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ABSTRACT—Implementation of the Platte River Recovery Implementation Program's adaptive management plan has proceeded with the understanding that management uncertainties, expressed as hypotheses, encompass complex physical and ecological responses. Adaptive management in the Platte River ecosystem relies on a combination of monitoring of physical and biological responses to management treatments, predictive modeling, and retrospective analyses. Given the abundance and diversity of fishes inhabiting waterways decreases with groundwater extractions and flow alterations, we used existing interior least tern productivity data and flow data collected from the Central Platte River area for retrospective analyses to assess the influence of forage fish availability on productivity during the brood-rearing season. Our analyses suggest that low flows during the least tern brood-rearing season do not have a negative relationship with interior least tern productivity. As such, we used this indirect line of evidence to build empirical support to assess the forage fish–related hypotheses in the Platte River Recovery Implementation Program's adaptive management plan, and we concluded forage fish abundance does not limit interior least tern productivity on the Central Platte River.

Key Words: Central Platte River, forage fish, interior least tern, Platte River Recovery Implementation Program, productivity

Introduction

The Platte River Recovery Implementation Program (PRRIP) is responsible for implementing certain aspects of the endangered interior least tern (*Sterna antillarum athalassos*; hereafter, least tern) recovery plan in the associated habitat reach (AHR) of the Platte River in central Nebraska. One of the program's management objectives is to increase least tern productivity within the AHR. Uncertainty related to the relationship between least tern productivity, prey (forage fish) availability, and river flow is captured in several priority hypotheses in the program's adaptive management plan (AMP; PRRIP 2006). To date, these hypotheses have served as guidance for the program to investigate the relationship between low flow during summer months in the Central Platte River and the abundance of small fishes common in the diet of least terns and its impact on least tern productivity (AMP; PPRIP 2006). However, no study has been conducted that suggests the fish community within the AHR reduces least tern productivity (USFWS 2006a, 2006b).

Within the Great Plains, the abundance and diversity of fishes in waterways has been shown to decrease with groundwater extractions and flow alterations (Marchetti and Moyle 2001; Falk et al. 2010; Kiernan et al. 2012; Perkin et al. 2014). Hence, it is hypothesized that low flows during the nesting season limit prey fish populations, which then limits least tern productivity (Fig. 1; Wilson et al. 1993; National Research Council 2004; USDOI 2006; Jenniges and Plettner 2008). The program's biological opinion indicates the program will investigate whether or not the fish community within the AHR provides an adequate forage base for least terns (USFWS 2006a, 2006b).

Ideally, the preferred condition would have been for the program to develop and implement a targeted research project or conservation monitoring protocol designed to specifically address management objectives and forage-based *a priori* hypotheses (Nichols and Wil-

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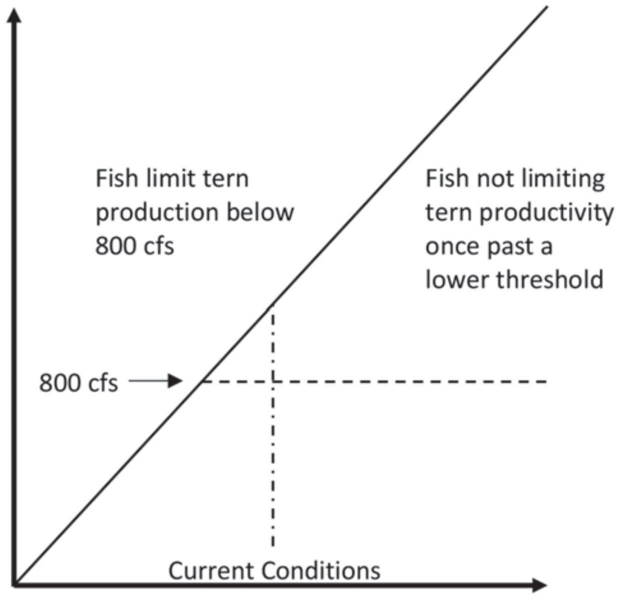

Figure 1. Hypothesized relationships between forage fish abundance and least tern productivity (Priority Hypothesis T2: Tern productivity is related to the number of prey fish <3 inches and fish numbers limit tern production below 800 cubic feet per second from May through September). One of the US Fish and Wildlife Service target flows is related to fish populations for tern prey base. If the prey base is limiting terns, and flows are released to increase the prey base, tern numbers should increase. If fish numbers are not limiting the tern population, increased numbers of fish will not increase tern numbers. Among the factors that may limit fish populations are nutrients, ambient air temperature, water temperature, solar energy, and species composition.

liams 2006) to test if forage availability limits least tern productivity below 22.65 cubic meters per second (cms; 800 cfs). Such a study would require extensive fish sampling and handling and weighing least tern chicks on a regular basis. To date, the monetary cost and potential for negative impacts to both least terns and the fish community have not been justified given the lack of information indicating abundance of appropriate-sized forage fish in the Platte River or any riverine system that would limit least tern productivity (Chadwick et al. 1997). Furthermore, the program has a limited ability to manage flows in the river and would have great difficulty showing a causative relationship between a decrease in the abundance and diversity of fish communities associated with reductions in flow and least tern productivity. Therefore, in the spirit of Platt's strong inference (Platt 1964), which has been used by the program with other questions related to the application of management actions and species response, a more systematic approach was used.

The program strives to use all available data in a credible manner to inform program decision making. Analyses of available forage fish data, discharge records, and data on least tern productivity and behavior on the Central Platte River proved to be uninformative and suggested a retrospective analysis might provide insight on certain program hypotheses. Retrospective analyses can be useful as a compromise between expedience and rigor when attempting to develop useful information for decision making (Smith 1998). The objective of this study was to utilize existing data to investigate if the fish community during the nesting and brood-rearing season was adequate to support least tern productivity within the AHR. Program priority hypothesis T2 is a syllogism between flow, forage fish availability, and least tern productivity. As such, it was hypothesized that decreases in flow, a proxy for forage fish availability, would influence productivity of least terns within the AHR. We used this deductive reasoning to build empirical support to assess the forage fish–related hypothesis T2 in the program's AMP.

Methods

Study Area

The program surveyed an area of 1,815 km^2 between Lexington and Chapman, Nebraska, USA (hereafter, AHR) for least tern nesting and foraging activity on an annual basis. Least tern nesting and foraging habitat surveyed within the AHR includes a 145 km reach of the Central Platte River and off-channel habitat (sand and gravel mines) within approximately 4.8 km of the river (Fig. 2).

Flow Measurements

Mean daily flow (m^3s^{-1}; henceforth, cms) records from 2001 to 2014 were obtained from the United States Geological Survey (USGS) gauging stations on the Platte River near the cities of Overton (06768000), Kearney (06770200), and Grand Island (06770500) in Nebraska. The gauge closest to the geographic location of each brood was identified. The flow records were used to calculate minimum and average mean flow for the 7, 14, and 21 days prior to the day when each brood's fate was determined.

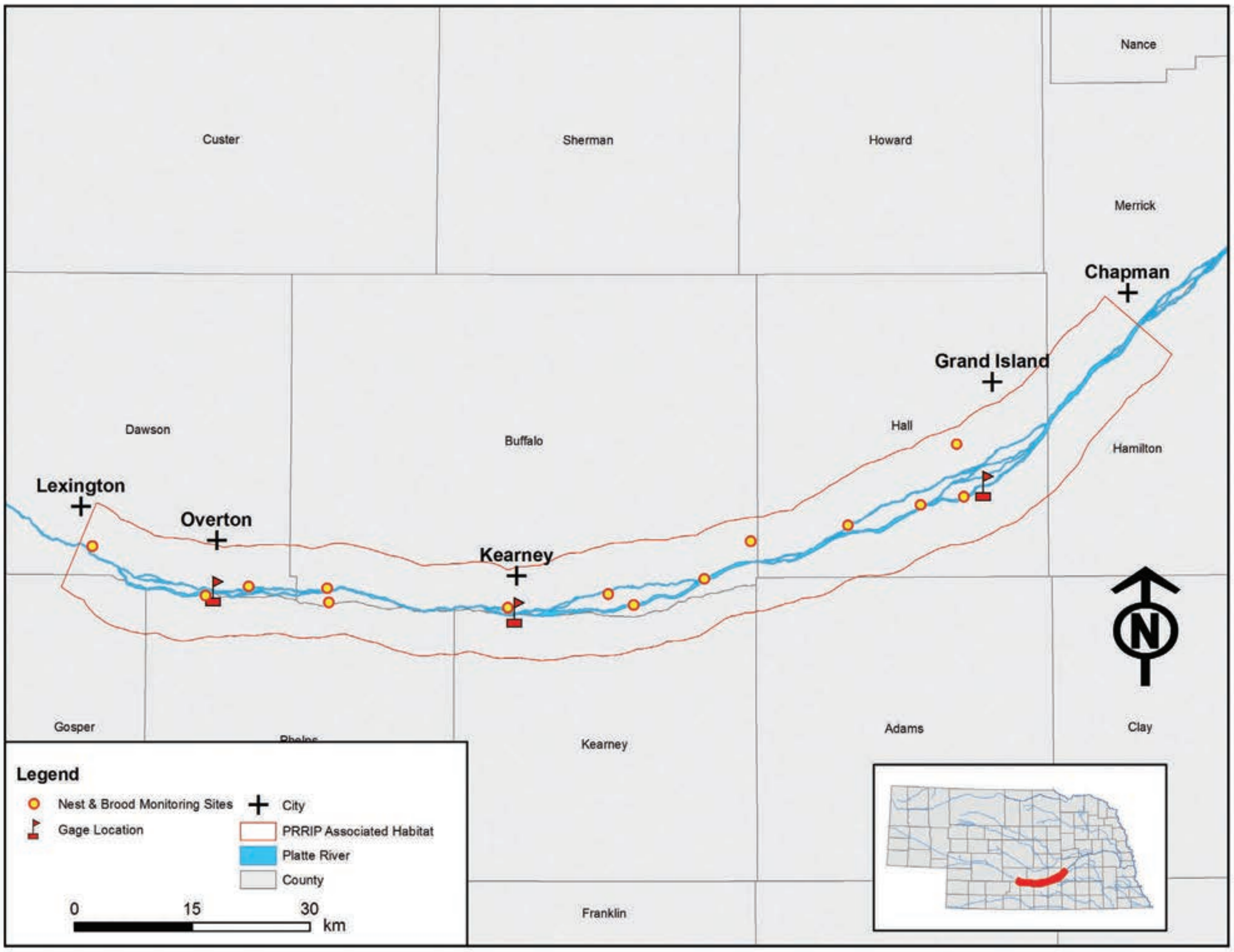

Figure 2. Study area (associated habitat reach) showing least tern and piping plover productivity data collection sites and locations of USGS gaging stations used in the analyses.

Least Tern Productivity Model

Given that we expected the probability of fledging to be related to flow, logistic regression models were used to relate flow to least tern productivity on off-channel nesting areas. An assumption of our logistic regression model was the proportion of fledglings from each brood (b_k) followed a binomial distribution:

$$b_k \sim Binomial\ (C_k, \eta_k)$$

where C_k is the number of chicks hatched from each nest, η_k is the probability a chick fledged from the *k*th brood ($k = 1, 2, \ldots, 457$) and whether or not a chick fledged was treated as a binomial trial within each brood. Broods with an unknown fate and broods that failed due to known cause such as flooding, predation, and adverse weather events were excluded from the analysis since these failures were not related to forage dynamics. Given the paucity of on-channel nesting during our study, on-channel nests and broods were also removed from our analyses. Seven total models were tested in an attempt to establish a relationship between productivity and flow. We assumed the logit of η_k depended on f_k which was the minimum or average mean daily flow 7, 14, and 21 days prior to the date of fate determination:

$$\text{logit}(\eta_k) = \alpha_1 + \alpha_2 f_k$$

We also included a model that did not include an influence of flow, which was:

$$\text{logit}(\eta_k) = \alpha_1$$

We randomly split the data into a training set with 229 observations and test set with 228 observations. A

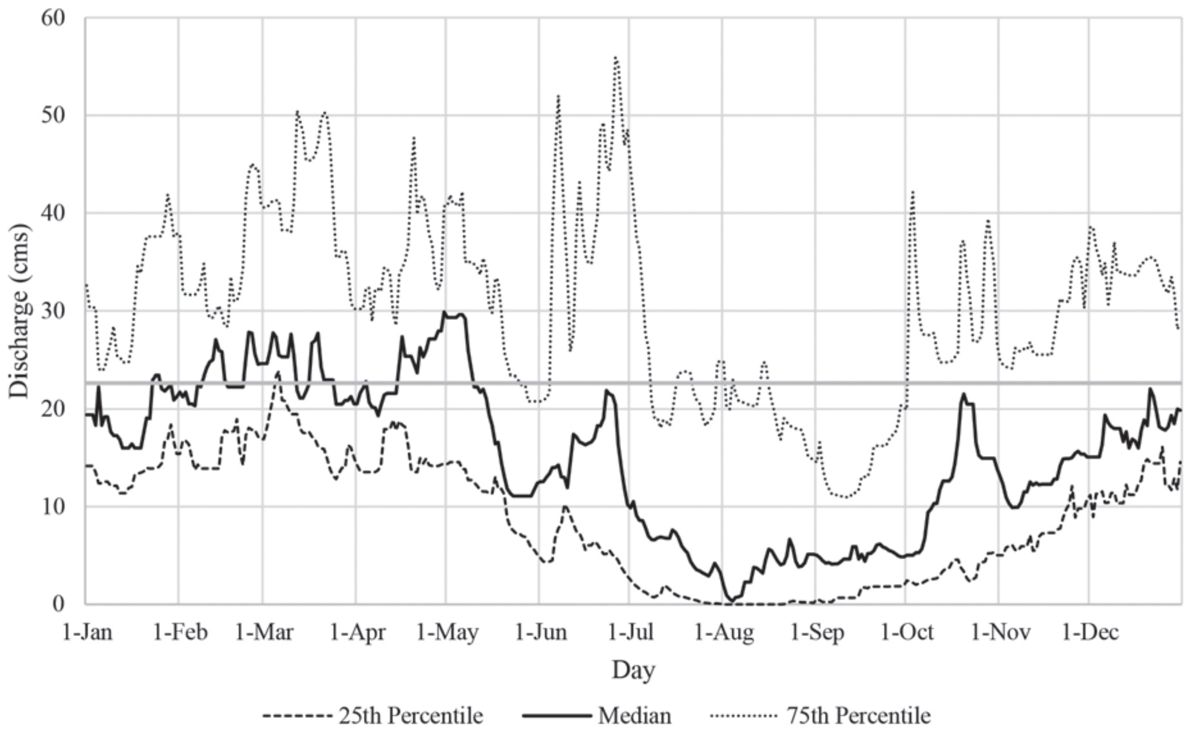

Figure 3. Annual hydrograph at USGS Grand Island stream gauge 06770500 in relation to the 22.65 cms discharge (horizontal gray line) hypothesized to limit least tern productivity, 2001–2014.

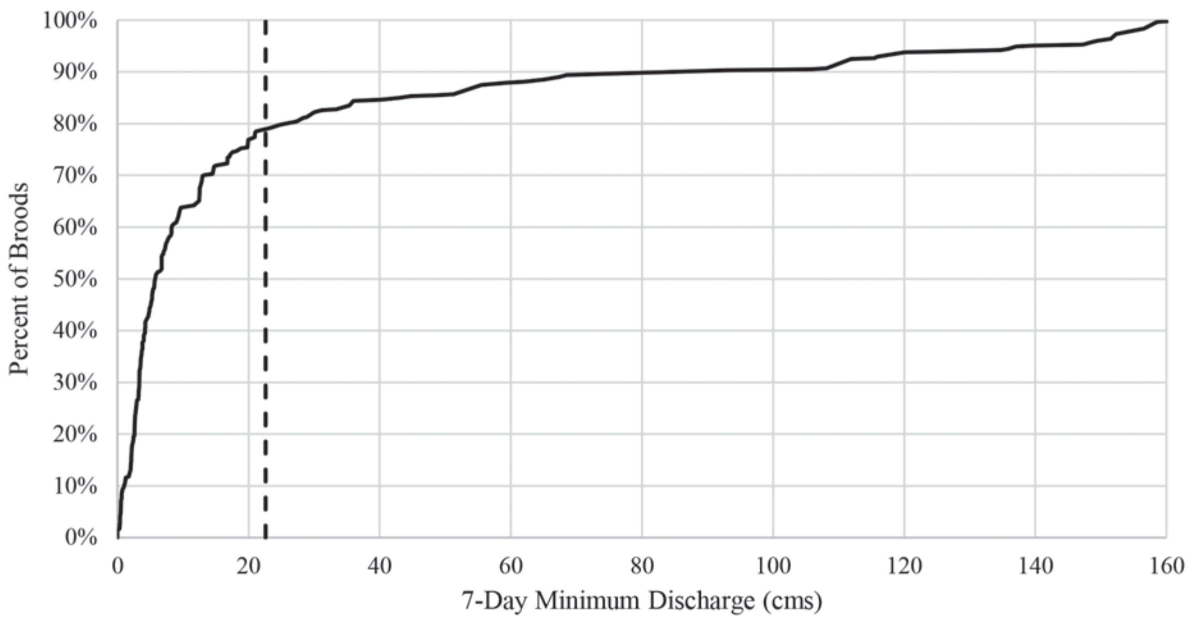

Figure 4. Distribution of 7-day minimum river discharge experienced by broods in relation to 22.65 cms discharge (dashed line) hypothesized to limit least tern productivity, 2001–2014.

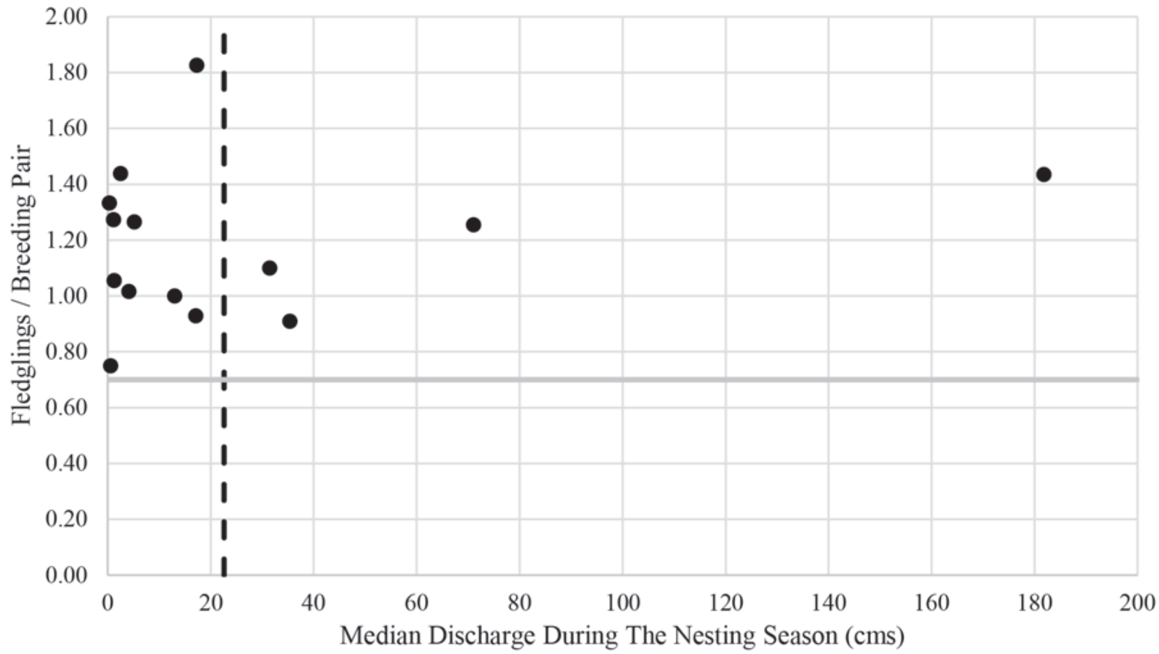

Figure 5. Fledglings per breeding pair in relation to median discharge during the 2001–2014 nesting seasons, including the Lutey (2002) fledge ratio objective (gray line) believed to be required to maintain a stable population and 22.65 cms discharge (black dashed line) hypothesized to limit least tern productivity.

generalized linear model and maximum likelihood was used to obtain parameter estimates using the training data set (Stroup 2012). We calculated the predictive deviance (i.e., −2 times the predictive log likelihood) using the test data. Predictive deviance is a measure of the model's predictive ability and has a similar interpretation as Akaike information criterion (AIC; Burnham and Anderson 2002; Hooten and Hobbs 2015). We also calculated and reported AIC scores for comparison.

Results

We observed 977 least tern nests from 2001 to 2014, of which 546 nests had ≥1 successfully hatched chick. Eighty-nine broods failed due to known causes not attributed to forage dynamics. The remaining 457 broods either fledged (n = 416) or failed due to unknown causes (n = 41). Only the 41 broods that failed due to unknown causes were identified as possible forage-related failures. Those 457 broods produced 1,040 chicks and 830 fledglings (Table 1). Of these broods, 79% had fates determined when the flow was ≤22.65 cms (800 ft^3s^{-1}), which resulted in 78% of the fledglings observed. During the least tern nesting and brood-rearing period, which begins in late May and extends through August, flows were below 22.65 cms in approximately 75% of years and approached 0 cms in 25% of years, 2001–2014 (Fig. 3). Overall, 79% of broods included in our analyses were exposed to river discharges below 22.65 cms within 7 days of brood fate determination and 50% of nests were exposed to discharges below 5.80 cms (Fig. 4). Discharge during the median nest initiation period only exceeded 22.65 cms in four out of 14 years (Fig. 5). There were no differences in fledge ratios when median discharge was less than 22.65 cms, and the fledge ratio exceeded the proposed fledge ratio target of 0.70 in all four years (Fig. 5). During the study period, the annual least tern fledge ratio (fledglings per breeding pair; Baasch et al. 2015) ranged from a low of 0.75 (2006) to a high of 1.83 (2001) and averaged 1.19 (Table 2).

Based on the criteria for analysis inclusion, 457 nests had known fates and were utilized to compare proportion of chicks fledged to discharge metrics. The predictive performance of all models were similar to the model with no covariates (Table 3). Model predictive deviances only varied by ~2 and AIC scores varied by ≤2

Table 1. Proportion of chicks fledged from all broods observed, 2001–2014.

Proportion of chicks fledged	Number of broods
0.00	41 (9.0%)
0.33	20 (4.4%)
0.50	38 (8.3%)
0.67	54 (11.8%)
0.75	1 (0.2%)
1.00	303 (66.3%)

Table 2. Annual least tern reproductive success within the AHR in relation to median discharge during the nesting season, 2001–2014.

Year	Fledglings	Breeding pair	Fledglings per breeding pair	Median discharge during nesting season (cms)
2001	42	23	1.83	17.3
2002	59	41	1.44	2.5
2003	57	54	1.06	1.3
2004	60	45	1.33	0.3
2005	62	49	1.27	5.2
2006	27	36	0.75	0.6
2007	40	44	0.91	35.4
2008	44	40	1.10	31.4
2009	46	46	1.00	13.0
2010	64	51	1.25	71.1
2011	89	62	1.44	181.8
2012	84	66	1.27	1.1
2013	64	63	1.02	4.1
2014	91	98	0.93	17.1
Average	59.2	51.3	1.19	27.3

Table 3. Model selection results for least tern brood survival as ranked by AIC and deviance.

Covariates	Deviance	AIC
Null	420.08	412.23
7-day minimum discharge	419.69	414.00
14-day minimum discharge	419.83	414.06
21-day minimum discharge	419.96	414.00
7-day mean discharge	419.98	414.00
21-day mean discharge	419.86	414.09
14-day mean discharge	420.13	414.20

AIC units. The model with 7-day minimum discharge had the lowest deviance of 419.69 and an AIC value of 414.00, but the predicted influence on proportion of chicks fledged was minimal and similar to other flow relationships (Fig. 6). The intercept only, or null model, had a deviance of 420.08 and an AIC of 412.23, which was the lowest calculated AIC value.

Discussion

Our data suggest that flows below 22.65 cms during the least tern nesting and brood-rearing season do not negatively affect productivity, thus implying that the fish community is adequate for maintaining least tern productivity on the Central Platte River. Furthermore, least terns have been observed foraging much farther (>10 km) from their nesting area than previously documented, making more area available for forage without any detectible decline in reproductively (PRRIP 2006; Sherfy et al. 2012). Though indirect, these conclusions are based on critical evaluations of existing data from Program hypotheses and questions related to least tern reproductive response to management actions. These conclusions are also made in the context of a North American resource management program that incorporates decision making influenced by scientific information, but also by budget, policy, and the constraints of the Central Platte River as a social-ecological system.

In any adaptive management program, information needs must be evaluated for their importance, assessed for potential negative impacts to the resources of concern, and prioritized by the monetary requirements needed to obtain such data. Our results reflect learning, an important aspect of adaptive management, and the use of retrospective analyses in the application of adaptive management (Walters and Holling 1990; Smith 1998). While this study is at best a passive approach to adaptive management, the information is credible and provides an updated understanding important for program decision making (Walters and Holling 1990). Results of our study indicate additional research or targeted monitoring are unlikely to improve the understanding of the relationships between the fish community and least tern productivity and will serve only as a delaying tactic in a search for scientific consensus that may not be achievable (Ludwig et al. 1993). Results of our retrospective analysis pass the test of management relevance as defined by Westgate et al. (2013) and should be used

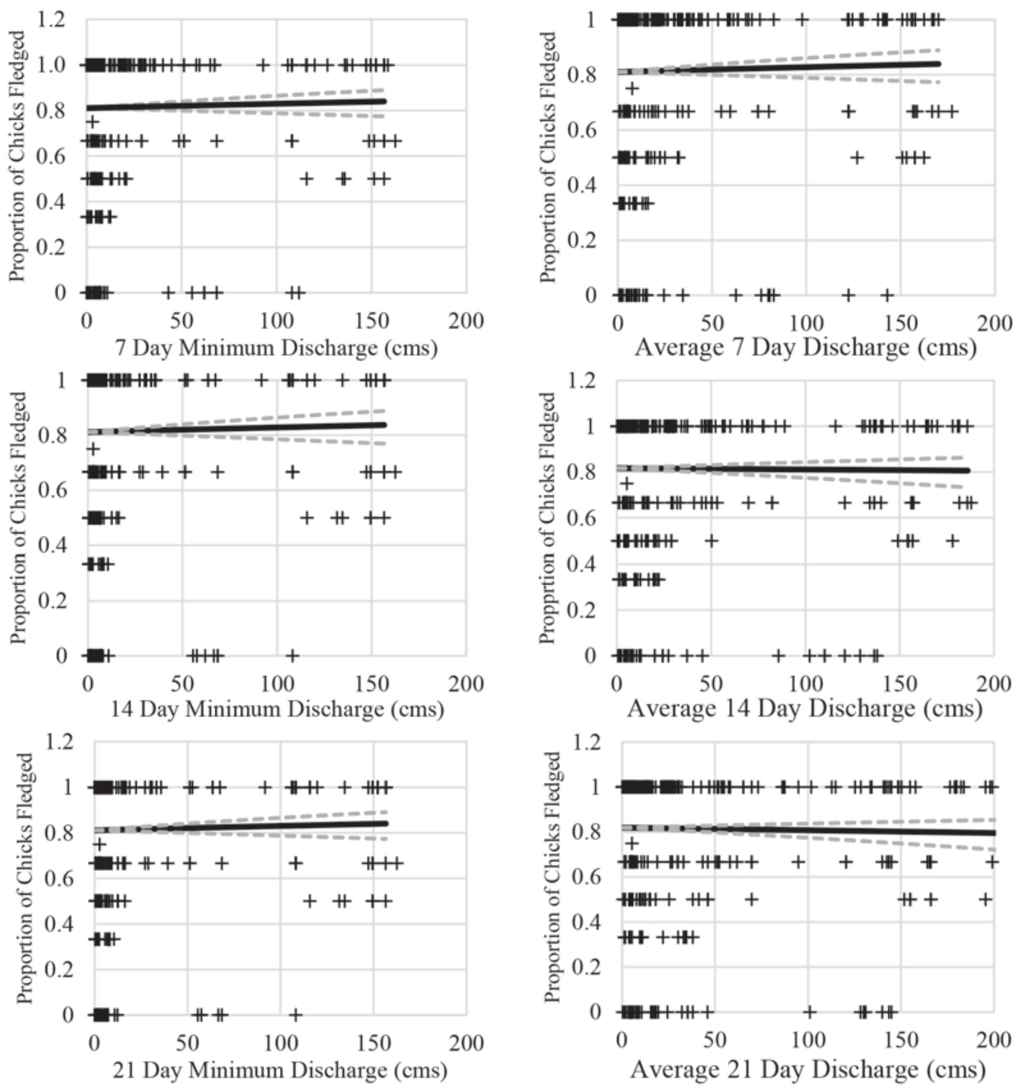

Figure 6. Predicted proportion of fledglings for each brood compared to flow metrics with 95% confidence intervals. The plus signs (+) show the empirical probabilities of fledging for each brood.

$$p_e = \frac{\text{Number of times an occupied site in 1977–86 was unoccupied in 2005–07}}{\text{Total number of occupied sites censused}}$$

No flow metric resulted in better predictions of fledging success than the null model, which indicates fledging success is independent of all variables tested.

by the program to adjust management actions accordingly. Such analyses and uses of existing data provide an example of hierarchal methodology useful to other species and/or ecosystem recovery programs when faced with a complicated question. In our case, an intricate hypothesis involving flow, the fish community, and least tern productivity was addressed by evaluating the relationship between flow and least tern productivity within the AHR. As with any syllogism, the formal argument in logic is formed by two statements and a conclusion which must be true if the two statements are true. However, if the conclusion is found to be false, one or both of the syllogistic statements will be equally false. Had we found the conclusion we investigated to be true, the program would have accepted the hypothesis T2 to be true or further investigation as to the causal effects would have been warranted.

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