hydropower releases has a strong and direct effect on the interpretation of habitat measurements, whether these are made in the field or via remote sensing (e.g., aerial photography). For topographic surveys, flow interpolation is necessary to connect measured waterline elevations (which occur at a specific time) to a specific flow. This can be used to establish a datum for local stage-discharge relationships used to estimate which flows will inundate higher elevations of a sandbar (Chapter 3). Similarly, if sandbar perimeters are walked while carrying a GPS unit, perimeter lines can be converted into polygons to estimate acreage (e.g., Brown and Jorgensen 2009). These acreage estimates are only appropriate for the flow at the time of sampling (e.g., the sandbar was 12.7 acres at 15,500 cfs, when it was sampled at 11:30 am on 12 May 2001), which also requires flow interpolation. This is equally true for aerial photography acreage estimates, which document habitat conditions only at the exact moment when a photo is taken. Flow interpolation is again required to connect these area estimates to the specific flow that described the waterline at the exact moment each sandbar was photographed, which often varies among photos that have been stitched together to cover any one reach of river.

Since gages are usually not available at each sandbar, the flows that correspond with observed waterlines must be interpolated from observed flows at gages that are upstream and/or downstream of each sandbar. Generally, this interpolation is least accurate when 1) gages are far apart, 2) intervening tributaries contribute flow (particularly if these lack gages), 3) river slopes vary between gages (as in pool/riffle stream profiles), or 4) when downstream changes in surficial geology or structures for irrigation water withdrawal or return result in sudden water gains or losses. Interpolation becomes even more challenging when hourly fluctuations in releases/flows are severe, as is the case during hydropower generation.

High releases/flows during the breeding season that flood nests or chicks

Periods of flooding mortality risk within the Least Tern breeding season

The following series of hydrographs relates hydrology with life history (e.g., the timing of various events within the Least Tern breeding cycle) to evaluate Least Tern nest and chick flooding risk. Least Terns arrive in Oklahoma in early to mid-May (Byre 2000) and typically initiate their first nests two to three weeks later, with peak nest initiation between late May and the first few weeks of June (Table 2). However, nest initiations have been recorded as early as mid-May and as late as mid-July.[1] When first breeding attempts fail due to flooding, predation, or any other cause, Least Terns will re-nest, for as many as three nesting attempts in one breeding season (Thompson et al. 1997). Variable mortality and re-nesting can result in variable nesting phenology among sites or years. In years when early-season high flows inundate most nesting sandbars or when there is considerable early season nest or chick mortality, many nests will be initiated late in June or early in July (Szell and Woodrey 2003).[1] Nests that are initiated later than 14 July may not be successful, since adults may not have enough time to raise young to fledging age prior to August 22, the date by which many terns in the southern Great Plains depart for fall migration.[1,2]

Depending on how many eggs are in laid in a nest, clutch completion takes 1-5 days, since female terns lay a new egg every other day, and clutch size varies from 1-3 (for ~99% of all clutches)(Thompson et al. 1997). Once a clutch is complete, eggs must be incubated for ~21 days before chicks hatch. After chicks hatch, they must survive ~20 days before they can fly, at which point they are considered “fledged” (Thompson et al. 1997). Given this phenology, using a 3-day average duration for the egg-laying period, a 21-day incubation period (which includes the last day of egg-laying), and a 20-day chick period (which includes the hatching date), an average “mortality risk period” for each nesting attempt (from nest initiation through fledging) can be defined as 42 days.

[1] Personal Communication. 2008. Kevin Stubbs, Biologist, U.S. Fish and Wildlife Service, Tulsa, OK.

[2] Unpublished Data. 2010. Greg Petrick, Arkansas Tech University, Russellville, AR.

Reproduction-limiting flows

The regular release of ~11-12,000 cfs from Keystone Dam during peak hydropower production (and additional contribution of base-flow and runoff in contributing areas) restricts tern nest initiation to elevations on sandbars that are still exposed at flows >~13,000 cfs. Flood control releases that are higher than peak hydropower releases will cause nest mortality if nests are inundated or chick mortality if whole sandbars are inundated. Nest and chick flooding risks differ, since chicks have the ability to move to the tops of sandbars and nests do not. Also, due to variation in the maximum elevations of sandbars, and variation across sites in the band of elevations at which terns place nests, flooding risk varies among sandbars.

Linking hydrographs and habitat measurements

When sandbars have been measured at low flows, and models have been created to estimate exposed acres of suitable habitat at any flow, it is simple to construct graphs of the minimum acres of suitable habitat that are exposed at each site on each day of the breeding season. These graphs translate the breeding season hydrograph into graphs of seasonal habitat availability (Figure 11).

While these graphs indicate the point where whole sandbars are inundated, resulting in nest ***and*** chick mortality, lesser flows can still destroy nests placed at elevations lower than sandbar tops. True nest flooding risk can only be assessed with data on nest elevations (Figure 12). This is what led to simulating nest flooding mortality in an individual-based model where model terns place nests at elevations that typify real-world nest site placement (Lott et al., in preparation (a, b). However, the preparation of seasonal habitat exposure graphs (e.g., Figure 11), is a first step at understanding how reservoir operations affect seasonal nesting habitat availability. Another useful approach is to factor the duration of nesting attempts into habitat summaries by determining if a sandbar is exposed for 42 consecutive days subsequent to each day of the nest initiation season (Figure 12).

While Figures 11 and12 link hydrographs and habitat measurements, and provide a sense of how sandbar inundation may limit Least Tern reproduce-tion, they fall short of fully accounting for nest flooding risk (or incidental take of nests due to flooding). When the actual location of nests can be accounted for, either via empirical data collection or through simulation (Lott et al., in preparation (a, b)), nest mortality can be assessed more realistically by accounting for flooding of the exact elevations where nests are placed.

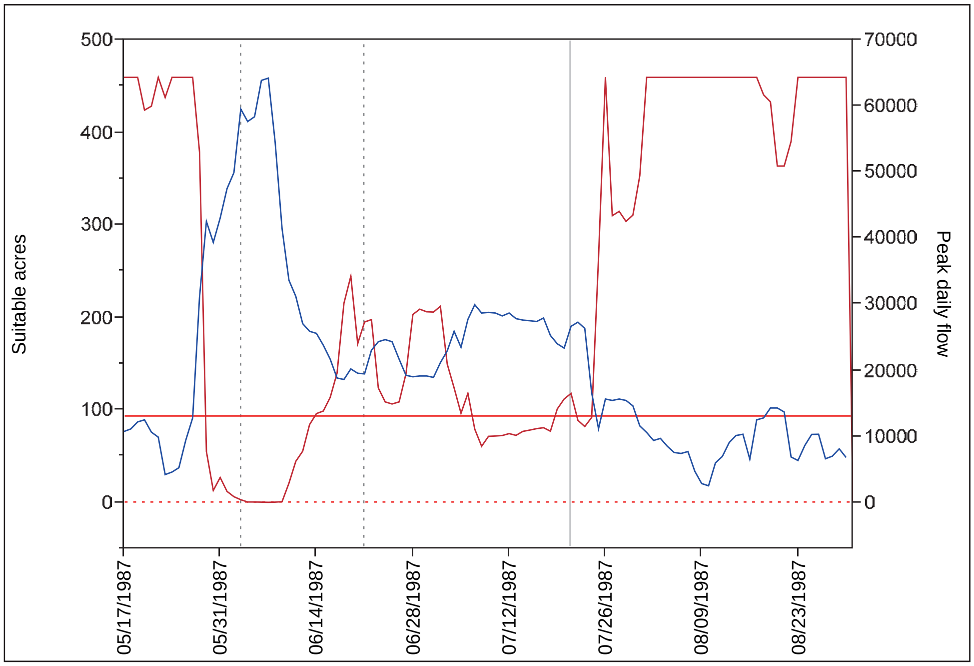

Figure 11. Given the type of habitat measurements reported in this document, it is possible to translate a time series of peak daily flows (blue line, scale on right y-axis) into a time series of sandbar exposure (red line, scale on the left y-axis). Note: All sites were briefly inundated (0 acres exposed) during maximum flows of around 65,000 cfs on 20 and 21 May. Flows below 13,000 cfs (the horizontal red line indicating the minimum flow for habitat suitability) do not increase the number of suitable acres, which for this set of habitat conditions (the excellent habitat conditions measured after the high flows of 2007-2008) is 458. X-axis reference lines are as in Figure 2.

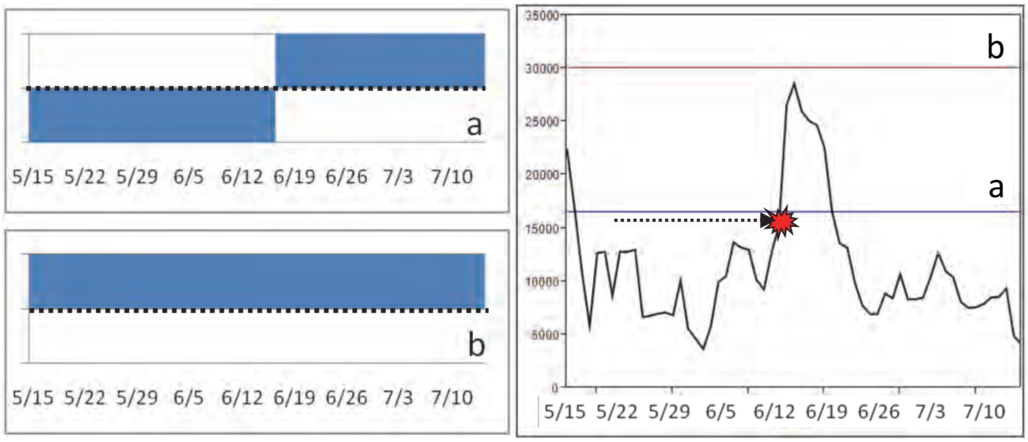

Figure 12. Seasonal sandbar exposure of two sites with different inundation thresholds. On the left, when lines are below center, successful nesting is not possible since whole sandbar inundation occurs within 42 days of nest initiation. When lines are above center, successful reproduction is possible as long as nests or chicks do not suffer other types of mortality. At site a, all early season nesting attempts would fail due to a mid-season flood (dotted black line and red symbol in the graph to the right). Successful nesting was only possible at site a after 20 June, the date by which the receding mid-season flood re-exposed the sandbar. In contrast, site b was never inundated, since this site had an exposed area at flows up to 30,000 cfs, allowing for successful reproduction across the entire season. Whether or not the peak flow of 28,600 cfs on 14 June would have resulted in nest mortality depends on actual nest elevations. Consequently, plots of whole site exposure under-estimate nest flooding risk, which can only be assessed with information on nest elevations.

3 Methods

Study area

Sandbar nesting habitat was measured along the Arkansas River from Keystone Dam to the backwaters of Webbers Falls Reservoir, near Muskogee, Oklahoma. While Keystone Dam provides local flood control for the Tulsa area, it also produces hydroelectric power that contributes to a regional grid, and participates, along with a number of other reservoirs, in integrated flood control and navigation operations affecting areas farther downstream on the Arkansas River (USACE 2002, 2003). Consequently, operations at Keystone Dam are adjusted relative to the operations of other reservoirs within the Arkansas River System (USACE 2002).

Throughout the entire tern nesting area below Keystone Dam, flows are strongly affected by dam releases, given the relatively small contributing drainage area downstream of the dam (Figure 13). Releases from the dam are driven by the interaction between current storage and inflows from several sources. Keystone Lake receives inflow from the entire upper Arkansas River drainage, after water is routed through Kaw Dam, 115 miles upstream (Figure 13). However, much of the water in the upper Arkansas is seasonally extracted for agricultural use in Colorado and Kansas prior to reaching Oklahoma. Just below Kaw Dam, the Arkansas receives flows from two moderately sized drainages: the Chikaskia River and the Salt Fork of the Arkansas River. Keystone Lake also receives inflows from the Cimarron River basin. Major precipitation and runoff events in any of the upstream watersheds during the Least Tern breeding season tend to result in inflows to Keystone Lake that require flood control releases, due to the reservoir's relatively small amount of flood storage (20 acre-ft/square mile, compared with 124 acre-ft/square mile in Lake Texoma behind Denison Dam).

Due to the lack of major tributaries, the area immediately below Keystone Dam receives very little new sediment input and the channel is sediment starved until well downstream of Tulsa. Consequently, only a single sandbar, Zink Island, which is an artificially created and maintained nesting site near Tulsa, is regularly used for tern nesting in the upper portion of this reach (Hill 1993, USFWS 2005a, Figure 14). Both Zink Island and the Tulsa USGS gage are immediately upstream of Zink Dam, a low headwater-quality dam. Similar low-head dams have been proposed for the Tulsa-Jenks areas

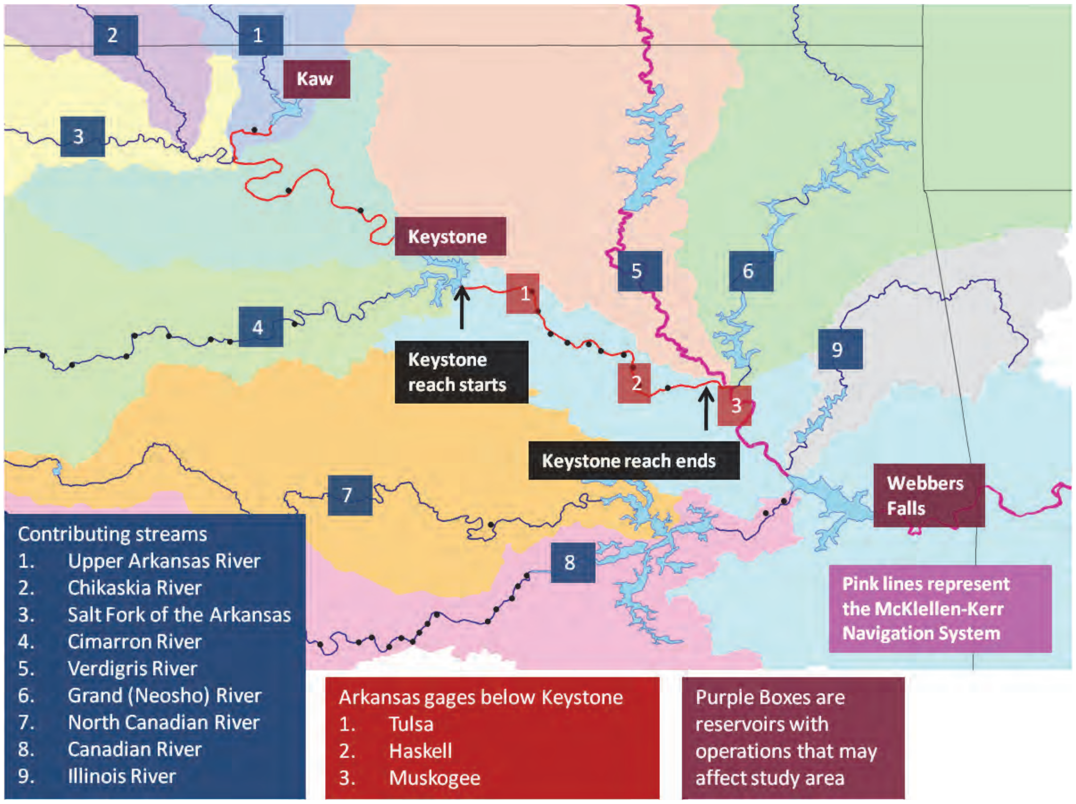

Figure 13. Regional context for the Arkansas River below Keystone Dam study area.

Figure 14. Zink Island, a mechanically created sandbar at Arkansas River Mile 523.4, near the city of Tulsa.

to retain water in the channel in the hours when releases for hydropower production do not occur, as part of a riverside development plan for Tulsa County (Carter & Burgess 2004). The majority of the sandbars in the Keystone Reach are downstream of this area, with most suitable SNH occurring within 15 miles upstream or downstream of the Haskell gage (56 miles downstream from Keystone Dam).

The lower portion of the Keystone reach terminates in the backwater of Webbers Falls Reservoir, near the confluence with the Verdigris and Grand (Neosho) Rivers in the uppermost reaches of the McClellan-Kerr Navigation System (the terminal port of Catoosa is upstream on the Verdigris) (Figure 13). The Muskogee USGS gage within this backwater records the influence of releases from Keystone Dam on the Arkansas, Choteau Dam on the Verdigris, and operations of Webbers Fall Lock and Dam on the Arkansas. Consequently, only the Tulsa and Haskell gages were used to document channel conditions on the Keystone reach of the Arkansas. During major releases from either Keystone Dam or terminal dams on the Verdigris or Grand Rivers, the Webbers Falls backwater can extend upstream for variable distances into the lower portions of the Keystone reach, as is observed by the “bathtub” rings of former reservoir shorelines on the sandbar at RM 465.7.

Two relatively large rivers, the Illinois River to the north and the very large drainage area of the Canadian River to the west, provide additional inflows to the McClellan-Kerr Navigation system just downstream of the Keystone reach. Regional rainfall events tend to affect more than one of these drainages simultaneously resulting in complex integrated water control operations where multiple dams, including Keystone, work together to provide flood control and maintain safe operational conditions on the navigation system downstream of Keystone Dam, which passes through the state of Arkansas before connecting with the Lower Mississippi River.

Hydrologic data methods

Detailed methods for all hydrologic data acquisition, proofing, and analysis are presented in Appendix A.

Field and GIS habitat measurements

Detailed methods for all field and GIS habitat measurements are presented in Appendix B.

Estimating acreage of SNH at different flows

For the purposes of this study, "suitable habitat" was defined as any cell where a tern could potentially nest, excluding only cells with habitat characteristics that would preclude tern nesting. The following six criteria were applied to define suitable SNH (see "A specific definition of SNH" in Chapter 1):

1. Cell must not be inundated at the current daily maximum flow;
2. Cell must not be inundated at a daily maximum flow typical of normal hydropower production during low-runoff conditions (e.g., 13,000);
3. Cell must be free of sandbar vegetation;
4. Cell must be >50 ft from the nearest patch of sandbar vegetation;
5. Cell must be >200 ft from the active channel margin;
6. Cell must be >250 ft from a large tree or trees.

Outputs from the Python script described in the previous section were used as inputs to the individual-based model (IBM) of Least Tern reproduction, TernCOLONY (Lott et al., in preparation (a, c)). TernCOLONY is programmed in a software platform called Repast Simphony (http://repast.sourceforge.net). This IBM platform updates the state of all habitat cells at each site on each day of the breeding season based on the time-series of sandbar-specific peak daily flows described above. The IBM software then calculates the acres of suitable SNH (and associated flows) for each site on each day, and exports this information to a Postgres Database (Lott et al., in preparation (a)), which was queried for the data summarized in this report. Both the Python ArcGIS script and the Repast habitat update and summary methods were extensively verified and compared with independent calculations (with tolerance levels of 0.01%) to ensure their accuracy.

SNH acreage summaries

Acreage summaries at benchmark flows

USFWS (2005a) explicitly references two benchmark flows for reporting acreage of SNH below Keystone Dam: 1) peak hydropower flows, with typical base flow and runoff, during the breeding season (defined as 13,000 cfs), and 2) frequently occurring flood control releases of 20,000 cfs. Given variation in the magnitude of breeding season flood control releases during the post-dam era (See Figure 3), acreages of exposed and suitable SNH are also presented at 10,000-cfs increments from 30,000 cfs to 50,000 cfs (at which point nearly all suitable SNH is inundated below Keystone Dam).

Summarizing key SNH quality covariates

Acres of sandbar vegetation are summarized by site to allow comparison with sandbar measurement datasets during time periods where vegetation succession has resulted in considerable loss of SNH, or to suggest where vegetation removal may benefit terns. These summaries are presented at 13,000 cfs, the minimum flow threshold for SNH suitability. At this same flow, site-based summaries are also presented (as distributions) for several habitat covariates that may influence nest site selection and/or reproductive success. These summaries include the distance from each suitable SNH cell to: 1) the nearest tree, 2) the riverbank, and 3) low sandbar vegetation. A metric of sandbar elevation is also reported that was developed to compare relative flooding risk among sites; this metric is called “freeboard at 13,000cfs.” This metric is calculated as the elevation difference between any one cell and the water surface elevation for the sandbar containing the cell at 13,000 cfs.

Seasonal availability of SNH

The TernCOLONY model was used to calculate exposed acres by flow for each site with daily flow inputs for each breeding season from 1977 to 2008 (see “Estimating acreage of SNH at different flows” in Chapter 3). These summaries describe how the full range of flows that have occurred during the post-dam era would affect seasonal habitat availability for the types of high-quality sandbars that were formed during the high flows of 2007-2008. Seasonal availability of SNH (e.g., Figure 11) is graphed by site, water year type, and across the whole period of record for the post-dam era. The same set of annual flow inputs (1977-2008) was used to examine seasonal habitat availability using the simulated degraded habitat set as well.

Individual sandbar exposure across whole Least Tern nesting attempts

Least Terns require 42 consecutive days of sandbar exposure for successful nesting (see “Periods of flooding mortality risk within the Least Tern breeding season” in Chapter 2). Therefore, the graphs in this report summarize the number of sites that remained exposed for 42 consecutive days beginning on each possible nest initiation date from May 15 to July 14.

Similar to acreage summaries, summaries for both excellent and degraded habitat conditions across the whole period of record for the post-dam era are presented.

Simulating the effects of nest and chick flooding, habitat restoration, and predator management on tern populations in TernCOLONY

Flooding mortality is affected by choices that individual terns make about where they will join a nesting colony (e.g., which sandbar) and the exact location where they will place a nest on a selected sandbar (Lott et al., in preparation (a, b)). These choices are affected by the prior distribution of nesting terns (e.g., site fidelity), the dates by which terns arrive throughout the study area, and seasonal variation in flows during colony formation and nest initiation, which varies from year to year (Lott et al., in preparation (a)). Consequently, true flooding risk cannot be assessed by hydrographs (Chapter 2) or even seasonal graphs of sandbar exposure (Chapter 4) without site-based information on nest elevations and inundation elevations during individual Least Tern nesting attempts.

TernCOLONY, an individual-based model of Least Tern reproduction (Lott et al., in preparation (a, b)), was used to assess tern nest and chick flooding mortality risk across the range of operations that have been observed in the post-dam era for both the excellent habitat conditions measured in 2008-2009 and the degraded conditions that were simulated to reflect SNH before the high flows of 2007-2008 (Simulation Experiments 1 and 2; see Table 3). TernCOLONY simulates ILT breeding seasons in daily time-steps, with flows (and sandbar exposure) varying each day at each sandbar in response to site-specific inputs for peak daily flows (Lott et al., in preparation (a)). During TernCOLONY simulations, individual terns make decisions about which sandbars they will nest on and the exact location (on selected sandbars) on which they will place a nest. Nest mortality then occurs mechanistically during simulations whenever water surface elevations are greater than nest elevations. Chick mortality occurs whenever water surface elevations are greater than the highest point on a sandbar.

Two different simulation experiments (see Table 3) were designed in TernCOLONY to: 1) evaluate the degree to which dam operations may cause Least Tern nest or chick mortality due to flooding; 2) evaluate whether or not the effects of dam operations on nest/chick flooding differ when habitat conditions are excellent (e.g., after the high flows of 2007-2008) from when

Table 3. Details of TernCOLONY simulation experiments used to evaluate the effects of Keystone Dam operations on Least Tern populations on the Arkansas River.

Experiment	1	2	3
Habitat inputs	Excellent, Degraded	Excellent, Degraded	Degraded, with and without four restoration sandbars
Predator inputs	None	Low (3), High (8)	High (8), Moderate (5)
ORV inputs	None	Low (3)	Low (3)
Flow inputs	1977-2008	1977-2008	1977-2008
Adult terns	400	400	400

Notes: Numbers in parentheses reflect predator or ORV intensity parameter values (see Lott et al. 2011a). See the section in Lott et al. (2011b) on model calibration for the basis for pairing intensities of “3” with excellent habitat conditions and “8” with degraded habitat conditions.

Based on previous simulations during model calibration, it was expected that reducing the predator intensity parameter from 8 to 5 would result in a ~35% reduction of the number of nest and chick predators in the model. This simple, heuristic approach was used to simulate a predator control program with moderate effectiveness.

they are poor (e.g., prior to these same high flows; and 3) evaluate if incidental take due to nest or chick flooding translates into poor regional reproductive success (or if some flooding losses can be compensated for via re-nesting). Simulation experiments are simply batches of simulated Least Tern breeding seasons with different combinations of model inputs that are designed to learn something about population or management dynamics from a simulation model (Grimm and Railsback 2005, Zurrell et al. 2010).

After these initial two simulation experiments, an additional simulation experiment (Experiment 3 in Table 3) was designed to evaluate the potential for three different management approaches (e.g., habitat restoration, predator control, and a combination of the two) to decrease nest/chick mortality due to flooding or predators and increase reproductive success. This simulation experiment used only degraded habitat condition inputs, since both flooding and predator mortality were minor, and reproductive success was high, with excellent initial habitat conditions (e.g., the need for management is much stronger when habitat conditions are degraded). For all simulations, an initial population size of 400 adult terns below Keystone Dam was specified to facilitate direct comparison of results among experimental groups and management treatments.

TernCOLONY produces many model outputs (Lott et al., in preparation (a)). The primary outputs explored through statistical analyses in this report are: 1) the three major causes of mortality in the model: flooding, predators, or parental abandonment (all of which can occur to either nests or chicks); and 2) the numbers of fledglings per simulated breeding season. The total number of fledglings metric was used rather than the commonly reported ratio statistic of annual reproductive success (number of fledglings/female), since the number of females did not vary significantly among simulations. For more information on TernCOLONY, the complete model description (Lott et al., in preparation (a)) and supporting documents (Lott et al., in preparation (b, c)) are available at http://www.leasttern.org. Output files for each of the simulation experiments reported here are available via request from the first author.

TernCOLONY simulation experiments

Experiment 1: Nest and chick flooding in the absence of predators/ORVs

By default, TernCOLONY simulates mortality from flooding, predators, and ORVs, the three main threats that have been proposed to limit ILT populations (USFWS 1985, 1990; Lott et al., in preparation (a)). However, the model can also be run with predator and ORV submodels turned "off." This feature was used to design an "unrealistic" simulation experiment (Grimm and Railsback 2005), where neither predators nor ORVs were allowed in the model. This helps to isolate the effects of dam releases/flows on tern nest and chick mortality (particularly in comparison with experiment 2, where predators and ORVs are allowed in the model). When predators and ORVs are not present, the remaining sources of nest and chick mortality in the model are: 1) flooding from high dam releases/flows, 2) site abandonment by adults during flooding events, and 3) inviability of all eggs in a clutch (this last cause of mortality was rare in this set of simulation experiments, so it was not included as a response variable in multivariate analyses of variance (MANOVAs).

This simulation experiment explored how much flooding mortality depends on initial habitat conditions by using habitat inputs representative of both the excellent conditions documented after the high flows of 2007-2008 and the degraded conditions that existed prior to these same high flows (see Chapters 3 and 4 for more detail on habitat inputs). For each set of habitat conditions, the time series of peak daily flows from all 32 years (1977-2008) of the post-dam era (see Chapters 2 and 3) were used as flow inputs to the model. By design, TernCOLONY includes stochasticity in submodels related to the processes of colony and nest site selection (Lott et al., in preparation (a)). This stochasticity can result in variable colony site selection and nest site placement among simulations that have the exact same inputs for habitat conditions and flows. This can translate into variable flooding mortality among simulations. Consequently, three replicate simulations were run for each unique set of model inputs to examine how much this stochasticity affects model outcomes.

Experiment 2: Nest and chick flooding with predators/ORVs present

This experiment was identical to Experiment 1 except that predators and ORVs were allowed into the model (Table 3). Low inputs were selected for ORVs, since ORV use of the Arkansas River below Keystone Dam is typically low[1] compared with other areas where heavy ORV use has been recorded (see Byre (2000) for the Canadian River near Norman, Oklahoma; or Gulf South Research Corporation (2005) for the Red River below Denison Dam).

During the TernCOLONY literature review, it became clear that predator mortality is higher when habitat conditions are degraded than when they are excellent (e.g., more predators are present on vegetated sandbars than bare sandbars). Consequently, TernCOLONY's predator mortality submodel was calibrated so that nest/chick mortality rates reproduced by the model when habitat conditions are degraded (or excellent) are within the range of nest/chick survival rates documented for these same habitat conditions in empirical studies (Lott et al., in preparation (b))[2]. For this reason, higher predator inputs were specified for simulations with degraded habitat than for simulations with excellent habitat inputs (Table 3). Consequently, in Experiment 2, differences in mortality causes and fledgling production between degraded and excellent habitat conditions are a result of: 1) differences in flooding risk between the two sets of initial habitat conditions, and 2) inherent differences in predator mortality between the two sets of habitat conditions. Including predators in the model creates the potential for the nest/chick mortality of both parents due to predators (this occurred rarely during these simulations, so this cause of mortality was not used as a response variable in MANOVAs).

[1] Personal Communication. 2008. Kevin Stubbs, Biologist, U.S. Fish and Wildlife Service, Tulsa, OK.

[2] With default values for the predator intensity parameter of "8" for degraded habitat inputs and "3" for excellent habitat inputs (see Lott et al. 2012b).

Experiment 3: Effectiveness of habitat restoration and predator control when habitat conditions are degraded

After reviewing Experiments 1 and 2 (Chapter 5), an experiment was designed to see if significant investment in sandbar habitat restoration and/or predator control could reduce flooding and/or predator mortality and increase fledgling production when habitat conditions are degraded. In Experiments 1 and 2, flooding mortality was particularly high at three heavily used sandbars when habitat conditions were degraded: those at RM 507.0, 489.8, and 523.4. For the habitat restoration scenario, budgetary constraints limited work to creating (and then maintaining) four high-elevation sandbars in a bare, high-quality state (similar to the sandbars that were created after high flows in 2007-2008). For this experiment, the sandbar at 489.8 was restored and new sandbars were created at RM 505 and 527. This resulted in alternative high-quality sites near all three sandbars where flooding mortality was highest in Experiments 1 and 2. A sandbar was also restored at RM 475.5, within a reach where little nesting occurred during Experiments 1 and 2. To investigate the potential effectiveness of predator control, a program that would result in a ~35% reduction in the number of nest and chick predators present within the study area was envisioned. This program would have variable effects on nest and chick mortality given the inherent stochasticity of Least Tern depredation in the real world and the TernCOLONY model. Four different scenarios were then simulated: no management (e.g., baseline conditions of degraded habitat with no management), habitat restoration only, predator control only, and a combination of habitat restoration and predator control.

Statistical analyses of simulation experiment results

Experiment 1 included a two-way MANOVA with an interaction term (Tabachnick and Fidell 2001) to evaluate whether two different levels of initial habitat conditions (excellent or degraded), three different levels of water year types (low, mid-season flooding, or high), or the interaction between initial habitat conditions and water year type (e.g., degraded conditions x low water year) affected nest or chick mortality due to flooding. Since predators were not allowed in Experiment 1, this MANOVA did not include the response variables of nest or chick mortality due to predators. All other potential types of mortality were also excluded from this analysis, since <10 mortalities due to other causes were observed for all experimental groups. A separate investigation explored the effects of the combinations of independent variables listed above on the total number of fledglings produced per breeding season using a two-way analysis of variance (ANOVA) with an interaction term (Zar 2009).

Experiment 2 included a two-way MANOVA with an interaction term to evaluate whether two different levels of initial habitat conditions (excellent or degraded), three different levels of water year types (low, mid-season flooding, or high), or the interaction between initial habitat conditions and water year type (e.g., degraded conditions x low water year) affected nest or chick mortality due to flooding, nest or chick mortality due to predators, or nest abandonment (which can be caused by heavy mortality from either floods or predators). This MANOVA did not include response variables for any other potential types of mortality, since <10 mortalities due to other causes were observed for all experimental groups. A separate investigation explored the effects of the combinations of independent variables listed above on the total number of fledglings produced per breeding season using a two-way ANOVA with an interaction term.

Experiment 3 included a two-way MANOVA to test for the effect of four different management treatments (no management, habitat restoration only, predator control only, or habitat restoration AND predator control), three different water year types (low, mid-season flooding, or high), or the interaction between management treatment and water year type (e.g., predator control only x high water year) on nest or chick mortality due to flooding, nest or chick mortality due to predators, and nest mortality due to site abandonment. This MANOVA did not include response variables for any other potential types of mortality, since <10 mortalities due to other causes were observed for all experimental groups. A separate investigation explored the effects of the combination of independent variables listed above on the total number of fledglings produced per breeding season using a two-way ANOVA with an interaction term.

Wilks' Lambda, the Multivariate F statistic, degrees of freedom, p values from significance tests for both main effects, and the interaction term are reported for all MANOVAs. The F statistic, degrees of freedom, and p values are reported for two-way ANOVAs. MANOVAs that produced significant results for main effects or interactions were followed by ANOVAs on each response variable with a Bonferroni-type adjustment so that alpha pooled across the set of response variables did not exceed 0.05 (Tabachnick and Fidell 2001). All statistical analyses were performed in JMP 9.0 (SAS Institute, Inc. 2010).

4 Results: Habitat Measurements

Acres of SNH at peak hydropower flows of 13,000 cfs

Given the definition of suitable Least Tern sandbar nesting habitat, there were 459 acres of exposed SNH at 32 sites on the Arkansas River below Keystone Dam at peak hydropower flows of 13,000 cfs after the large habitat-forming flows of 2007 and 2008 (Figure 15). Most sandbars on this reach of river were relatively small at peak hydropower releases of 13,000 cfs. At this flow, seven sandbars had less than 5 acres of exposed SNH, six sandbars had between 5 and 10 acres, twelve sandbars had between 10 and 20 acres, five sandbars had between 20 and 30 acres, and two sandbars had >50 exposed acres. The simulated degraded conditions dataset included 25 sites that totaled 121 acres of SNH at 13,000 cfs. Of 25 sandbars, 18 had less than 5 acres of exposed SNH at 13,000 cfs and the largest sandbar had 30 acres of SNH at 13,000 cfs.

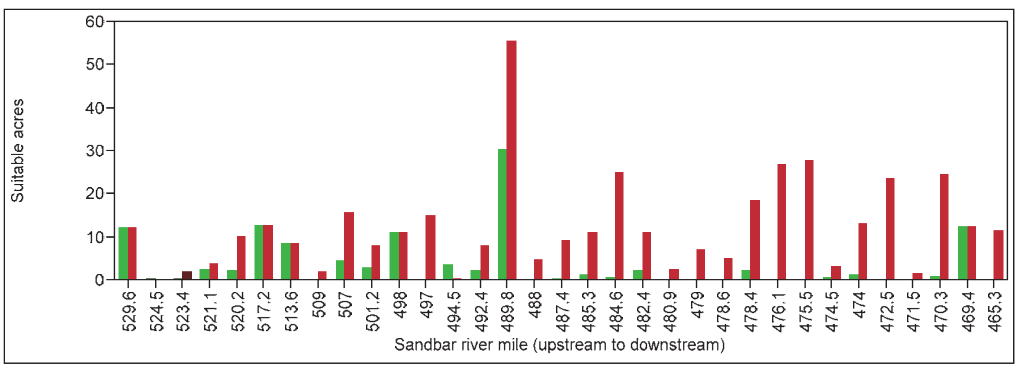

Figure 15. Acres of SNH by site below Keystone Dam on the Arkansas River at 13,000 cfs. Red bars indicate the excellent conditions that existed after the high flows of 2007-2008. Green bars indicate degraded habitat conditions that existed prior to these high flows.

SNH exposure at different benchmark flows

Both the number of exposed acres and the number of sites with any exposed acres decrease as flows increase. Figure 16 plots exposed suitable SNH acreage by five different benchmark flows (peak hydropower flows and flood control releases of four increasing magnitudes) for two different sets of habitat conditions: degraded conditions prior to the high flows of 2007-2008 and excellent conditions after these high flows. Figure 17 plots the number of sites with ANY suitable SNH exposed at each of these same five benchmark flows for the same two sets of habitat conditions.

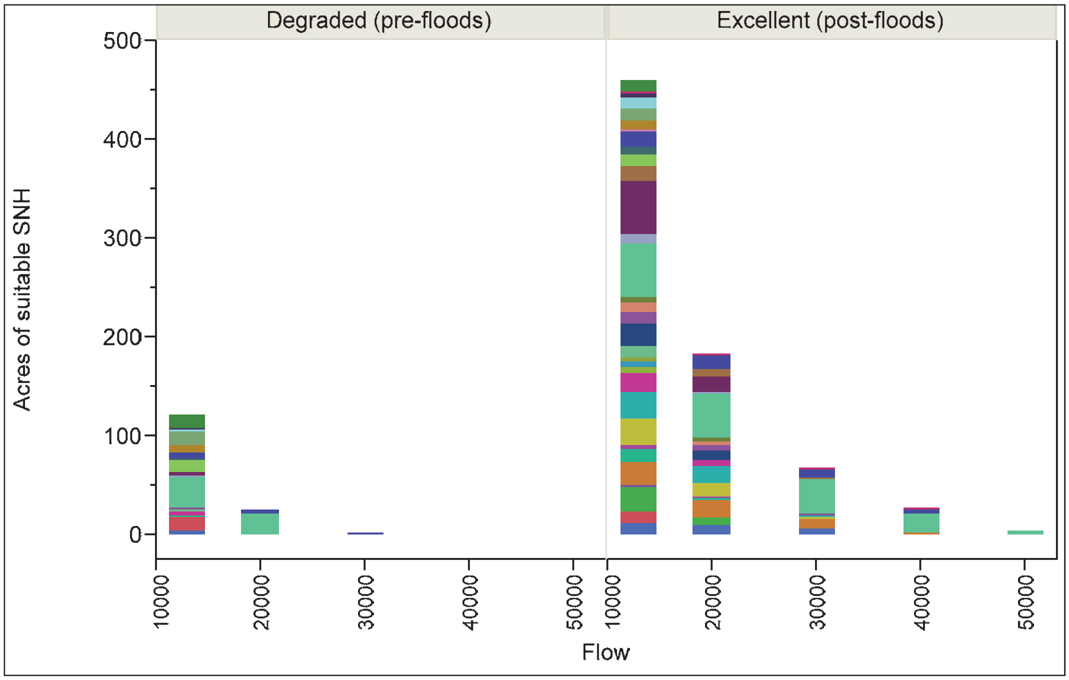

Figure 16. Stacked bar charts of exposed acres of suitable SNH by site (for two different sets of habitat conditions) for each of five benchmark flows: peak hydropower flows of 13,000 cfs and then flood control releases of 20,000-50,000 cfs in 10,000-cfs increments. Each colored section of a stacked bar represents the contribution of one site to the total.

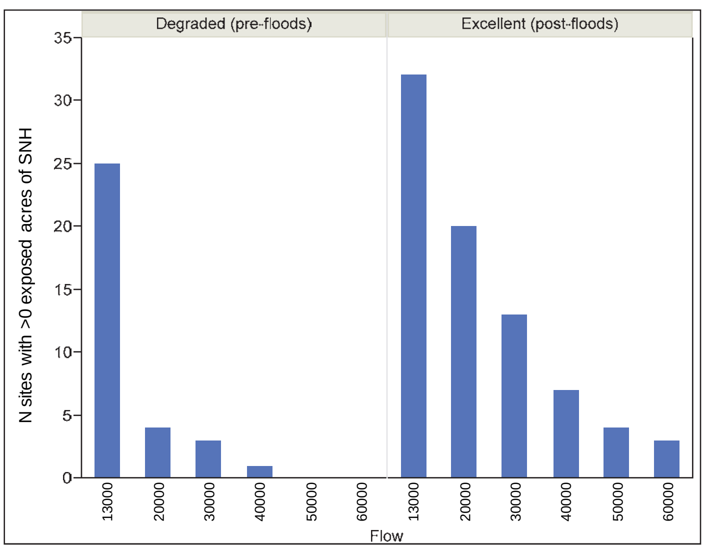

Figure 17. Number of sites with >0 acres of exposed, suitable SNH by flow benchmark for two different sets of habitat conditions: degraded conditions prior to the high flows of 2007-2008 and excellent habitat conditions documented in 2008-2009.

At 20,000 cfs, a fairly common flood control release during the Least Tern breeding season, 183 acres of suitable SNH were available at 20 sites after the high flows of 2007-2008, compared with 24 acres at only four sites prior to these habitat-forming flows (Figures 16 and 17). At 30,000 cfs, 67 acres were available at 13 sites after the high flows of 2007-2008, compared with 1 acre spread among three sites before. After the high flows of 2007-2008, 26 acres were still available at seven sites at 40,000 cfs, compared with less than 0.10 acre at one site before. Prior to the high flows of 2007-2008, no sites had exposed SNH at flows > 40,000 cfs. After the high flows of 2007-2008, 4.4 acres were still available at four sites at 50,000 cfs and 0.2 acre was available across three sites at 50,000 cfs. No sites had any SNH exposed at 60,000 cfs for either set of habitat conditions.

While these habitat summaries at benchmark flows are informative, given the frequency of flood control releases between 13,000 and 50,000 cfs from Keystone dam (Figure 3), and extreme variation in SNH exposure within this range (Figures 16-18), assessment of true flooding risk for tern nests and chicks also requires considering the timing, magnitude, and duration of flood control releases (see below).

Seasonal exposure of suitable SNH acres (variation among years)

Figure 18 illustrates temporal patterns in the exposure of suitable SNH that might be expected given the habitat conditions that 1) prevailed after the high flows of 2007-2008, and 2) existed prior to the high flows of 2007-2008, given 3o annual hydrographs from the post-dam era (1979-2008). Acres are summed across all sites. Note: While flows <13,000 cfs expose larger sandbar areas, these locations are not considered suitable SNH (Chapter 1). Consequently, the maximum amount of exposed suitable SNH does not increase at flows <13,000 cfs. All sandbars below Keystone Dam are inundated when the cumulative acreage total is 0.

Flows affect regional sandbar availability differently depending on initial habitat conditions and water year type. For example, in 5 of the 10 low water years illustrated in Figure 18 (1981, 1991, 1994, 1996, and 2003), relatively minor flood control releases (around 20,000 cfs) inundated at least some SNH during the central part of the ILT breeding season. However, given the outstanding habitat conditions that were present after the high flows of 2007-2008, several hundred acres of SNH were still exposed during each of these high-flow events. In contrast, these same moderate flood control releases inundated nearly all suitable SNH during the low-water years of 1994 and 2003.

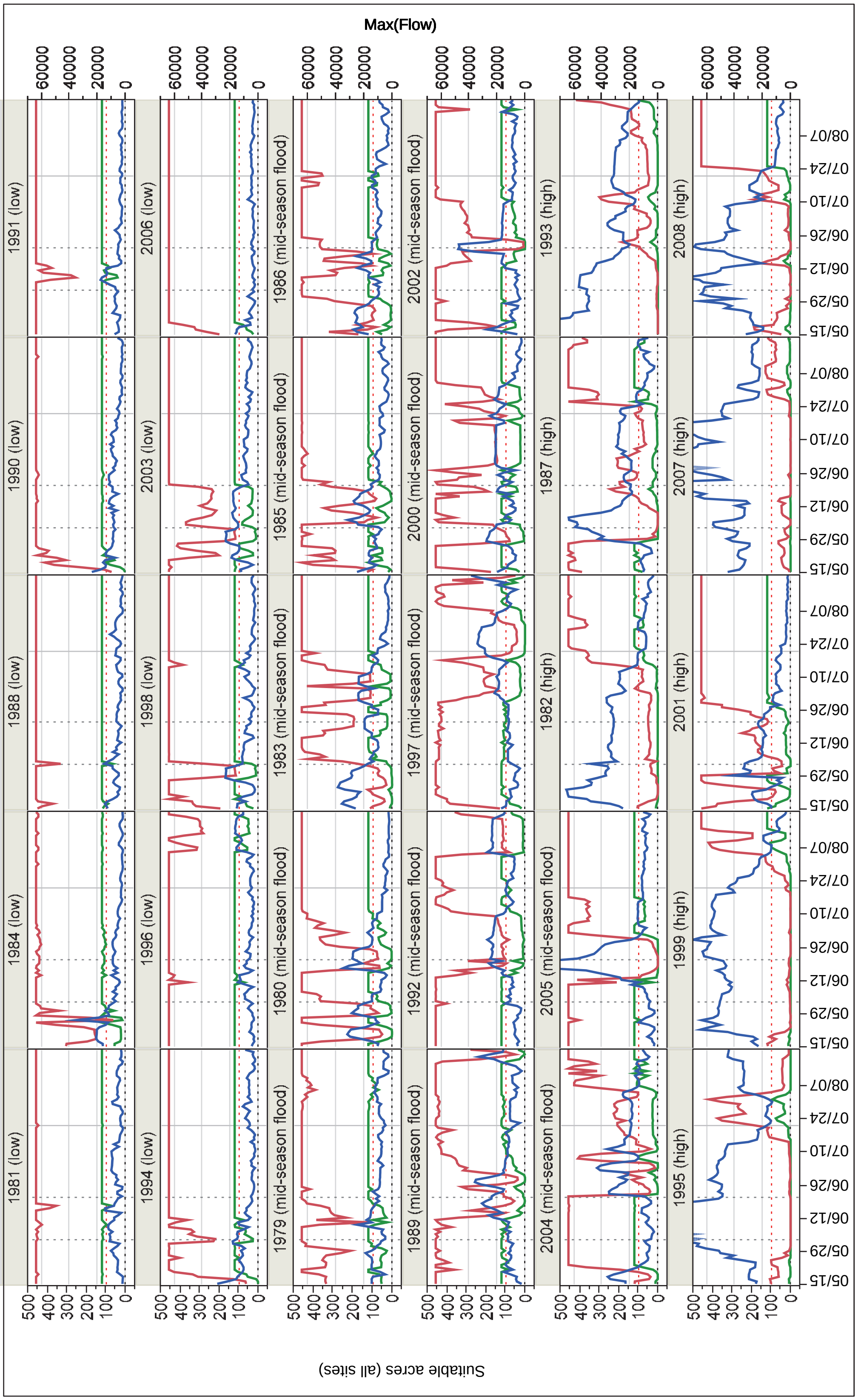

Figure 18. Seasonal exposure of suitable SNH acres summed across all sites below Keystone Dam for two different sets of habitat inputs: red line = excellent conditions after high flows of 2007-2008; green line = degraded habitat conditions prior to these flows. When the dotted black line at 0 on the x axis is obscured, all sandbars are inundated. Blue line (scale on right axis) is peak daily flow. X-axis reference lines are as in Figure 2. Red-dotted reference line from the right y-axis is the minimum suitable habitat flow of 13,000 cfs.

The effects of initial habitat conditions on regional SNH availability were even stronger during years with flood control releases >20,000 cfs (Figure 18). For example, in the 12 years with mid-season flooding, all SNH would have been inundated in only 2 of 12 years (2002, 2005) during peak ILT nesting given the excellent conditions that prevailed after the 2007-2008 high flows. In contrast, all SNH would have been inundated during peak ILT nesting in 10 of 12 mid-season flooding years given the degraded habitat conditions that were present prior to the high flows of 2007-2008.

Similar patterns were present during the seven high-water years. In six of these seven years, nearly all SNH was inundated for the entire nest initiation season when habitat conditions were degraded. While several high-water years also resulted in near-complete inundation of all SNH when habitat conditions were excellent (e.g., 2007), there were at least five of seven high-water years where sandbar exposure after early season floods (and continued exposure throughout the breeding season) would have allowed for successful nesting at some sites (Figure 18).

Continuous exposure of SNH during ILT reproduction (summary by water year type)

Many Least Tern colonies occur on relatively small sandbars and there is not always a strong relationship between sandbar size and colony size (USACE 2011). Therefore, in addition to summarizing sandbar exposure by acres (Figure 18), Figure 19 summarizes whether or not individual sandbars would have ***any*** acres of SNH that would be exposed for 42 continuous days starting on each day of the nest initiation period. The minimum number of days required for a successful Least Tern nesting attempt is 42, barring mortality due to some cause other than flooding (Figure 12).

Figure 19 is a regional summary of continuous 42-day sandbar inundation/ exposure during the Least Tern breeding season. As described in the previous section, the number of sites that were continuously exposed for long enough to support successful ILT reproduction (in the absence of non-flooding mortality) was strongly tied to both initial habitat conditions (excellent or degraded) and water year type.

During nine of the ten low-water years displayed in Figure 19, ~30 sites with suitable SNH remained continuously exposed for 42 straight days for most of the ILT breeding season (particularly after 3 June, the date by which 25%

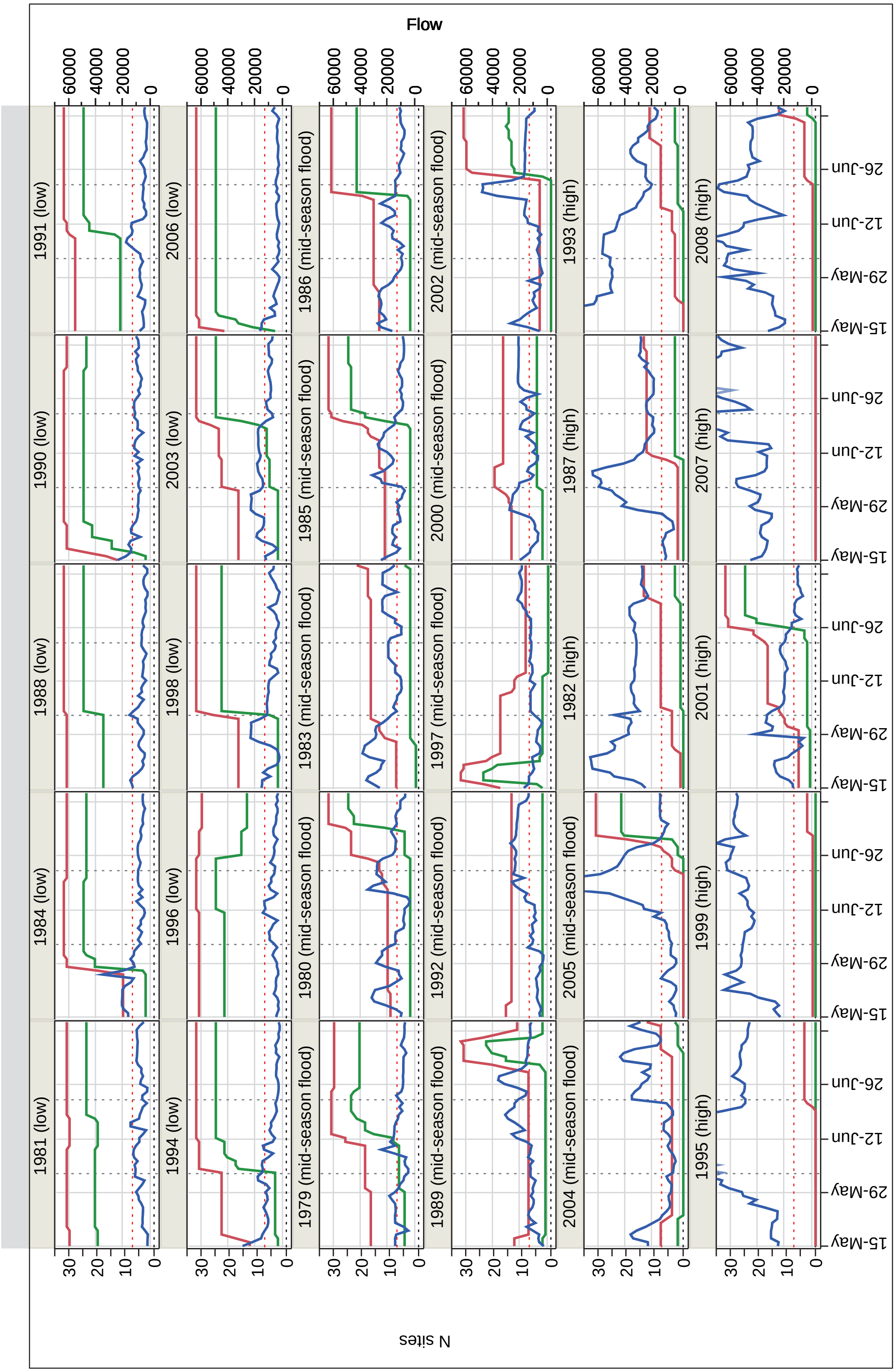

Figure 19. Number of sites below Keystone Dam with >0 acres of SNH exposed for 42 consecutive days subsequent to each day of the nest initiation period (left y-axis, red lines = excellent habitat conditions, green lines indicate degraded habitat conditions). When red or green lines obscure the black dotted line at 0, no sites were exposed long enough for nests initiated on the indicated date to survive. Blue line (right y-axis) is peak daily flow. Red horizontal dotted line is 13,000 cfs. X-axis lines at 3 June and 21 June indicate the central 50% of all nest initiations in an average year.

of nests would be initiated in an average year) given the excellent habitat conditions after the high flows of 2007-2008. In 2003, the low-water year with the highest flows, ~20 sites were available for most of the breeding season. In contrast, given the degraded habitat conditions that prevailed prior to the high flows of 2007-2008, ~20-25 sites with suitable SNH were available for 42 consecutive days during the peak ILT nesting season in only seven of these same 10 years. In 1991 and 1994, fewer sites were available during the first part of the season and in 2003, very few sites were exposed for 42 consecutive days during the peak ILT nesting season. In sum, low-water years seemed to present ample opportunities for successful ILT nesting conditions, but this number decreased when habitat conditions were degraded.

The difference in the number of sites with continuous SNH exposure during the ILT nesting season was much stronger for excellent versus degraded habitat conditions during years that contained flood control releases >20,000 cfs (Figure 19). For example, given degraded habitat conditions, <5 sites would have been exposed for 42 continuous days during the peak ILT nesting season (in June) in 11 of 12 years with mid-season flooding >20,000 cfs, and 0 sites would have been exposed for 42 continuous days during this period in three of these years. In contrast, given the excellent conditions that prevailed after the high flows of 2007-2008, at least eight sites (and some times as many as 15 sites) would have been exposed for 42 continuous days in 11 out of 12 years during this same period. Given the outstanding conditions after the 2007-2008 high flows, <5 sites would have been exposed for 42 continuous days during the peak ILT nesting season in only 3 of 12 years (Figure 19).

During four of eight high-water years, flows were so high that no sites would have been exposed for 42 consecutive days during the central 50% of the ILT nest initiation season given BOTH the degraded habitat conditions that were present prior to the high flows of 2007-2008 and the excellent habitat conditions after 2007-2008 (Figure 19). However, in the remaining four of eight high-water years, less than two sites would have been exposed for 42 consecutive days during peak ILT nesting with degraded conditions whereas somewhere between five and twelve sites would have been exposed for 42 consecutive days during this same period given excellent habitat conditions.

While Figures 18 and 19 address the effects of the timing, magnitude, and duration of flood control releases on habitat exposure, regional nest or chick mortality still depends on: 1) the degree to which Least Terns form colonies on higher sandbars with lower flooding risk, and 2) the exact elevations at which terns place nests on the sandbars where they form colonies. This is the type of evaluation that can be explored via simulations with the TernCOLONY model (Chapter 5).

Sandbar habitat quality

Figures 20-23 summarize data on habitat quality for all sandbars below Keystone Dam at flows of 13,000 cfs for both excellent (2008-2009) and degraded (2006) habitat conditions. Reference lines on graphs indicate low thresholds for suitable habitat as well as thresholds above which all cells are assumed to be high quality (see Lott et al., in preparation (a)). Habitat cells each represent 36 ft^2 of suitable SNH (see "Automation of geo-processing tasks using Python" in Appendix B).

Sandbar vegetation

After the habitat-forming flows of 2007 and 2008, only 11.9 acres of low sandbar vegetation was present on five of 32 sandbars with suitable SNH below Keystone Dam (Figure 20). The majority of this vegetation was at a single site with a 6.7-acre patch. The other 27 sandbars with suitable SNH were completely bare. Prior to the high flows of 2007-2008, there were 37 acres of vegetation on 14 of 25 sandbars, with five of these patches greater than 5 acres (Figure 20).

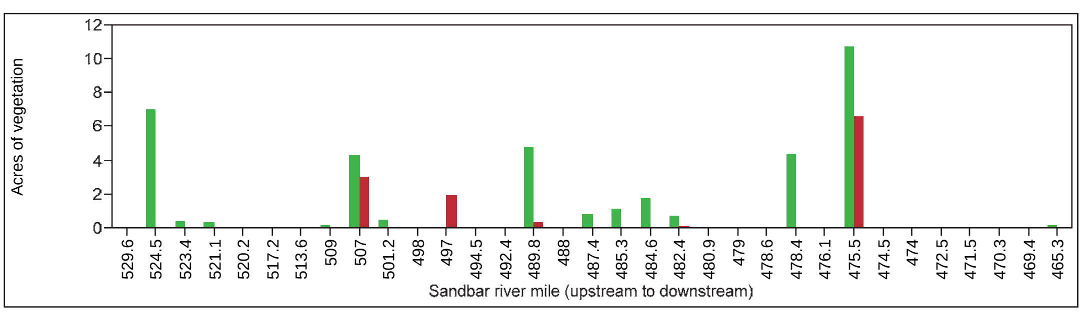

Figure 20. Acres of sandbar vegetation by site below Keystone Dam on the Arkansas River. Red bars indicate the excellent conditions that existed after the high flows of 2007-2008. Green bars indicate degraded habitat conditions that existed prior to these high flows.

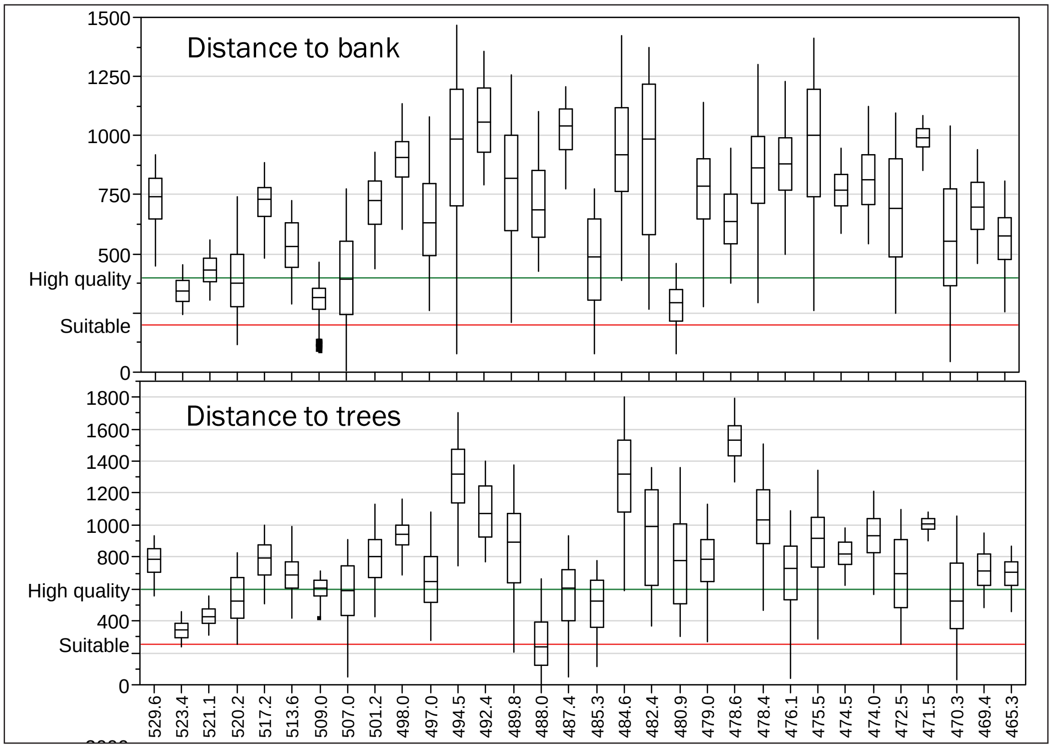

Figure 21. Box and whisker plots illustrating distances from each habitat cell on each sandbar to the riverbank or large trees (covariates of habitat quality that may affect site selection or reproductive success [Lott et al., in preparation (a)]). Green horizontal lines indicate thresholds above which habitat is considered high quality. Red horizontal lines indicate thresholds below which habitat is considered low quality.

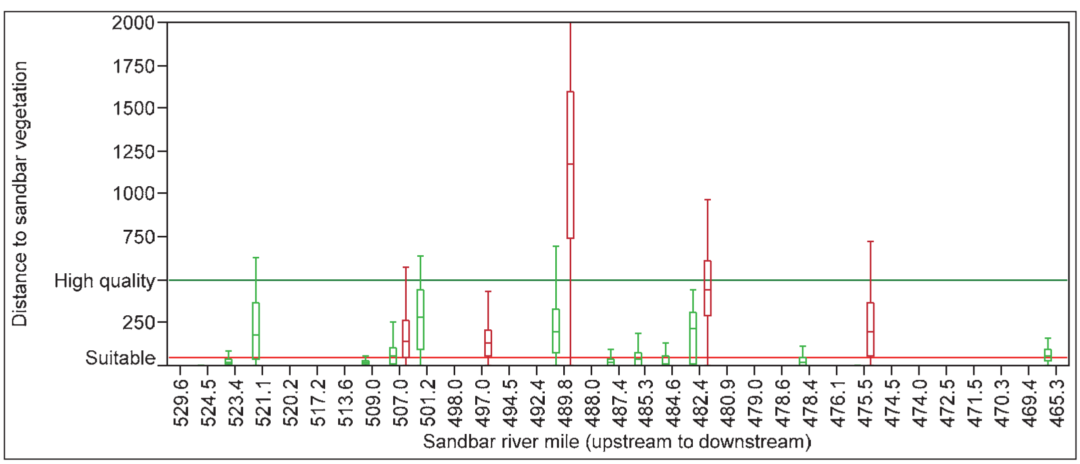

Figure 22. Box and whisker plots illustrating distances from each habitat cell on each sandbar to the nearest sandbar vegetation patch (a covariate of habitat quality that may affect site selection or reproductive success [Lott et al., in preparation (a)]). Green box and whisker plots represent the degraded sandbars that existed prior to the high flows of 2007-2008. Red box and whisker plots represent the excellent conditions measured in 2008-2009. Sites with no data are completely free of vegetation. The green horizontal line indicates the threshold above which habitat is considered high quality. The red horizontal line indicates the threshold for this variable below which habitat is considered low quality.

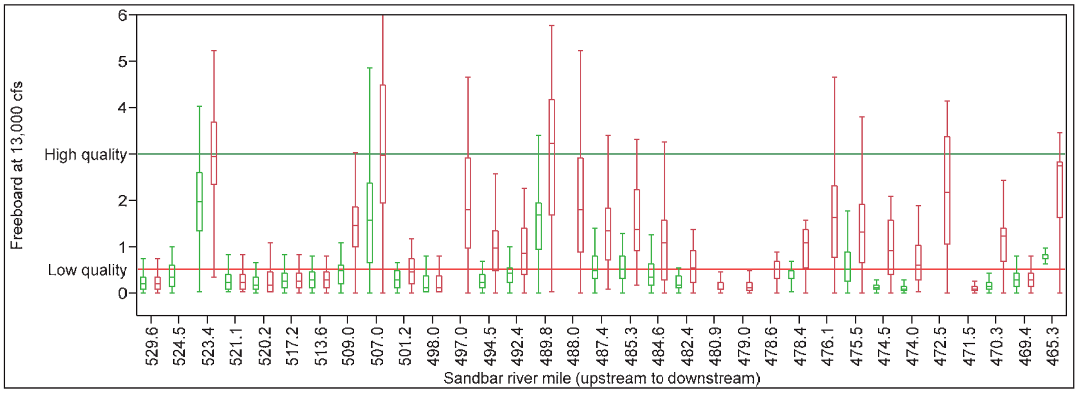

Figure 23. Box and whisker plots illustrating the distribution of freeboard (in feet) at 13,000 cfs for each habitat cell on each sandbar. Lower values for freeboard indicated greater flooding risk. Green box and whisker plots represent the degraded sandbars that existed prior to the high flows of 2007-2008. Red box and whisker plots represent the excellent conditions measured in 2008-2009. The green horizontal line indicates the threshold above which habitat is considered high quality. The red horizontal line indicates the threshold for freeboard, below which habitat is considered low quality.

Distance to the bank/active channel margin

All sites had >75% of their cells above the minimum distance from the bank for habitat suitability (Figure 21). Most sites had median distances between 500 and 1000 ft and 23 out of 32 sites had at least 25% of their cells >700 ft from the bank. Distances presented in Figure 28 represent habitat conditions measured in 2008-2009 (this metric did not vary substantially between degraded and excellent habitat condition data sets).

Distance to large trees

Of 32 sandbars, 26 had >50% of their cells >600 ft from any large trees and many sites had a large number of cells >1000 ft from large trees (Figure 21). A small number of sites had habitat cells that may have been unsuitable due to their proximity to trees. However, each of these sites also had many habitat cells that were far enough from large trees to be suitable. Only two sites had no cells that were >600 ft from large trees, representing low-quality habitat for this variable, including the heavily used restoration site at Zink Island (523.4). Distances in Figure 21 represent habitat conditions measured in 2008-2009 (this metric did not vary substantially between degraded and excellent habitat condition data sets).

Distance to low vegetation on sandbars

Prior to the high flows of 2007-2008, on the 14 of 25 sandbars that contained vegetation patches, most remaining habitat cells were <750 ft from sandbar vegetation. In fact, >75% of all habitat cells on these sites were close enough to existing sandbar vegetation to be considered low quality. After the high flows of 2007-2008, 27 of 32 sites had no vegetation. While three of the remaining five sites had a majority of low-quality habitat cells due to their proximity to sandbar vegetation, the two remaining sites with vegetation patches also included many habitat cells that were great distances from vegetation (Figure 22).

Freeboard relative to sandbar water surface elevations at 13,000 cfs

Freeboard is the difference in elevation between any one habitat cell and the water surface elevation. For this analysis, freeboard was calculated at the standard flow of 13,000 cfs to make freeboard measurements comparable among sites at the most management-relevant benchmark flow. Generally, most sites had higher values for freeboard at 13,000 cfs after the high flows of 2007-2008 than before (Figure 23). The high quality threshold for freeboard at 13,000 cfs is 3 ft, indicating cells that would remain exposed at flows of ~30,000 cfs. After the high flows of 2007-2008, 13 of the 32 sandbars below Keystone Dam had at least some cells exposed above this line. Prior to these high flows, only 3 of 25 degraded sandbars had any habitat cells with 3 ft of freeboard at 13,000 cfs. The low quality threshold of 0.5 ft indicates cells where sand would be expected to be saturated at flows of 13,000 cfs, since capillarity tends to wick water upward within 6 in. of the waterline. Even after the high flows of 2007-2008, 10 of 32 sites had at least 75% of their habitat cells below this threshold, indicating high flooding risk. Prior to the high flows of 2007-2008, 12 of 25 sites had at least 75% of their habitat cells below this threshold.

5 Results: TernCOLONY Model Simulations

Flooding mortality in the absence of predators/ORVs (Experiment 1)

When predators and ORVs were excluded from simulations, nest mortality due to flooding was by far the most common cause of mortality, followed by chick mortality due to flooding (Figure 24). In the absence of predators and ORVs, other sources of mortality (e.g., nest/chick abandonment, death of both parents due to predators, and egg inviability) were minor in most years (Figure 24).

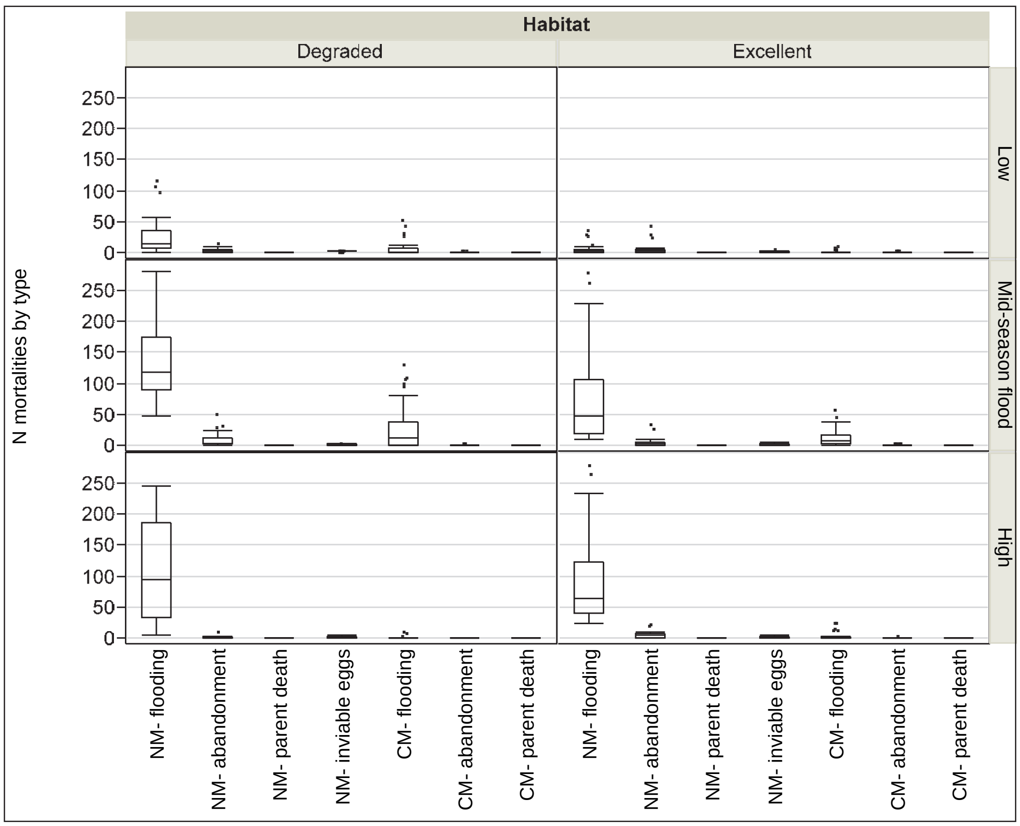

Figure 24. Causes of mortality during TernCOLONY simulations for Experiment 1 (see Chapter 3, "Methods" for more detail) where predators and ORVs were not present. NM = nest mortality, CM = chick mortality. Results are summarized by initial habitat conditions and water year type. Box plots summarize results across all simulated breeding seasons within each water year type x habitat input combination. Since there were 12 annual flow inputs for low-water years, 12 annual flow inputs for mid-season flooding years, and 8 annual flow inputs for high-water years (and 3 replicate simulations for each annual flow input), box plots summarize 36 simulated breeding seasons for low and mid-season flooding years and 24 simulated breeding seasons for high-water years.

Nest mortality due to flooding was more common during some years than others (Figure 25) and was more common at a subset of all possible nesting sites than others (Figure 26).

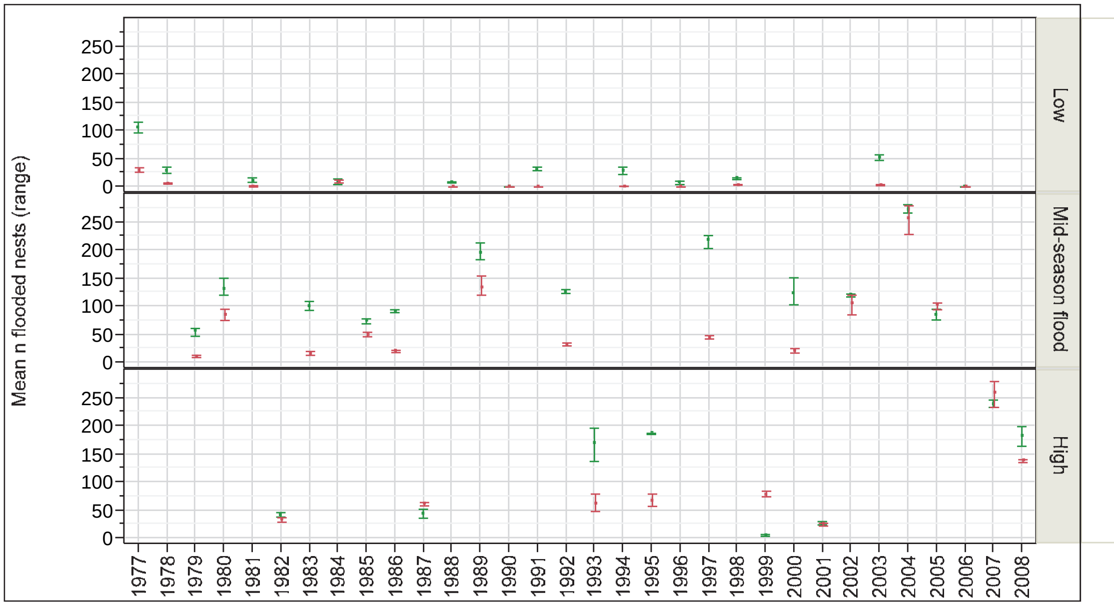

Figure 25. Number of flooded nests per year during simulated Least Tern breeding seasons in the TernCOLONY model (for Experiment 1, see Chapter 3, "Methods"). Green points and error bars represent simulations with degraded habitat inputs and red points and error bars represent simulations with excellent habitat conditions. In this plot, dots represent median values and whiskers represent ranges for three replicate simulations per annual flow input. Results are chronological and blocked by water year type.

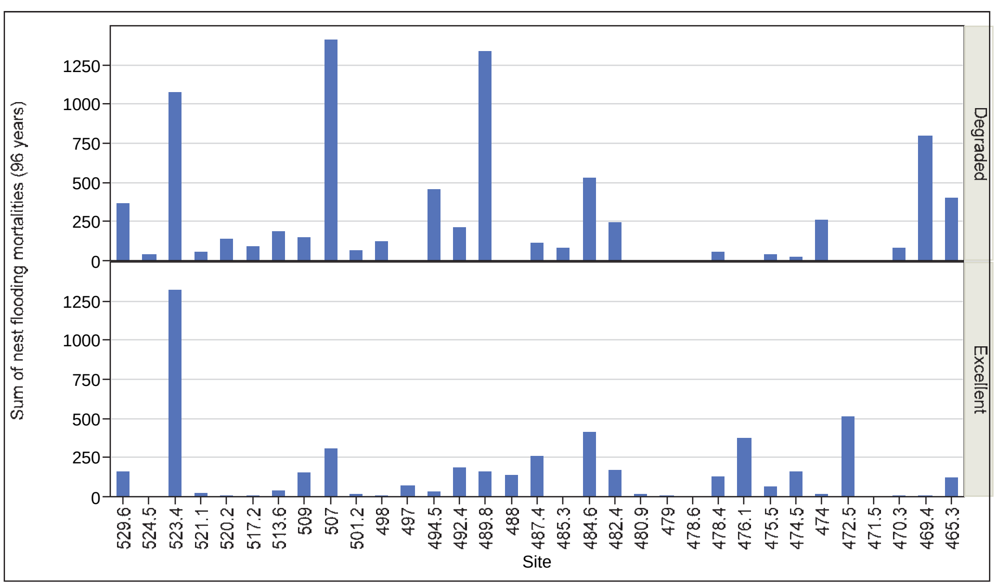

Figure 26. Nest flooding mortality by site during TernCOLONY simulations for Experiment 1. Top panel = degraded habitat conditions; bottom panel = excellent habitat conditions.

In some years (e.g., 2005, Figure 27), terns compensated for heavy egg losses due to nest flooding by re-nesting and still achieved relatively high reproductive success. However, this was not possible in other years where the timing or magnitude of flooding events limited re-nesting opportunities (e.g., 1997, Figure 27). Initial nest losses due to flooding and the ability to re-nest after flooding events depend on both the timing and duration of flooding events and initial habitat conditions (Figure 27).

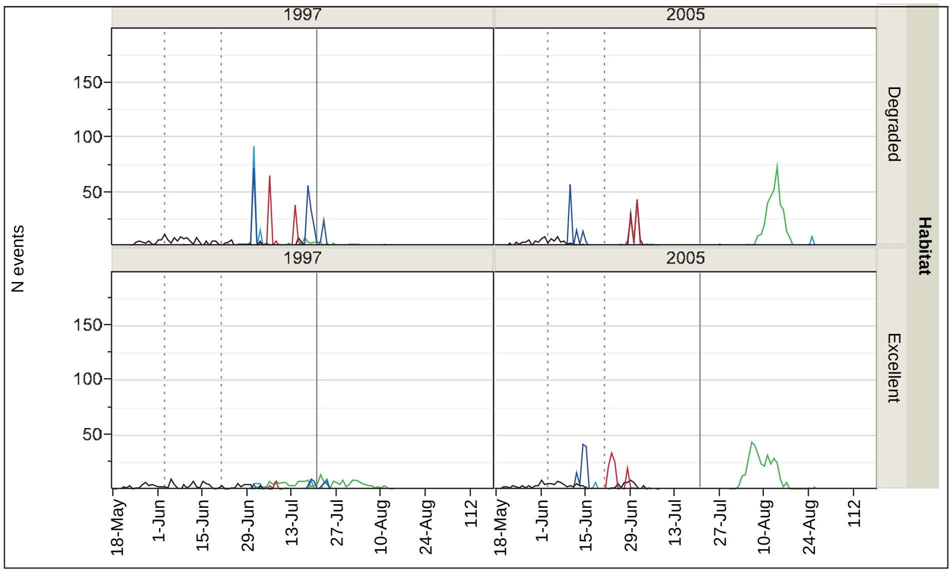

Figure 27. In 2005, the timing of flooding events (blue lines) was early enough in the breeding season to allow for substantial re-nesting after nest failure (red lines indicate the initiation of second nests, black lines indicate the initiation of first nests). In fact, all fledgling production in 2005 (green lines indicate chick fledging events) was due to re-nesting after flooding mortality. In contrast, when habitat conditions were degraded (top panels), consecutive flooding mortality events in 1997 (blue lines) wiped out all first nesting AND re-nesting attempts and did not leave enough time for more re-nesting prior to the end of the Least Tern breeding season. Consequently, no fledglings were produced in 1997 in simulations with degraded habitat inputs (top left panel). However, the late-June/early July high-water events of 1997 did NOT cause nest flooding with excellent habitat condition inputs (because sites were high enough for nests to survive high flows), resulting in little need for re-nesting (the absence of red lines) and consistent fledgling production (green lines) in 1997 when habitat conditions were good. X-axis reference lines are the same as in Figure 2.

A two-way MANOVA revealed a significant multivariate response for the interaction between initial habitat conditions and water year type, Wilks' Lambda = 0.93, F (4, 370) = 3.3, p = 0.0113. Subsequent analyses demonstrated that habitat conditions affected the number of nest mortalities due to flooding, F (1, 186) = 13.9, p < 0.0003, with degraded habitat conditions resulting in significantly more nest mortalities (89 ± 6.3; least squares mean

± SE) than excellent habitat conditions (56 ± 6.3) (Figure 28). Water year type also significantly affected the number of nest mortalities due to flooding, F (2, 186) = 41.3, p < 0.0001, with low-water years resulting in significantly fewer nest mortalities due to flooding (18 ± 7.13; least squares mean ± SE) than both high-water (95 ± 7.14) and mid-season flooding years (103 ± 7.14) (Figure 29). The interaction between habitat conditions and water year type did not significantly affect nest mortality due to flooding, F (2, 186) = 2.5, p >0.05. Chick mortality due to flooding was significantly affected by the interaction between initial habitat conditions and water year type, F (2, 186) = 5.4, p = 0.0054. The nature of this interaction is illustrated in Figure 30. Subsequent analyses illustrated a significant simple effect for the mid-season flooding type, F (1, 186) = 16.6, p <0.0001. Simple effects for low-water and high-water year types were not significant (both p values >0.05).

A two-way ANOVA with the number of fledglings as the response variable across the entire experiment (where 96 Least Tern breeding seasons were simulated per set of habitat inputs) yielded a significant main effect for initial habitat conditions, F (1, 186) = 7.6, p = 0.0063, where fewer fledglings were produced with degraded habitat conditions (287 ± 9.6; least squares mean ± SE) than excellent habitat conditions (324 ± 9.6) (Figure 31). This ANOVA also yielded a significant main effect of water year type on fledgling production, F (2, 186) = 18.26, p < 0.0001, with high (277 ± 13.3) and mid-season flooding (278 ± 10.8) years having lower fledgling production than low-water years (361 ± 10.8) (Figure 32). The interaction between habitat conditions and water year type was not significant, F (2, 186) = 2.25, p = >0.05. Note: the high numbers of fledglings reported here are unrealistic, since predator mortality was not present in Experiment 1.

Flooding mortality when predators/ORVs are present (Experiment 2)

Experiment 1 was designed to evaluate flooding mortality on its own, given the unrealistic situation where predators and ORVs are absent. Experiment 2 uses the same habitat, flow, and bird population size inputs as Experiment 1, but allows predators and ORVs to enter the model, with predators being more abundant when habitat conditions are degraded than when they are excellent. In Experiment 2, nest mortality due to flooding is still an important cause of mortality (compare Figure 33 below with the similarly structured Figure 24 for Experiment 1). However, nest and chick mortality due to predators, as well as nest abandonment during periods of high predator mortality are also large contributors to regional reproductive losses (Figure 33).

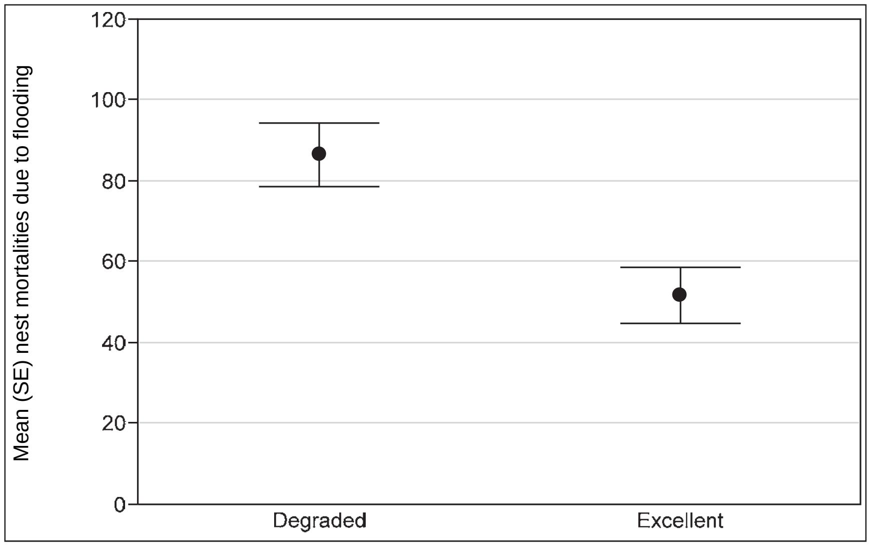

Figure 28. Nest mortality due to flooding by initial habitat conditions for Experiment 1, where no predators or ORVs are allowed in the model (see text for results of statistical tests).

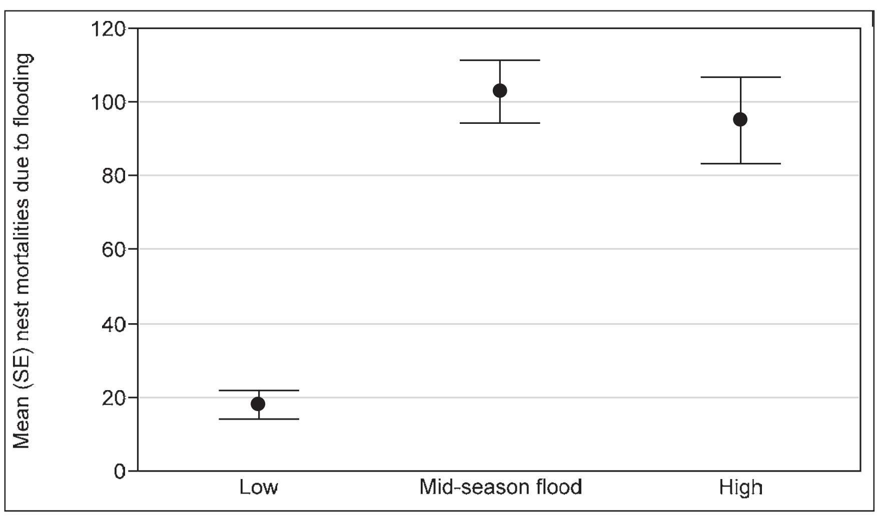

Figure 29. Nest mortality due to flooding by water year type for Experiment 1, where no predators or ORVs are allowed in the model (see text for results of statistical tests). Y-axis scaled the same as Figure 28 to facilitate comparison among main effects.

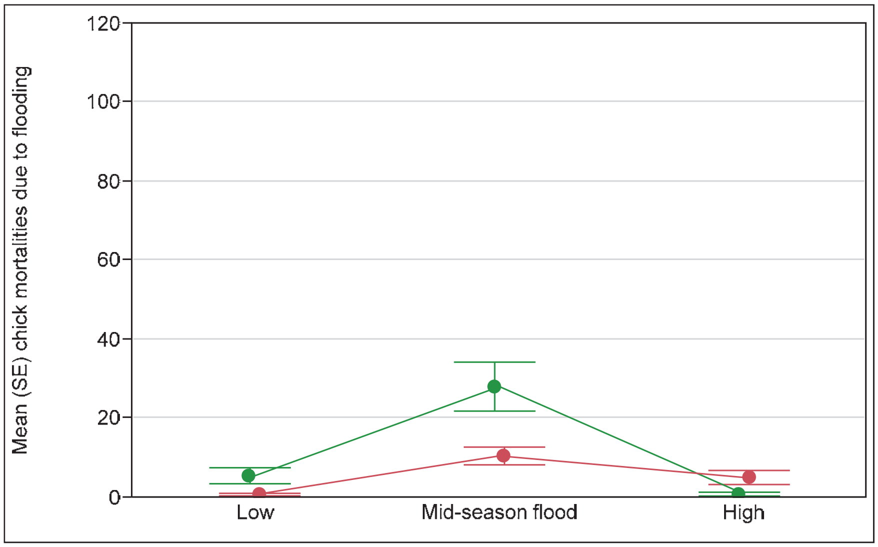

Figure 30. Interaction plot for chick mortality due to flooding by experimental group for Experiment 1, when predators and ORVs are not allowed in the model (see text for results of statistical tests). Green line = degraded habitat conditions. Red line = excellent habitat conditions. Y-axis scaled the same as Figures 28 and 29, which present results for nest mortality, to illustrate the lesser magnitude of chick mortality due to flooding in all cases.

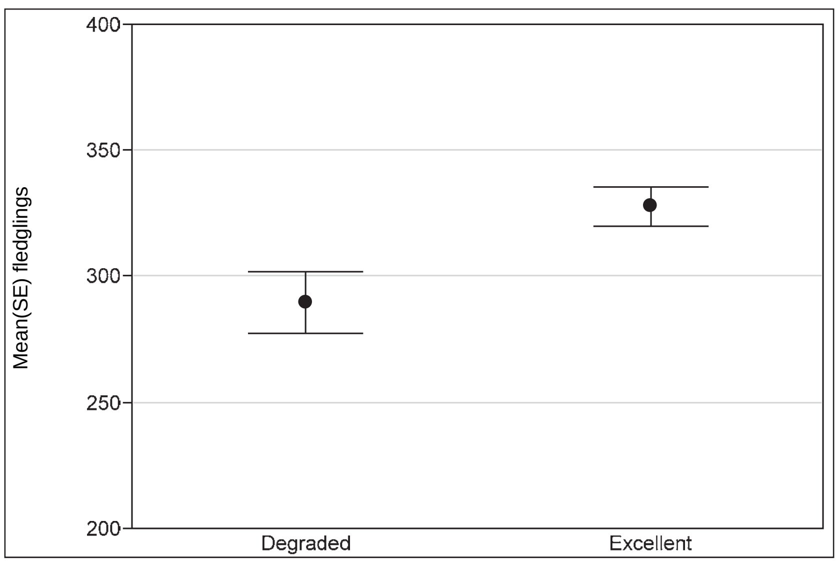

Figure 31. Fledgling production by initial habitat conditions for Experiment 1, where no predators or ORVs are allowed in the model (see text for results of statistical tests).

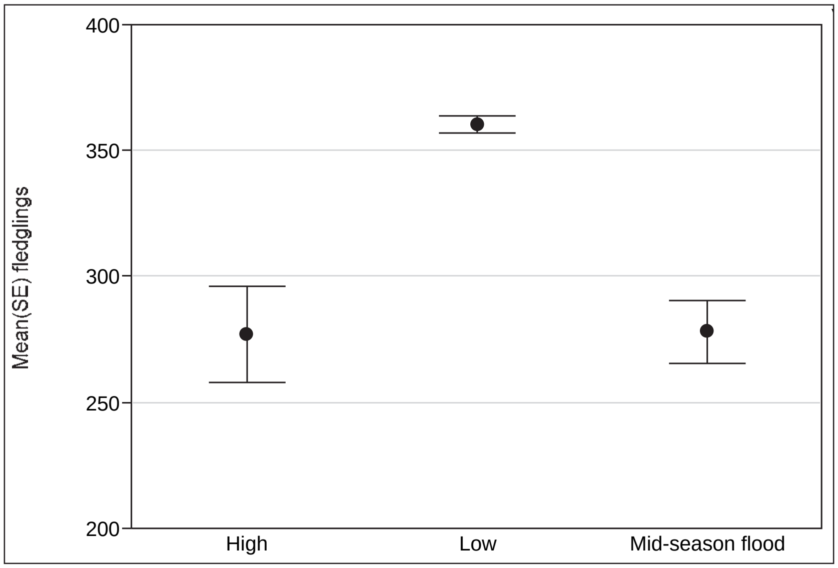

Figure 32. Fledgling production by water year type for Experiment 1, where no predators or ORVs are allowed in the model (see text for results of statistical tests). Y-axis scaled the same as Figure 31 to facilitate direct comparison among main effects.

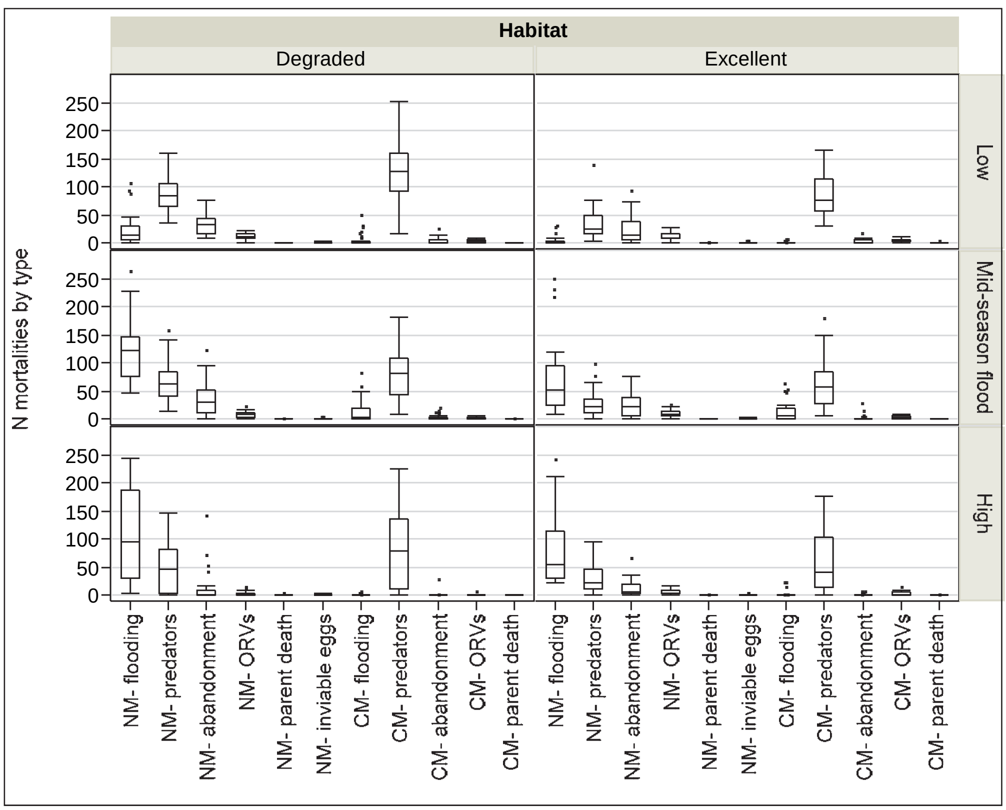

Figure 33. Causes of mortality during TernCOLONY simulations for Experiment 2 (see Chapter 3, "Methods" for more detail) when both predators and ORVs are allowed in the model. NM = nest mortality, CM = chick mortality. Results are summarized by initial habitat conditions and water year type. See Figure 24 caption for a description of data summarized in box plots.

A two-way MANOVA revealed a significant multivariate response for the interaction between initial habitat conditions and water year type, Wilks' Lambda = 0.52, F (10, 364) = 2.1, p = 0.0215. Alpha was adjusted for subsequent analyses on five dependent variables using a Bonferroni-type adjustment where the experiment-wise alpha level was set to 0.05, resulting in an alpha level of 0.01 for single variable tests.

At an alpha level of 0.01, habitat conditions affected the number of nest mortalities due to flooding, F (1, 186) = 18.0, p < 0.0001, with degraded habitat conditions resulting in significantly more nest mortalities due to flooding (83 ± 5.4; least squares mean ± SE) than excellent habitat conditions (50 ± 5.4) (Figure 34). Water year type also significantly affected the number of nest mortalities due to flooding, F (2, 186) = 52.8, p < 0.0001, with low-water years resulting in significantly fewer nest mortalities due to flooding (14 ± 6.2; least squares mean ± SE) than both high-water (92 ± 7.6) and mid-season flooding years (95 ± 6.2) (Figure 35).

At an alpha level of 0.01, nest mortality due to predators was significantly affected by the interaction between initial habitat conditions and water year type, F (2, 186) = 3.5, p = 0.0337. The nature of this interaction is illustrated in Figure 36. Subsequent analyses illustrated a significant simple effect for water year type, with low-water years and mid-season flooding years having significantly more nest mortality due to predators than high-water year types when habitat conditions are degraded, low-water years = F (1, 186) = 45.8, p <0.0001, mid-season flooding years = F(1, 186) = 32.8, p <0.0001. Nest mortality due to predators was not significantly higher when habitat conditions were degraded, F (1, 186) = 4.8, p = 0.0297.

At an alpha level of 0.01, nest abandonment was significantly affected by water year type, F (2, 186) = 8.6, p = 0.0003, but not initial habitat conditions, F (1, 186) = 4.6, p = 0.0328 or the interaction between initial habitat conditions and water year type, F (2, 186) = 0.6, p = 0.5493. Nest abandonment was less common during high-water years (13 ± 3.4; least squares mean ± SE) than during low-water years (30 ± 2.8) and mid-season flooding years (30 ± 2.8), when nest predator mortality was highest (Figure 37).

At an alpha level of 0.01, chick mortality due to flooding was significantly affected by water year type, F (1, 186) = 13.6, p <0.001, but not initial habitat conditions, F (1, 186) = 0.4, p = 0.5383 or the interaction between initial habitat conditions and water year type, F (2, 186) = 1.3, p = 0.2662.

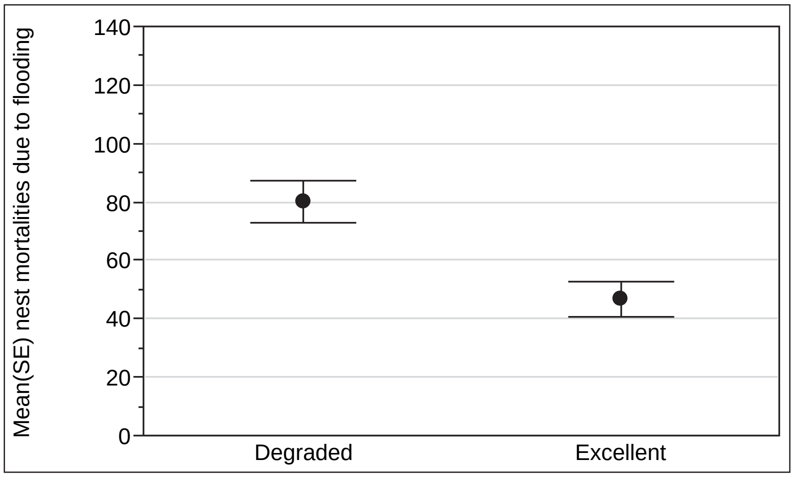

Figure 34. Nest mortality due to flooding by initial habitat conditions for Experiment 2, where both predators and ORVs are allowed in the model (see text for results of statistical tests).

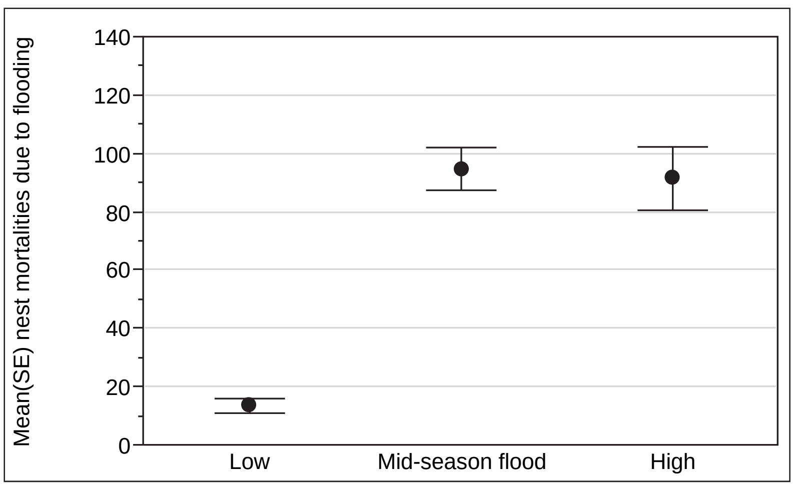

Figure 35. Nest mortality due to flooding by water year type for Experiment 2, where both predators and ORVs are allowed in the model (see text for results of statistical tests). Y-axis is scaled identically to Figure 34 to facilitate direct comparison between main effects.

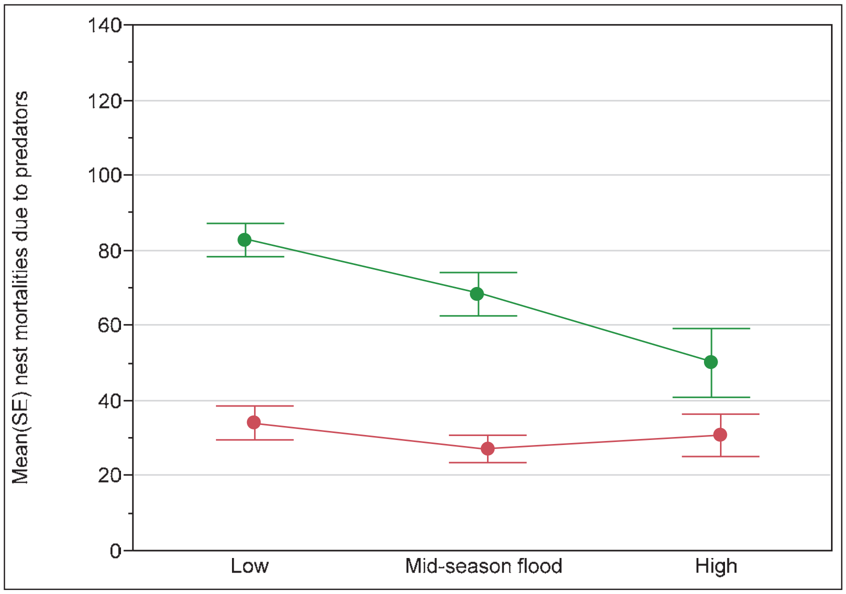

Figure 36. Interaction plot for nest mortality due to predators for Experiment 2, where both predators and ORVs were allowed in the model (see text for results of statistical tests). Green line = degraded habitat conditions. Red line = excellent habitat conditions. Y-axis scaled the same as Figures 34 and 35, which present results for nest mortality, to facilitate comparison of flooding mortality versus predator mortality.

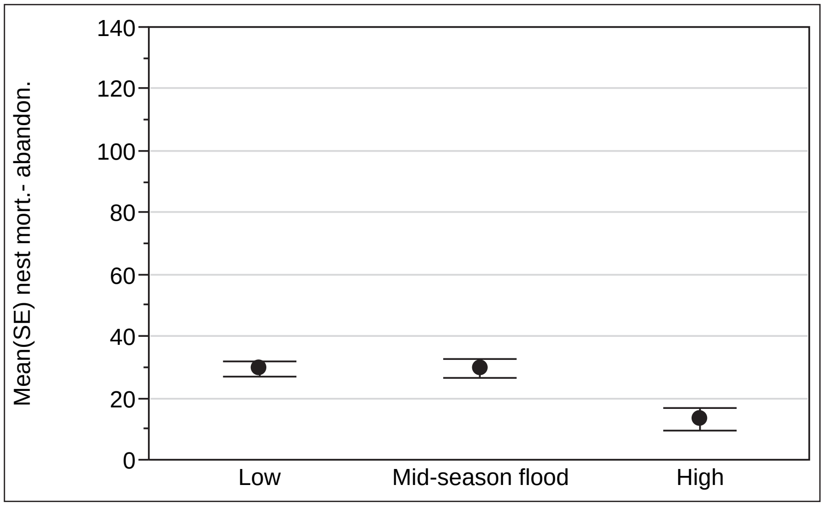

Figure 37. Nest mortality due to abandonment by water year type for Experiment 2, where both predators and ORVs are allowed in the model (see text for results of statistical tests). Y-axis is scaled identically to Figures 34-36 to facilitate direct comparison among mortality types.

Chick mortality due to flooding was higher during mid-season flooding years (13 ± 1.5; least squares mean ± SE) than both low-water years (3 ± 1.5) and high-water years (2 ± 1.9) (Figure 38).

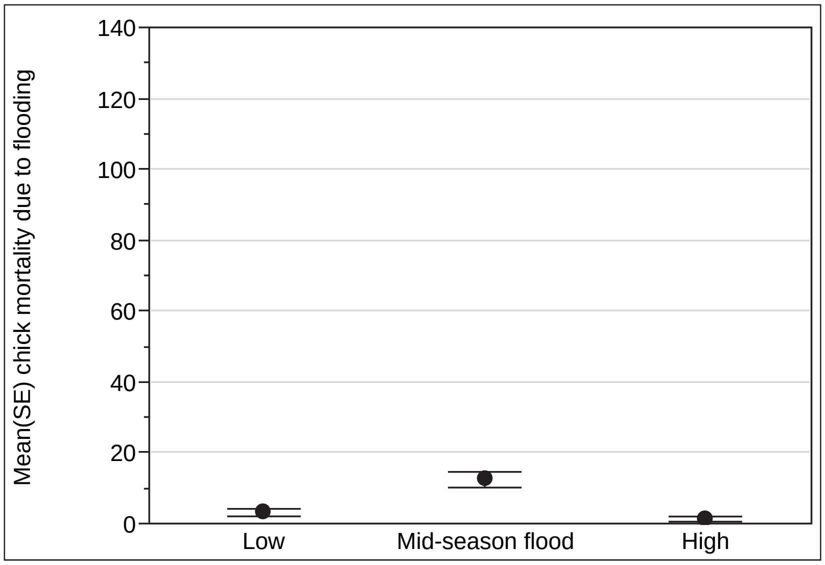

Figure 38. Chick mortality due to flooding by water year type for Experiment 2, where both predators and ORVs are allowed in the model (see text for results of statistical tests). Y-axis is scaled identically to Figures 34-37 to facilitate direct comparison among mortality types.

At an alpha 0.01, chick mortality due to predators was significantly affected by initial habitat conditions, F (1, 186) = 17.0, p <0.0001 and water year type, F(2, 186) = 12.3, p <0.0001, but not by the interaction between initial habitat conditions and water year type, F (2, 186) = 1.2, p = 0.3170. Chick mortality due to predators was higher with degraded habitat conditions (98 ± 5.0; least squares mean ± SE) than excellent habitat conditions (69 ± 5.0) (Figure 39) and higher during low-water years (107 ± 5.6) than mid-season flooding years (72 ± 5.6) and high-water years (71 ± 6.9) (Figure 40).

A two-way ANOVA with number of fledglings as the response variable across the entire experiment (where 96 Least Tern breeding seasons were simulated per set of habitat inputs) yielded a significant main effect for initial habitat conditions, F (1, 186) = 187.0, p < 0.0001, where fledgling production was considerably lower with degraded habitat conditions (95 ± 6.8; least squares mean ± SE) than excellent habitat conditions (227 ± 6.8) (Figure 41). This ANOVA also yielded a significant main effect of water year type on fledgling production, F (2, 186) = 21.96, p < 0.0001, with both high (149 ± 9.5) and mid-season flooding (132 ± 7.7) years having lower fledgling production than low-water years (202 ± 7.7) (Figure 42). The interaction between initial habitat conditions and water year type was not significant, F (2, 186) = 1.34, p = >0.05.

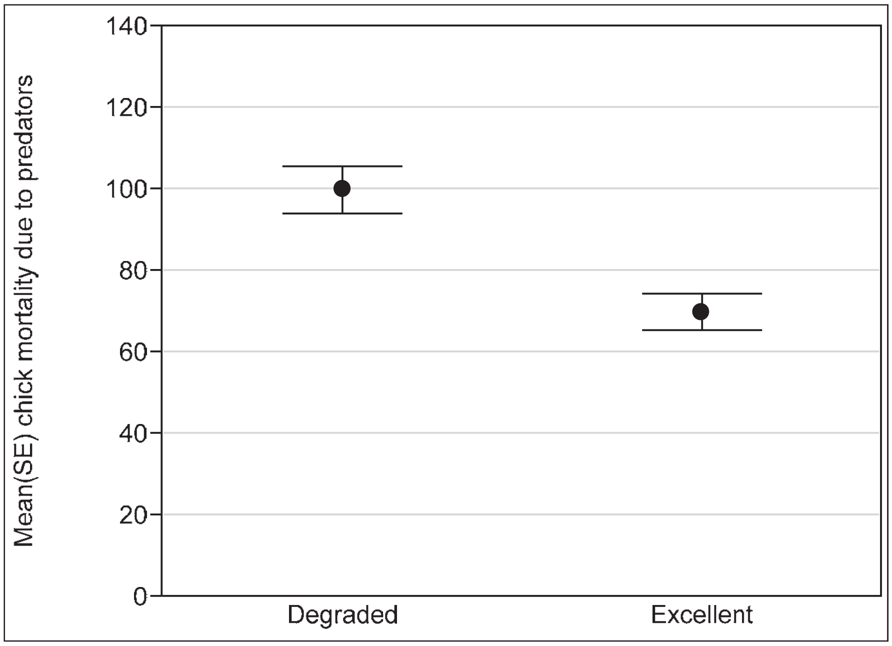

Figure 39. Chick mortality due to predators by initial habitat conditions for Experiment 2, where both predators and ORVs are allowed in the model (see text for results of statistical tests). Y-axis is scaled identically to Figures 34-38 to facilitate direct comparison among mortality types.

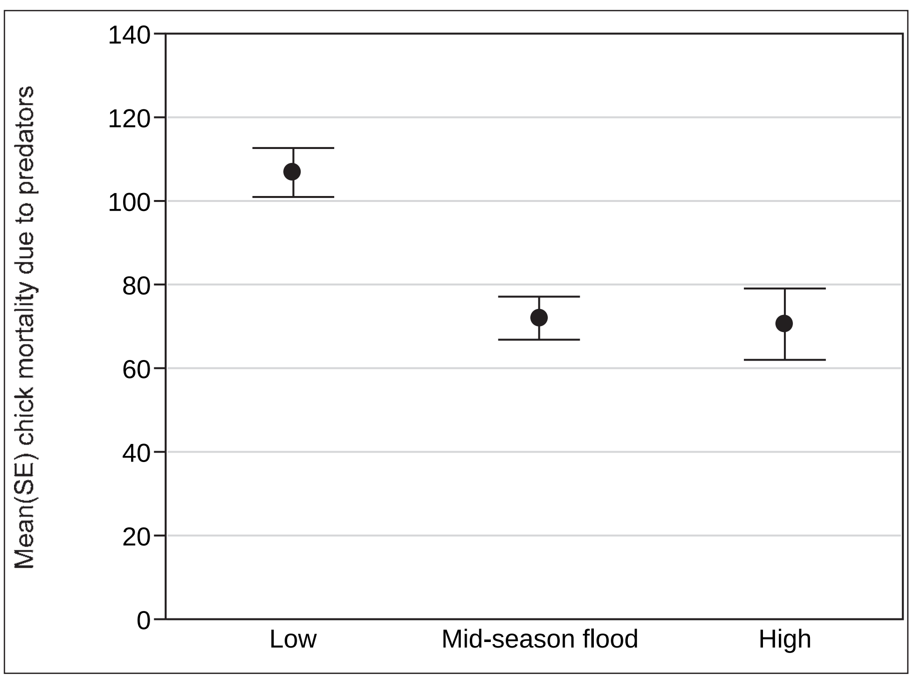

Figure 40. Chick mortality due to predators by water year type for Experiment 2, where both predators and ORVs are allowed in the model (see text for results of statistical tests). Y-axis is scaled identically to Figures 34-39 to facilitate direct comparison among mortality types.

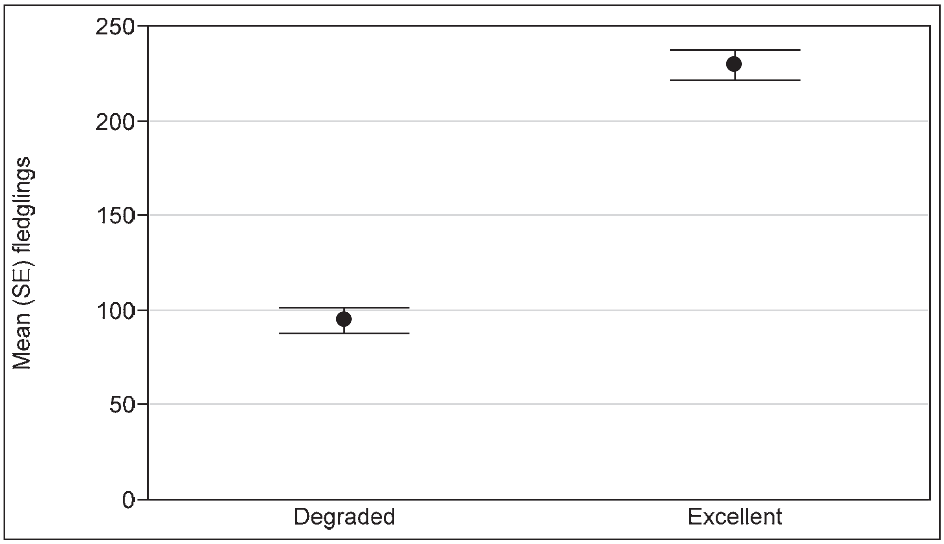

Figure 41. Fledgling production by initial habitat conditions for Experiment 2 where both predators and ORVs were allowed in the model (see text for results from statistical tests).

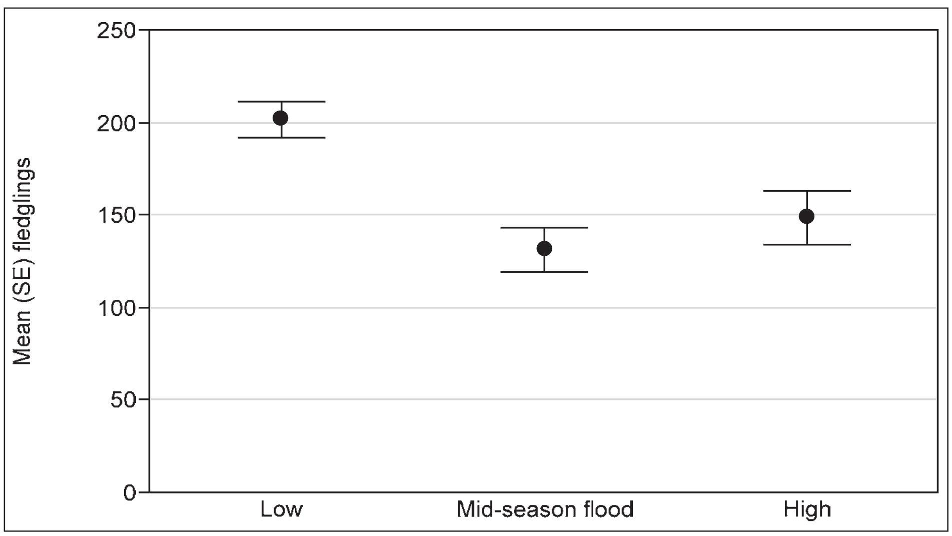

Figure 42. Fledgling production by water year type for Experiment 2 where both predators and ORVs were allowed in the model (see text for results from statistical tests). Y-axis is scaled the same as Figure 41 to facilitate direct comparison between main effects.

Statistical tests for both Experiment 1 and Experiment 2 yielded similar results for nest and chick flooding mortality (e.g., nest flooding was more common with degraded habitat conditions and during years with mid-season flooding). The fact that both main effects were significant in Experiment 1 (when predators were not present) and Experiment 2 (when predators were present), illustrates the importance of flooding as a dominant mortality process. Differences in fledgling production between degraded and excellent habitat conditions and among water year types were larger in

Experiment 2 than in Experiment 1 due to the inclusion of direct mortality due to predators, increased site abandonment (also attributable to predators), and mortality due to ORVs. The prominence of both predator-related mortality and flooding mortality in Experiment 2 suggested that both habitat restoration (to decrease flooding mortality) and predator control (to decrease direct and indirect mortality associated with predators) are worthy of consideration to increase regional reproductive output.

Comparison of management treatments (Experiment 3)

This experiment compared three active management alternatives (habitat restoration, predator control, and the combination of both habitat restoration and predator control) with a no-action alternative. The goal was to determine if any of these management treatments could effectively reduce nest/chick mortality due to flooding, predators, or site abandonment and increase fledgling production below Keystone Dam when habitat conditions are degraded and active management is most necessary due to low fledgling production (see results from Experiment 2).

A two-way MANOVA revealed a significant multivariate response for management treatment, Wilks' Lambda = 0.86, F (15, 1016) = 3.7, $p <$ 0.0001. There was not a significant multivariate response for the main effect of water year type, Wilks' Lambda = 0.95, F (10, 736) = 1.7, p = 0.0718, or the interaction between management treatment and water year type, Wilks' Lambda = 0.93, F (30, 1474) = 0.9, p = 0.6816. For subsequent one-way ANOVAs on the effects of management treatment on the five dependent variables considered in this analysis, a Bonferroni-type adjustment was used where the experiment-wise alpha level was set to 0.05, resulting in alpha levels of 0.01 for single variable tests (Tabachnick and Fidell 2001).

At an alpha level of 0.01, management treatment significantly affected nest mortality due to predators, F (3, 380) = 18.0, $p <$ 0.0001. The predator management only treatment (38 ± 3.3; mean ± SE) and the predator management plus habitat restoration treatment (45 ± 3.3) resulted in fewer predator mortalities than both the no-management treatment (60 ± 3.3) and the habitat restoration only treatment (68 ± 3.3) (Figure 43). The predator management treatment did not significantly affect the number of nest mortalities due to flooding, F (3, 380) = 0.0, p = 0.9950, nest mortalities due to site abandonment, F (3, 380) = 0.9, p = 0.4483, chick mortalities due to flooding, F (3, 380) = 1.0, p = 0.4128, or chick mortalities due to predators, F (3, 380) = 2.3, p = 0.0797, (Figure 44).

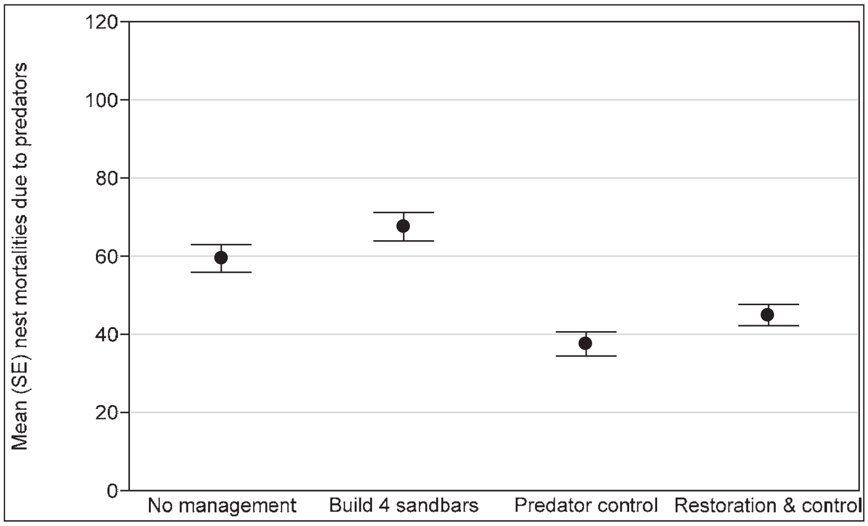

Figure 43. Nest mortality due to predators by management treatment for Experiment 3 (see text for results of statistical tests).

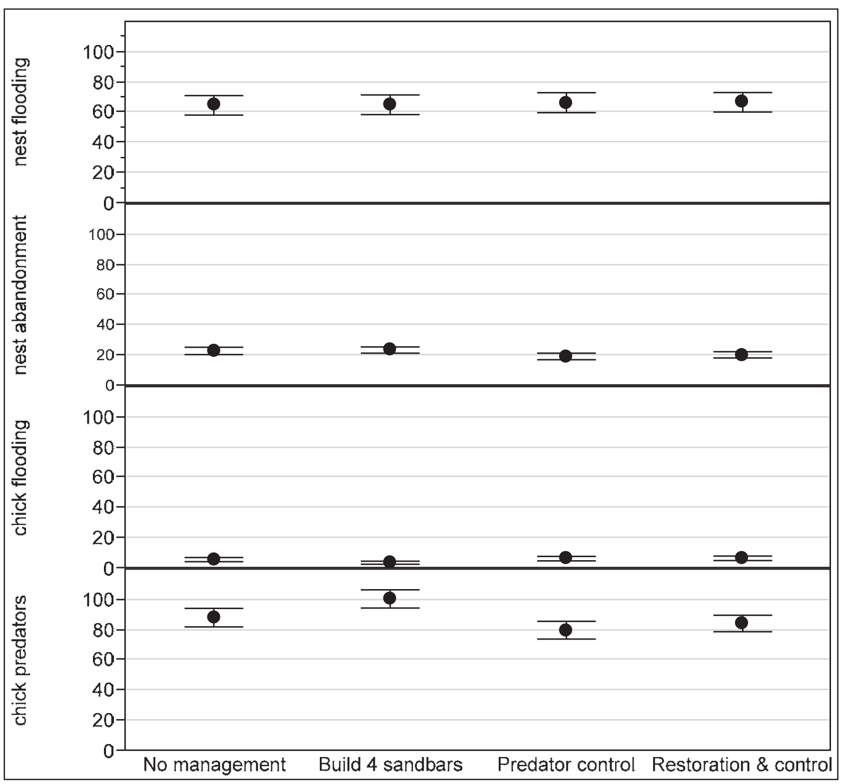

Figure 44. Mean (SE) mortalities due to nest flooding, nest abandonment, chick flooding, and chick predators by management treatment (see text for results of statistical tests). The y-axis is scaled identically to Figure 43 to facilitate direct comparison among mortality types.

A two-way ANOVA with number of fledglings as the response variable across the entire experiment (where 96 Least Tern breeding seasons were simulated per set of habitat inputs) yielded a significant main effect for management treatment, *F* (3, 372) = 14.8, $p < 0.0001$. In this scenario, fledgling production was higher with both the predator control only (127 ± 6.5; least squares mean ± SE) and predator control with habitat restoration (142 ± 6.5) management treatments than the no-management (92 ± 6.5) and habitat restoration only (94 ± 6.5) management treatments (Figure 45). This ANOVA also yielded a significant main effect of water year type on fledgling production, *F* (2, 372 = 33.5, $p < 0.0001$, where fledgling production was higher during low-water years (149 ± 5.2; least squares mean ± SE) than both mid-season flooding years (91 ± 5.2) and high-water years (101.5 ± 6.4) (Figure 46). The interaction between management treatment and water year type was not significant, *F* (6, 372 = 1.8, $p = >0.05$).

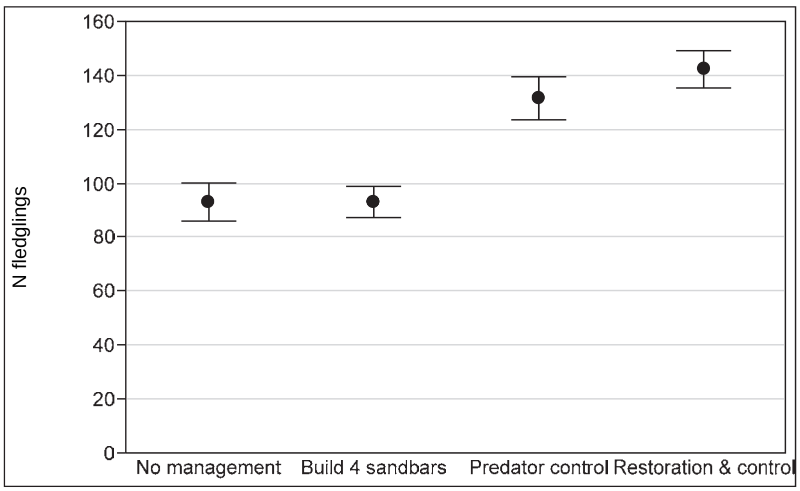

Figure 45. Fledgling production by managment treatment for Experiment 3 (see text for results from statistical tests).

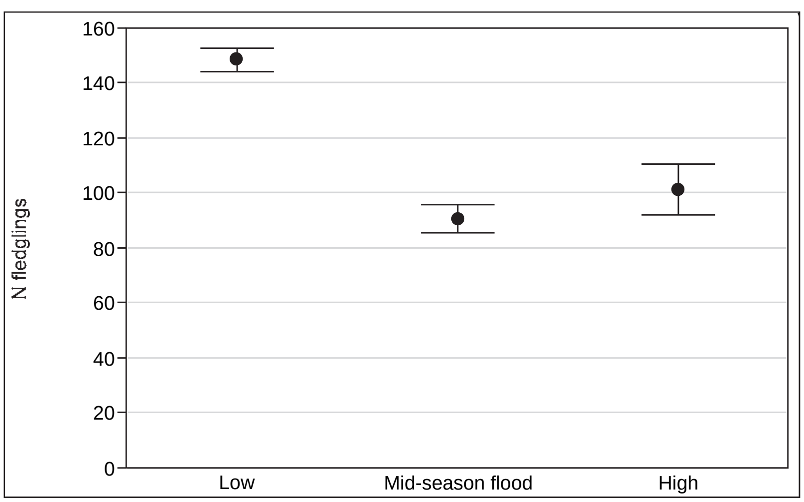

Figure 46. Fledgling production by water year type for Experiment 3 (see text for results from statistical tests). The y-axis is scaled the same as Figure 45 to facilitate direct comparison between main effects.

6 Discussion

Evaluating the effects of dam operations on ILT reproduction

This report combines habitat measurements with hydrologic analyses to illustrate how Keystone Dam operations affect seasonal Least Tern sandbar nesting habitat (SNH) exposure on the Arkansas River across the range of hydrographs that have been documented during the post-dam era (1977-2008). A series of simulation experiments were run in TernCOLONY, an individual-based model of Least Tern reproduction (Lott et al., in preparation (a, b)) to evaluate how frequently dam operations, combined with downstream flows, may cause incidental take due to nest and chick flooding given both the excellent habitat conditions that were measured in the field in 2008-2009 and degraded habitat conditions that were simulated to represent conditions prior to the high, habitat-forming flows of 2007-2008 (described in USFWS (2005a)). These simulations allowed evaluation of whether or not nest/chick flooding resulted in reduced regional reproducetive output, or if Least Terns were able to compensate for flooding losses by re-nesting after flooding events. Informed by these initial simulations, an experiment was designed to see if habitat restoration, predator control, or a combination of these two management strategies could be effective at reducing incidental take due to flooding, or mortality due to predators and, ultimately, increase regional reproductive output.

Summary of findings

- The high flows of 2007-2008 created numerous, high-elevation, bare sandbars below Keystone Dam. Afterwards, ~459 acres of suitable sandbar nesting habitat (SNH) were present at peak hydropower flows of 13,000 cfs at 32 total sites occurring along a ~60-mile stretch from Tulsa to the backwaters of the Webbers Falls Reservoir (near Muskogee). Of these 32 sites, 24 were within a 40-mile stretch between RM509 and RM469.
- Prior to the high flows of 2007-2008, at 13,000 cfs, only ~121 acres of suitable SNH were exposed at 25 sites in this same area.
- During relatively common and minor flood control releases of 20,000 cfs, only 183 acres of SNH were available at 20 sites given the excellent habitat conditions measured in 2008-2009 and only 24 acres of SNH at four sites were exposed with degraded habitat conditions.

- Flood control releases >30,000 cfs, which occur in many years, would inundate all but 13 sites in the excellent habitat conditions dataset and all but three sites in the degraded conditions dataset.
- When habitat conditions were degraded, fewer SNH acres and sites were available across the entire Least Tern breeding season (or for enough consecutive days to permit successful nesting attempts) than when conditions were excellent.
- In the 32 years between 1977 and 2008, since both Kaw and Keystone Dam have been present, there have been three recurring seasonal flow patterns during the Least Tern breeding season.

    - Low-flow years (37.5% of all years in the post-dam era) present little flooding risk to Least Tern nests and chicks and the greatest risk to predators.
    - Mid-season flooding years (37.5% of all years in the post-dam era), present the highest flooding risk to Least Terns, since low, early-season flows facilitate nest initiation prior to high flows that may cause nest or chick mortality.
    - High-water years (25% of all years in the post-dam era) have mixed effects on Least Tern reproduction. In some cases, floods remain high enough for long enough to preclude nesting entirely. In other cases, floods may recede early enough (and continue to recede) so that successful nesting is possible. In other cases, variable high flows (with some low-water periods during nest initiation) may result in considerable flooding mortality.

- Flooding mortality, as simulated in the TernCOLONY model, was common during years with major flood control releases (mid-season flooding years and high-water years) and relatively rare during low-water years.
- Although extensive flooding mortality still occurred in TernCOLONY simulations when habitat conditions were excellent, it occurred less frequently than when habitat conditions were degraded.
- Nest flooding mortality occurred much more frequently than chick flooding mortality, since most large flood control releases occurred during the first half of the Least Tern breeding season.
- In TernCOLONY simulations, both direct and indirect mortality due to predators (e.g., adult abandonment of active nests or young chicks) was higher when habitat conditions were degraded (and considerable

vegetation/prey base was present on sandbars) than when sandbars were mostly bare.

- The degraded habitat dataset used in TernCOLONY simulations was designed to reflect conditions prior to the high, habitat-forming flows of 2007-2008. Therefore, considerable investment in habitat restoration (restoration/creation of four high-quality sandbars) did not significantly reduce flooding mortality or increase reproductive success at the scale of the regional nesting populations. There are two reasons for this result:
    - Considerable nesting still occurred on non-restoration sandbars and flooding mortality did not decrease on these sandbars.
    - Predators were abundant when habitat conditions were degraded and frequent direct mortality due to predators (and some indirect mortality due to site abandonment) resulted in relatively low regional reproductive success.
- Predator mortality was greatest in low-water years since nests and chicks were not destroyed by floods in these years and were exposed to predation risk for a larger number of days.
- The only management treatments that increased fledgling production below Keystone Dam in TernCOLONY simulations were those that included a predator control component. Combining predator management with habitat restoration did not result in significantly greater fledgling production than predator control on its own.

Under what conditions might direct management for ILT populations be necessary?

In TernCOLONY simulations with model inputs based on the excellent habitat conditions documented after the high flows of 2007-2008, nest and chick mortality due to flood control releases from Keystone Dam was limited to a small number of years. Similarly, predator mortality was also somewhat limited when habitat conditions were excellent. Given the long reproductive lifespan of Least Terns, the low frequency of years where flooding significantly reduces fledgling production when habitat conditions are excellent seems very likely to be compensated for by the high frequency of years where successful reproduction is possible.

Conversely, fledgling production was relatively low when habitat conditions were degraded, the result of frequent nest mortality due to flooding and frequent nest and chick mortality due to predators. Consequently, direct management to reduce nest flooding or predator mortality may be necessary when habitat conditions are degraded. Of course, the frequency and magnitude of investment in direct management to reduce ILT mortality and increase reproductive success will depend on the relative frequency of excellent versus degraded habitat conditions on any river. This type of information will only be available if habitat measurement occurs more regularly (and is evaluated in more depth) than it has been in the past.

It can be assumed that the outstanding habitat conditions that prevailed on the Arkansas River after the high dam releases of 2007 and 2008 are rare occurrences during the post-dam era (Leslie et al. 2000, USFWS 2005a). While habitat conditions below Keystone Dam were never measured prior to this study, high flows with magnitudes and durations similar to the flows that created the outstanding sandbars reported herein (e.g., >50,000 cfs for >3 weeks) have occurred in 6 of 32 years since 1977: 1987, 1993, 1995, 1999, 2007, and 2008. Given the absence of regular habitat monitoring, it is unclear how much high quality SNH was created during these high-flow events. It is also unclear how long the high-quality SNH that may have been created during these events lasted in post-flood years. Depending on how hydrographs in the years subsequent to habitat-forming flows affect the key ecological processes of natural succession and erosion, SNH conditions may remain outstanding for 4-7 years (USACE 2011) or may return to a degraded state relatively quickly (within 1-2 years).

The need to measure SNH after habitat-renewal events as well as when habitat conditions are degraded

Nearly all Section 7 consultations for ILT have expressed concern that the amount or quality of SNH may limit ILT populations (USFWS 2003, 2005a, 2005b, 2006). However, many of these consultations have focused on degraded habitat conditions that tend to occur towards the end of drought cycles, when habitat-forming flows are infrequent. Conversely, major habitat-forming flows have occurred on many rivers across the range of ILT in recent years (e.g., major floods on the Missouri and Mississippi Rivers in 2011, the Arkansas River floods documented here, habitat-forming flows on the Lower Platte River in 2008 and 2010, and high flows on the Red River in 2007). Several publications have documented major increases to ILT population size or reproductive success after such events (Sidle et al. 1992, Leslie et al. 2000, USACE 2011).

It is assumed that habitat measurements after major habitat-forming flows, as reported here, would help to document the types of SNH conditions that result in population increases or increases in reproductive success. Such measurements may provide insight on the types of sandbars that these floods create (e.g., their elevations, shapes, and locations within the channel), which could then serve as models for restoration sandbars that may need to be created during periods where mechanical habitat restoration is necessary in the absence of habitat-renewing high flows (USACE 2011, Appendix B).

On the Arkansas River below Keystone Dam, habitat measurements when conditions are highly degraded could replace the simulated dataset for degraded habitat conditions that was created for this report (which was necessarily based on literature review and assumptions, as documented in Appendix B). More regular habitat measurement would document the variation and frequency of different habitat conditions on the Arkansas River and provide additional habitat inputs for TernCOLONY simulations across a broader range of real conditions than the two extreme sets of habitat inputs explored here. More extensive evaluation of tern population dynamics and management alternatives across a larger range of initial habitat conditions will help to refine adaptive management strategies over time.

Conclusions

This report outlines a habitat evaluation approach that provides unique insight into how dam operations affect regional ILT populations. The field and GIS protocols described here could be replicated to provide Least Tern SNH habitat measurements on other rivers that would be major improvements of single-instance habitat estimates from remote sensing data sources (e.g., USACE 1999, USFWS 2003, Sherfy et al. 2008). Similarly, the hydrologic analyses in this report could easily be replicated for other rivers, using publically available data, to provide time series inputs of peak daily flows for habitat summaries that could provide insights on the effects of system operations on tern populations. Finally, the simulation model that has been used in this report, TernCOLONY, has been designed to easily incorporate habitat and flow inputs from any river (Lott et al. 2012c). The approach outlined in this report (habitat measurements followed by simulation experiments in TernCOLONY) could easily be applied to evaluate the effects of dam operations on all rivers with Least Tern populations and to suggest productive directions for management. The approach could be administered as part of routine biological assessments for Section 7 consultations or as standard components of adaptive management programs.

This study found that Keystone Dam flood control operations have limited negative impacts on Least Tern reproduction when habitat conditions are as outstanding as they were after the habitat-forming flows of 2007-2008. It was also found that active management may only be necessary during periods between major habitat renewal events, when habitat conditions are degraded. TernCOLONY may be a useful tool for simulating the potential effectiveness of different management approaches when management is deemed necessary. Experiment 3 is a simple example of one approach towards this type of analysis (and was by no means exhaustive). This report may inspire biologists, stakeholders, and river managers to use the online version of the TernCOLONY model at http://www.leasttern.org to explore potential management actions in greater detail.

When the relatively minor effects of dam operations on ILT during periods with excellent habitat conditions (Arkansas River, this report; Missouri River, USACE 2011, Appendix B) are compared with the frequency of nest flooding mortality and/or low reproductive outputs that have been observed when habitat conditions are degraded (this report, Leslie et al. 2000, Kruse et al. 2001), it appears that active management may only be required during periods after floods when habitat conditions are degraded. Active (and costly) management decisions, such as predator and/or vegetation control, will always be subject to multi-factor analyses (Schultz et al. 2010). Existing bird monitoring programs, which regularly visit nesting sandbars several times each growing season, could provide valuable and up-to-date information to managers about when major habitat loss may be imminent due to recruitment of new pioneering vegetation such as willow or cottonwood (e.g., Johnson 2000). This type of monitoring feedback to an adaptive management program may increase cost-effectiveness, facilitating the removal of young seedlings, since vegetation removal rapidly becomes less effective and more costly over time (see Wiley and Lott (in preparation)). Since habitat restoration and predator control are both costly management strategies, it seems advisable to explore potential management alternatives via simulation prior to implementation. This process will identify which approaches might be most effective or cost-effective. Future work of this nature is advisable for a number of below-dam river segments across the range of ILT, given the importance of these discrete segments to the health of the larger ILT metapopulation.

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Appendix A: Hydrologic Data Summary and Analysis Methods

Preparation of dam release and flow data for analyses

Sources of hydrologic data

Exploration of the effects of Keystone Dam operations on ILT habitat required analysis of peak daily flows (see Chapter 2), which were summarized from hourly release/flow data. Hourly Keystone Dam release data were retrieved directly from the U.S. Army Corps of Engineers (USACE) Tulsa District Water Control and online from the U. S. Geological Survey (USGS) instantaneous data archive at http://ida.water.usgs.gov/ida/ for the Tulsa gage and Haskell gages. Nearly complete hourly flow datasets were compiled for the dam and both gages in the study area for the 19 breeding seasons between 1990 and 2008. Mean daily flow records for these same gages were retrieved for the 32 years from 1977-2008 using the USGS' National Water Information System, available at: http://waterdata.usgs.gov/ok/nwis/nwis.

To provide context for habitat measurements relative to dam operations, the time series needed to be as extensive as possible for each of the flow metrics that matter for ILT (see Chapter 2). Since hourly data for the entire post-dam period of record were not available, large data sets with overlapping hourly and mean daily flows were used to construct models that predicted, for example, peak daily flows from mean daily flows for the range of years for which only mean daily flows were available. These models (and their predictive error) are described below. Prior to model building, existing datasets were proofed for obvious data entry errors (since each of these datasets had been previously proofed with variable intensity).In some cases, interpolated values were also proofed for missing data, where this seemed appropriate, prior to model construction (see below).

Hydrologic data proofing and interpolation of missing values

Several steps were necessary to prepare the raw data received for analysis. First, a small number (<10) of records from the Keystone Dam dataset were visually inspected and eliminated because they had implausible values (e.g., an hourly release value of 136,000 cfs that was completely surrounded by hourly flows of 13,600 cfs with no indication of higher flows at downstream gages). It was assumed that abnormal values such as these indicated recording errors. Next, several hours were determined to have more than one record (e.g., data were recorded on the hour and on the half hour). Since most hours had only a single record, averages were calculated for hours that had more than one record and these single values were recorded in the database.

Each hourly release/flow dataset was then inspected for completeness. Two types of missing data situations occurred: 1) a small number of hours were missing for a given day, or 2) all hours were missing for a given day. In nearly all cases, when 1 to 8 hr were missing in a single day, straight line interpolation could be used between existing data records to interpolate flow values for missing hours.

After interpolation, several days remained that were completely missing data. It was decided not to interpolate hourly flow data for these days; instead, these days were removed from all analyses that required hourly flow data. Of 1900 possible days per dataset (with 100 days per season), the following number of days were completely missing hourly flow data: Keystone dam (44 days; 30 of which were from 1997), Tulsa gage (108 days; 17 from 2002 and 65 from 2007), Haskell gage (136 days; 35 from 1990, 28 from 2001, and 43 from 2004). Aside from the years specifically noted above, most other year/gage combinations had only a small number of days with missing hourly flow data.

Hydrologic data analyses

Defining daily operational modes

After data proofing, hourly dam release data from May 15-August 22 were examined for the 19 years between 1990 and 2008 (a total of 1900 days). Peak daily releases very clearly reflected only four distinct daily modes of dam operation. Of the 1,856 days for which data were available, data could be classified for 1,841 days. Classified data fell into the following four categories:

1. Very low flows: 129 days (<7.0%) had peak daily flows between 0 and 900 cfs (96 of these days had peak flows lower than 100 cfs).
2. Single-turbine hydropower production for at least 1 hr: 196 days (10.6%) had peak daily flows between 4,600 and 6,360 cfs.

3. Two-turbine hydropower production for at least 1 hr with no flood control releases: 827 days (~44.9%) had peak daily flows between 9,470 and 13,000 cfs.
4. Flood control releases: 689 days (~37.4%) had peak daily flows between 13,380 and 139,800 cfs.

Boundaries between the first three categories were clear from natural breaks in the data. The boundary between two-turbine hydropower production and flood control releases was set at 13,000 cfs, since days with peak daily releases <13,000 usually had several hours with releases lower than the daily maximum, indicating water conservation for future hydropower production during peak demand. In contrast, days with peak daily flows >13,000 tended to have releases >13,000 for all hours of the day, indicating flood control operations.

Models used to generate peak daily flow time series

Following exploratory analysis, separate linear regression models were constructed to predict peak daily flows from mean daily flows during: 1) flood control operations, and 2) all other operational modes where dam releases were below the peak hydropower maximum (Table A1). This was necessary since the relationship between mean daily flows and peak daily flows changed at lower flows, due to high variability in hourly flows (and frequent very low flows) during hydropower operations. Models to predict peak daily flows from mean daily flows during flood control operations were strongly predictive, with relatively small intercepts, reflecting the long duration of most flood control releases. In contrast, models to predict peak daily flows from mean daily flows during hydropower operations were less predictive, and had larger intercepts; particularly close to the dam (e.g., the Tulsa gage), where hourly flow/stage variation is strongest.

The equations from these models, based on 19 years of data, were used to predict peak daily flows from the 32-year time series of mean daily flow data that was acquired from USGS gages and contained no missing data. The amount of error in these predictions is deemed sufficiently small to justify extending the time series of peak daily flows, which most accurately reflect flooding risk, to allow inference across the full range of operations that have occurred in the 32-year post-alteration era (1977-2008), rather than only the 19 years since 1990 where hourly data were available.

Table A1. Models for predicting peak daily flows from mean daily flows on the Arkansas River.

Gage	Mode	n days	r^2	Equation (peak daily flows from mean daily flows)
Tulsa	Flood control	658	0.97	TulsaPeak = 1040.196 + 1.0321251*TulsaMean
Tulsa	Hydro-power	1133	0.56	TulsaPeak = 5427.2738 + 0.7738477*TulsaMean
Haskell	Flood control	679	0.98	HaskellPeak = 178.62887 + 1.057942*HaskellMean
Haskell	Hydro-power	1085	0.85	HaskellPeak = 1378.5091 + 1.0080818*HaskellMean

Modeling flow downstream from dams

In reviewing many of the time series of daily flow data that were acquired, it became apparent that flows (and thus water surface elevations) varied regularly, in a downstream direction.However, flows varied in ways that would be difficult to predict in models, due to the large number of factors affecting this variation within and among years. In order to account for real patterns in the downstream increase or attenuation of flows, historic daily flows for sandbars between bracketing gages were interpolated by distance to estimate sandbar-specific flows. This process was complicated by the fact that it takes time for water to travel between gages. For example, on the Arkansas River, it often takes water ~24 hr to travel from the Tulsa gage to the Haskell gage. Therefore, for interpolation of sandbar-specific flows on the Arkansas, a lag of 1 day was applied to daily flow values between the Tulsa and Haskell gages. In all years, lagged peak daily flows at Haskell correlated better with the previous day's flow at Tulsa than with the same day's flow.

Creation of sandbar-specific flow to WSE models

As dam releases and downstream flows increase or decrease, water surface elevations increase or decrease in concert. The numeric relationship between flow increases and increases in water surface elevations (WSE) can be described for any cross-sectional area where both flow and elevations have been measured. The relationship between flow and WSE, commonly expressed as a "rating curve" or "stage-discharge model" can be used to predict WSE from flow, or conversely, flow from WSE. Since flow/discharge is difficult and costly to measure directly, rating curves are typically constructed from periodic discharge measurements at gages, compared with observations of stage (e.g., elevation, in 100ths of survey feet above or below the gage datum) (Charlton 2008). Then, regular observations of stage, which are easy to make, are paired with this stage-discharge relationship to construct a time series of flows from regular (e.g., hourly) observations of stage. These predicted values comprise the time series of observational data on “flows” in USGS hourly or mean daily flow datasets from gages.

Unfortunately, cross-sectional areas at gages are not representative of cross sections elsewhere in a channel (Tracy-Smith 2006, Charlton 2008). In fact, stage-discharge relationships vary locally in response to the changing cross-sectional area of the channel, and are affected by complex interactions between the local topography of a cross section and regional elements of channel geometry and planform (e.g., is the cross section situated in a narrow or wide bend of the river, in a pool or riffle, upstream or downstream of a major sandbar or a scour hole?). Consequently, stage-discharge relationships should be constructed from empirical data for each sandbar (since each sandbar occurs within a different cross-sectional area of the channel) via repeat visits to each site to document relationships between flows (which would be interpolated from bracketing gages, since flow measurements are uncommonly performed) and stage/WSE measurements at the location of each sandbar cross section (e.g., Tracy-Smith 2006).

In this study, each sandbar was visited only one time to make habitat measurements. Therefore, sandbar-specific, flow-WSE models based on local, empirically collected data on local water surface elevations could not be constructed. Consequently, cross-sectional variation within the study area was ignored, clinal variation in stage-discharge relationships between gages was assumed, and flow-water surface elevation relationships for any one sandbar were interpolated from flow-WSE relationships at bracketing gages using straight line interpolation via distance. For example, if a sandbar was halfway between two gages, with a predicted WSE at 12,000 cfs for the upstream gage of 510 ft and 500 ft for the downstream gage, the WSE at the sandbar would be predicted at 505 ft. Predicted elevations at gages were based on log-quadratic equations that predicted elevation from flow at both gages (Figure A1).

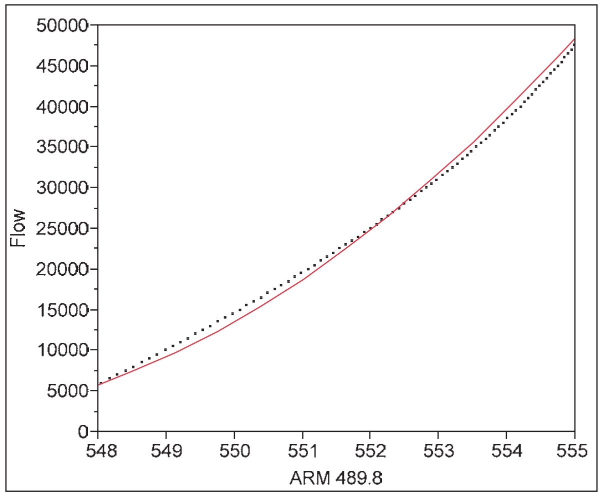

Figure A1. Example of a site-specific log-quadratic relationship used to predict flow (in cfs) from elevation measurements (in hundredths of US Survey feet) for a sandbar at Arkansas River Mile 489.8. For example, Elevation = exp(6.355024855-0.014663026*ln(flow)+0.001046049*ln(flow)^2).

Appendix B: Habitat Measurement Methods

Identification of sandbars for habitat measurements

Sampling on the Arkansas River was completed between December 2008 and April 2009, during restricted time periods when cold weather conditions were not too hazardous for sampling, and before dam releases associated with spring rains in 2009 inundated suitable nesting habitat. Attempts were made to provide digital elevation models (based on field survey techniques) and field vegetation delineations for all sandbars with suitable SNH in the study area. In order to access sandbars for field sampling, airboats were used to cover the often large distances between boat ramps and sandbars, since airboats were the most suitable watercraft to safely navigate the range of conditions encountered on the river. Specifically, numerous shallow areas made the use of boats with outboard motors difficult or unsafe during regularly occurring low-water conditions.

The productivity of daily field efforts was limited by the low density of boat ramps and declining day length during the fall/winter work period. Out-and-back round trips from a single boat ramp were typically the most time-efficient way to access sandbars in need of sampling. However, when sandbars were half-way between two distant boat ramps, much potential work time was lost because of the absolute requirement for daylight travel (due to the abundance of large woody debris and other navigation hazards). This practicality limited the amount of time spent on habitat measurements in any one day. Field topographic surveys using this method were considerably less costly than LIDAR data collection to construct digital elevation models for sandbars on this relatively short river reach (<80 miles) with relatively few suitable sandbars (~30). However, this may not be the most cost-effective way to sample SNH on longer reaches with larger or more numerous sandbars (e.g., the Red River), particularly when these reaches have few access points and uncertain conditions for overnight camping, which could minimize travel time to sampling sites.

To ensure complete coverage of the study area reaches, detailed field notes were compiled about the length of river traveled each day and GPS line files were collected during boat operations to record the areas that had already been visited. Multiple boat ramps were used to access the river and researchers traveled upstream and downstream from each of these ramps until it was clear from the notes and line files that the study area had been completely covered. During field surveys, a wide range of low-flow conditions were encountered (mostly lower than two-unit peak hydropower releases), from 500 to 14,000 cfs. Therefore, each time a sandbar was encountered, a decision had to be made concerning whether or not this sandbar met the sampling criteria (e.g., it would still be exposed at 13,000 cfs). At flows <3,000 cfs, so much of the channel's bed was exposed that decisions about numerous sandbars had to be made on a daily basis.

Well downstream from dams, mono-cultures of hydrophytic vegetation were encountered regularly (dominated by Yellow-Nut Sedge) indicating modal (e.g., two-unit hydropower) water lines during the growing season (Figures 6 and 10 in main report). At these sites, all areas above this line of vegetation were sampled. If this line of vegetation was missing, other evidence was evaluated to estimate if the entire sandbar would be underwater at 13,000 cfs. Since much of the sampling occurred in late fall-winter, when two-unit hydropower releases are rare due to low power demand, obvious and direct evidence was often lacking (e.g., wet sand lines), indicating two-unit hydropower releases. Still, coarse gravel bars less than 1ft above water level elevations could be categorically excluded during the relatively low flows that occurred during habitat measurements. From stage-discharge relationships, it was clear that these bars would be under water during two-unit hydropower releases in the breeding season. All attached sandy or sparsely vegetated areas less than 400 ft in width that lacked a high-flow back channel were also excluded, since these areas do not generally support ILT nesting. After reviewing field data and previous bird survey data, two sites measured from data summaries were removed, since the models predicted that these two sites would lack exposed sand at flows > 13,000 cfs. Also, neither site had a history of nesting between 2005 and 2009 (unpublished data, U.S. Army Engineer District, Tulsa).

After these exclusions, topographic surveys were conducted on all bare or sparsely vegetated sandbars (sandbars with small vegetation stands or large stands with stems <1 in. diameter) identified during field surveys. Topographic surveys were not conducted for other landforms within the riparian corridor (e.g., high-elevation forested islands, wetland islands at the head of reservoirs, sandbars that were completely covered in dense stands of ≥1-in. diameter shrubs and saplings), since these do not support tern nesting, and have low potential as future nesting habitat in the absence of major mechanical vegetation removal and sediment manipulation.

When field sampling was complete, bird monitoring data from 2009 (the breeding season after the surveys) were reviewed. The data showed that birds were nesting at 10 sites that were not identified as suitable during the surveys (consequently, these sites were not measured). These sites were all low sandbars with small numbers of nests that were either inundated at the higher end of the range of flows during the sampling period or perhaps eroded by high flows in 2008 and re-deposited by high flows that occurred after the 2009 sampling. Consequently, “simulated” low sandbars were created at these sites based on aerial imagery and similarities with sites that were measured so that they would be accounted for in the description of SNH below Keystone Dam (Figure B1).

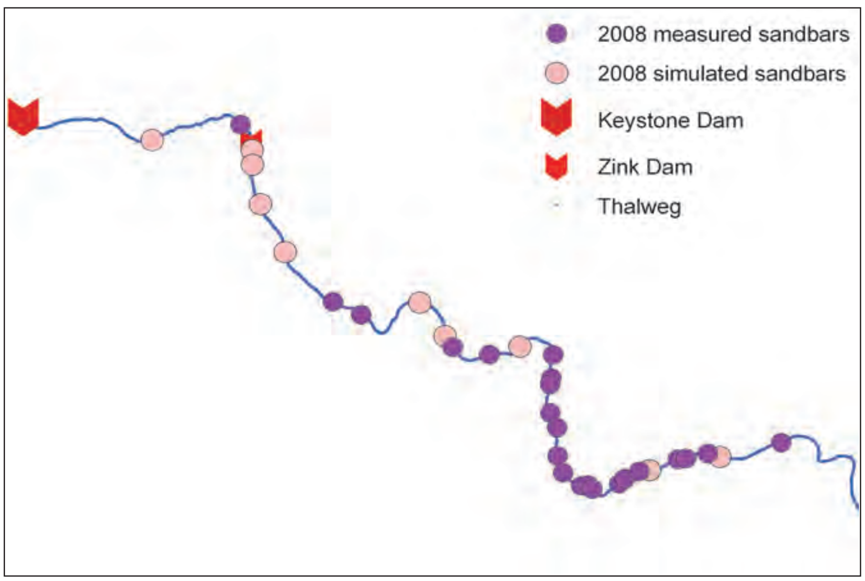

Figure B1. Locations of all 22 field-measured sandbars (purple dots) and 10 simulated sandbars (pink dots) below Keystone Dam. Simulated sandbars were low sandbars that were not observed/selected for measurement during field topographic surveys of 2008-2009 and were subsequently created in ArcGIS (because survey data indicated Least Terns were using them) based on the properties of other low sandbars in the measured sandbar dataset.

Field topographic surveys

Field crews of 3-4 people conducted topographic surveys of sandbars using a variety of standard surveying methods. These same crews collected data on vegetation at each sandbar (Wiley and Lott, in preparation). Three different elevation data collection methods were used to create topographic datasets that were later merged to create digital elevation models for sandbars (see “Automation of geoprocessing tasks using Python” in this appendix).

1. The field crew leader operated a Nikon NPL-522 pulse laser total station (paired with a TDS Nomad tripod data collection unit) and communicated with team members via radio and handsignals (Figure B2). A Rodman was equipped with a standard prism rod to collect point elevation data on sandbars (Figure B3). The Rodman used a sub-decimeter horizontal accuracy GeoXT GPS unit (with antenna) to collect coordinates for three points, spaced approximately 100 ft apart as an equilateral triangle, for local position control. Control points included the total station, a north-oriented back-sight monument, and the position of a laser level (see below). Lacking shoreline benchmarks, these positions were used to adjust the topographic data points for each sandbar to global positions (see Spatial adjustment). Topographic points were obtained using a total station with a vertical precision of less than 0.1 US Survey Foot. Topographic points were collected at obvious topographic break points and along transects (spaced 50 to 200 ft apart) that were generally perpendicular to the long axis of each sandbar. Depending on the size and topographic variability of the sandbar, between 100 and 500 survey points were typically collected at each setup location.
2. Another member of the survey crew operated a Spectra LL400 laser level (Figure B4) with a sliding beam receptor mounted on a stadia rod (Figure B5). The position and elevation of the laser level was first established by the GPS unit and the total station and the height of instrument (HI) measured to the nearest 0.1 survey foot. The sliding receptor was then repeatedly positioned at 0.5-ft intervals above and below the setup HI along multiple elevation-driven paths around the rotating laser unit. GPS points were collected at 50- to 100-ft intervals along these elevation-driven contours, typically resulting in the collection of 100-300 topographic points per site by this method. These were later merged with the total station elevation points to create detailed site topographic networks.
3. Simultaneously, a crew member employed a GeoXT GPS unit to collect important line features (Figure B6). Line features collected included the main river water line (both existing and previous high water line, if present), back-channel water lines, a low vegetation line (the waterside root base ground elevation of the Yellow Nut-Sedge), a coarse woody wrack line (if present), and the perimeters of various vegetation groupings. Elevations of these line features were surveyed at multiple points using the total station, and point elevations along lines were averaged to establish a single elevation for line features representing flat planes (e.g., the water's edge).

Figure B2. Survey crew leader operates the total station.

Figure B3. Rodman with prism rod.

Figure B4. Laser level.

Figure B5. Sliding beam receptor mounted on stadia rod.

Figure B6. Walking a waterline with a GPS unit.

Post-processing of field survey data

Spatial adjustment

Topographic positions acquired using the total station were spatially adjusted (moved) to fit the GPS-derived local control points. The total station datasets for each surveyed sandbar were adjusted from the default setup frame (State Plane; X=0-5000’, Y=0-5000’, Z=100’ assumed elevation) to the actual position using the affine spatial adjustment tool in ArcMap 9.3. The spatial adjustment relied on the three critical points established by both GPS and the total station during the survey (see “Field topographic surveys” in this appendix). The three critical points include the total station, the north-oriented, back-sight monument paced at a distance of approximately 100 ft, and (for this sampling protocol) the laser level position, which was set at a right angle to the back-sight line at a distance sufficient to create an approximate equilateral triangle with these three points at the vertices.

Vertical datum adjustment

At each sandbar, a GeoXT GPS unit was used to collect a long-duration (3-5 minutes) estimate for the elevation of the total station, to which all other elevation measurements were normalized. While GPS units provide sub-decimeter horizontal accuracy, GPS-acquired elevations are quite inaccurate (e.g., vertical accuracy ranging ±1-9 ft). Sets of precisely measured ***local elevations*** could not be linked to a regional network of standard survey ***benchmark elevations*** (e.g., USGS benchmarks), since these rarely exist within practical proximity to the sandbars measured. Given both time and budgetary constraints, which allowed only one visit to each of the sandbars measured, controlled survey benchmarks could not be established along riverbanks near sandbars (e.g., Tracy-Smith 2006). Therefore, an alternative, albeit less desirable, approach was employed to adjust the topographic data to the local elevation datum (e.g., NGVD 1929) using linear interpolation. Flow models were used to estimate the water level elevation for a sandbar at the time of survey incorporating elements of time, distance, and slope to interpolate water surface elevations (WSE) at sandbars from stage elevations at bracketing flow gages (see below). A standard vertical adjustment was then applied to all topographic data points to this benchmark elevation. For example, if the initial, GPS-collected WSE was 519.59 ft above MSL and the interpolated WSE (reflecting the gage datum of NVGD 1929) was 525.39 ft above MSL, all elevations at the site were adjusted by 5.80 ft. Topographic three-dimensional sandbar models were then constructed using the datum-adjusted elevations.

Linear flow interpolation treats the surface of the river as an inclined plane of uniform slope. The elevation of any point along this plane (e.g., a sandbar water line) is then determined relative to precisely measured elevations at two points along the plane (stage measurements at USGS gages, added to NGVD elevations for 0.0-ft stage at each gage). Once the distance of the desired location between these two points is calculated (distances were measured along the apparent thalweg line, which was delineated from aerial imagery), the rate of fall (slope of the plane) is calculated over the length of this plane. Consequently, the water surface elevation of a sandbar at any location along this plane is calculated as the water surface elevation at the upstream gage plus the slope of the plane multiplied by the distance of the sandbar from the upstream gage.

This method is complicated by variable hourly dam releases, which can sometimes result in large hourly changes in stage. Similarly, large variation in the magnitude of dam releases (and antecedent channel conditions) can result in variation in the amount of time that it takes a particular release event to travel between gages (see “Downstream travel of hydropower releases and waterline flow interpolation” in Chapter 2 of the main text). Therefore, flow velocity between gages (in mph along the thalweg) was first estimated and the amount of time that it would take water to travel from an upstream gage to a sampled sandbar or from the sampled sandbar to a downstream gage was then added or subtracted. This step used a visual, pattern-oriented approach, where hourly hydrographs for both gages were plotted and water travel times between gages were estimated using the most recognizable flow patterns (e.g., hydropower generation peaks and valleys) within 1-2 days prior to sampling, depending on the downstream distance of sandbars from gages.

Preparing spatial data for acreage summaries

GIS protocols for bank feature delineation

Flows yielding greater than bank-full stage did not occur between photo dates and the dates of field sampling. Consequently, it was expected that bank-side habitat conditions would be relatively similar between photos taken, for example, in 2006, and field sampling in fall/winter 2008-2009. This was confirmed by a close match between feature delineations from aerial photography and the observations of field crews.

Large trees and forest edges were delineated along the channel up and down stream of all surveyed sandbars. Edges of these features closest to sandbars were typically drawn at a scale of 1:10,000. However, a scale of 1:5,000 (or smaller) was sometimes used when it was difficult to determine detail due to inconsistent imagery quality. The following rules were established to identify “large trees”:

- Tree canopies >30-ft diameter (indicative of trees from 15-50 ft in height within the study area) must be visible at a minimum scale of 1:5000.
- Trees must be tall enough to cast a visible shadow.

The active channel margin was delineated within 1 mile of all surveyed sandbars. Characteristics that indicated the active channel margin varied among photos, depending on the river stage at which they were taken. The active channel margin was defined by the presence of any of the four following features:

- The water/land interface when photos were taken at high flows
- The bare sand/persistent vegetation interface at lower flows
- The presence of bank-stabilizing structures such as revetments
- Other visible topographic breaks (e.g., erosion scarps)

Conversion of field-collected line files to polygon and point files

Field crews collected GPS edges of a number of sandbar features (e.g., vegetation patches, waterlines) using a GeoXT GPS unit in line data collection mode, collecting vertices at 10-ft intervals. GPS data were post-processed to increase position accuracy using Trimble Pathfinder software and exported to standard ArcGIS shape files in state plane coordinates. Vegetation lines were used in the creation of polygons depicting vegetation patches on sandbars (Figure B7). Line shape files representing sandbar water lines or other equal elevation features were converted into points (at 10-ft increments) with the same elevation assigned to each point.These new point elevation files were merged with other point elevation data collected using either the total station or a laser level (Figure B7). Composite point elevation files were then used to create digital elevation models (TINs) for each sandbar (Figure B8). Waterline shape files were also closed to create "clip" polygons to delineate the outer boundaries of sandbars, limiting the water side extent of digital elevation models (Figures B7 and B8).

Automation of geo-processing tasks using Python

A script was developed in the programming language Python to automate the following geo-processing tasks in ArcGIS that needed to occur at each sandbar (script and documentation available at http://www.leasttern.org):

- Adjustment of all field-collected point elevations to the NGVD datum based on sandbar-specific adjustment factors (see "Datum adjustment" section above).
- Creation of digital elevation models for each sandbar (TINS) reflecting this datum adjustment.

Figure B7. Several spatial data files were generated from field data to provide inputs for a Python script (see below) that was used to automate several time-consuming geo-processing steps that were necessary for acreage summary. Red plus signs within the interior of this sandbar indicate GPS points where elevation data were collected using a total station at topographic breakpoints or along survey transects. The dense collection of red points along the sandbar's perimeter illustrates a water's edge line file, after it has been converted to points. The dark green polygon at the top left of the image represents a patch of vegetation that was originally delineated as a line and later closed to complete a polygon. The light green frame around elevation sampling points represents the "clip" file that was created to define the outer boundaries of the sampling site by: 1) closing the waterline line file to create a polygon; 2) creating a second polygon of larger spatial extent; and then 3) erasing the sandbar polygon from the larger polygon to create the clip file that is needed to limit the spatial extent of continuous digital elevation surfaces (TINS) created from point elevation data. The dark green line indicates large trees (or lines of trees) and the brown line indicates the edge of the active channel. These lines were delineated from aerial photography near the time of sampling.

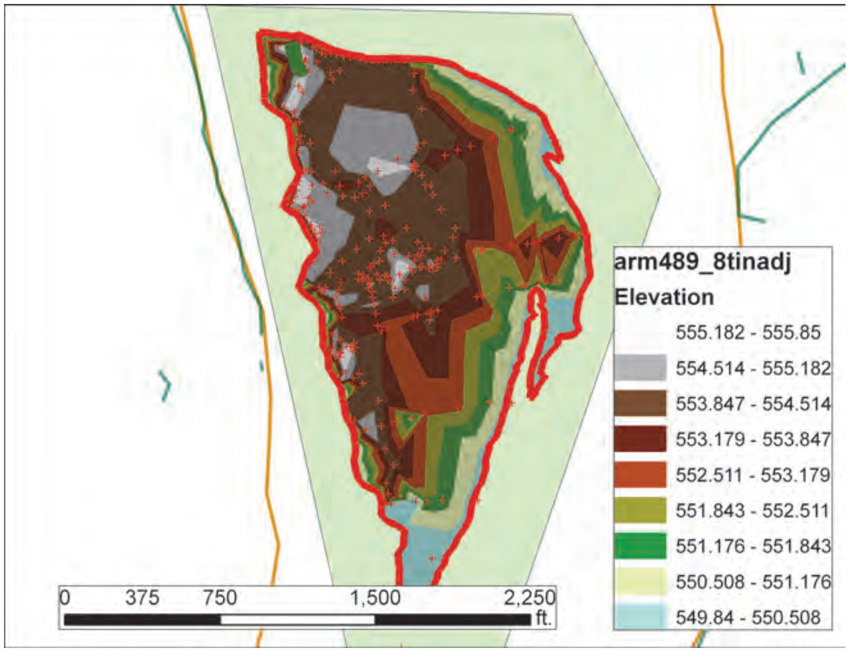

Figure B8. Example of a TIN digital elevation model created from datum-adjusted topographic points, with the outer extent of sampling set by the "clip" file.

- Creation of raster grid files within the sampling area of each sandbar, with points at the center of each 36-ft^2 cell, used to calculate:
  - o Distances from each point to the nearest large tree.
  - o Distances from each point to sandbar vegetation polygons.
  - o Distances from each point to the bank.
- For each point, the script also:
  - o Extracted point elevations from the datum-adjusted TIN.
  - o Used sandbar-specific elevation to flow relationships to assign an inundation cfs value to each point.
  - o Determined if a point was contained within a sandbar vegetation polygon.

Creating simulated sandbars for un-surveyed sites in 2008-2009

From reviewing bird monitoring data, talking with field crews, reviewing aerial photos, and personal field experience in the summer of 2009, it was ascertained that each of the 10 sandbars that were missed during the winter 2008-2009 field surveys were relatively low elevation. Therefore, simulated sandbars were created in the locations that were not measured in winter 2008-2009, but where birds nested in 2009, using the following steps:

- While viewing aerial photography and bird monitoring datasets in ArcGIS, polygons were drawn to delimit sandbar waterlines at approximately 13,000 cfs.
- A sandbar-specific flow–to-elevation equation was then generated for each of these sites and the elevation corresponding to 13,000 cfs was assigned to each waterline.
- These “waterline” polygons were converted to points at 10-ft intervals and the same elevation was assigned to each point.
- These “waterline” polygons were also used to create the necessary “clip” files for each simulated sandbar as inputs to the Python script described above.
- Several contour lines were then drawn inside each of the waterline polygons and assigned those elevations equivalent to flows that resulted in sandbar inundation at the relatively low flows (e.g., 16,000 cfs) that have typified flooding risk at sandbars in these locations in the past (e.g., prior to the 2007 high flows) and which seemed reasonable based on impressions of these sandbars during the 2009 breeding season.
- These point and line elevation shape files were then used as inputs to create draft TINs for each of these simulated sites in the ArcGIS extension 3D analyst.
- Between 300 and 500 random points (depending on the size of the sandbar) were then created within each waterline polygon and elevations were extracted from the draft TIN for each of these points.
- These points, the waterline points, and their associated elevations, were then merged into input files for the Python script described above to create simulated sandbars with identical properties (e.g., cells with values for the same covariates) as the sandbars that were measured.

The creation of these “simulated” sandbars was a somewhat artistic process, driven by observations and assumptions rather than data. However, this step was deemed essential, since the consequences of omitting the low sandbars that were missed in 2008-2009 from simulations of flooding mortality in the TernCOLONY model would have been an unrealistic assessment of flooding risk for terns (e.g., model terns would not have the opportunity to select low sandbars where flooding risk is high).

Creating simulated sandbars for degraded conditions in 2006

Aerial photographs and bird monitoring data (Tulsa District, unpublished data) for the period immediately prior to the habitat-forming flows of 2007-2008 were reviewed, resulting in the following observations:

- Only one site that contained nesting from 2004-2006, prior to high flows, was completely removed by the high flows of 2007-2008.
- Twenty-four remaining sandbars existed in exactly the same location prior to high flows. Pre-flood sandbars tended to be smaller (and mostly covered in vegetation) than post-flood sandbars measured in the same location in 2008-2009.
- Eight sandbars measured in 2008-2009 occurred in totally new locations, where sandbars were not present prior to the high flows of 2007-2008.

In summary, the high flows of 2007-2008 created sandbars in eight new locations, removed one sandbar completely, and renewed habitat conditions at 24 previously used nesting sandbars by removing vegetation and depositing new sand. Since there were no sandbar measurements prior to the high flows of 2007-2008, it was impossible to ascertain quantitatively how much each of the existing sites increased in elevation with new sand deposition. However, qualitative descriptions of flooding risk prior to the 2007-2008 high flows (USFWS 2005a) suggested that most sandbars would have been inundated at much lower flows than the flows required to inundate the higher sandbars that were present in 2008-2009. A set of 25 “degraded” sandbars was created in ArcGIS using the following protocols:

- For the 24 sandbars that existed in the same location in 2006 as the sandbars measured in 2008-2009, aerial photography was used to draw new waterlines at 13,000 cfs (which frequently resulted in smaller sandbars than those measured in 2008-2009) and vegetation polygons indicative of pre-flood conditions.
- For the one pre-flood sandbar that was completely removed by the 2007-2008 high flows, a small and low sandbar was created using the same protocols indicated in the section above titled “Creating simulated sandbars for un-surveyed sites in 2008-2009.”
- The following rules of thumb were used to adjust the elevations of sandbars measured in 2008-2009 to reflect the lower elevations that

were indicative of pre-flood sandbars in the simulated 2006 sandbar dataset.

- o For each sandbar, the percentage difference was calculated between the flow that would completely inundate a 2008-2009 sandbar at a flow of 70,000 cfs (the sustained high flow that occurred in 2007 during new sandbar formation). For example, if measurements indicated that a sandbar would be inundated at a flow of 30,000 cfs, it was then concluded that this sandbar had a maximum elevation that was 43% of the maximum flow of 70,000 cfs.
- o Each of these sandbar-specific percentages was then multiplied by 40,000 cfs, which matched the maximum sustained flows in 2001 and 2000, the most recent high flows of >3 days in the years preceding the habitat conditions described in USFWS (2005a). For example, the inundation elevation of the sandbar described above was calculated as 43% of 40,000 cfs, or 17,143 cfs.
- o Next, sandbar-specific flow to elevation equations were used to calculate the elevations corresponding to these inundation flows and an elevation difference between these two flows was calculated (these ranged from 0.64 to 2.38 ft). This elevation was then subtracted from each cell in the 2008-2009 sandbar to estimate the cell's elevation in 2006.

Despite the assumptions required to create this simulated habitat dataset, this is a necessary, if heuristic, step to compare the effects of dam operations during periods with degraded habitat conditions (which have frequently occurred during the period of record, although they have never been measured) to the excellent SNH conditions that were measured after the high flows of 2007-2008. Analyses similar to the ones in this report should be repeated as soon as real habitat measurements reflecting degraded habitat conditions are available.

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14. ABSTRACT:

This report describes Least Tern (*Sternula antillarum*) sandbar nesting habitat (SNH) on the Arkansas River below Keystone Dam from field and GIS measurements after the 2008 nesting season. This season was preceded by 2 years with high-magnitude, long-duration dam releases (>50,000 cfs for >3 weeks), which resulted in major habitat renewal; replacing small, low-elevation sandbars that were mostly covered with vegetation with large, completely bare, high-elevation sandbars. Habitat measurements are reported relative to hydrographs that describe Keystone Dam operations for hydropower production and flood control (based on a post-dam era of 1977-2008). Habitat measurements for 2008-2009 were compared to a degraded habitat dataset that was simulated in ArcGIS based on descriptions in the most recent USFWS biological opinion for the Arkansas River. TernCOLONY, an individual-based model of Least Tern reproduction, was then used to evaluate how dam operations affect ILT reproduction, given these two sets of habitat conditions, across the range of dam operations. In simulations, infrequent nest flooding mortality was observed when habitat conditions were outstanding (e.g., after the high flows of 2007-2008). Conversely, regular nest mortality due to flooding, as well as higher predation rates, resulted in low reproductive success when habitat conditions were degraded. Given this baseline understanding, three different management alternatives were simulated that were designed to reduce flooding and/or predator mortality when habitat conditions are degraded (e.g., mechanical sandbar habitat restoration, predator control, and a combination of the two). Only management treatments that included predator control components were effective at increasing regional reproductive output. Since ILT populations experience periods with excellent habitat conditions and degraded habitat conditions at the decadal scales that affect population trajectories, widespread application of this type of evaluation would be helpful to assess the persistence of regional ILT populations considered important to the ILT metapopulation.

15. SUBJECT TERMS

Arkansas River	Keystone Dam	Sandbar nesting habitat
Interior Least Tern	Least Tern	TernCOLONY
	Nest mortality	

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