SRP15392

RIVER RESEARCH AND APPLICATIONS

River. Res. Applic. **24**: 789–803 (2008)

Published online 17 April 2008 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/rra.1082

RECENT HABITAT ASSOCIATION AND THE HISTORICAL DECLINE OF *NOTROPIS SIMUS PECOSENSIS*

CHRISTOPHER W. HOAGSTROM,* JAMES E. BROOKS and STEPHEN R. DAVENPORT

U.S. Fish and Wildlife Service, New Mexico Fishery Resources Office, 3800 Commons Ave. NE, Albuquerque, New Mexico 87109-5831, USA

ABSTRACT

Small-bodied, riverine minnows that historically characterized fish assemblages of Great Plains rivers in North America have declined because of river fragmentation, dewatering, river channel degradation, river salinization and nonnative species introductions. The Pecos bluntnose shiner *Notropis simus pecosensis*, a member of this guild, persists in one segment of the Pecos River, New Mexico, USA. We characterized habitat associations for the species at two spatial scales. In general, *N. s. pecosensis* associated with fluvial habitats, but velocity association depended on body size, with larger individuals using swifter habitats. All *N. s. pecosensis* associated with relatively low depths (3–51 cm), which were most abundant in sites with relatively wide river channels (>25 m), especially when discharge was between 0.5 and 4.0 $m^3 s^{-1}$. The Pecos River sub-segment that is occupied by the core population of *N. s. pecosensis* (V-ii) had a unique combination of being buffered from direct dam effects by intervening segments and sub-segments, high sub-segment length, substantial sediment inputs from numerous uncontrolled tributaries, substantial base flow provided by irrigation return flows and groundwater inflows, high channel width in relation to discharge and low salinity. Although no unoccupied Pecos River segment appears to be suitable for *N. s. pecosensis*, habitat restoration opportunities exist within all occupied sub-segments (V-i, V-ii and V-iii) via base flow enhancement and river channel restoration. Restoration that offsets chronic effects of dams may be necessary to conserve the species. Restoration would also benefit other rare riverine minnows that coexist with *N. s. pecosensis*. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: riverine minnow; river fragmentation; aquatic habitat; flow management; size-related habitat use; threatened species; Pecos River; river restoration

Received 11 June 2007; Revised 24 September 2007; Accepted 3 October 2007

INTRODUCTION

In North America, flow regime and channel alterations have dramatically affected large-river fish assemblages (Hughes *et al*., 2005). Fish faunal response to alterations appears to be deterministic because remnant populations persist where habitats are least altered (Bonner and Wilde, 2000; Quist *et al*., 2004; Welker and Scarnecchia, 2004). Local geomorphology, dam operations, groundwater withdrawals and species introductions interact, causing fish assemblages of isolated river segments to diverge over time within a given watershed (Lynch and Roh, 1996; Hoagstrom, 2003; Marchetti *et al*., 2006). This is because fish distributions correspond closely to geomorphic conditions (Walters *et al*., 2003; Lamouroux and Cattanéo, 2006).

The Pecos bluntnose shiner *Notropis simus pecosensis* is a federally threatened minnow, endemic to the mainstem Pecos River, USA (USFWS, 1987, 1992). Although historically more widespread, it is presently restricted to a single river segment, bounded by dams (Propst, 1999). *N. s. pecosensis* is a member of a riverine minnow guild that is in decline (Cross and Moss, 1987; Fausch and Bestgen, 1997; Dudley and Platania, in press). These species occupy fluvial habitats of wide, shallow rivers of the Great Plains (Cross and Moss, 1987; Lehtinen and Layzer, 1988; Polivka, 1999). A defining characteristic of riverine minnows is the production of semibuoyant, nonadhesive eggs and pelagic early protolarvae that are prone to downstream displacement (Platania and Altenbach, 1998).

Five abiotic features have been hypothesized to be important for the decline of riverine minnows. First, fragmentation of rivers by dams has isolated sub-populations, which has led to their incremental loss.

*Correspondence to: Christopher W. Hoagstrom, Department of Zoology, Weber State University, 2505 University Circle, Ogden, UT 84408-2505, USA. E-mail: christopherhoagstrom@weber.edu

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Sub-populations in short river segments are less likely to persist because a high percentage of the eggs and protolarvae may be displaced into reservoirs where they are presumably lost (Fausch and Bestgen, 1997; Platania and Altenbach, 1998; Dudley and Platania, 2007). Dams also preclude recolonization from other river segments (Winston *et al*., 1991; Pittenger and Schiffmiller, 1997; Luttrell *et al*., 1999; Wilde and Ostrand, 1999) and disrupt longitudinal gene flow (Alò and Turner, 2005). Dudley and Platania (2007) concluded that river segments less than 100 km in length were unlikely to support riverine minnows because of egg and protolarvae displacement.

Second, dewatering corresponds to declines of riverine minnows because fluvial habitat declines (Cross and Moss, 1987; Luttrell *et al*., 1999; Bonner and Wilde, 2000). This may limit survival by reducing spawning success (Durham and Wilde, 2006) or eliminating suile habitats (Hoagstrom *et al*., in press). Surface-flow intermittence is the primary threat to the survival of *N. s. pecosensis* (USFWS, 1987, 1992).

Third, dams often dramatically alter flow regimes. Flashy flow regimes may be important to induce spawning by riverine minnows (Lehtinen and Layzer, 1988; Bestgen *et al*., 1989). Such regimes also tend to favour riverine species over small-stream species and nonnatives (Cross and Moss, 1987; Gido *et al*., 2004; Hoagstrom *et al*., 2006). However, dewatering and flood control often create highly stable flow regimes that correspond to the decline of riverine minnows (Anderson *et al*., 1983; Bonner and Wilde, 2000; Hoagstrom *et al*., 2007).

Fourth, riverine minnows are relatively intolerant of high salinities (Echelle *et al*., 1972; Ostrand and Wilde, 2004). For example, salinity is especially high in the Lower Pecos River because of saline irrigation return flows and brine aquifer intrusion (Taylor, 1902; USNRPB, 1942; Hendrickson and Jones, 1952) which has corresponded to dramatic changes in the fish fauna, including the decline of riverine minnows (Hoagstrom, 2003).

Fifth, riverine minnows are characteristic of wide, shallow rivers with shifting-sand substrate (Cross and Moss, 1987). These features create a dynamic habitat mosaic, which riverine minnows are well suited to occupy (Matthews and Hill, 1980; Polivka, 1999). Habitat diversity in sand-bed rivers is a function of bedload transport that creates a variety of bedforms, depending on immediate conditions (Simons *et al*., 1965; Jackson, 1975). Dams reduce bedload supply, whereas dewatering and flood control reduce bedload transport (Collier *et al*., 1996). This ultimately degrades the dynamic habitat mosaic via channel incision, channel narrowing and sediment stabilization.

Here, we use field data to summarize the body size to depth and velocity association of *N. s. pecosensis* and assess the influence of channel width and discharge on the abundance of associated depth-velocity point measurements. We then use existing data on river segment length, channel width, flow regime and salinity to compare conditions in the occupied river segment with those of other river segments historically inhabited by *N. s. pecosensis*. This provides guidance regarding ongoing conservation efforts, potential for river restoration and potential for reintroduction of *N. s. pecosensis*. It can also be applied more broadly, for conservation of all riverine minnows.

METHODS

Study area

Major development of the Pecos River climaxed by 1940 (Table I), but few Pecos River fish collections were made by that time (Platania, 1993; Hoagstrom, 2003), so the pre-development distribution of *N. s. pecosensis* is uncertain. It is known from the mainstem Pecos River between Santa Rosa Dam and Red Bluff Dam (Chernoff *et al*., 1982; Propst, 1999). Historically, habitat conditions were relatively similar (perennial flow, wide and sandy river channel) from the Gallinas River confluence in New Mexico to near the Live Oak Creek confluence in Texas (Newell, 1891; Taylor and Hoyt, 1906; Freeman and Mathers, 1911; USNRPB, 1942; Dearen, 1996). Hence, it is a reasonable assumption that *N. s. pecosensis* occupied this entire stretch of river, roughly 980 river-km in length.

N. s. pecosensis presently occupies the mainstem Pecos River between the Fort Sumner Irrigation District Diversion Dam and Brantley Reservoir, an undammed segment of roughly 334 km (Propst, 1999). The flow regime of this segment depends largely upon operations of the Fort Sumner Irrigation District Diversion Dam at the upstream edge of the occupied segment and Sumner Dam 26 km farther upstream. These two dams capture or divert all inflows. Under normal operations, only conveyance releases designed to transport irrigation storage from Sumner Reservoir to Brantley Reservoir pass over the Fort Sumner Irrigation District Dam (Boroughs and Abt, 2003). Base-flows are derived from within the occupied river segment and include Fort Sumner Irrigation District

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DOI: 10.1002/rra

Table I. Chronology of major dewatering events affecting the Pecos River within the historical distribution of *Notropis simus pecosensis*

Event	Year*	Segments affected
Northern (Hagerman) canal (Rio Hondo drainage)	1904	V-iii–IX
Upper basin diversions, downstream to Puerto de Luna	By 1910	I–IX
Avalon and McMillan dams	By 1911	VI–IX
Tributary and mainstem diversions in Texas	By 1914	IX
Balmorhea Dam (Toyah Creek drainage)	1916	IX
Storrie Dam (Gallinas River drainage)	1918	I–IX
Rios Hondo, Felix, and Peñasco diversions	By 1930	V-iii–IX
Roswell Artesian Basin overdraft	By 1931	V-iii–IX
Bonito Dam (Rio Hondo drainage)	1931	V-iii–IX
Carlsbad Valley and Black River diversions	By 1933	VII–IX
Fort Sumner Irrigation District Diversion Dam	By 1935	V-i–IX
Red Bluff Dam	1936	VIII–IX
Sumner Dam	1937	IV–IX
Toyah Basin overdraft	By 1960	IX
Santa Rosa Dam	1980	II–IX
Brantley Dam (replaced McMillan Dam)	1988	VI–IX

Year listings preceded with the word 'by' indicate many years of prior development, culminating by the given year. Segment numbers refer to Table II.
Sources: USNRPB (1942), Lingle and Linford (1961), Thomas *et al*. (1963), Hufstetler and Johnson (1993) and Byrd *et al*. (2002).

returns, groundwater inflows and sewage returns (Mower *et al*., 1964; Mourant and Shomaker, 1970; Shomaker, 1971). Base flow is locally variable depending on sources.

In addition to reservoir releases, ephemeral, uncontrolled tributaries deliver periodic floods that provide natural flood peaks and alluvial sediment inputs. Effects of tributaries are most evident between Taiban Creek and the Rio Hondo, where the river channel is relatively wide with a shifting sand substrate (USACE, 1999; Hoagstrom and Brooks, 2005; Hoagstrom *et al*., in press). The river channel upstream from Taiban Creek is sediment-starved and dominated by coarse substrates, whereas the river channel downstream from the Rio Hondo is narrow and canal-like (USACE, 1999).

N. s. pecosensis is inequitably distributed within the occupied river segment (Hoagstrom *et al*., in press). The core population is found between the confluences of the Pecos River with Taiban Creek and the Rio Hondo. The species is rare upstream of Taiban Creek and primarily displaced young-of-year are present downstream of the Rio Hondo.

Depth and velocity association and availability

We studied *N. s. pecosensis* depth and velocity association and depth and velocity availability at six sites (Figure 1) that represented the range of conditions available in the occupied segment. Site 1 (river-km 1084) was sediment-starved and dewatered by Sumner Dam and the Fort Sumner Irrigation District Diversion Dam. Site 2 (river-km 1038) had a shifting sand-bed and continuous base flow from irrigation return flows and groundwater inflows. Site 3 (river-km 997), a replacement for Site 2 after access to that site was denied, was relatively similar. Site 4 (river-km 958) had similar substrate to sites 2 and 3, but the river channel was narrower and base flow was less. Site 5 (river-km 918) was relatively similar to Site 4, except bridge abutments that were part of the site increased local channel width. Site 6 (river-km 872) had a very narrow river channel and a compacted, silt-sand substrate with high base flow from additional groundwater and sewage return inflows.

We collected fish with a 3.2 mm-mesh seine, 3.0 m long and 1.2 m deep, conducting between 13 and 29 seine hauls per visit (normally 20). We selected seine locations (mesohabitats) visually by observing substrate, bedform, vegetation, woody debris and hydraulics (Gee and Northcote, 1963; Vadas and Orth, 1998). Mesohabitats were defined as areas with relatively uniform depth and velocity (Jackson, 1975). We seined mesohabitats in proportion

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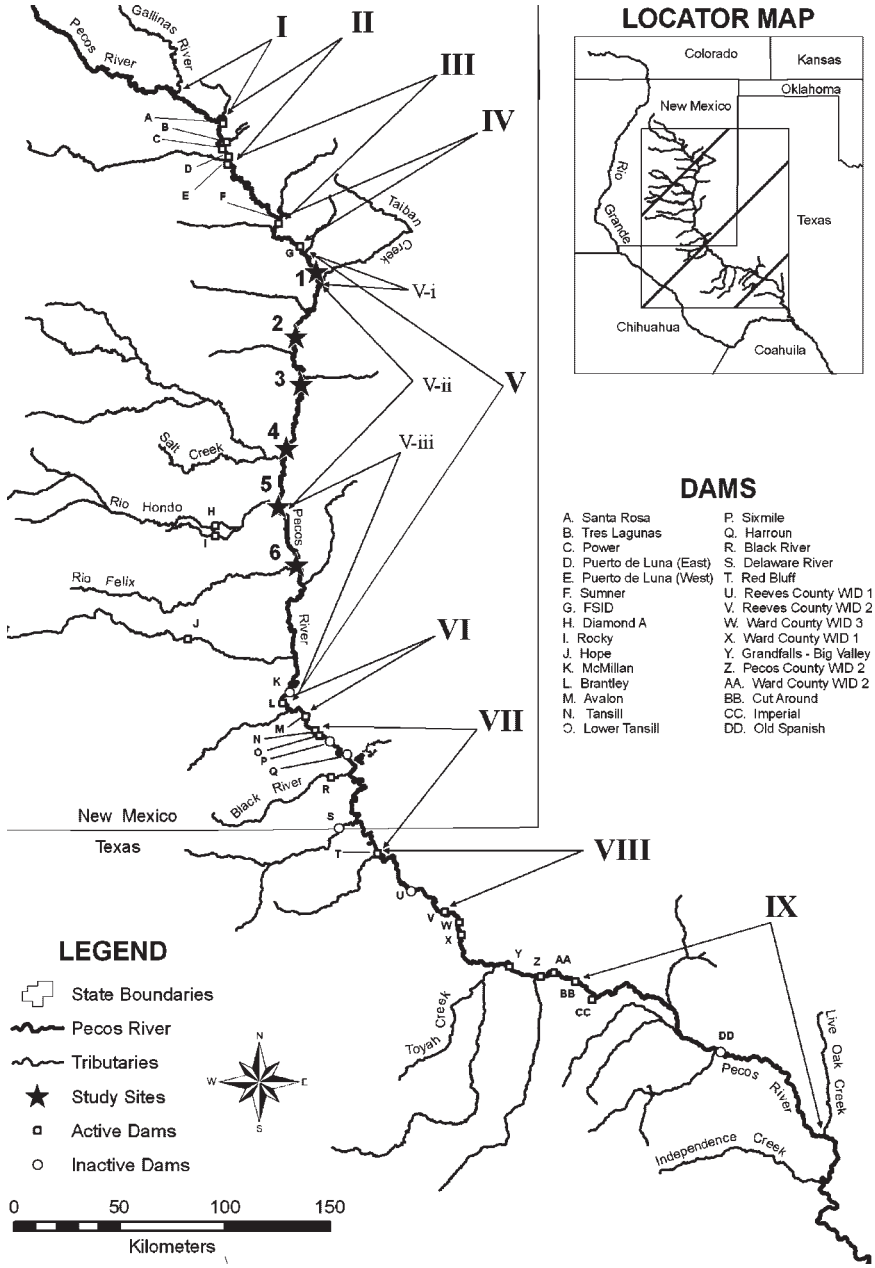

Figure 1. Map of Pecos River segments (Roman numerals) within the presumed historical range of *Notropis simus pecosensis*. Major, mainstem and tributary dams (squares and circles) and *N. s. pecosensis* habitat study sites (stars) are indicated. Tributary dams were B, C, E, H, I, J, R, S and CC. All other dams were on the mainstem Pecos River. Gaps between river segments represent river reaches that lack riverine characteristics because of impoundment and dewatering

to their abundance (Matthews, 1985; Taylor *et al*., 1996). Seine haul length and width varied with mesohabitat characteristics. We measured depth to the nearest cm and mean column velocity to the nearest cm s^{-1} at nine points, distributed evenly along three equally spaced transects (three points per transect) within the area of each seine haul (Gido and Propst, 1999). The same number of points was measured for every seine haul, regardless of mesohabitat dimensions so that each mesohabitat sample was represented equally in analyses.

We preserved fishes by seine haul in 10% formalin. Later, specimens were transferred to 70% ethanol, after which they were identified to species and measured to the nearest 0.01 mm standard length (SL) using an electronic

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caliper. All specimens were donated to the Museum of Southwestern Biology, Division of Fishes, University of New Mexico, Albuquerque.

Fish depth and velocity association commonly varies depending on body size, particularly within fluvial species (Lister and Genoe, 1970; Everest and Chapman, 1972; Mullen and Burton, 1995). We used seine haul point measurements independently for each individual collected to assess body size versus depth and velocity association. That is, each individual collected was associated with nine depth-velocity point measurements. We kept depth-velocity point measurements independent in analyses to retain the maximum amount of information available in the data. In other words, association of *N. s. pecosensis* with individual depth-velocity point measurements provided a finer scale of resolution than association with a mean of nine depth-velocity points would have.

We assessed the association of *N. s. pecosensis* SL with depth and velocity by comparing mean association by length group. Length groups were defined by calculating optimal category intervals (C; length groups) using the Sturges formula as follows:

$$C = R\left((1 + 3.322)\left(\log_{10}N\right)\right)^{-1}$$

where R = total length range and N = total number collected (Sturges, 1926). We used 95% confidence limits (Zar, 1999) as a descriptive tool to compare mean depth and velocity association among length groups to form length classes (i.e. a combination of length groups with similar depth and velocity association).

During all but three fish collection visits, we quantified discharge along 15 transects at each study site, spacing transects 30 m apart and measuring depth to the nearest cm and mean column velocity to the nearest cm s^{-1} at 2 m intervals. Spacing of transects and points was standardized to facilitate comparisons of depth and velocity availability among and within sites (Gorman and Karr, 1978; Freeman *et al*., 2001). We estimated discharge of each sampling visit as average discharge of the 15 transects (Irvine *et al*., 1987). We plotted mean wetted width with 95% confidence limits by discharge for each study site to illustrate the relation of wetted width to discharge. We defined the range of depths and velocities that was associated with each *N. s. pecosensis* length-class as the mean ± standard deviation and plotted the abundance of associated depth-velocity points by study site and discharge to assess variation in habitat availability.

Pecos river segment comparison

We compared contemporary abiotic features (length, average discharge, discharge flashiness, salinity and channel width) of Pecos River segments (delineated by dams) within the presumed historical range of *N. s. pecosensis* (Table II; Figure 1). To enhance comparisons, we divided the occupied segment (segment V) into three

Table II. Delineation of Pecos River segments that maintain substantial unimpounded habitat within the historical range of *Notropis simus pecosensis*

Segment	Upstream boundary	Downstream boundary	USGS gage
I	Gallinas River confluence	Santa Rosa Reservoir	08382650
II	Santa Rosa Dam	Puerto de Luna Dam East	08382830
III	Puerto de Luna Dam East	Sumner Reservoir	08383500
IV	Sumner Dam	FSID Dam*	08384500
V-i	FSID Dam*	Taiban Creek confluence	08385500
V-ii	Taiban Creek confluence	Rio Hondo confluence	08385630
V-iii	Rio Hondo confluence	Brantley Reservoir	08396500
VI	Brantley Dam	Avalon Reservoir	08401500
VII	Lower Tansill Dam	Red Bluff Reservoir	08405200
VIII	Red Bluff Dam	Reeves County WID 2 Dam*	08412500
IX	Cut Around Dam	Live Oak Creek confluence	08446500

Segments are listed in upstream to downstream order. The occupied segment (V) is subdivided for comparisons of distinct sub-segments. Gaging stations used to represent each river segment are listed by station number.
*FSID = Fort Sumner Irrigation District, WID = Water Improvement District.

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sub-segments (V-i, V-ii, V-iii), defined by major habitat differences that corresponded to differences in the distribution of *N. s. pecosensis* (Hoagstrom *et al*., in press). Segment V-ii supported the core population of *N. s. pecosensis*. All data on abiotic features, except for segment length, were taken from representative U.S. Geological Survey surface water gaging stations (Table II) available on the Internet (http://waterdata.usgs.gov/nwis/rt). Based on our field observations, stream conditions of these stations were characteristic of the segment they represented. We used data for water years (October through September) 1995 through 2003 because they were available for all stations, roughly corresponded to our study period, and represented a range of climatic conditions from drought to wet periods. Specific conductance measurements were not available for all gaging stations. We characterized river segment length in river-km based on published distances (USNRPB, 1942; Grozier *et al*., 1966; Byrd *et al*., 2002).

We used median discharge and the R-B Index to characterize the flow regimes of each segment. Median discharge represented average flow. The R-B Index represented discharge flashiness (Baker *et al*., 2004). It is a discharge oscillation to total discharge ratio that typically varies from 0.0 to 1.5, derived with the formula:

$$\text{R} - \text{B Index} = \left(\sum_{i=1}^{n} |q_i - q_{i-1}|\right)\left(\sum_{i=1}^{n} q_i\right)^{-1}$$

where q is mean daily discharge. Higher values indicate flashier flow regimes, that is, relatively low base-flow and a relatively high frequency of short-lived, high-discharge events (flash floods).

We conducted a Principle Components Analysis (PCA) on four of the abiotic features among Pecos River segments and sub-segments (Legendre and Legendre, 1998). We included median discharge, R-B Index values, segment length and the simple linear regression line slope of width versus discharge in the PCA. We were unable to include specific conductance because data were not available for all river segments. We considered principle components (PCs) to be nontrivial if empirical eigenvalues exceeded null eigenvalues calculated using the broken-stick model (Jackson, 1993).

RESULTS

We collected fishes on 93 occasions between February 1992 and November 1996 under a wide range of conditions (Table III). Collections were made during all seasons. Although discharge varied by date and site, flow was perennial during the entire study period. A total of 1840 seine hauls produced 947 *N. s. pecosensis*. The species was present in 293 (16%) of all seine hauls. Individuals ranged from 10.3 to 65.2 mm SL.

Depth-velocity association and distribution

The Sturges equation indicated that 5.0 mm SL groups were appropriate for analysis. A plot of mean velocity association by length group indicated five distinct velocity-association length classes, whereas mean depth association showed little correspondence to length group (Figure 2). Velocity association increased substantially by length class, but depth association did not (Table IV).

Table III. Number of data collections (visits) and the minimum, median and maximum discharge (Q) measured by study site

Site	Visits	Min. Q ($m^3 s^{-1}$)	Median Q ($m^3 s^{-1}$)	Max. Q ($m^3 s^{-1}$)
1	20	0.26	2.0	9.4
2	6	0.57	2.7	4.0
3	8	0.39	2.1	17.3
4	20	0.21	2.0	24.3
5	20	0.40	2.2	17.7
6	18	0.54	2.9	5.6

Discharge was determined as the average of 15 transects spaced 30 m apart. Depth and velocity measurements were spaced every 2 m along each transect

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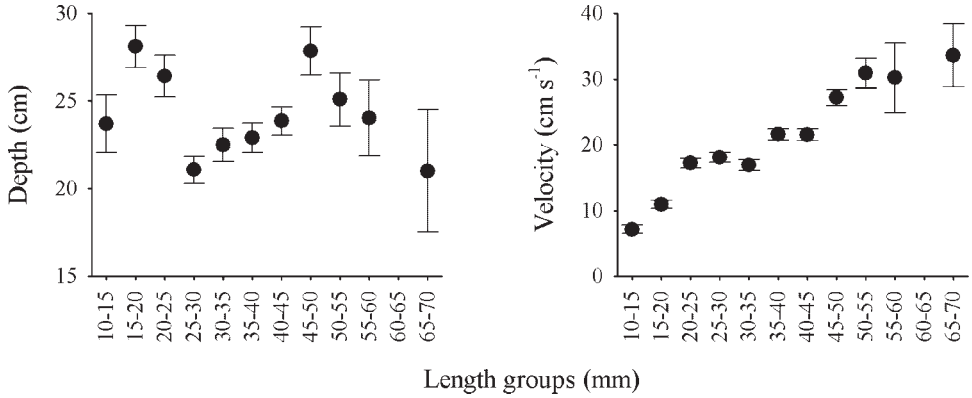

Figure 2. Mean depth and velocity association with 95% confidence intervals (error bars) for each *Notropis simus pecosensis* 5-mm length group

Wetted width increased with discharge at upstream study sites with wider channels, but remained relatively low at downstream sites with narrower channels (Figure 3). Abundance of depth-velocity points that were associated with *N. s. pecosensis* (henceforth, associated points) varied by length class, study site and discharge (Figure 4). Study sites with wider river channels and shifting-sand substrate (2 and 3) tended to have more associated points than other sites. Abundance of associated points was particularly low at study site 6, which had a very narrow channel and a silt-armored substrate. Abundance of associated points varied with discharge, particularly for length classes 4 and 5 (Figure 4). At wider study sites, associated points increased in abundance as discharge increased between 0 and 4 $m^3 s^{-1}$, but declined at higher discharge. At study site 6, abundance of associated points decreased at lower discharges, becoming rare for all length classes above 5 $m^3 s^{-1}$.

Pecos river segment comparison

Four PCs modelled 100% of the total variation in four abiotic features among Pecos River segments and sub-segments (Table V). However, the first and fourth PCs were trivial because broken-stick eigenvalues exceeded empirical eigenvalues. Sub-segment V-ii, which supports the core population of *N. s. pecosensis*, was distinguished from all other segments and sub-segments by PCs 2 and 3, which reflected the combination of high segment length, high width versus discharge and moderate but substantial median discharge (Figures 5 and 6). Sub-segment V-ii also had lowest specific conductance of all segments for which data were available (Figure 6).

DISCUSSION

Habitat association

Pecos River sub-segment V-ii, which supports the core population of *N. s. pecosensis* (Hatch *et al*., 1985; USFWS, 1992; Hoagstrom *et al*., in press), was distinguished by the combination of substantial median discharge,

Table IV. Number of individuals (*N*), mean standard length (SL), mean depth (Depth) and mean velocity (Velocity; all means are given ± the standard deviation) for *Notropis simus pecosensis* length classes (Class)

Class*	*N*	SL (mm)	Depth (cm)	Velocity (cm/s)
1	69	14 ± 1.0	24 ± 20.7	7 ± 7.9
2	161	17 ± 1.4	28 ± 23.2	11 ± 12.0
3	367	27 ± 4.3	23 ± 17.0	17 ± 13.0
4	258	40 ± 2.8	23 ± 14.2	22 ± 14.4
5	92	49 ± 3.6	27 ± 15.3	28 ± 15.5

*Length classes (standard length) are: 1 = 10–15 mm; 2 = 15–20 mm; 3 = 20–35 mm; 4 = 35–45 mm; 5 = 45–70 mm.

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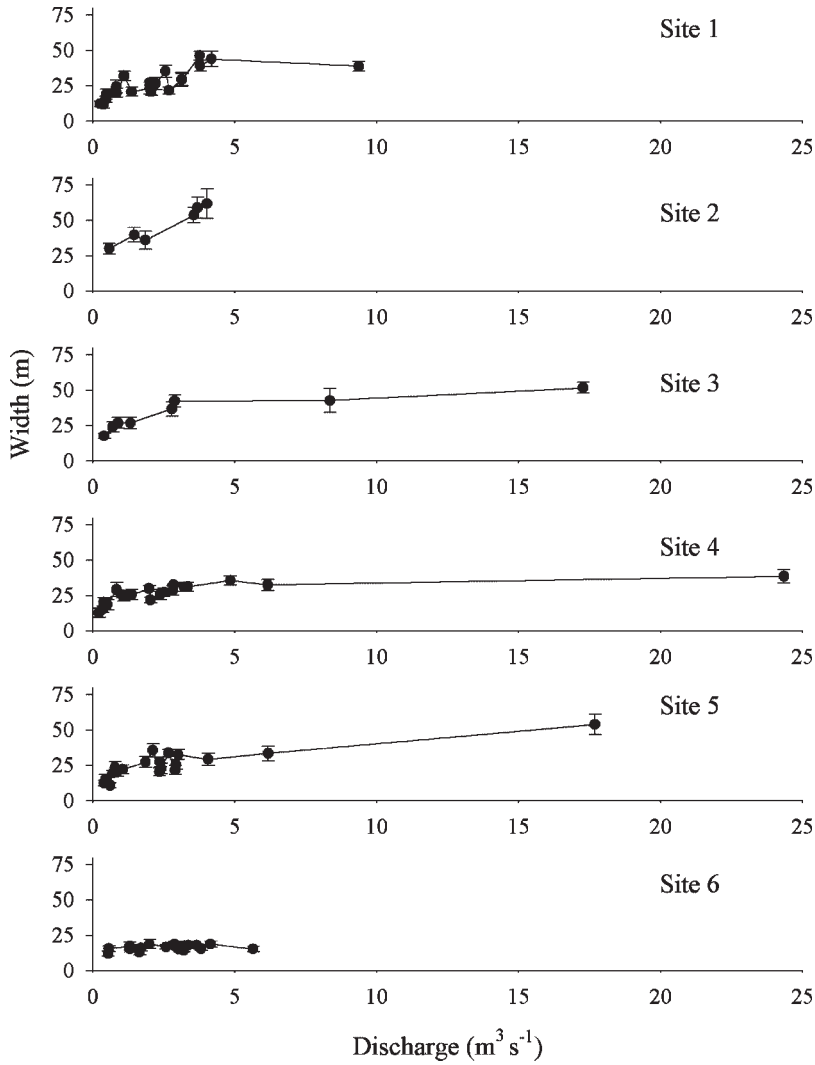

Figure 3. Mean Pecos River channel width with 95% confidence intervals (error bars) based on 15 evenly spaced transects (30 m) by discharge for each study site

high sub-segment length, a very high width to discharge relation and low salinity. Within segment V, sub-segment V-ii was distinguished by high relative abundance of depth-velocity points associated with *N. s. pecosensis*, which is a product of a wider river channel and a shifting-sand substrate.

Sub-segment V-ii has unique habitat conditions because it is buffered from the effects of dams. Segment IV and sub-segment V-i buffer the downstream effects of Sumner and Fort Sumner Irrigation District dams. Abundant, uncontrolled tributaries throughout sub-segment V-ii provide flash-flood inflows that include ample sediment (sand) inputs. Irrigation return flows and groundwater inflows sustain moderate base-flow. Sub-segment V-iii buffers the upstream effects of Brantley Dam. All of these factors facilitate a partial recovery of riverine habitat in sub-segment V-ii (*sensu* Kinsolving and Bain, 1993; Johnson, 2002; Phillips and Johnston, 2004), providing suitable conditions for *N. s. pecosensis*.

Geographical and historical factors also distinguish sub-segment V-ii. The river valley is relatively narrow and confined by bluffs (Newell, 1891). This helps maintain direct connections between the Pecos River and its tributaries, which facilitates the delivery of flood water and alluvial sediment. Also, the narrow river valley supports only a small amount of row-crop agriculture (USNRPB, 1942). In contrast, the Pecos River in sub-segment V-iii is

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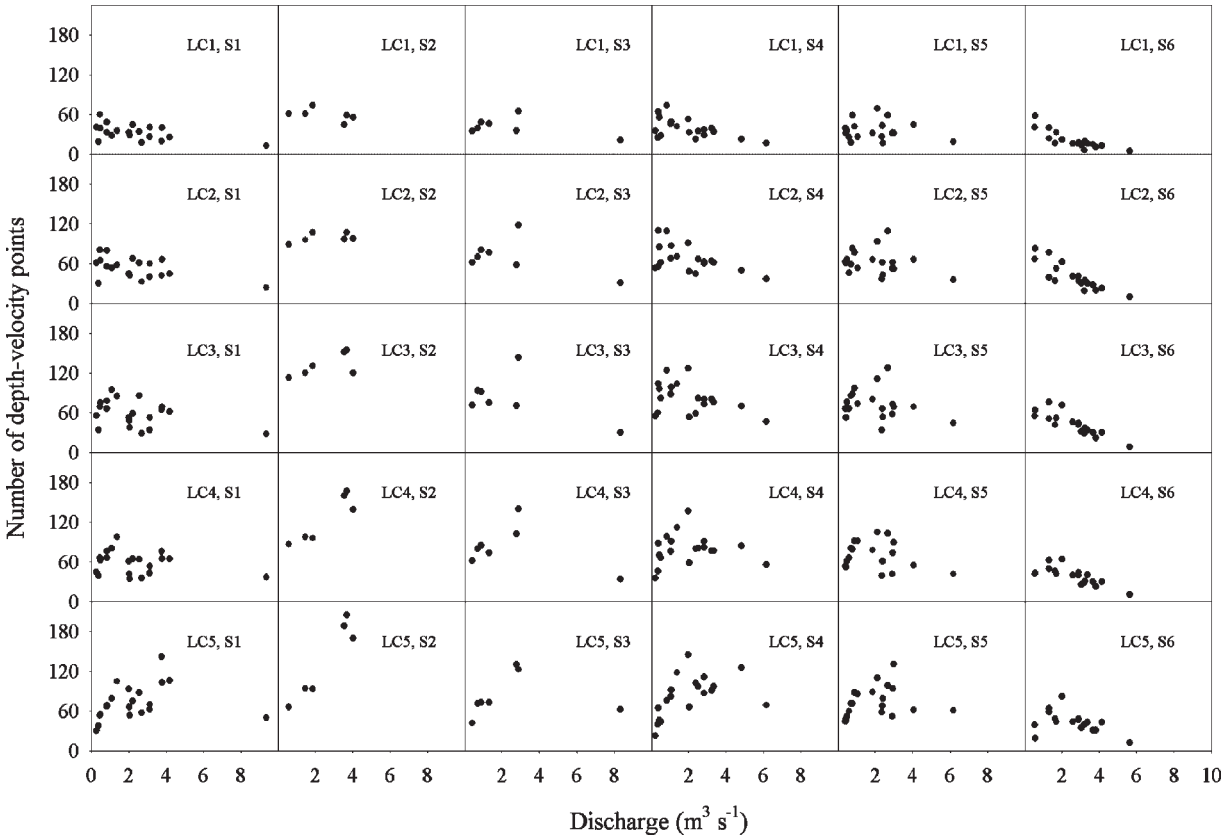

Figure 4. Abundance of depth-velocity points associated with each *Notropis simus pecosensis* length class (LC1 through LC5) by study site (S1 through S6) and discharge between 0 and $10\,m^3\,s^{-1}$. See Table IV for depth and velocity ranges that were associated with each length class

isolated from the majority of its tributaries and is confined by agriculture on both sides (USNRPB, 1942; Cox and Havens, 1974; USACE, 1999).

Sub-segment V-ii had a relatively flashy flow regime for such a large watershed (Baker *et al*., 2004). The range of discharge flashiness that is suitable for *N. s. pecosensis* is unstudied, but riverine fishes of the Great Plains tolerate relatively high levels of disturbance (Fausch and Bestgen, 1997). Exceedingly stable flow regimes may cause habitat loss and degradation (Cross and Moss, 1987; Bonner and Wilde, 2000) or create unsuitable conditions for

Table V. Eigenvalues, null eigenvalues based on the broken-stick model, explained proportion of variation, and eigenvector loadings for the principle components (PCs) based on four physical attributes of 11 Pecos River segments and sub-segments

Attribute	PC			
	1	2	3	4
Eigenvalue	1.55	1.12	0.97	0.37
Null eigenvalue	2.08	1.08	0.58	0.25
Proportion of variation	0.39	0.28	0.24	9.3
Median discharge	0.66	0.30	0.28	−0.63
R-B Index	−0.72	+	+	−0.68
Segment length	+	−0.82	−0.39	−0.38
Width/discharge slope	−	−0.47	0.87	+

Eigenvector loadings between −0.20 and 0.20 are expressed only as − or + to emphasize attributes with stronger relations to each PC.

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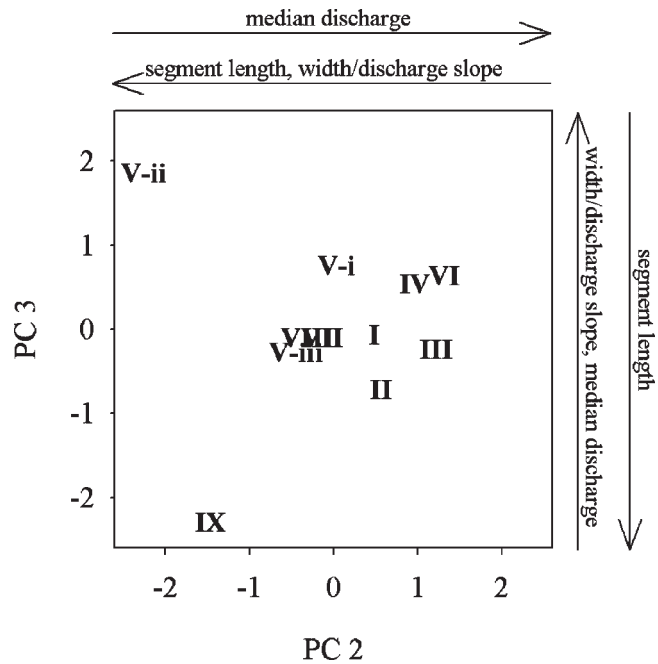

Figure 5. Scatter plot of the principle components 2 and 3 based on four features of the 11 Pecos River segments and sub-segments (Roman numerals). Labelled arrows indicate the direction of feature correlations with each principle component. Segments VII and VIII plot on top of each other

reproduction (Lehtinen and Layzer, 1988; Durham and Wilde, 2006). Hence, a relatively unstable flow regime could be important for *N. s. pecosensis*.

Habitat degradation is most extreme in short river segments and downstream river segments. Short segments are not buffered from direct dam effects and have little capacity to be rejuvenated by uncontrolled tributaries. Downstream segments (VI through IX) suffer from cumulative upstream water withdrawals, flood control and salinity increase along with local developments. Also, downstream segments were developed early in the history of the Pecos River (USNRPB, 1942; Lingle and Linford, 1961), so they had a longer time to suffer degradation.

The Pecos River downstream from segment IX is replenished by spring flows that elevate discharge and reduce salinity (Rhodes and Hubbs, 1992; Hoagstrom, 2003). This region is remote from the direct impacts of dams and row-crop agriculture (USNRPB, 1942; Lingle and Linford, 1961). However, it is indirectly affected by upstream developments. Pristine habitat conditions were never quantified, but contemporary conditions are more typical of a small, spring-fed river than a large, alluvial one (Rhodes and Hubbs, 1992; Hoagstrom, 2003). Based on historical accounts, this is a dramatic change (Dearen, 1996). It is uncertain whether *N. s. pecosensis* historically occupied this segment or could be repatriated there.

Nonnative species

We did not study effects of nonnative fishes on *N. s. pecosensis*. The Arkansas River shiner *Notropis girardi* was introduced to the Pecos River by 1978 (Bestgen *et al*., 1989). Although originally present in river segments V, VI and VII, it has persisted only in river segment V, where it is largely restricted to sub-segment V-ii (Hoagstrom and Brooks, 2005). Thus, *N. girardi* and *N. s. pecosensis* rely on the same sub-segment, where they have coexisted for over 28 years.

Like *N. s. pecosensis*, *N. girardi* is federally threatened (USFWS, 1998). Coexistence of two threatened riverine minnows (one native, one introduced) is the strong evidence that habitat conditions in sub-segment V-ii are superior for riverine minnow conservation. Further, Rio Grande speckled chub *Macrhybopsis aestivalis* and Rio Grande

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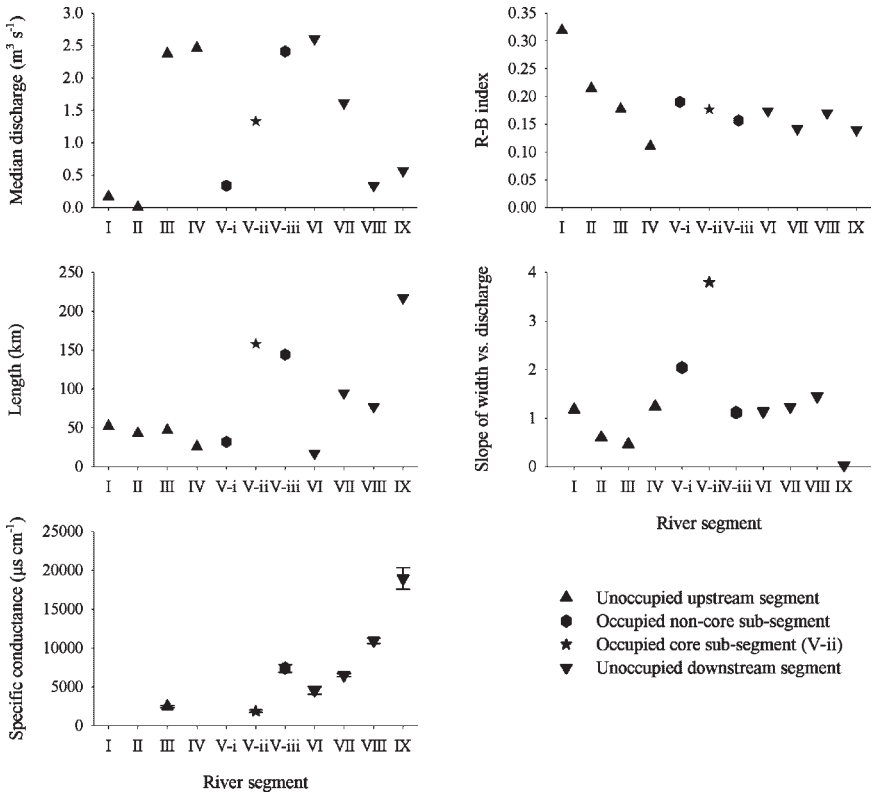

Figure 6. Abiotic characteristics of Pecos River segments within the historical range of *Notropis simus pecosensis* including average discharge (median), discharge flashiness (R-B Index), segment length (length), regression line slope of the width versus discharge relation (slope of width vs. discharge) and salinity (mean specific conductance with standard deviation)

shiner *Notropis jemezanus* (both riverine minnows) have declined from most of their native range (Propst *et al*., 1987; Platania, 1991; Contreras-Balderas *et al*., 2002; Edwards *et al*., 2002; Hoagstrom, 2003), but remain in sub-segment V-ii (Sublette *et al*., 1990; Hoagstrom and Brooks, 2005). Thus, sub-segment V-ii deserves the attention of conservationists and natural resource managers.

Riverine minnow conservation

Restoration of river segment connectivity is desirable for long-term conservation of riverine minnows (Dudley and Platania, 2007). However, there is no barrier between sub-segments V-i and V-ii, yet *N. girardi*, *N. jemezanus* and *N. s. pecosensis* are virtually absent from sub-segment V-i (Hoagstrom and Brooks, 2005; Hoagstrom *et al*., in press). Similarly, there is no barrier between sub-segments V-ii and V-iii, yet adult *N. girardi*, *N. jemezanus* and *N. s. pecosensis* are virtually absent from sub-segment V-iii, despite the periodic abundance of displaced young-of-year (Hoagstrom and Brooks, 2005; Hoagstrom *et al*., in press). Hence, river segment connectivity is not the only prerequisite for riverine minnow conservation. Degraded river segments will not support riverine minnows, whether they are connected to high-quality river segments or not. Thus, river channel degradation and streamflow intermittence are major conservation concerns. Based on our analyses, channel widening in sub-segment V-iii could expand the distribution of *N. s. pecosensis* downstream, whereas enhanced base flows and sediment supply in sub-segment V-i could expand the distribution upstream. These activities would also benefit sub-segment V-ii.

Although the Pecos River is replenished in sub-segment V-ii, perpetual replenishment cannot be guaranteed because upstream dams exert chronic influences that may cause long-term degradation (Ward *et al*., 1999). Maintaining the hydraulic and geomorphic contributions of uncontrolled tributaries will be critical, but additional

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conservation measures also merit consideration. River channel restoration may be necessary to maintain high channel width and adequate sediment supply. Variable channel width among study sites 2 through 5 indicates that conditions are not uniform in sub-segment V-ii. Surveys at study site 4 indicated that the river channel narrowed between 1992 and 1999 (unpublished work), but it is unknown whether this change occurred locally or throughout the entire sub-segment.

Base-flow enhancement may be necessary to sustain healthy riverine minnow populations. Habitat commonly associated with all *N. s. pecosensis* length classes was most abundant at intermediate discharge (i.e. 0.5–4.0 $m^3 s^{-1}$), indicating that flows within this range are beneficial. Although flows were perennial during our study, surface-flow intermittence may occur during dry periods (Mower *et al*., 1964; Hatch *et al*., 1985). When intermittence occurs, the abundance of *N. s. pecosensis* declines precipitously (Hoagstrom *et al*., in press). Such population bottlenecks threaten genetic diversity (Alò and Turner, 2005; Osborne *et al*., 2005; Turner *et al*., 2006) and extended periods of intermittence threaten the species (USFWS, 1987, 1992).

Riverine minnows of the Pecos River drainage require high-quality river segments. Only one such segment remains because of a unique set of geographical and historical conditions. However, developments elsewhere threaten to degrade this river segment. Conservation activities designed to benefit riverine minnows will also protect and restore this last high-quality riverine habitat of the drainage.

ACKNOWLEDGEMENTS

The U. S. Bureau of Reclamation, Albuquerque Area Office funded portions of this project under agreement number USFWS 14-16-0002-91-916. Administrative support was provided by many including Susan Maestas, James P. Wilber, Lori Robertson and Gary Dean. Field and laboratory work were assisted by many, including Nathan L. Allan, Jude R. Smith, David L. Propst, Robert D. Larson, Paul L. Tashjian, Brian K. Lang, Barry G. Wiley, Matthew R. Brown, Amber L. Hobbes, Jason E. Davis and Julie A. Jackson. Editorial comments were provided by Robert K. Dudley and Megan J. Osborne and two anonymous reviewers. Figure 1 was prepared by Heber Lefgren.

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DOI: 10.1002/rra