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Streamflow and Endangered Species Habitat in the Lower Isleta Reach of the Middle Rio Grande

By Ken D. Bovee, Terry J. Waddle, and J. Mark Spears

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
Volume		
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
Flow rate		
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

SI to Inch/Pound

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Area		
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
Volume		
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
Flow rate		
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
meter per second (m/s)	3.281	foot per second (ft/s)
centimeter per second (cm/s)	0.0328	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second per square kilometer [(m^3/s)/km^2]	91.49	cubic foot per second per square mile [(ft^3/s)/mi^2]
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F = (1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F–32)/1.8
Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).
Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84).
Elevation, as used in this report, refers to distance relative to the vertical datum.
NOTE TO USGS USERS: Use of hectare (ha) as an alternative name for square hectometer (hm^2) is restricted to the measurement of small land or water areas.

Abbreviations, Acronyms

Abbreviation or Acronym	Description
BIBD	Bernardo Interior Drain near Bernardo
BOR	Bureau of Reclamation
DU7	Drain Unit 7 Extension
GPS	Global Positioning System
LFC	Low Flow Channel (also known as Rio Grande Conveyance Channel at San Acacia)
LSJRD	Lower San Juan Riverside Drain
LWD	Large Woody Debris
MRGCD	Middle Rio Grande Conservancy District
NRCS	National Resources Conservation Service
Q	Discharge or Streamflow, in Cubic Feet per Second
Q_{AVS}	Discharge Available for Bernardo Siphon Diversion
Q_{RES}	Discharge Residual from Mass Balance
Q_{RGASAD}	Rio Grande Discharge Above San Acacia Dam
Q_{RGBSAD}	Rio Grande Discharge Below San Acacia Dam
Q_{RP}	Discharge at Rio Puerco Study Site
Q_{RS}	Discharge at Rio Salado Study Site
Q_{SD}	Discharge Demand at Bernardo Siphon
Q_{SDIV}	Discharge of Actual Bernardo Siphon Diversion
Q_{SEV}	Discharge at Sevilleta Study Site
Q_{SMCD}	Discharge to Socorro Main Canal Diversion
RGFB	Rio Grande Floodway near Bernardo
RGFSA	Rio Grande Floodway at San Acacia
RGHTS	Rio Grande Habitat Time Series
RPA	Reasonable and Prudent Alternative
RPB	Rio Puerco near Bernardo
RTK	Real-Time Kinematic
SFRD	San Francisco Riverside Drain
SFRDO	San Francisco Riverside Drain Outfall
SMCNSA	Socorro Main Canal North at San Acacia
TIN	Triangular Irregular Network
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator (coordinate projection)
YOY	Young of Year (also, juveniles)

Streamflow and Endangered Species Habitat in the Lower Isleta Reach of the Middle Rio Grande

By Ken D. Bovee,[1] Terry J. Waddle,[1] and J. Mark Spears,[2]

Abstract

San Acacia Dam is located in a reach of the Rio Grande that has been designated as critical habitat for two endangered species, the Rio Grande silvery minnow (*Hybognathus amarus*) and the southwestern willow flycatcher (*Empidonax traillii extimus*). Under present operations, the Rio Grande upstream from the dam is used to convey irrigation water to the Socorro main canal at San Acacia Dam. In order to increase operational flexibility and improve irrigation delivery efficiency, the “Bernardo Siphon” has been proposed to intercept up to 150 cubic feet per second from the Lower San Juan Riverside Drain on the east side of the Rio Grande and transport it under the river into a drainage canal on the west side. Irrigation deliveries to the Socorro main canal would be conveyed by way of the drainage canal rather than the Rio Grande. The objective of this study was to provide the Bureau of Reclamation (BOR) and other stakeholders with a tool to evaluate the effects of different operational modes of the Bernardo siphon on habitat for *H. amarus* and *E. t. extimus* in this section of river.

We used a two-dimensional hydraulic simulation model to simulate hydraulic conditions for a range of discharges at three study sites in the Rio Grande between the proposed siphon location and San Acacia Dam. Suitable habitat characteristics were defined for *H. amarus* by consensus of a panel of experts and for *E. t. extimus* on the basis of a study conducted in 2003 by BOR. Habitat suitability maps for each targeted life stage and simulated discharge were constructed using a Geographic Information System (ArcGIS) and the results compiled into tables relating discharge to areas of suitable habitat. A separate analysis was conducted to calculate an index of connectivity among habitat patches at low flows. A hydrologic model was constructed to synthesize flows, by reach, without the siphon, which was used as a baseline for comparison with similarly-synthesized discharges with the siphon under different operating rules. Results from the hydrologic time series were combined with the discharge–habitat relations to develop habitat time series models, statistics, and scoring metrics for comparisons of alternative rules of operation for the Bernardo siphon.

Suitable habitat for *H. amarus* was defined as areas having suitable hydraulic conditions alone and as areas having suitable hydraulics in association with large woody debris. Suitable hydraulic habitat for adults was maximized at discharges between 40 and 80 cubic feet per second, and declined rapidly at discharges larger than 150 cubic feet per second. When large woody debris was included in the definition of suitable habitat, discharges between 40 and 200 cubic feet per second provided maximum suitable habitat for adults. Juvenile hydraulic habitat was maximized at discharges between 20 and 80 cubic feet per second, and hydraulic habitat associated with large woody debris was largest at flows between 40 and 150 cubic feet per second. Nesting habitat area for *E. t. extimus* increased monotonically at discharges larger than 5 ft^3/s, but decreased rapidly below that flow.

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[2] Bureau of Reclamation, Denver Technical Center, Denver, Colo. 80225.

Introduction

San Acacia Dam is a low-head diversion structure located on the Rio Grande approximately 19 km (12 mi) upstream from the city of Socorro, N. Mex. (fig. 1). The diversion was constructed by the Middle Rio Grande Conservancy District (MRGCD) in 1934 and rehabilitated by the Bureau of Reclamation (BOR) in 1957 to deliver water for irrigation to farms in the Socorro area. Water is diverted to the Low Flow and Socorro Main canals by closing some or all of the 29 radial gates shown in figure 2. The capacity of the Socorro Main Canal is 265 ft^3/s, a flow volume that often exceeds the entire discharge of the Rio Grande at that point during summer months. As a result of the diversion, the streamflow downstream from San Acacia Dam can be greatly diminished during the irrigation season (March 1–October 31).

San Acacia Dam is located within a reach of the Rio Grande that has been designated as critical habitat for two endangered species, the Rio Grande silvery minnow (*Hybognathus amarus*, hereinafter *H. amarus*) and the southwestern willow flycatcher (*Empidonax traillii extimus,* hereinafter*, E. t. extimus*). The critical habitat designation in the Rio Grande for *H. amarus* (U.S. Fish and Wildlife Service, 2003a) extends from Cochiti Dam in Sandoval County, N.M. to a utility line crossing the Rio Grande, a permanent identified landmark in Socorro County, N. Mex. (fig. 1). Two issues relating San Acacia Dam to the well-being of these listed species include potential habitat losses and habitat fragmentation (U.S. Fish and Wildlife Service, 2007). In particular, the impetus for the present study originated with concern over fragmentation of habitat for *H. amarus*.

The Rio Grande silvery minnow is a pelagic spawner, producing semibuoyant, nonadhesive eggs that passively drift downstream while developing. Spawning by *H. amarus* is associated with snowmelt runoff during May or June and during precipitation-induced high-flow events throughout the summer. Recently hatched larval fish remain a part of the drift for approximately 3 days after hatching (Platania and Altenbach, 1998). The passive drifting of eggs and larvae exposes them to displacement downstream past San Acacia Dam or into the headworks of the Socorro Main Canal. Once displaced, the fish are effectively denied reentry into the Rio Grande upstream from the dam. Concerns over this issue led the U.S. Fish and Wildlife Service, in its 2003 Biological Opinion, to direct the Bureau of Reclamation (BOR) to restore connectivity between the reaches upstream and downstream from San Acacia Dam (U.S. Fish and Wildlife Service, 2003b).

The Biological Opinion presented numerous Reasonable and Prudent Alternatives (RPAs) to avoid the likelihood of jeopardizing the continued existence of *H. amarus*. These RPAs address issues of flow, habitat maintenance and restoration, captive propagation and augmentation, and water quality. Among the listed RPAs was a directive to complete fish passage at San Acacia Diversion Dam to allow upstream movement of *H. amarus* by 2008 (Tetra Tech EM Inc., 2004).

The Habitat Restoration Plan for the middle Rio Grande (Tetra Tech EM, Inc., 2004) outlined some recommended characteristics of the required fish passage structure for *H. amarus*, as determined by the 2003 swimming performance study conducted by Bestgen and others (2003):

1. Maximum velocities encountered by fish should not exceed 100 cm/s at 23ºC or 80 cm/s at 15ºC.
2. A mix of flow velocities should be present in the passage structure, provided by refuges, resting pools, or boundary layer velocities.
3. Maximum water velocities in shorter rock-channel passage structures should not exceed 100 cm/s or 75 cm/s in longer ones, provided that lower velocity boundary areas, boulder velocity breaks, channel margins, or resting pools are available.

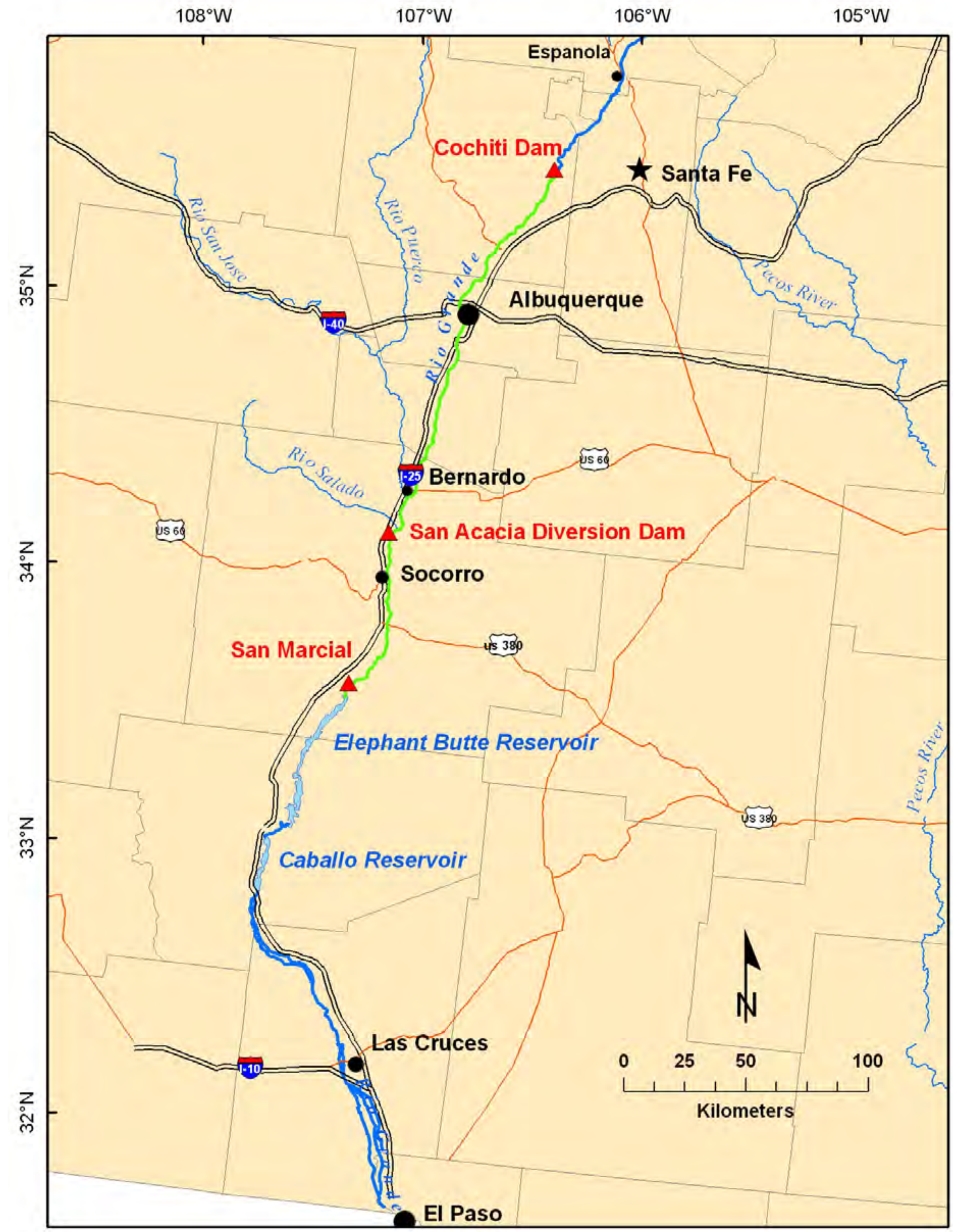


Figure 1. Map showing the New Mexico portion of the Rio Grande, the location of the San Acacia diversion dam, and the approximate extent of the critical habitat designation for *H. amarus* (in green).

Figure 2. San Acacia diversion dam and diversion headworks. Photograph by Paul Tashjian accessed from http://www.fws.gov/southwest/bhg/images/san1.htm, November 2007.

4. Larger, cobble-sized rock in the passage structure should be included to provide a more natural array of cover where resting fish could seek refuge.
5. Attraction flow velocity (at the outlet of the passage structure) should be somewhat faster than the water into which it flows. Attraction flows should be tranquil, not turbulent.

Although design specifications for a passage facility at the San Acacia Dam were not included in the Habitat Restoration Plan, meeting the criteria listed for the passage structure would likely depend on the physical structure itself and the amount of streamflow directed into it. Consequently, the efficiency of a fish passage facility at San Acacia Dam would be affected by the amount of streamflow in the Rio Grande immediately upstream from the dam and the amount diverted for irrigation. Conversely, the amount of water available for diversion could be affected by the mandated streamflow directed to the passage facility. The effect of either facility on the other would depend on the instream flow or diversion demand and how the flow allocation would be enforced.

Under present operations, the MRGCD uses the Rio Grande to convey irrigation water in the Bernardo and San Acacia areas. Depending on the season, a high percentage of this water can be lost to evaporation before being diverted from the river at the San Acacia Diversion Dam. Use of the river as a conveyance channel also constrains how MRGCD can operate the system for the benefit of its water users. In order to increase operational flexibility and improve irrigation delivery efficiency for the Socorro division, a project known locally as the “Bernardo Siphon” has been proposed (Charles Fisher, Bureau of Reclamation, written commun. February 2, 2008). Although the proposed fish passage facility and the Bernardo siphon are separate entities in terms of their purposes, they are linked in that flows diverted into the siphon would not be available for use in the fishway. Conversely, instream-flow requirements could affect the amount of water available for diversion into the siphon. Figure 3 illustrates the configuration of the San Acacia diversion and delivery system and is useful in describing changes associated with the proposed Bernardo siphon.

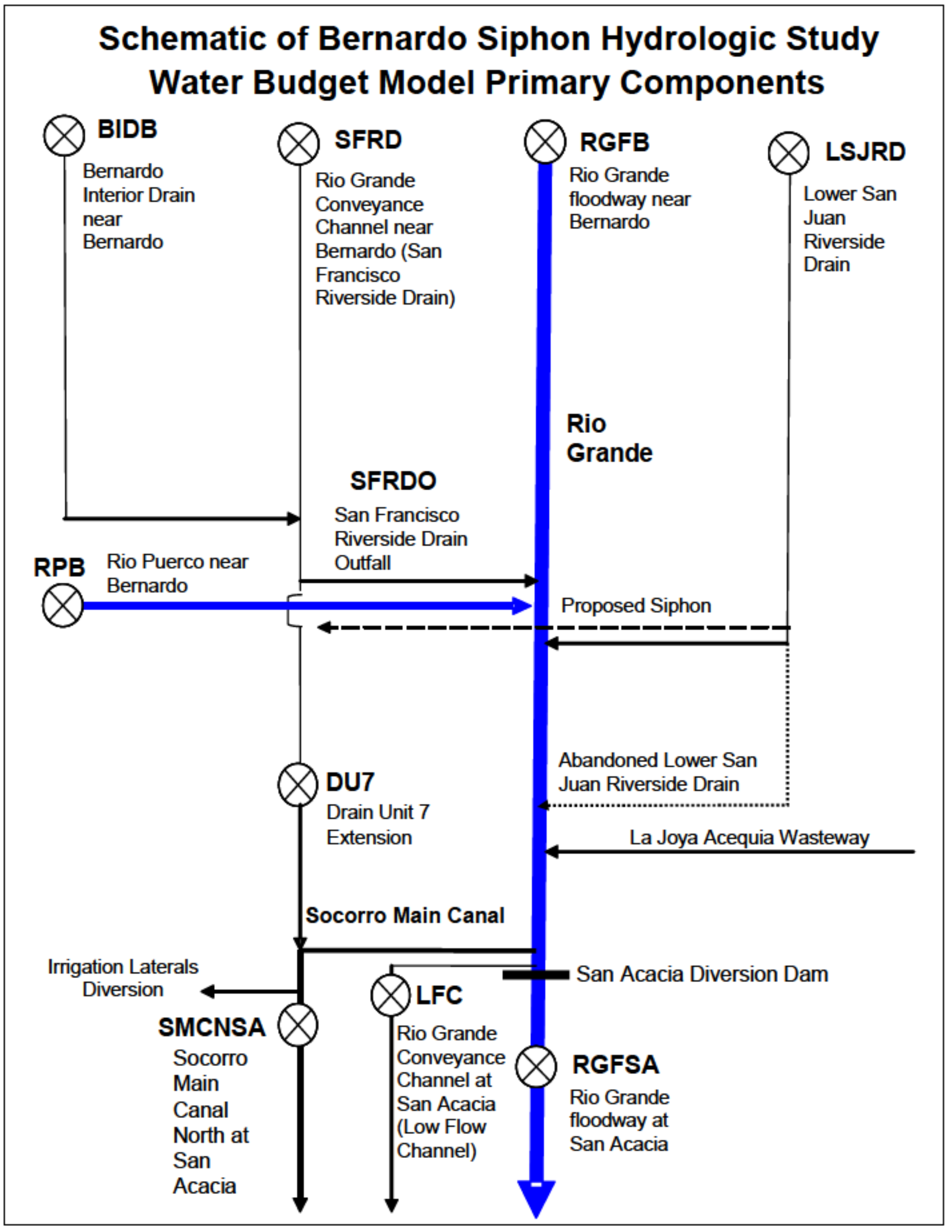


Figure 3. Schematic diagram of the San Acacia diversion and delivery system.

Drainage and return flows from the east side of the Rio Grande within the Belen Division of the MRGCD irrigation system are presently conveyed to the river at the Lower San Juan Riverside Drain (LSJRD in figure 3), located approximately 16 km (10 mi) upstream from the San Acacia diversion. Diversions to the Socorro main canal and Rio Grande conveyance channel (SMCNSA and LFC, respectively) occur at the San Acacia diversion dam. The Bernardo siphon would move Belen Division return flows, most of which had been previously diverted at Isleta Dam, from the east side of the river to the west side for reuse (Subhas K. Shah, Middle Rio Grande Conservancy District, written commun., February 8, 2008). In concept, the siphon would intercept up to approximately 150 ft^3/s of flow from the Lower San Juan Riverside Drain on the east side of the Rio Grande and transport it under the river into Drain Unit 7 on the west side (fig. 3). Drain Unit 7 would then serve as the conveyance channel to deliver water to the Socorro main canal at its current junction at the San Acacia diversion dam.

By redirecting flow from the Belen division from the Lower San Juan drain to the siphon, diversions at the San Acacia headworks could be reduced or eliminated. Remaining streamflow could be allowed to pass through one or more open gates in the diversion dam or diverted to the proposed fish passage structure. A potential drawback to the siphon proposal is that the Lower San Juan Riverside Drain is occasionally a major source of streamflow in the Rio Grande between the drain and San Acacia Dam. During the irrigation seasons of water years 1999–2004, for example, the average monthly contribution of the Lower San Juan drain to this reach of the Rio Grande ranged from 5 to 46 percent (fig. 4). In 2002 and 2003, the drain contributed over one-half the late summer flow in the Rio Grande on 24 and 17 days, respectively.

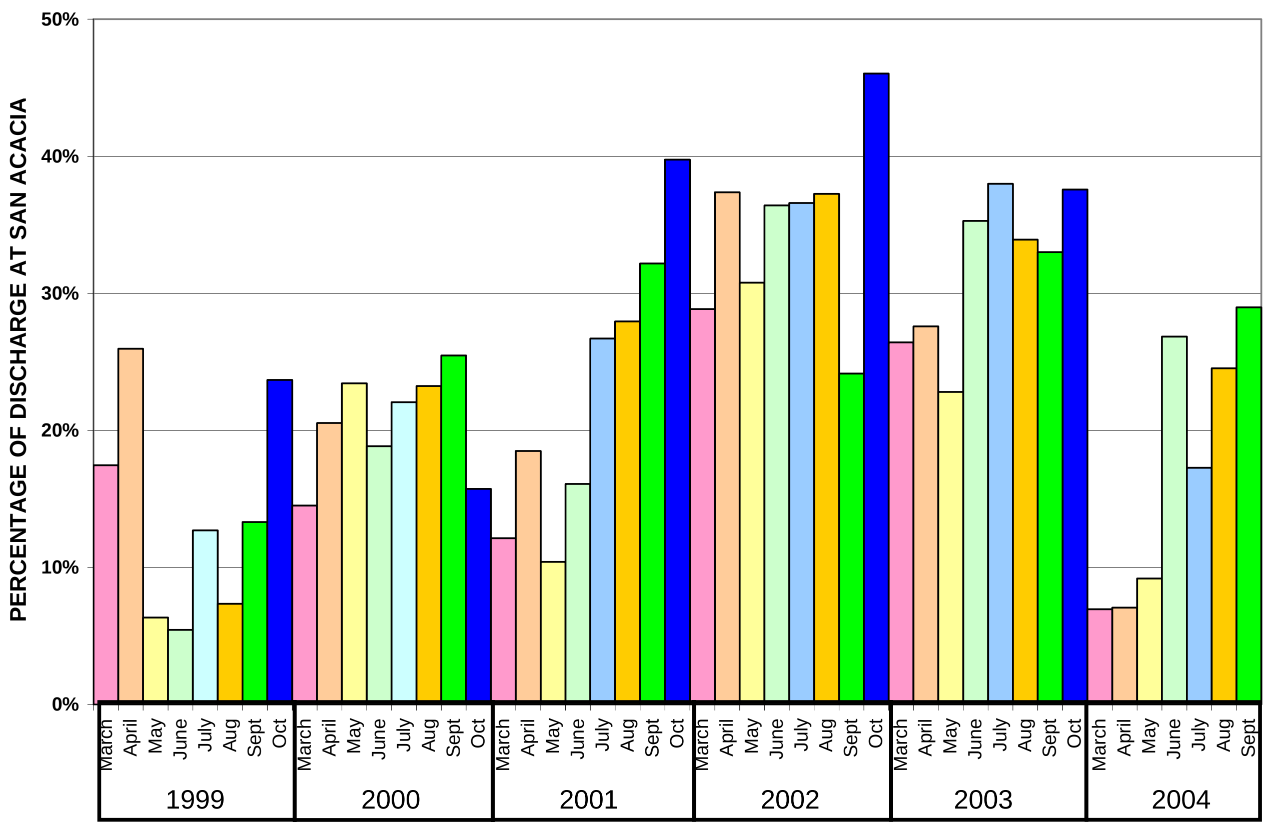


Figure 4. Contribution of the Lower San Juan Riverside Drain to the total Rio Grande streamflow measured at San Acacia Dam, 1999–2004.

Study Objectives

The goal of the present study was to provide information relating instream habitat characteristics and streamflow for the Rio Grande from Salas Arroyo/Lower San Juan Riverside Drain to San Acacia Dam. Specific objectives of the study were to quantify changes in low flow habitat features for *H. amarus* and *E. t. extimus* in this section of river. A secondary objective was to provide BOR and other stakeholders with a tool to evaluate the effects of different operational modes of the Bernardo siphon on habitats and irrigation deliveries.

Methods

Our methodology followed the steps illustrated in figure 5 and listed here. Each step is described in detail in subsections of this report as indicated by subject in brackets:

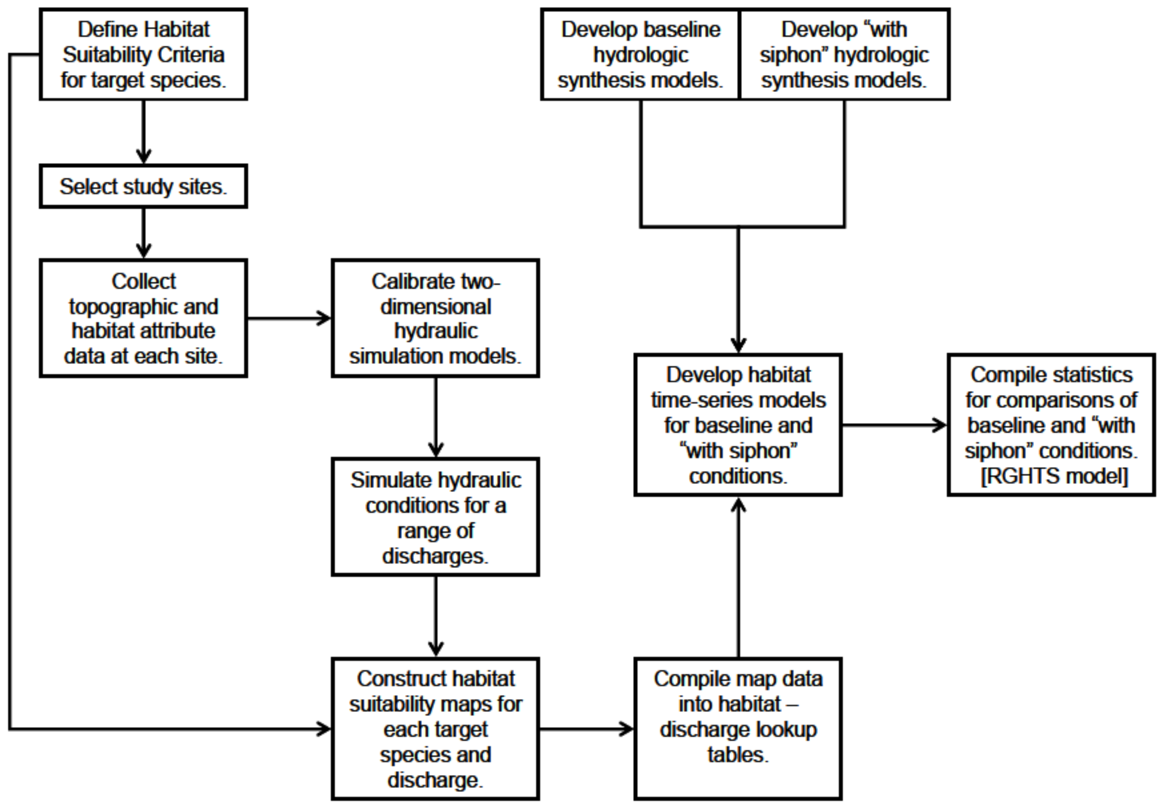


Figure 5. Flow chart of activities and procedures used to quantify effects on habitat for *H. amarus* and *E. t. extimus* associated with the proposed Bernardo siphon.

1. Define suitable habitat characteristics for targeted life stages of *H. amarus* and *E. t. extimus*.–[Habitat Classification].
2. Select study sites within the affected reach of the Rio Grande–[Study Sites].
3. Collect detailed topographic and attribute data at each site–[Data Collection].

4. Calibrate two-dimensional hydraulic simulation models and simulate hydraulic conditions for a range of discharges–[Hydraulic Modeling].
5. Construct habitat suitability maps for each targeted life stage and simulated discharge–[GIS Operations].
6. Develop hydrologic model(s) to synthesize flows, by reach, without siphon and with siphon under different operating rules–[Hydrologic Synthesis].
7. Develop time-series models to quantify the effects of different siphon operations on pertinent state variables–[Habitat Time Series].
8. Compile statistics and scoring metrics for comparisons of alternatives [RGHTS model].

Habitat Classification

Rio Grande Silvery Minnow

Descriptions of suitable habitat for *H. amarus* were summarized in the recovery plan (U.S. Fish and Wildlife Service, 2007), citing numerous unpublished sources. These reports indicated that *H. amarus* used only a small portion of the available wetted area of the river. In general, the species was most often found in areas of low or moderate water velocity (for example, eddies formed by debris piles, pools, and backwaters) and was rarely found in habitats with high water velocities, such as main channel runs, which are often deep and swift (U.S. Fish and Wildlife Service, 2007).

Young-of-year (YOY) were nearly exclusively associated with shallow areas having low or no water velocity and a fine particulate substrate (Pease and others, 2006). Such conditions were most common in secondary channels, main channel margins, backwaters, and around deposits of large woody debris. Adults demonstrated a shift from low- to moderate-velocity areas and used a broader spectrum of habitats, including main and side channel runs. Both life stages demonstrated an affinity for eddies formed by debris piles, particularly during winter (U.S. Fish and Wildlife Service, 2007).

Prior to the initiation of the field survey in June, 2007, a group of experts (table 1) was assembled to define the hydraulic and structural features characterizing suitable habitat for *H. amarus*. At this discussion, two targeted life stages were identified as juveniles (YOY) and adults. Spawning habitat was not included as a targeted life stage, by consensus of the group.

A review of the criteria developed at the June 2007 workshop revealed some inconsistencies with the criteria contained in the recovery plan. A second review was conducted during November, 2007 to reconcile the differences between these two sets of criteria and provide justification for deviations of the final criteria from those contained in the recovery plan. Table 2 summarizes the three criteria sets, with the justification for changes incorporated in the final criteria used in our habitat modeling efforts.

In addition to the depth and velocity criteria listed in table 2, structural criteria for large woody debris (brush piles and tree snags) were added as a habitat component. Woody debris was identified as an important structural component for *H. amarus* habitat in the recovery plan (U.S. Fish and Wildlife Service, 2007). Evidence presented in the recovery plan and reinforced by the technical advisory committee suggested that woody debris was used by *H. amarus* in all seasons but was a more significant habitat component during winter. Consequently, separate habitat simulations were performed using the hydraulic criteria alone and the hydraulic criteria in association with woody debris. It was further stipulated that suitable areas associated with debris piles should be within 0.5 m of the deposit for adults and 0.25 m for juveniles.

Table 1. Experts consulted for the development of habitat suitability criteria for the Rio Grande silvery minnow.

Name	Affiliation	Email address
Altenbach, Chris	City of Albuquerque	caltenbach@cabq.gov
Remshardt, Jason	U.S. Fish and Wildlife Service	Jason_Remshardt@fws.gov
Parody, Jennifer	U.S. Fish and Wildlife Service	Jennifer_Parody@fws.gov
Tashjian, Paul	U.S. Fish and Wildlife Service	Paul_Tashjian@fws.gov
Gensler, David	Middle Rio Grande Conservancy District	DGensler@mrgcd.com
Lundhal, Anders	New Mexico Interstate Stream Commission	Anders.Lundahl@state nm.us
Tave, Douglas	New Mexico Interstate Stream Commission	Douglas.Tave@state nm.us
Probst, David	New Mexico Department of Game and Fish	DPropst@state nm.us
Wilkinson, Peter	New Mexico Interstate Stream Commission	peter.wilkinson@state nm.us
Medley, Nic	New Mexico Interstate Stream Commission	nic medley@state nm.us
Floyd, Randy	New Mexico Department of Game and Fish	RFloyd@state nm.us
Hatch, Michael	SWCA Environmental Consultants	mhatch@swca.com
Porter, Michael	Bureau of Reclamation	MPorter@uc.usbr.gov
Dudley, Robert	University of New Mexico	dudleyrk@unm.edu
Platania, Steven	University of New Mexico	platania@unm.edu
Thompson, Brett	U.S. Army Corps of Engineers	brett.w.thompson@usace.army mil
Massong, Tamara	U.S. Army Corps of Engineers	tamara.m massong@usace.army mil
Caldwell, Colleen	New Mexico State University	ccaldwel@nmsu.edu
Haggerty, Grace	New Mexico Interstate Stream Commission	grace haggerty@state nm.us

Table 2. Summary of habitat suitability criteria for the Rio Grande silvery minnow, with justification for deviations from criteria in the U. S. Fish and Wildlife Service recovery plan (1999).

	Criteria source		
Criteria type	**Technical advisory group June 2007**	**Recovery plan 1999**	**Technical advisory group (final) November, 2007**
Adult depth range	• 10 cm, no upper limit	• 50 cm, no lower limit given	5 cm [a]–50 cm [b]
Juvenile depth range	• 5 cm, no upper limit	• 50 cm, no lower limit given	5 cm [a]–50 cm [b]
Adult velocity range	0–60 cm/s	0–40 cm/s	1 cm/s [c]–40 cm/s [d]
Juvenile velocity range	0–30 cm/s	0–40 cm/s	1 cm/s [c]–30 cm/s [e]

Justification for modifications:

[a] Minimum depth set at 5 cm for potential habitat use at shallower depths consistent with feeding biology .
[b] Maximum depth changed to 0.5 m for consistency with recovery plan.
[c] Minimum velocity set at 1 cm/s to differentiate flowing water from stagnant pools.
[d] Maximum velocity for adults reduced for consistency with recovery plan.
[e] Maximum velocity for juveniles reduced from recovery plan to reflect sustained swimming performance of post-larval fish.

Southwest Willow Flycatcher

The southwestern willow flycatcher probably resides in Mexico or Central America during the winter (Phillips, 1948; Beattie, 1995) but nests along the Rio Grande in late May to early June (Brown, 1988; U.S. Fish and Wildlife Service, 2002). Nesting habitat is described as thickets of patchy to dense riparian vegetation along streams or other wetlands, near or adjacent to surface water or underlain by saturated soil. Suitable vegetation includes trees and shrubs greater than 4 m in height, having dense foliage and a high percentage of canopy cover. A key feature that differentiates *E. t. extimus* from other subspecies of willow flycatchers is its affinity for nesting sites in close proximity to open water (Beattie, 1995; U.S. Fish and Wildlife Service, 2002). In many cases, *E. t. extimus* nest in vegetation that is rooted in or overhangs standing water. Occupied sites are typically located along slow-moving stream reaches, at river backwaters, in swampy abandoned channels, oxbows, and marshes, and at the margins of impounded water (for example, beaver ponds, inflows of streams into reservoirs). Where *E. t. extimus* occur along moving streams, those streams tend to be of relatively low gradient and slow moving with few riffles (U.S. Fish and Wildlife Service, 2002). Minimum patch size may be another constraint on suitability of *E. t. extimus* nesting areas as nesting rarely occurs in patches less than 0.1 ha in area (U.S. Fish and Wildlife Service, 2002).

In 2003, BOR completed a vegetation survey of the middle Rio Grande, including the Bernardo–San Acacia reach. The survey was based on a combination of photographic interpretation and field verification, resulting in a GIS-based map (a shapefile) of polygons larger than 0.1 ha containing suitable vegetation for nesting *E. t. extimus*. This shapefile served as our template for suitable vegetation criteria for this study (Darrell Ahlers, Bureau of Reclamation, Fisheries and Wildlife Resources Group, Denver, Colo., written commun. June 2007). In that same survey, researchers found 91 percent of *E. t. extimus* nests to be within 50 m of open water. An additional 3 percent of the nests were located within 100 m of open water. Based on this information, we stipulated a maximum usable distance from open water as 50 m from the active shorelines of the Rio Grande, including standing water in isolated pools, over a range of discharges from zero to 1,000 ft^3/s. Suitable nesting habitat was considered to contain all areas of suitable vegetation within this 50-m buffer.

Study Sites

Three study sites were selected within the 10-mile reach between the Lower San Juan Riverside Drain and San Acacia Dam (fig. 6). Site selection was based in part on representativeness and in part by accessibility. Two sites were located near the upstream and downstream boundaries of the study area and the third was located near the middle. Representativeness was addressed by adjusting the upstream and downstream boundaries of each reach in order to capture its overall characteristics in the vicinity of the site. The lengths of the sites varied from 1.2 to 1.58 km in length (fig. 6). The size of the sites was intentionally limited in order to increase data density and level of detail within the time constraints of the data-collection window (between the snowmelt recession and the onset of the monsoon season).

Data Collection

Modeling of habitat in a study site requires information about the hydraulic conditions prevailing in the site and the physical features used by target organisms. For the models used in this study, the site-specific data must be distributed in a spatially accurate manner. Three basic types of data are required: (1) topographic data describing the river channel; (2) data describing the conditions of flow, including the discharge, water-surface profile, and changes in water-surface elevation with changes in discharge; and (3) locations of inflow and outflow boundaries. This information provides the boundary conditions for simulating discharge and habitat in each study site.

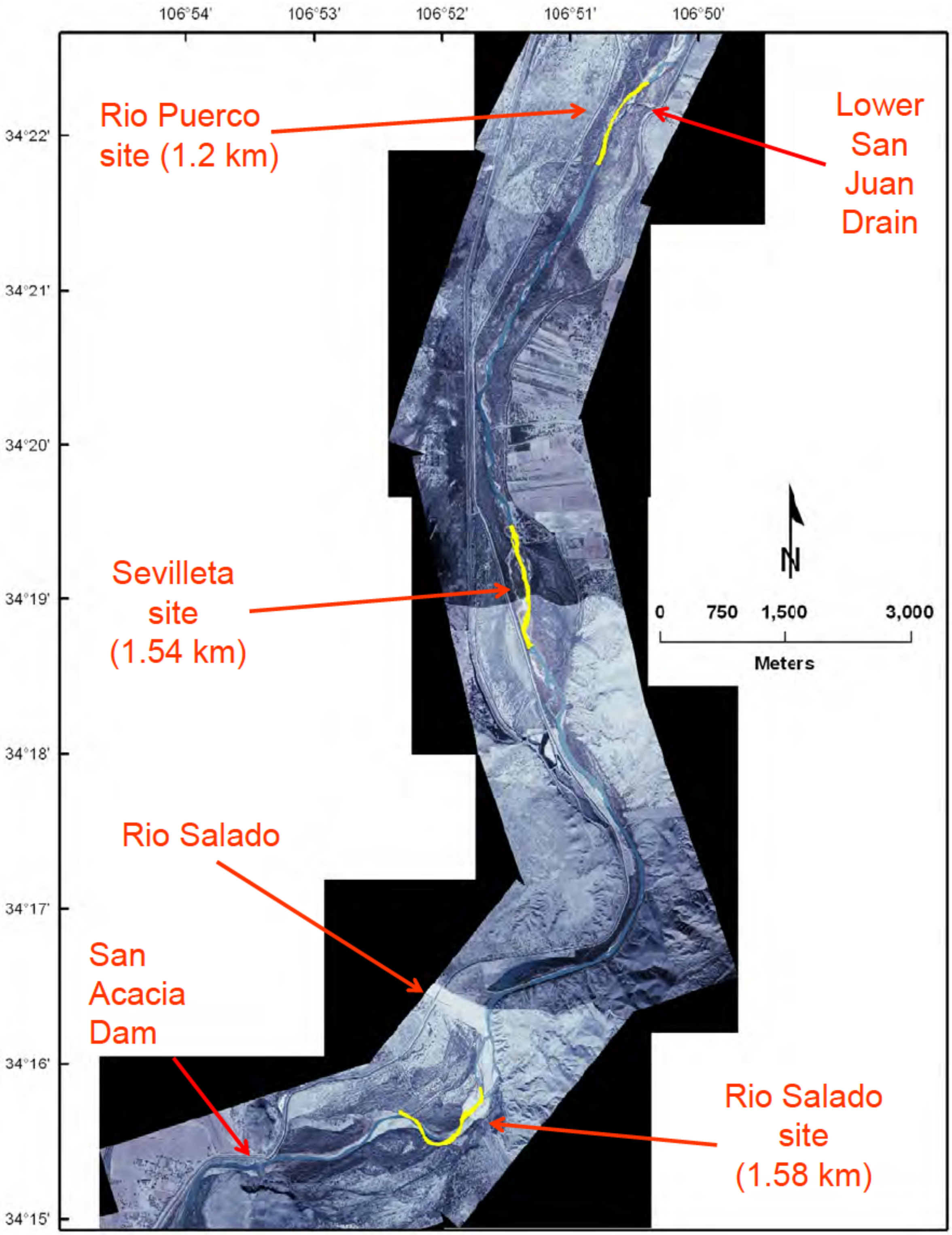


Figure 6. Aerial photograph mosaic of the lower Isleta study area, showing locations of study sites.

These data are typically collected using standard surveying and stream-gaging gear. In this application, spatial data were collected using a survey-grade global positioning system (GPS) and a total station. GPS equipment consisted of Trimble® 4800 and 5800 receivers using real-time kinematic positioning (RTK) and multipath reduction (Trimble Navigation, Ltd., *http://www.trimble.com*). Such survey-grade systems use carrier phase processing that enables centimeter accuracy. A Leica TC800 total station was used to collect spatial data in areas where the GPS equipment would not work due to overhead vegetation. All data were recorded in Universal Transverse Mercator (metric) coordinates, zone 13 N, using the WGS84 horizontal datum.

In August of 2006 we established survey control benchmarks for the three study areas by using the RTK GPS equipment. Survey control based on a BOR benchmark (RP1128a) located at UTM coordinates: 3800704.583N, 328760.556E, 1436.087 m above mean sea level. Benchmarks at each study site consisted of 1.52-m (5-ft) lengths of 3.8-cm (1.5-inch) galvanized pipe driven flush to the ground where practical or driven until an impenetrable object was contacted. Both a primary and backup benchmark were established in the flood plain or on the levee near each study site. These bench marks were marked with a reference point X and labeled BR1 through BR 6 by using a cold chisel to mark galvanized caps screwed to the top of each pipe. Subsequent site surveys were conducted originating from these benchmarks.

Change in water-surface elevation due to change in discharge is usually determined from empirical measurements obtained at the study site. The U.S. Geological Survey New Mexico Water Science Center measured discharge and water-surface elevation at the three study sites over a range of flow during spring of 2007 and provided rating tables for each site (Appendix 1). We also measured discharge and water-surface elevation at each study site at the same time we measured the water-surface profile. We fit a power function to these data to enable extrapolation to an unmeasured range of discharges that were needed for the objectives of this study. The range of extrapolation lies considerably beyond the range of the available data as shown in figure 7. Though it is recognized that the accuracy of the extrapolated values diminishes the farther away the extrapolation proceeds from observed values, time and resource constraints of the project dictated using the extrapolated values. The simulated flow range was $0.142 < Q < 28.317$ m^3/s ($5 < Q < 1{,}000$ ft^3/s). The black line in figure 7 illustrates the range of the rating curve provided by the New Mexico Water Science Center. Extrapolated points were based on the equation shown in the figure, where y = Elevation and x = Discharge. The specific discharges and corresponding control section offset water-surface elevations are contained in Appendix 2.

Topographic data were collected using a combination of transects and feature-following breaklines. Transects were placed at approximate 15-m intervals measured by pacing. This interval typically produced five to six transects per channel width. Certain features such as gravel bars, dominant sandbars and spits, islands, and side channels were measured following features such as top or toe of the bank, channel thalweg, edge of the bar, or other topographic breaks that would influence flow characteristics. Inlets and outlets of subsidiary channels also were measured along transects.

The objectives of this study focused on describing habitat for low-flow conditions. Thus, we attempted to measure the channel at the lowest discharge that could be obtained after the snowmelt recession and before the summer monsoon season. Measurements at the three sites were conducted at flows ranging from 5.19 m^3/s (183 ft^3/s) to 9.13 m^3/s (322 ft^3/s).

The data-collection period was selected to afford the greatest chance of measuring water-surface profile and discharge during steady low-flow conditions. We noted changes in elevation of the water surface at the reference posts installed by the New Mexico Water Science Center during these measurements. Steady flow conditions prevailed during measurements of the water-surface profiles and discharges at the Sevilleta and Rio Salado study sites. At the Rio Puerco study site, however, receding discharge from the Rio Puerco resulted in a falling water-surface elevation during the period of measurement. We adjusted our water-surface profile measurements to accommodate the unsteady flow

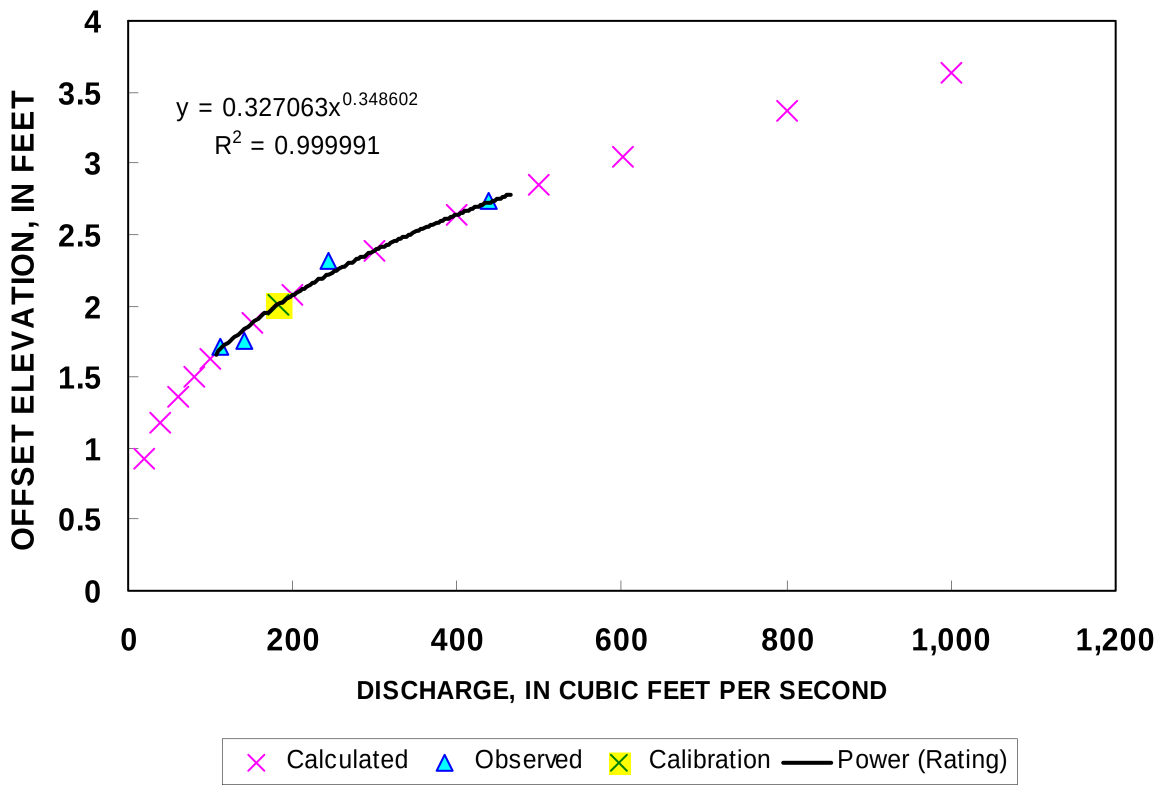


Figure 7. Stage–discharge relation for the Rio Salado site.

at this site by calculating the rate of change in stage that occurred while the water-surface profile measurements were made and prorating the rate to the time at which each measurement was made.

Study-site logistics dictated use of the GPS equipment to measure the water-surface profile. The vertical component of GPS measurements is known to exhibit the greatest measurement error. To reduce the influence of this error, each water-surface profile measurement was repeated three to five times, and the resulting elevations were averaged in an attempt to reduce the effects of random vertical measurement error.

The habitat criteria developed for *H. amarus* included descriptions of woody debris in the form of brush accumulations and large objects such as tree trunks. The spatial survey incorporated these items by measuring a series of points around each brush pile or large woody object. Figure 8 exemplifies the density of the surveyed topographic data.

The topographic data for each site were obtained with three GPS rovers and the total station. Data from the four sources were combined to produce one digital elevation model for each study site. At the end of each field day, data from all rovers and the total station were combined into one file and inspected for areas of missing coverage. Any missing areas were filled in the next day while en route to the unfinished portion of the study site.

Hydraulic Modeling

The River2D model (Ghanem and others, 1996; Steffler and Blackburn, 2002) was used to perform all the hydraulic simulations in this study. According to the authors of River2D (University of

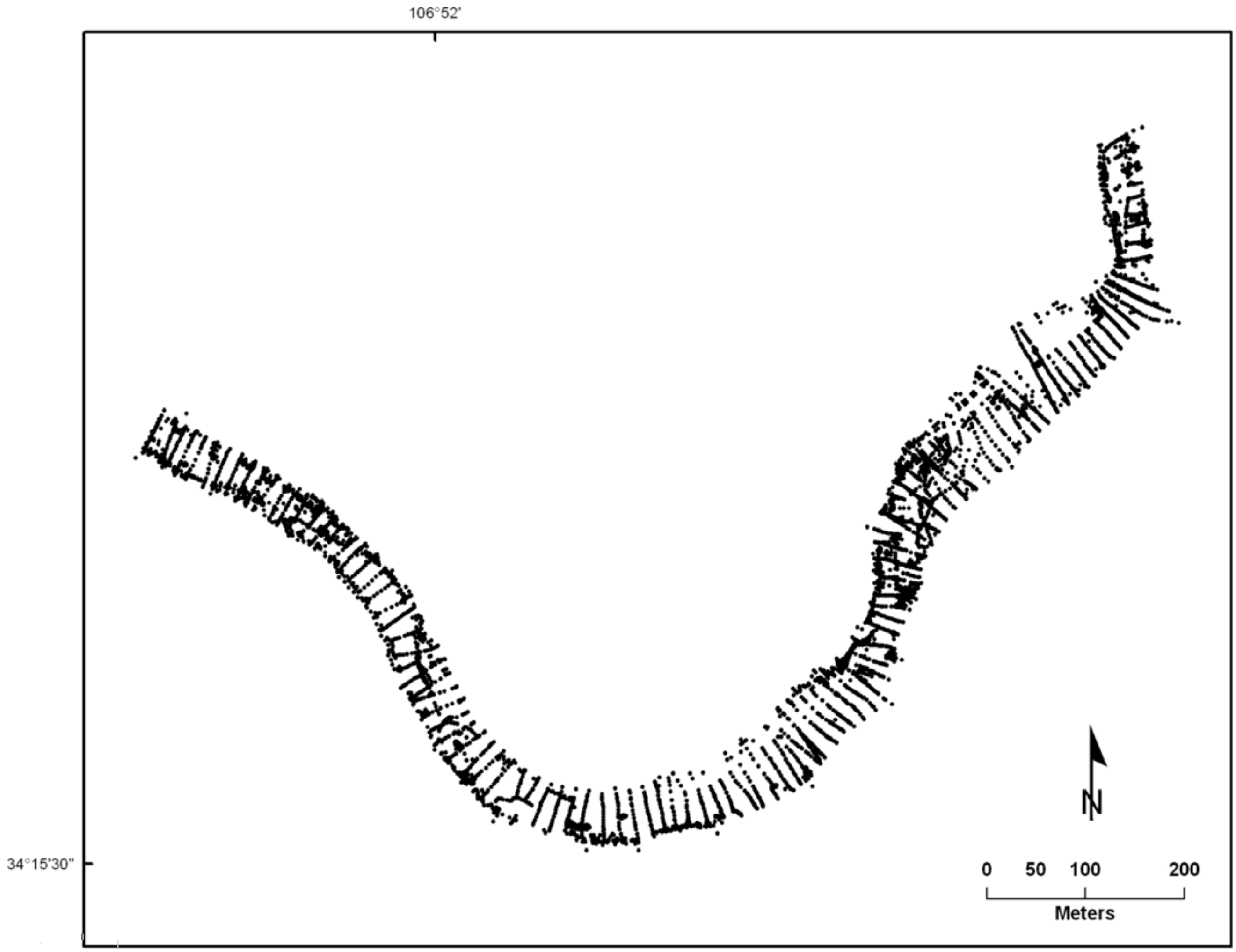


Figure 8. Data density obtained at the Rio Salado study site.

Alberta, 2006), “Accurate representation of the physical features of the river channel bed is probably the most crucial factor in successful river flow modeling. In addition to accurate and extensive field data, judgment and experience are necessary to connect the scattered data points into a digital surface representation.” One of the components of the River2D suite of programs is a bed-topography editor, capable of rapid triangulation and contouring of point data (Steffler, 2002).

Elevation contours were generated from the topographic database using a linearly interpolated triangulated irregular network (TIN) process. Operating solely on the raw data, this algorithm can produce unrealistic contours in some locations. For example, two points high on a bank may connect with a point in midchannel when, in fact, there is an intervening toe of the bank slope that is masked by the initial TIN. A major task when refining the raw topographic data is to visually inspect the entire study area to identify unrealistic contours. The contours are refined by connecting known points (such as adjacent toe of bank points) with breaklines that force the TIN to follow more realistic contours. It is useful to overlay the observed data on an aerial photograph and use the photograph as a guide to the areas with erroneous contours. This process was completed for each study site and resulted in three final bed files that represented the best description of the study areas that could be derived from the collected data.

Boundary condition information included the computational boundary used to limit the extent of the flow simulations, inflow discharge, and outflow water-surface elevation. These data were added to the bed files before their use in the River2D model. The final bed files were used as the starting point for building a computational mesh used by the flow model.

The River2D model (Steffler and Blackburn, 2002) uses the finite-element method to perform numerical calculation of flow conditions. This method allows an irregular computational mesh that enables areas of biological significance to be represented in greater detail than needed for representing flow characteristics alone. The computational mesh can be thought of as an overlay on the enhanced bed file that applies additional criteria regarding mesh configuration.

Mesh configuration criteria include capture of essential bed contour characteristics, gradual change in size of mesh elements, adequate mesh density to capture flow phenomena, and adequate density of inflow and outflow boundary nodes. A number of tools are provided in the R2D_Mesh program (Waddle and Steffler, 2002) to aid in building a mesh that satisfies these criteria. The constructed computational mesh and enhanced bed files constituted the input data required by the River2D model.

The River2D model uses the finite-element method to solve the "shallow water" equations. The following description of River2D is adapted from Steffler and Blackburn (2002).

Basic Governing Equations

The basic equations of two-dimensional models describe mass and momentum conservation in two dimensions. In River 2D, the differential equation of mass continuity is represented as,

$$\frac{\partial H}{\partial t}+\frac{\partial (HU)}{\partial x}+\frac{\partial (HV)}{\partial y}=0 \tag{1}$$

where H is the depth of water, U and V are the velocity components in the x and y directions respectively, and t is time.

The conservation of x momentum equation is represented as

$$\begin{aligned}&\frac{\partial q_x}{\partial t}+\frac{\partial}{\partial x}(Uq_x)+\frac{\partial}{\partial y}(Vq_x)+\frac{g}{2}\frac{\partial}{\partial x}H^2\\&=gH(S_{0x}-S_{fx})+\frac{1}{\rho}\left(\frac{\partial}{\partial x}(H\tau_{xx})\right)+\frac{1}{\rho}\left(\frac{\partial}{\partial y}(H\tau_{xy})\right)\end{aligned} \tag{2}$$

where: S_{0x} = bed slope in the x direction, $S_{fx} = \tau_{bx}/(\rho gH)$ is the friction slope in x, τ_{bx} is the bed shear in x, ρ is density, and g is the gravitational constant. A similar equation describes the y component of momentum

$$\begin{aligned}&\frac{\partial q_y}{\partial t}+\frac{\partial}{\partial x}(Uq_y)+\frac{\partial}{\partial y}(Vq_y)+\frac{g}{2}\frac{\partial}{\partial x}H^2\\&=gH(S_{0y}-S_{fy})+\frac{1}{\rho}\left(\frac{\partial}{\partial x}(H\tau_{yx})\right)+\frac{1}{\rho}\left(\frac{\partial}{\partial y}(H\tau_{yy})\right)\end{aligned} \tag{3}$$

Relations for the bed and side shear stresses must be specified. "Since these stresses arise primarily from turbulent flow interactions, there is considerable uncertainty in their evaluation." Typically, a two-dimensional form of Manning's equation is used for the friction slope,

$$S_{fx}=\frac{n^2U\sqrt{U^2+V^2}}{H^{4/3}} \tag{4}$$

and a Boussinesq type eddy viscosity is used for the transverse shear,

$$\tau_{xy} = \nu_t \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \tag{5}$$

The parameters n and ν_t are not constants or fluid properties, but depend on the flow situation. As a result, they become the "tuning" or calibration parameters that may be changed to bring a model prediction into agreement with measured data" (Steffler and Blackburn, 2002). Note: ν_t is commonly called the eddy viscosity and n is usually referred to as "Manning's n."

Model Calibration

Once the bed file and boundary condition preparation steps have been completed, the River2D model is run to a steady-state solution. Calibration of the model consists of adjusting model parameters until a reasonable match is obtained between the simulated and observed water-surface elevation profile measured at the calibration discharge. The water-surface profile produced by the model is compared with the observed water-surface profile and differences noted. Adjustments are made to the roughness assigned to each point in the bed file and the model is rerun until there is good agreement between the observed and the simulated water-surface profiles. An example of observed and simulated water-surface profile is shown in figure 9. Rather than attempting to achieve an exact match, the preferred solution is to adjust the simulated water-surface profile to produce a "best fit" that threads with minimum error among the observed water-surface profile points. The maximum deviation between calibrated and observed water-surface elevation at this study site was approximately 2 cm. This value is within the known vertical working accuracy (±2 cm) of our survey-grade GPS equipment.

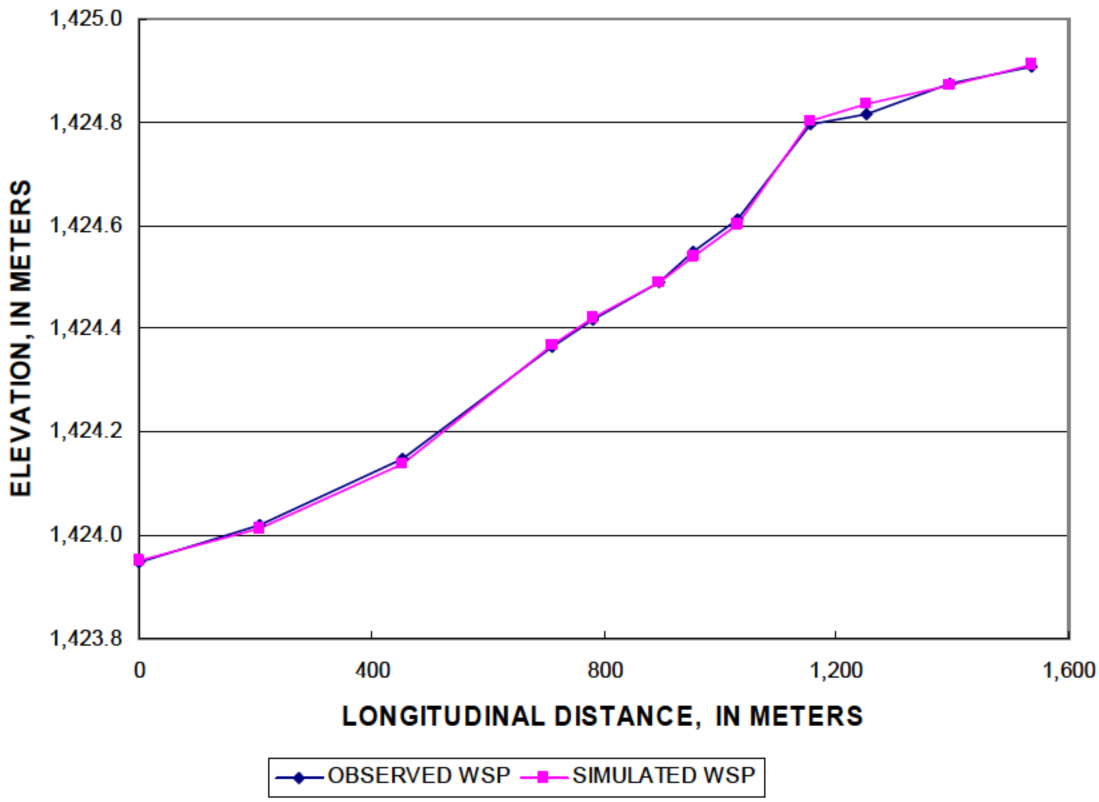


Figure 9. Water-surface profile (WSP) calibration for the Rio Salado study site.

Steady-flow conditions prevailed during measurement of water-surface profile and discharge at the Sevilleta and Rio Salado sites. The falling hydrograph that occurred during measurement of the Rio Puerco site profile and discharge necessitated adjustment of the observed water-surface profile values to approximate a steady condition. In addition, the discharge from the Rio Puerco that occurred from the evening of July 5 through July 6, 2007, deposited sediment in the Rio Grande floodway channel near the upstream end of the Rio Puerco site. This additional sediment resulted in an accretion to the channel that was not captured in our original topographic survey. The measured water-surface elevations upstream from the confluence with the Rio Puerco were likely elevated by a like amount. As a result, the simulated water-surface elevations upstream from Rio Puerco were approximately 6 cm lower than the measured elevations. The simulated profile otherwise matched the observed data within 3 cm or less, indicating that the simulation was probably correct for the surveyed topography. We assumed, however, that the streambed accretion near the Rio Puerco was a temporary anomaly and that with little or no inflow from the Rio Puerco, the channel in the Rio Grande would return to approximately the pre-storm topography we measured. Calibration values and error statistics are contained in Appendix 3. Once calibrated at each study site, the River2D model was run for 15 discharges at each site, ranging from a low flow of 5 ft^3/s to a maximum of 1,000 ft^3/s.

GIS Operations

Rio Grande Silvery Minnow

The sequence of habitat simulations for *H. amarus* followed three parallel tracks as illustrated in figure 10. The first sequence, illustrated by the tan boxes in figure 10, involved the development of maps of suitable hydraulic features for adult and juvenile fish. The second sequence, indicated by the light green boxes, was the definition of large woody debris (LWD) deposits and overlaying the LWD maps with those for hydraulic habitat. The third sequence, shown in yellow boxes, analyzed the relationship between discharge and patch-to-patch connectivity to address the issue of micro-scale habitat fragmentation at very low flows. Each series culminated in the construction of lookup tables containing the range of simulated discharges and associated habitat areas for each target species and life stage (pink boxes). Lookup tables are used during the habitat time-series analysis for interpolating habitat values at discharges that were not simulated.

Sequence 1: Development of Hydraulic Habitat Maps

Output from the River2D model for a particular discharge was exported as a text file containing the coordinates, depths, and velocities for each node in the computational mesh. This information was used to generate a map layer of the nodes and the attributes of depth, velocity, and water-surface elevation. An interpolated surface (a Triangular Irregular Network, or TIN) was constructed for each hydraulic variable, using the nodal data as mass points. Each TIN was converted to a 0.5-m by 0.5-m grid, reclassified according to the habitat classification criteria (table 2), and the reclassified grids combined to create a single grid depicting suitable depth and velocity conditions for adult and juvenile *H. amarus*, respectively. The composite grids were converted to polygon format (fig. 11), and the area for each polygon was calculated.

A water-surface polygon was created by reclassifying the depth grid for each simulated discharge according to depths greater than zero and depths less than or equal to zero. The reclassified grid was converted to polygon format, and polygons having depth less than or equal to zero were eliminated. The water-surface polygon served two functions. First, it was used to clip the hydraulic habitat maps to eliminate small polygons that occurred outside the shoreline boundary as an artifact of the grid process. Elimination of these small polygons has little effect on the total habitat area but can

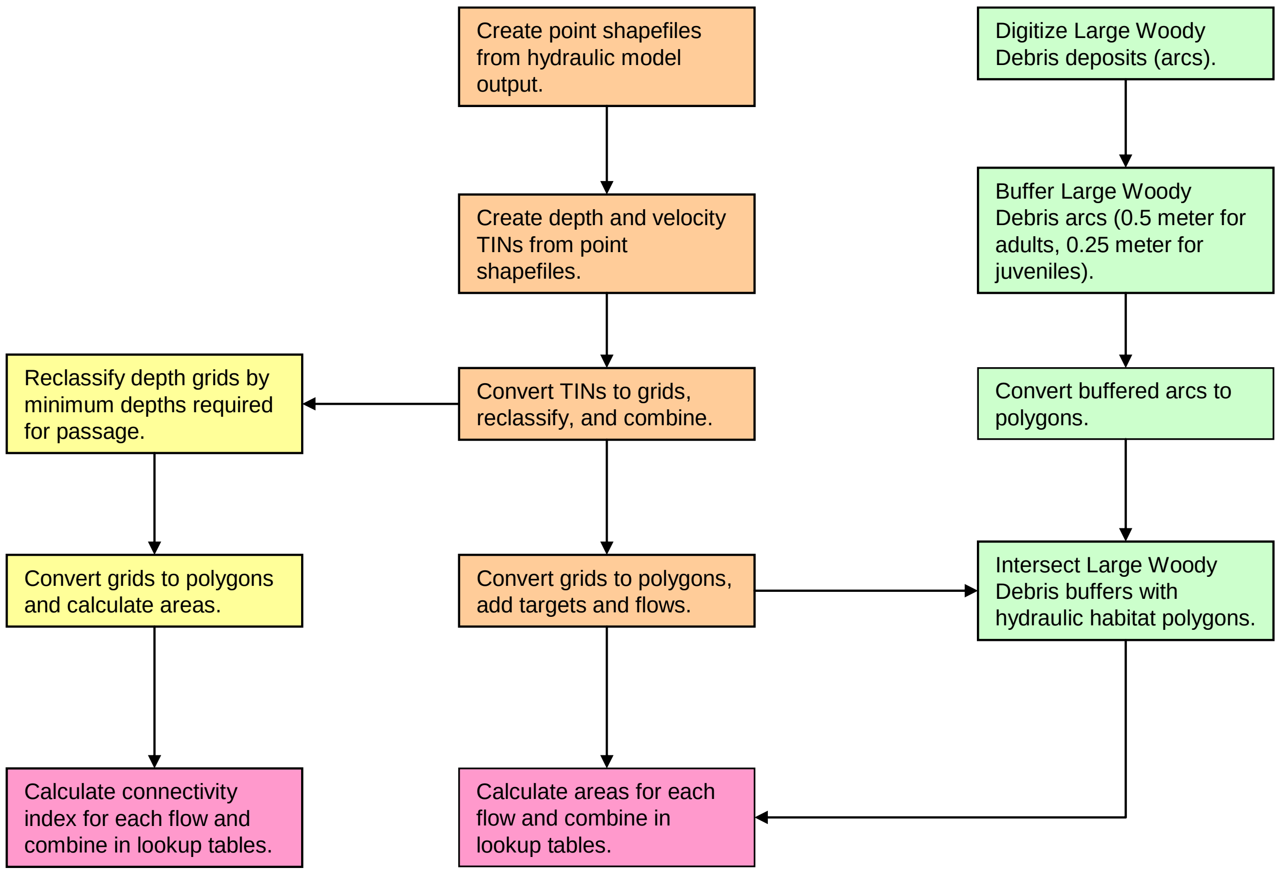


Figure 10. Sequence of GIS operations used in the habitat mapping process for *H. amarus*.

affect other habitat metrics, such as mean patch size and patch count. The second function of the water-surface polygon was to delineate the shoreline for use in the habitat maps for *E. t. extimus*.

This procedure was repeated for the 15 simulated discharges originating from the River2D model. Polygon areas were computed in the attribute tables for each map and exported to a spreadsheet for subsequent extraction of habitat metrics and development of the flow versus habitat lookup tables used in time-series analysis.

Sequence 2: Development of Large Woody Debris Overlays

A point shapefile was created from the original survey data, containing only those points coded as LWD deposits (brush piles or tree snags). From these data, an outline of each LWD deposit was developed by hand-digitizing arcs connecting these points. Two buffers were then created from the completed LWD arc shapefile, a 0.5-m buffer for adults and a 0.25-m buffer for juveniles. The original LWD arc shapefile and the two buffered shapefiles were then converted to polygons and the buffers intersected with each of the 15 hydraulic habitat shapefiles for both life stages (fig. 12). As with the hydraulic habitat maps, areas were computed for the intersected polygons and the attribute tables exported for conversion to lookup tables.

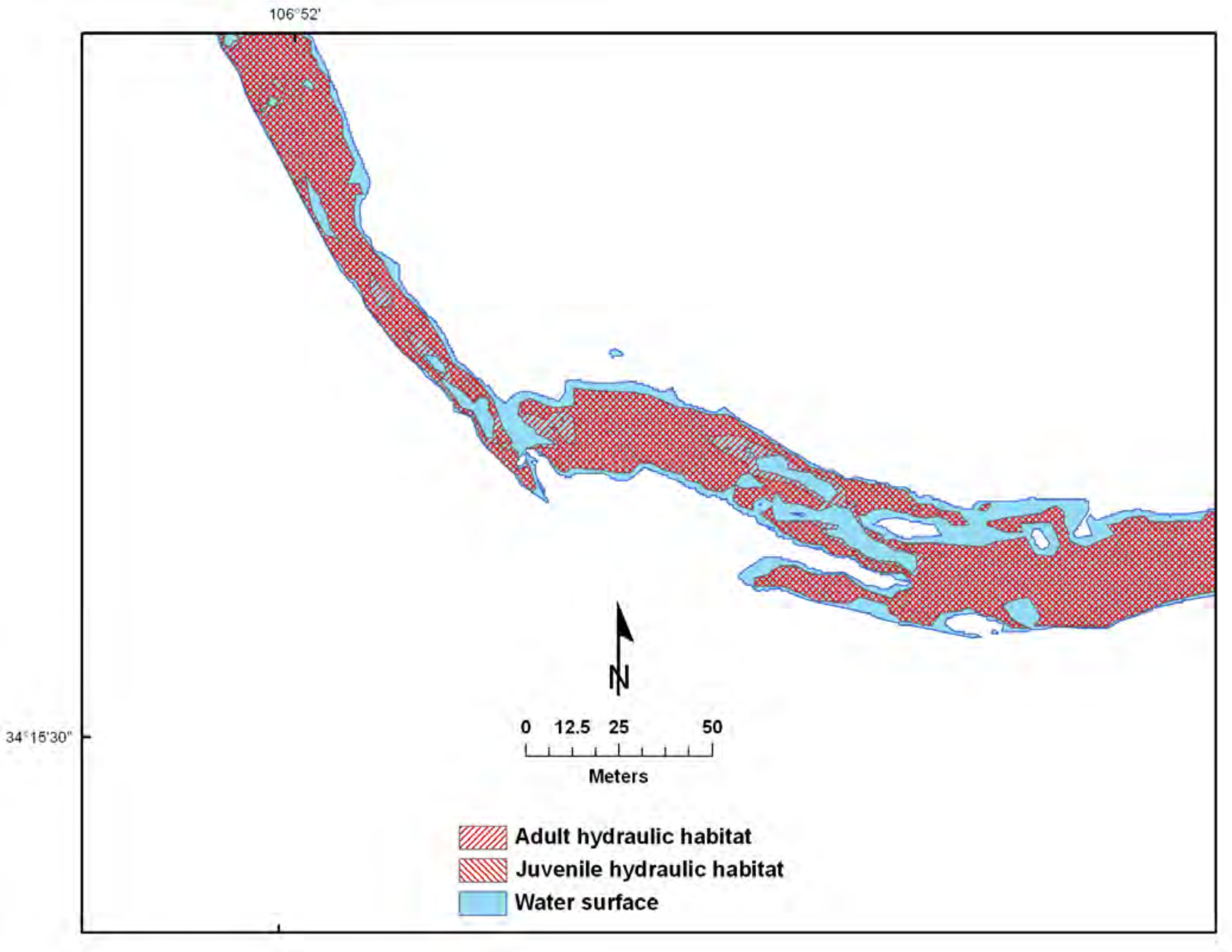


Figure 11. Hydraulic habitat map for a portion of the Rio Salado site, showing suitable conditions for adult and juvenile *H. amarus* at a discharge of 20 cubic feet per second.

Sequence 3: Development of Connectivity Indexes

At very low discharges, patches of otherwise suitable habitat for *H. amarus* can become isolated with no surface-water connection between them. To address this issue, we developed surface-water shapefiles for minimally passable depths. To create these shapefiles, the original depth grids created for the hydraulic habitat analysis (sequence 1) were reclassified to account only for grid cells having a depth of 3 cm or greater. The minimally passable depth was smaller than the minimum depth for suitable habitat, a distinction based on the idea that the fish can pass through areas that would otherwise be too shallow to be used as habitat (Michael Porter, Bureau of Reclamation, oral commun. November 2007). One such shapefile was created for each of the 15 simulated discharges for each site. Each shapefile was then edited to remove isolated patches that did not also contain suitable hydraulic habitat for adult *H. amarus* (fig. 13). This step eliminated disconnected wetted areas that would not likely be occupied by the minnow and irrelevant to the derivation of a connectivity index.

Unlike the previous habitat models, we estimated a connectivity index for zero flow. The rating curve for each site was extrapolated from 5 ft^3/s down to 0 ft^3/s and the difference in stage computed.

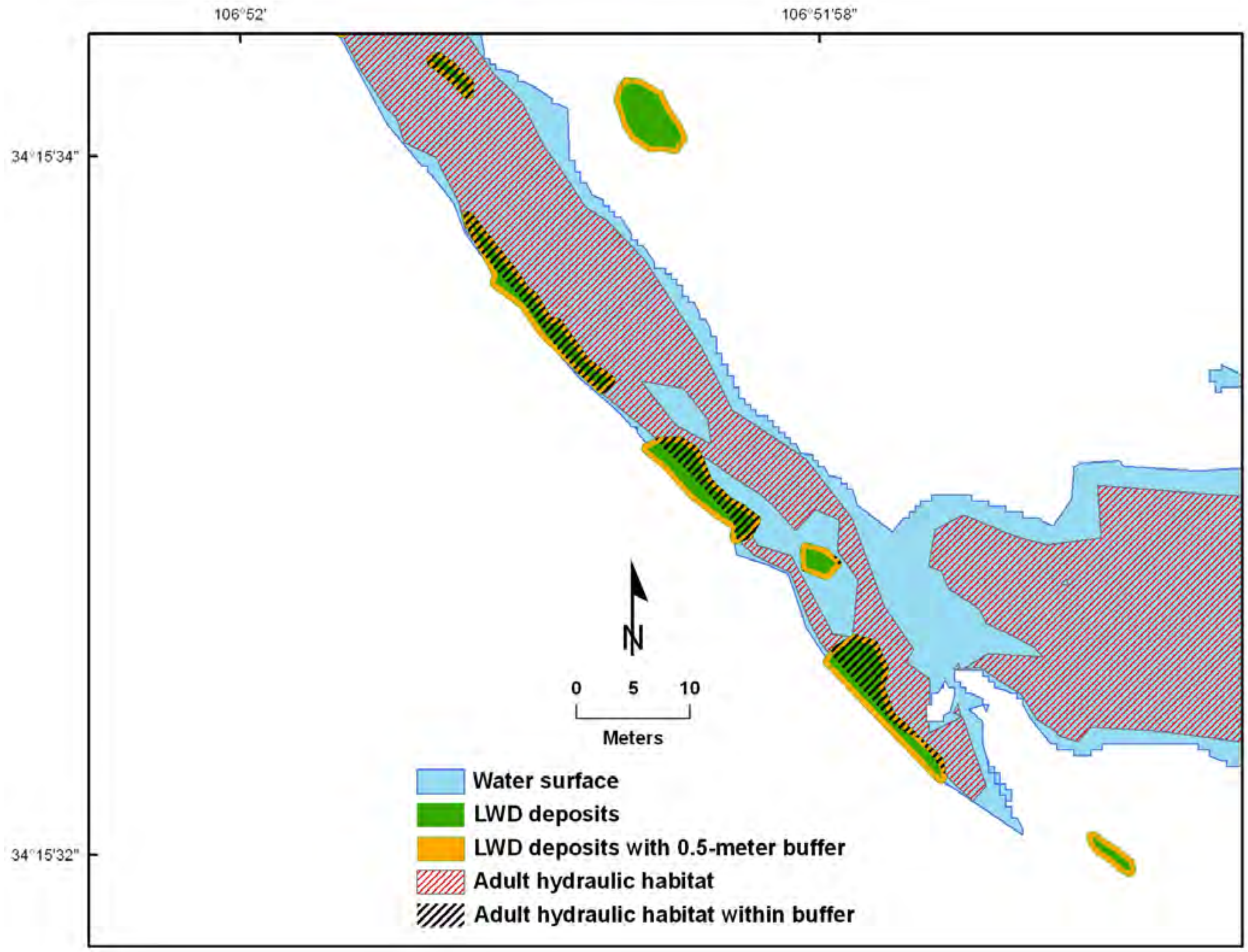


Figure 12. Large woody debris buffers intersected with suitable hydraulic habitat layers for adult *H. amarus* in a portion of the Rio Salado site at a discharge of 20 cubic feet per second.

This stage differential was then subtracted from the 5-ft^3/s depth grid, resulting in grid of the wetted patch distribution at 0 ft^3/s. The zero flow grid was then converted into polygon format (fig. 13).

Several alternatives were considered for computation of a connectivity index. The simplest version was the inverse of the patch count. As discharge decreased, the number of discrete patches increased. If there was only one patch, connectivity was 100 percent. If there were 25 patches, the inverse patch count was 4 percent. The disadvantage of the inverse patch count as a connectivity index was that at some locations and discharges the main channel area was completely connected but one or more disconnected pools were present. If there were two patches, one representing the fully connected main channel and one representing a small isolated pool, the inverse patch count is 50 percent. In this example, we believed that the inverse patch count index was unrealistically low. To overcome this perceived deficiency, we developed an area-based index. This index is the sum of the areas of all discrete patches, except the largest contiguous patch in the matrix, divided by the total area of all patches, including the largest. This ratio was then subtracted from 1.0. Consequently, if there is one large patch with an area of 33,000 m^2 and one small patch with an area of 300 m^2, the connectivity index would be 1–(300/33,300), or 99.09 percent.

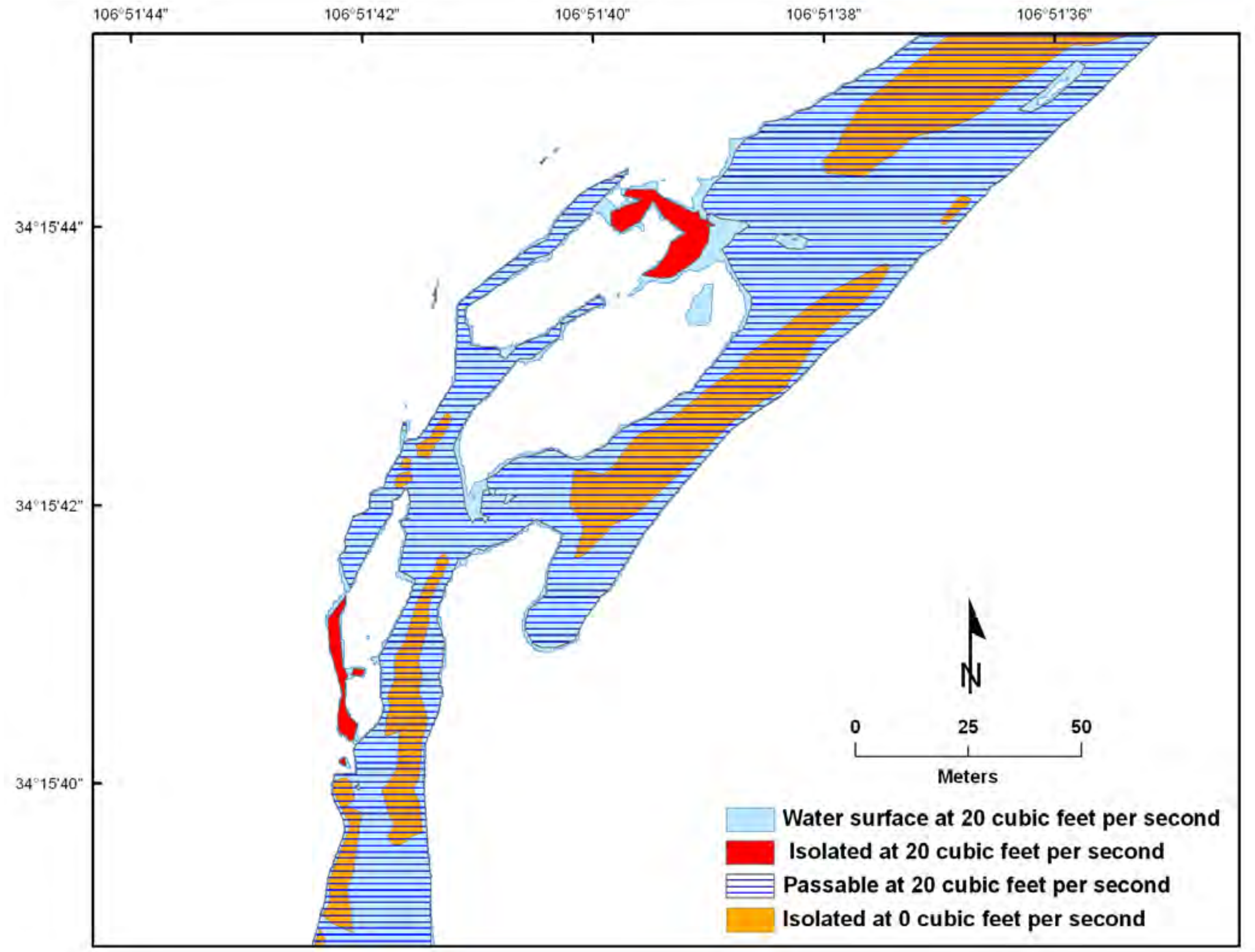


Figure 13. Habitat connectivity for *H. amarus* in a section of the Rio Salado site at 20 cubic feet per second and at 0 cubic feet per second.

Southwestern Willow Flycatcher

A shapefile containing polygons of suitable vegetation for nesting *E. t. extimus* was provided by BOR (Darrell Ahlers, Bureau of Reclamation, Fisheries and Wildlife Resources Group, Denver, Colo., written commun. June 2007). This shapefile was projected into the same coordinate system and datum as those developed at the Fort Collins Science Center and examined for patches smaller than 0.1 ha. There were none. A 50-m buffer was created around the water-surface maps for each of the sites and discharges used for *H. amarus* habitat analysis. The suitable vegetation shapefile was then intersected with each of the buffered water-surface layers to create new shapefiles containing only those areas having suitable vegetation within 50 m from open water (fig. 14). Polygon areas were calculated and exported for development of lookup tables similar to those developed for *H. amarus*.

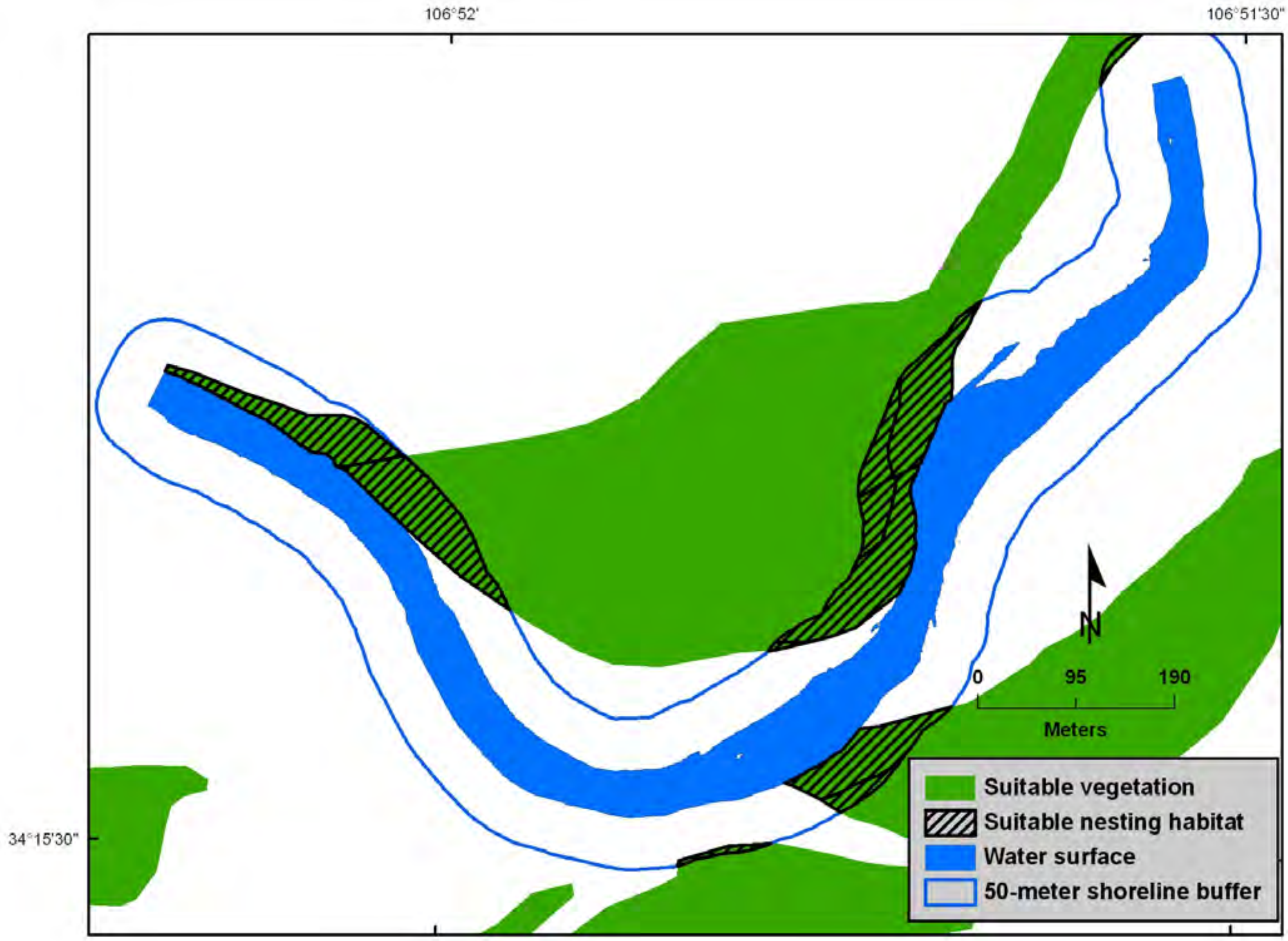


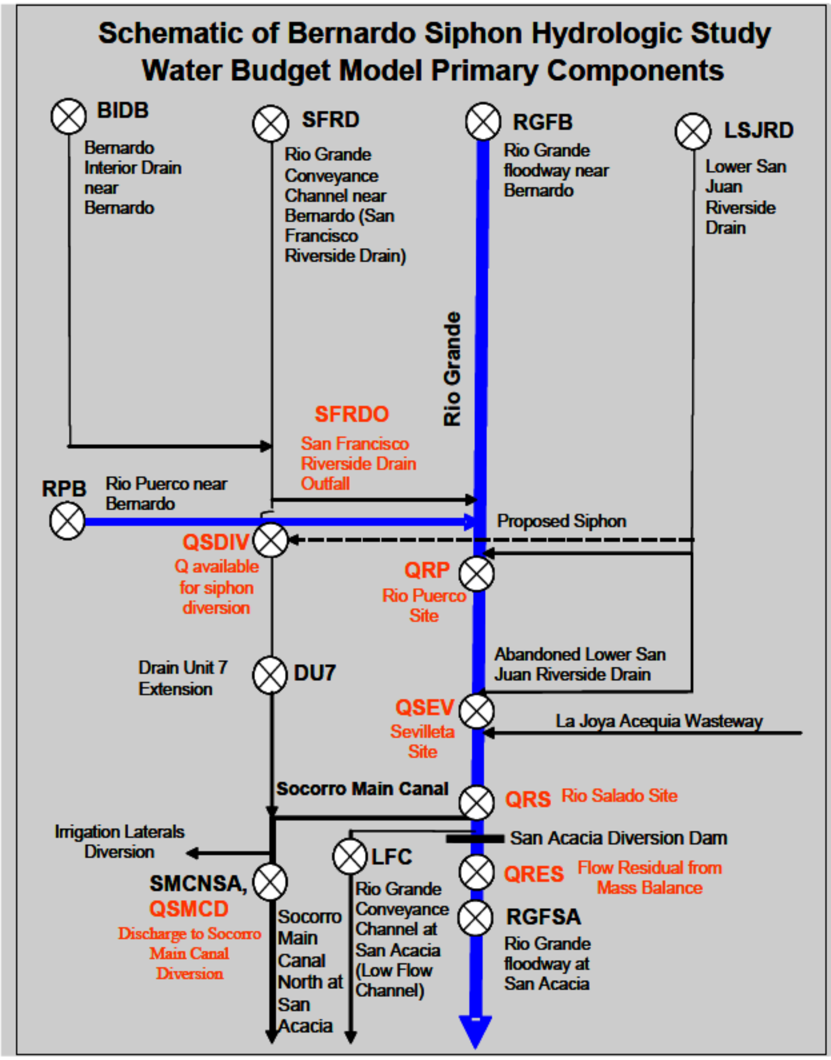
Figure 14. Intersection of a 50-meter water's edge buffer at 20 cubic feet per second in the Rio Salado site with polygons of suitable vegetation for nesting *E. t. extimus*.

Hydrologic Synthesis

Model Overview

The hydrologic analysis was performed using a mass-balance water budget model approach. The model was developed with an Excel® spreadsheet following the schematic diagram of the San Acacia diversion and delivery system illustrated in figure 15. Historical conditions were evaluated under existing instream-flow requirements, and river discharges were calculated for the three habitat evaluation sites. Historical irrigation demands were based on supply canal flow records.

Initially, a model component was developed on a monthly time step for the period of 1976 to 2004, excluding January to December 1979, October to December 1980 and January 1982 to December 1984. The periods modeled were a function of available flow data. Specifically, Lower San Juan Riverside Drain gage data were not available for the excluded periods in 1979, 1980, and 1982–84, and data for several gages were not available beyond September 30, 2004. The monthly time-step model



Abbreviation	Data period	Gage or formula
BIDB	POR	Gage
SFRD	POR	Gage
RGFB	POR	Gage
LSJRD	POR	Gage
RPB	POR	Gage
DU7	2000-2004	Gage
SFRDO		6, 7
SMCNSA	POR	Gage
LFC	POR	Gage
RGFSA	POR	Gage
QSMCD		8
QRES		9
QSDIV		10 - 13
QRP		16, 19
QSEV		17, 20
QRS		18, 21

Figure 15. Schematic diagram of the San Acacia diversion and delivery system with hydrologic nodes having calculated values (red) and gage data (black), cross-referencing equations used in the hydrologic synthesis model.

component was evaluated with regard to adjustments needed to better reflect current conditions and the period of record to be modeled at a daily time step.

The MRGCD changed its operations significantly during the late 1990s, resulting in consistently higher Belen Division drain flows. Use of pre-1999 data would have required adjustments to the measured drain flows to reflect current conditions. For this reason, the daily time-step components were confined to the irrigation seasons (March 1–October 31) from 1999 to 2004. We also stipulated that irrigation demand would be limited to the reported capacity of the supply canal (265 ft^3/s).

Hydrologic Data and Limitations

The hydrologic model was based on stream-gage data for the various conveyance channels within the study area of the Rio Grande hydrologic system. These stream gages are listed below and are shown schematically in figure 15:

1. Rio Grande Floodway near Bernardo (RGFB)
2. Rio Grande Floodway at San Acacia (RGFSA)
3. Rio Grande Conveyance Channel (Low Flow Channel) at San Acacia (LFC)
4. Bernardo Interior Drain Near Bernardo (BIDB)
5. San Francisco Riverside Drain (SFRD)
6. Socorro Main Canal North at San Acacia (SMCNSA)
7. Rio Puerco at Bernardo (RPB).

A common problem in performing hydrologic mass-balance analyses is the lack of completely concurrent data for all the input components to the model. Our synthesis was no different. Flow data for the USGS gaging station at the Socorro Main Canal North (SMCNSA) existed for the model period through September 30, 2003, and this station had been discontinued. The MRGCD established a new gaging station near the old station location, with data available from January 1, 2001, to present. The overlapping data from these two data sets were evaluated with regard to the consistency between the USGS and MRGCD records. Based on this analysis and previously reported estimates of lateral deliveries (J.W. Hernandez, New Mexico Water Resources Research Institute, Las Cruces, N. Mex., written commun. November 1999), the USGS data for SMCNSA were increased by 10 percent to reflect the total irrigation demand.

Flow data for the MRGCD's Lower San Juan Riverside Drain (LSJRD) were available for the entire modeling period, March 1, 1999–October 31, 2004. However, available data suggested a constant loss of 9 ft^3/s between the gage and the confluence of the drain with the Rio Grande (S.S. Papadopulos, S.S. Papadopulos and Associates, Boulder, Colo., written commun. June 2002). Consequently, we reduced the gaged flows at LSJRD to account for these losses.

Near the upstream boundary of the study area, the Bernardo interior drain (BIDB) and the San Francisco Riverside Drain (SFRD) empty into the Drain Unit 7 extension (DU7). The MRGCD installed a gage on the Drain Unit 7 extension, and flow data from that gage were available from January 1, 2000, through October 31, 2004. The total inflow was calculated as the sum of the discharges of BIDB and SFRD and the outflow measured as the flow at DU7. An analysis of the inflow compared to outflow for the period January 2000 to September 2004 did not reveal consistent loss or gain trends associated with the drains. Therefore, the inflow or sum of the SFRD and BIDB gage values were not adjusted.

Unmeasured River Inflow, Losses, and Gains

The sources of unmeasured flow into the study reach of the Rio Grande include the Rio Salado and numerous other natural drainage channels or arroyos, the San Francisco Riverside Drain Outfall, the abandoned portion of the LSJRD and the wasteway from the La Joya Acequia supply canal (fig. 15). With the exception of the San Francisco Riverside Drain Outfall, individual flow rates for these inflow sources were not estimated. Total unmeasured accretions and depletions were calculated as a daily residual, the difference between the total inflow measured at the upstream end of the study area and the total outflow measured at San Acacia Dam and SMCNSA headworks.

MRGCD installed a stream-gaging station on the SFRD Outfall that has been in operation since January 1, 2003. Data from this station were used to back-calculate discharges for the period of record prior to installation of the gage. Specifically, a relationship between these data and the overlapping combined BIDB gage and SFRD gage data (January 1, 2003, to September 30, 2004) was developed and used to extend the record for the SFRD Outfall gage. The estimated return flow to the Rio Grande, SFRDO, was calculated based on this analysis. The analysis revealed that when the combined SFRD and BIDB flow was greater than 200 ft^3/s, the median discharge for SFRDO was 49.5 percent of the portion of the flow over 200 ft^3/s. When the inflow was less than 200 ft^3/s, the median discharge for

SFRDO was 1.2 percent of the total flow. The estimated daily return flow from SFRDO was based on these generalized relationships. When the sum of BIBD and SFRD is greater than 200 ft^3/s:

$$Q_{SFRDO} = 0.5\ (Q_{BIDB} + Q_{SFRD} – 200) \qquad (6)$$

and when the total inflow is less than 200 ft^3/s,

$$Q_{SFRDO} = 0.012\ (Q_{BIDB} + Q_{SFRD}) \qquad (7)$$

Minimum Instream Flows

Instream-flow requirements can operate as constraints on the amount of water available for diversion through the Bernardo siphon and are sometimes important determinants of the daily discharges in the Rio Grande between the LSJRD and San Acacia Dam. These instream-flow requirements can be modified in two different locations within the model (see the following discussion on the habitat time-series model). In addition, the effects of instream-flow requirements on availability of water for diversion and on downstream in-channel discharges vary depending on the point of enforcement. If the instream-flow requirements are enforced at the top of the study area, the results can be quite different from those obtained by enforcing the instream-flow requirement at San Acacia Dam. Consequently, we constructed two versions of the hydrologic synthesis model, one enforcing the instream-flow requirements at the LSJRD siphon location and one enforcing them at San Acacia Dam.

Instream-flow requirements were established by the U.S. Fish and Wildlife Service (USFWS) in the Biological Opinion for the Rio Grande silvery minnow (U.S. Fish and Wildlife Service, 2003b). Different instream flow rules and points of enforcement were included in the Biological Opinion, beginning with definitions of dry, average, and wet water years. Definitions of dry, average, and wet years were based on the Natural Resources Conservation Service’s (NRCS) April 1 “Most Probable” Streamflow Forecast at the Otowi gage (near Santa Fe) as follows:

1. Dry year: NRCS April 1 Streamflow Forecast at Otowi Gage is less than 80 percent of average.
2. Average year: NRCS April 1 Streamflow Forecast at Otowi Gage is 80 to 120 percent of average.
3. Wet year: NRCS April 1 Streamflow Forecast at Otowi Gage is 120 percent or higher of average.

The average to which these criteria refer is defined by NRCS as the average streamflow at the point of reference (Otowi Gage) for the 30–year period from 1971 through 2000.

The hydrologic year as defined in the Biological Opinion starts at the beginning of runoff in a given year and ends at the beginning of runoff the subsequent year. Each year is assessed individually, and the determination of the hydrologic year type is made once the April 1 forecast has been released. Additional modifications in defining a hydrologic year type may be made if the May 1 forecast differs substantially from earlier forecasts. If additional information is needed, the USFWS may also request that NRCS provide a May 15 forecast to assist in the decisionmaking process.

The instream-flow requirements are also subject to provisions of the Rio Grande Compact, an interstate agreement governing the allocation of water from the Rio Grande among Colorado, New Mexico, and Texas. Articles VI and VII govern the amount of water that can be held within the States of Colorado and New Mexico, the annual volume deliverable to Texas, and how the upstream States are credited or debited their allocations (see sidebars). These two articles are especially pertinent to the enforcement of the instream-flow requirements contained in the Biological Opinion because when either is in effect, the hydrologic year is effectively defined as dry regardless of flow predictions.

ARTICLE VI

Commencing with the year following the effective date of this Compact, all credits and debits of Colorado and New Mexico shall be computed for each calendar year; provided, that in a year of actual spill no annual credits nor annual debits shall be computed for that year. In the case of Colorado, no annual debit nor accrued debit shall exceed 100,000 acre-feet, except as either or both may be caused by holdover storage of water in reservoirs constructed after 1937 in the drainage basin of the Rio Grande above Lobatos. Within the physical limitations of storage capacity in such reservoirs, Colorado shall retain water in storage at all times to the extent of its accrued debit. In the case of New Mexico, the accrued debit shall not exceed 200,000 acre-feet at any time, except as such debit may be caused by holdover storage of water in reservoirs constructed after 1929 in the drainage basin of the Rio Grande between Lobatos and San Marcial. Within the physical limitations of storage capacity in such reservoirs, New Mexico shall retain water in storage at all times to the extent of its accrued debit. In computing the magnitude of accrued credits or debits, New Mexico shall not be charged with any greater debit in any one year than the sum of 150,000 acre-feet and all gains in the quantity of water in storage in such year. The Commission by unanimous action may authorize the release from storage of any amount of water which is then being held in storage by reason of accrued debits of Colorado or New Mexico; provided, that such water shall be replaced at the first opportunity thereafter. In computing the amount of accrued credits and accrued debits of Colorado or New Mexico, any annual credits in excess of 150,000 acre-feet shall be taken as equal to that amount.

In any year in which actual spill occurs, the accrued credits of Colorado, or New Mexico, or both, at the beginning of the year shall be reduced in proportion to their respective credits by the amount of such actual spill; provided that the amount of actual spill shall be deemed to be increased by the aggregate gain in the amount of water in storage, prior to the time of spill, in reservoirs above San Marcial constructed after 1929; provided, further, that if the Commissioners for the States having accrued credits authorize the release of part, or all, of such credits in advance of spill, the amount so released shall be deemed to constitute actual spill. In any year in which there is actual spill of usable water, or at the time of hypothetical spill thereof, all accrued debits of Colorado, or New Mexico, or both, at the beginning of the year shall be cancelled. In any year in which the aggregate of accrued debits of Colorado and New Mexico exceeds the minimum unfilled capacity of project storage, such debits shall be reduced proportionally to an aggregate amount equal to such minimum unfilled capacity. To the extent that accrued credits are impounded in reservoirs between San Marcial and Courchesne, and to the extent that accrued debits are impounded in reservoirs above San Marcial, such credits and debits shall be reduced annually to compensate for evaporation losses in the proportion that such credits or debits bore to the total amount of water in such reservoirs during the year.

-Excerpt from the Rio Grande Compact

ARTICLE VII

Neither Colorado nor New Mexico shall increase the amount of water in storage in reservoirs constructed after 1929 whenever there is less than 400,000 acre-feet of usable water in project storage; provided, that if the actual releases of usable water from the beginning of the calendar year following the effective date of this Compact, or from the beginning of the calendar year following actual spill, have aggregated more than an average of 790,000 acre-feet per annum, the time at which such minimum stage is reached shall be adjusted to compensate for the difference between the total actual release and releases at such average rate; provided, further, that Colorado, or New Mexico, or both, may relinquish accrued credits at any time, and Texas may accept such relinquished water, and in such event the state, or states, so relinquishing shall be entitled to store water in the amount of the water so relinquished.

-Excerpt from the Rio Grande Compact

The instream-flow requirements expressed in the Biological Opinion also vary according to enforcement location and address only two instream flows specifically at San Acacia Dam. From November 16 to June 15, the Biological Opinion states that an unspecified continuous flow must be maintained from Cochiti Dam to the southern boundary of *H. amarus* critical habitat during dry and average years and 100 ft^3/s at San Marcial (approximately 65 km downstream from San Acacia) in wet years. From June 16 to November 15 there is an instream-flow requirement of 50 ft^3/s at San Acacia Dam in average years and 100 ft^3/s in wet years. In dry years or when Article VI or Article VII of the Rio Grande compact is in effect, there is no instream-flow requirement at San Acacia for the June 16–November 15 period.

To estimate the discharges necessary at the San Acacia Dam to deliver the required flows downsteam from San Marcial during the November 16–June 15 period, we conducted a paired data analysis of both sites (table 3). Owing to the vague downstream requirements for average and dry years in the Biological Opinion, we stipulated a streamflow of approximately 10 ft^3/s at San Marcial to satisfy the criterion of a measurable discharge at the southern critical habitat boundary. The travel time between the two gages was unknown, so we used lag times of 1 to 2 days for the comparison of mean daily discharges. We arrayed the data in descending order and sorted according to the discharges at San Marcial. To estimate the San Acacia discharge needed to deliver 100 ft^3/s to San Marcial, we selected a range of San Acacia discharges corresponding to discharges between 95 ft^3/s to 105 ft^3/s at San Marcial. A similar process was used to estimate the San Acacia discharge needed to deliver 10 ft^3/s to San Marcial. We derived a trimmed mean of these data (the average of San Acacia discharges between the mean plus one standard deviation and the mean minus one standard deviation) as a more representative central value for the data. Based on this analysis, we estimated that, on average, a discharge of 312 ft^3/s at San Acacia Dam would be required to deliver 100 ft^3/s at San Marcial. A discharge of approximately 200 ft^3/s was the estimated discharge needed at San Acacia in average and dry years to deliver 10 ft^3/s at San Marcial.

It became apparent during our analysis that the Rio Grande had a general tendency to lose water between San Acacia and San Marcial during the November–June period. The gage records revealed what happened rather than why it happened, but we suspect that the losses were attributable to low precipitation and relatively high groundwater recharge during this 6-month period. Depending on the day-to-day circumstances, the flow required from San Acacia to deliver 100 ft^3/s at San Marcial was as low as 169 ft^3/s and as high as 854 ft^3/s (table 3).

Table 3. Comparison of discharges at the San Acacia and San Marcial gages with varying lag times and averaging strategies for the period November 16–June 15.

Discharge range at San Marcial gage, in cubic feet per second	Discharge downstream from San Acacia Dam, in cubic feet per second (average)		Discharge downstream from San Acacia Dam, in cubic feet per second (trimmed mean)		Discharge range downstream from San Acacia Dam, in cubic feet per second
	One Day Lag	Two Day Lag	One Day Lag	Two Day Lag	
95–105 (100)	380	403	312	354	169–854
5–15 (10)	240	320	200	237	145–672

For the purposes of our model, the default values used as the instream-flow requirements to satisfy the Biological Opinion are summarized in table 4. These default values can be changed in the model relatively easily if justified. Only the values for the November 16–June 15 period are subject to modification, however, as the Biological Opinion is specific for the June 16–November 15 instream flow demands. Users have the option of overriding the Biological Opinion instream-flow requirement in the model at any time with a higher discharge. If the user-specified instream-flow requirement is larger than the Biological Opinion demand in the model, the former takes precedence over the latter. The mass-balance spreadsheet contains a column for “Critical Fisheries Demand,” which is the larger of the two instream-flow requirements (refer to “Parameters” page discussion under “Rio Grande Habitat Time Series Model”).

Table 4. Summary of default instream-flow requirements applied to the hydrologic synthesis model of the lower Isleta reach of the Rio Grande.

Water year type	Criteria	Discharge at San Acacia Dam, in cubic feet per second	
		June 16–November 15	**November 16–June 15**
Wet	Greater than 120 percent of the 30-year average	100	312
Normal	Between 80 and 120 percent of the 30-year average	50	200
Dry	Below 80 percent of the 30-year average	0	200

Model Algorithms

The model balances the various measured inflow and outflow discharges and calculates a residual value representing unmeasured accretions and depletions under existing conditions as described in the following steps. Hydrologic nodes, periods of record, and applicable equations related to the hydrologic mass balance are summarized in figure 15.

1. The flow diverted at the San Acacia Diversion Dam into the Socorro Main Canal is calculated as

$$Q_{SMCD} = Q_{SMCID} – Q_{BIDB} – Q_{SFRD} + Q_{SFRDO} \quad (8)$$

where
Q_{SMCD} = discharge to Socorro Main Canal diversion,
Q_{SMCID} = irrigation demand =larger of (1.1 * $Q_{SMCNSA)}$ or 265),
Q_{BIDB} = discharge from Bernardo interior drain near Bernardo,
Q_{SFRD} = discharge from San Francisco riverside drain, and
Q_{SFRDO} = estimated discharge from San Francisco riverside drain outfall (return flow to Rio Grande).

2. The residual between river inflows and outflows is calculated as

$$Q_{RES} = Q_{SMCD} + Q_{LFC} + Q_{RGFSA} – Q_{RGFB} – Q_{SFRDO} – Q_{RPB} – Q_{LSJRD} \quad (9)$$

where

Q_{RES} = the residual discharge,
Q_{LFC} = discharge to Rio Grande conveyance channel at San Acacia (low flow channel),
Q_{RGFSA} = discharge at the Rio Grande floodway at San Acacia,
Q_{RGFB} = discharge at the Rio Grande floodway at Bernardo,
Q_{RPB} = discharge of the Rio Puerco near Bernardo,
Q_{LSJRD} = discharge of the Lower San Juan Riverside Drain, and
all other variables previously defined.

3. The discharge upstream from the San Acacia Diversion Dam with no siphon diversion from LSJRD is calculated as

$$Q_{RGASAD} = Q_{RBFB} + Q_{SFRDO} + Q_{RPB} + Q_{LSJRD} + Q_{RES} \quad (10)$$

where

Q_{RGASAD} = discharge of the Rio Grande above San Acacia diversion dam with no siphon diversion.
All other terms have been previously defined.

The amount of water available for siphon diversion is a function of the discharge calculated in Step 3 and the instream flow demand, defined as the Critical Fisheries Demand as previously described. In the case where the instream-flow requirement is enforced at the San Acacia dam, the amount of water available for diversion at the siphon is calculated as

$$Q_{AVS} = Q_{RGASAD} – Q_{IFR} \quad (11)$$

where

Q_{AVS} = discharge available for diversion to the siphon,
Q_{RGASAD} = Rio Grande discharge above the San Acacia dam, and
Q_{IFR} = the critical fisheries instream flow demand.

In the case where the instream-flow requirement is enforced at the Lower San Juan drain, the amount of water available for diversion is calculated as

$$Q_{AVS} = Q_{RGFB} + Q_{SFRDO} + Q_{RPB} + Q_{LSJRD} + 0.28Q_{RES} – Q_{IFR} \quad (12)$$

wherein all terms have been defined previously. In either case, if the calculated value for Q_{AV} is less than or equal to zero, there is no water available for diversion. Furthermore, the amount available cannot exceed the inflow from the Lower San Juan Riverside Drain (Q_{LSJRD}).

4. The demand for the siphon diversion is calculated as a function of the irrigation demand and the amount of water available for siphon diversion by

$$Q_{SD} = Q_{SMCNSA} – Q_{BIDB} – Q_{SFRD} + Q_{SFRDO} \quad (13)$$

where

Q_{SD} = siphon demand. All other terms have been previously defined.

5. The actual siphon diversion (Q_{SDIV}) is the lesser of the amount available for diversion (Q_{AVS}) or the siphon demand (Q_{SD}).

6. Irrigation demands that cannot be met by the siphon diversion must be made up by diversions to the Socorro Main Canal diversion. The discharge downstream from San Acacia Dam (Q_{RGBSAD}) is determined by the discharge arriving at the dam and the amount diverted into the Socorro Main Canal (Q_{SMC}). The flow diverted to the Socorro main canal (Q_{SMC}) is calculated as

$$Q_{SMC} = Q_{SMCNSA} – Q_{BIDB} – Q_{SFRD} + Q_{SFRDO} – Q_{SDIV} \quad (14)$$

and the flow in the Rio Grande downstream from San Acacia Dam (Q_{RGBSAD}) is

$$Q_{RGBSAD} = Q_{RGASAD} – Q_{SDIV} – Q_{SMC} – Q_{LFC} \quad (15)$$

7. The daily discharge at the three habitat sites was calculated in the daily time-step runs assuming linear distribution of the residual throughout the study reach. Specifically, the distance between each

site and San Acacia was divided by the distance between the Bernardo gage and San Acacia Dam (14 miles), and the product of this fraction and the residual were added to the total inflow. The equations used for each site, with and without the siphon diversion, are as follows:

$$Q_{RPWOS} = Q_{RGFB} + Q_{LSJRD} + Q_{RBP} + Q_{SFRDO} + 0.28(Q_{RES}) \quad (16)$$
$$Q_{SEVWOS} = Q_{RGFB} + Q_{LSJRD} + Q_{RBP} + Q_{SFRDO} + 0.57(Q_{RES}) \quad (17)$$
$$Q_{RSWOS} = Q_{RGFB} + Q_{LSJRD} + Q_{RBP} + Q_{SFRDO} + 0.93(Q_{RES}) \quad (18)$$
$$Q_{RPWS} = Q_{RGFB} + Q_{LSJRD} + Q_{RBP} + Q_{SFRDO} + 0.28(Q_{RES}) – Q_{SDIV} \quad (19)$$
$$Q_{SEVWS} = Q_{RGFB} + Q_{LSJRD} + Q_{RBP} + Q_{SFRDO} + 0.57(Q_{RES}) – Q_{SDIV} \quad (20)$$
$$Q_{RSWS} = Q_{RGFB} + Q_{LSJRD} + Q_{RBP} + Q_{SFRDO} + 0.93(Q_{RES}) – Q_{SDIV} \quad (21)$$

where

Q_{RPWOS} = Discharge at the Rio Puerco site without siphon,
Q_{SEVWOS} = Discharge at the Sevilleta site without siphon,
Q_{RSWOS} = Discharge at the Rio Salado site without siphon,
Q_{RPWS} = Discharge at the Rio Puerco site with siphon,
Q_{SEVWS} = Discharge at the Sevilleta site with siphon, and
Q_{RSWS} = Discharge at the Rio Salado site with siphon.
All other terms have been previously defined.

Habitat Time Series

The basic concept of the habitat time series has been in use since the early 1980s (Bovee, 1982; Bovee and others, 1998) and remains a powerful tool for examining the effects of alternative water-management practices on riverine habitats. The habitat time series has its origins in the National Environmental Policy Act (NEPA) of 1969 [42 U.S.C. 4321], which requires the determination of the environmental consequences of a Federal action and its alternatives. This requirement applies equally to Environmental Assessments (EA) and Environmental Impact Statements (EIS). By virtue of its ability to quantify the effects of a proposed action and alternatives to that action, the habitat time series was designed to be compatible with NEPA and similar applications.

The habitat time series is fundamentally simple, as illustrated in figure 16. The driving variable is a time series of discharges, representing either a baseline condition or an alternative. In the case of the Rio Grande, the baseline condition is defined by the flows at each of the sites without the siphon (equations 16–18) and the alternative by the flows with the siphon in operation (equations 19–21). For every discharge in the flow time series, there is a corresponding habitat area, derived from the habitat mapping and compiled in the habitat–discharge lookup tables. The habitat time series is merely a transformation of the discharge for a time step into the corresponding habitat area for the same time step. The resulting habitat time series (fig. 16C) may be quite different from the hydrologic time series (fig. 16A) from which they were derived, however, because the habitat–discharge functions (fig. 16 B) typically are nonlinear.

Rio Grande Habitat Time Series (RGHTS) Model

The Rio Grande habitat time series model (RGHTS) was developed in an Excel® workbook and organized as illustrated in figure 17. Individual components of the RGHTS model are described approximately in their order of appearance in figure 17.

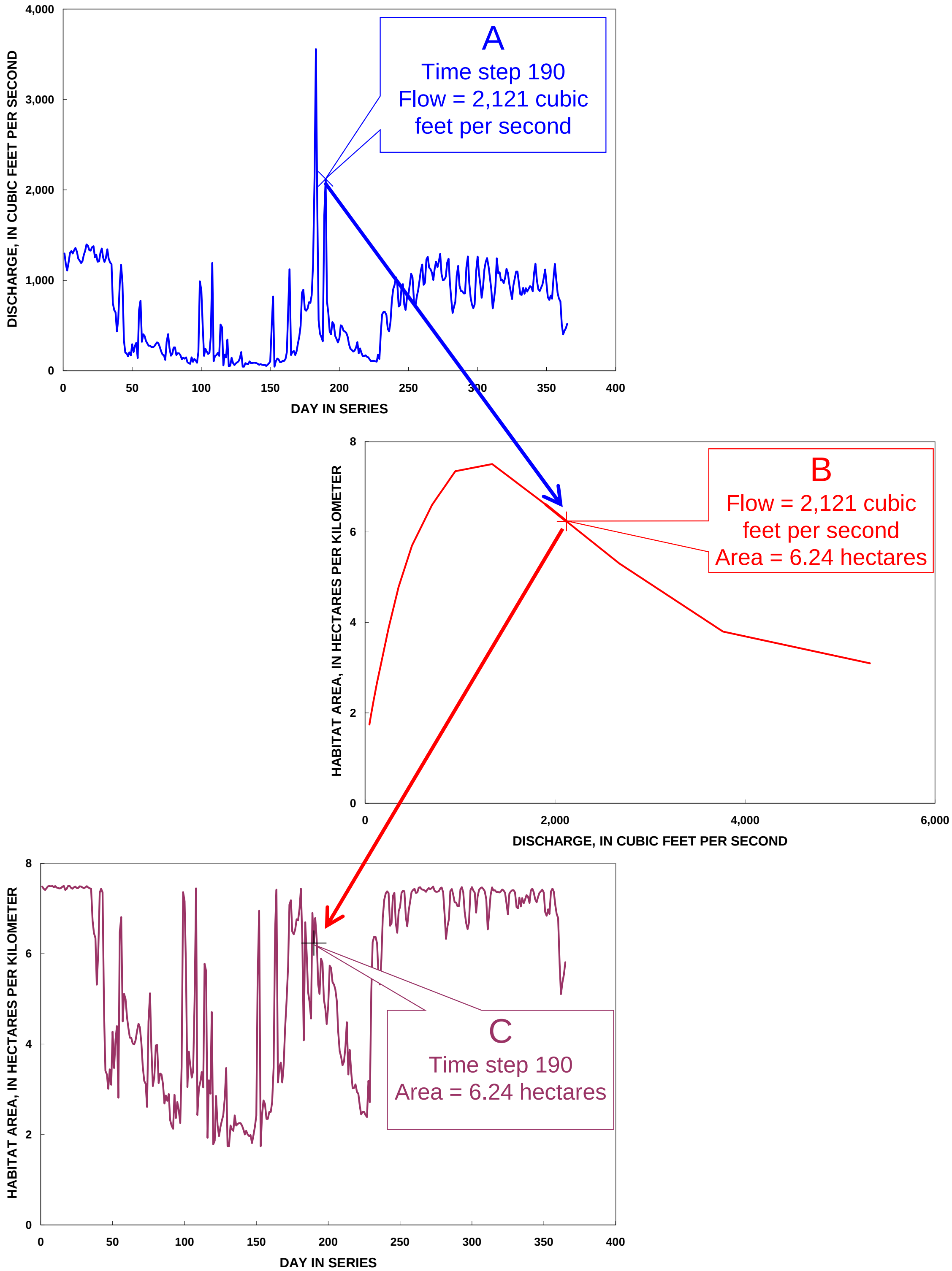


Figure 16. Elements used in the construction of a habitat time series: (A) flow time series; (B) discharge–habitat function; and (C), the resulting habitat time series.

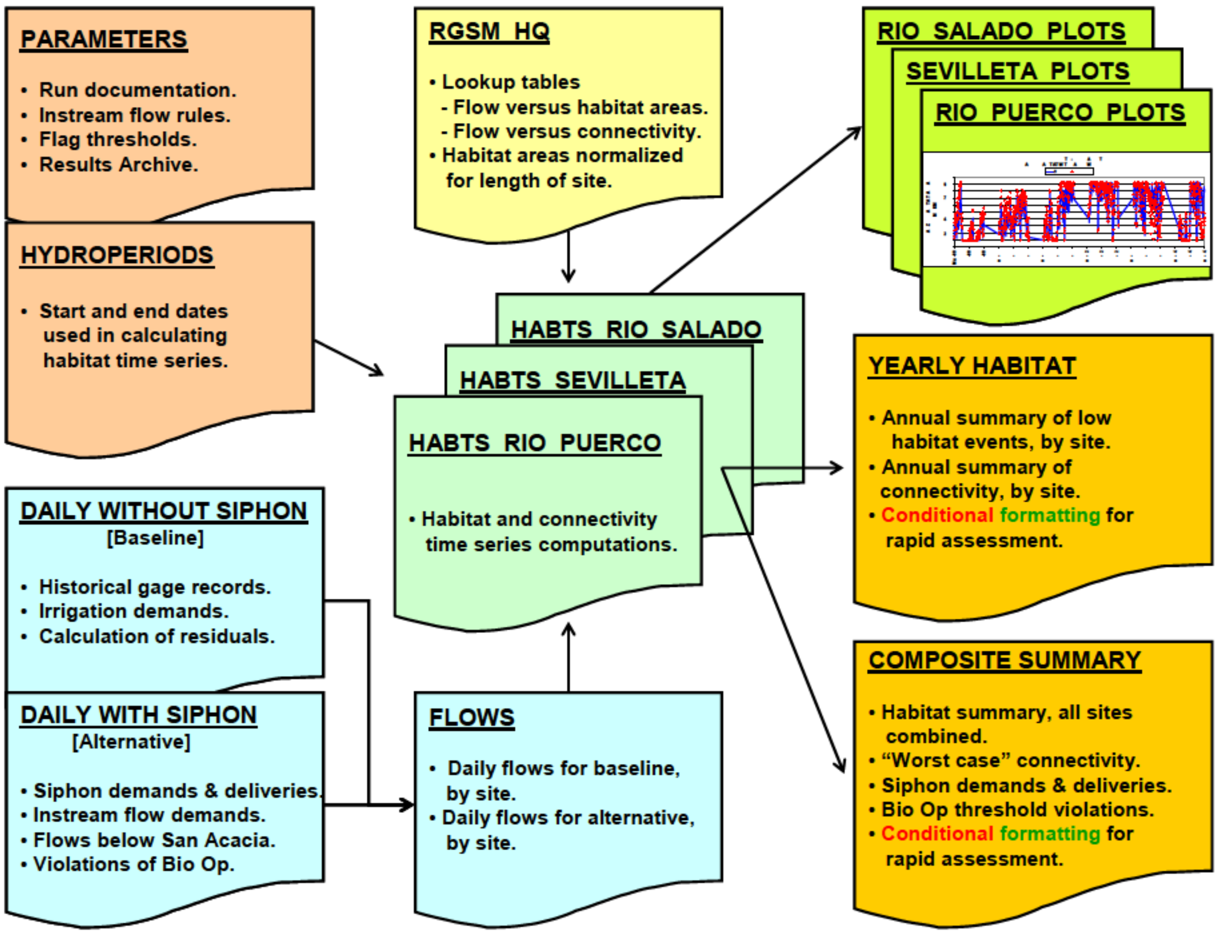


Figure 17. Organization of the Rio Grande habitat time-series workbook. Page titles in workbook are indicated by upper case, underlined labels.

Parameters

The "Parameters" page (fig. 18) is the first page encountered in the RGHTS model. The contents of the page are used to document the characteristics of the model run, to control the rules affecting the hydrologic mass-balance, to set formatting and computational thresholds, and to archive run results.

Run Documentation

The RGHTS model is intended to be used to evaluate multiple alternatives, but they can only be tested one at a time. Consequently, in the pursuit of a mutually satisfactory solution, it is inevitable that many individual model runs will be made, each different in some way from the previous run. Without some form of documentation, the various model runs can blend themselves into an amorphous collection of statistics and graphics. A serious problem can arise when one of the solutions in the collection is obviously superior to all the rest, but no one can remember how it was derived.

Rio Grande Habitat Time Series				
Version Prototype 9				
Parameters				
Default values below will be used to run the model unless alternate values are entered in the User Input cells below.				
	Units	**Default**	**User Input**	
1. Run date	**MM/DD/YYYY**	2/27/2008		
2. Model Titles		Base	Without Siphon	
		Alternative	With Siphon, Alternative 1	
3. IFR Enforcement location			at San Acacia dam	
	Instream Flow Override	**Instream Flows from Biological Opinion**		
4. Instream Flow Requirements		**Wet Year**	**Average Year**	**Dry Year**
March 1 -- June 15	0	312	200	200
June 15 -- September 30	10	100	50	0
	Flag IF % of Demand			
5. Siphon Delivery Flags	Satisfied is less than:		**San Marcial Delivery Flags**	
March	75.00%		Count as violation if flow below San Acacia Dam	
April	75.00%		is less than	
May	75.00%		95%	
June	75.00%		of the November - June	
July	75.00%		Biological Opinion Demand.	
August	75.00%			
September	75.00%			
October	75.00%			
6. Minimum Connectivity Flags	Flag IF Connectivity	Allowable Days		
	Index is less than:	Below threshold		
	0.990	5		
	Archive Run Results			

Figure 18. The “Parameters” page of the Rio Grande habitat time-series workbook.

Run documentation refers to an orderly process of keeping track of the particulars of each model run. The Parameters page contains two basic entries that are useful in the tracking process, highlighted with a light green background in figure 18. The first is the run date. The default value for the run date is “today’s date” and is automatically updated by the model whenever a new run is completed. This entry is useful for tracking the chronological sequence of model runs and for identifying the most recent of two or more supposedly identical runs. The run date is automatically recorded at the tops of all the habitat summary pages as well as on the habitat time-series computation (HABTS_<site name> pages.

The second entries for run documentation fall under the heading “Model Titles.” The default values for model titles are labeled “With Siphon” and “Without Siphon,” neither of which is particularly enlightening because every comparison will include these two components. A more useful entry would be a distinct name that is cross-referenced to a narrative describing the baseline and each alternative in some detail. For example, in figure 18, the title for the alternative is “With Siphon, Alternative 1.” Some of the conditions applicable to this alternative are also listed on the parameters page, including the location of enforcement and magnitudes of instream-flow requirements. At a minimum, this information should be incorporated into the narrative description of the alternative. A simple method for doing this is to use a screen capture (shift-PrintScreen) of the Parameters page at the end of each run and paste the images sequentially into a PowerPoint® folder. Like the run date, the model titles are automatically recorded at the tops of the summary pages and the habitat time-series computation pages.

Instream-Flow Enforcement Rules

This section of the Parameters page consists of two components, listed by title on figure 18 as "IFR Enforcement Location" and "Instream-flow requirements." The instream-flow enforcement rules are the essential means by which the hydrologic mass balance can be modified for the "With Siphon" alternative. In essence, variations to the instream-flow enforcement rules define the alternatives being tested. These rules govern the distribution of inflows among potential siphon deliveries, daily flows at the habitat sites, flow diverted at the Socorro Main Canal headworks, and flows delivered to San Marcial.

As discussed in the "Hydrologic Synthesis" section, there are different versions of the hydrologic models that determine where and how the instream-flow requirements are enforced. The choices available for enforcement location include: (1) at the Bernardo siphon, (2) at San Acacia Dam, and (3) "None." The first two options define where the instream-flow requirements listed in the "Instream-flow requirements" section are enforced. The enforcement location is important because the section of the Rio Grande between the siphon location and San Acacia Dam is subject to varying gains and losses of discharge in different months and water years (fig. 19). For the period of record used in our model, this reach tended to gain water during the driest water years (2002 and 2003) and lose water during May and June of the wettest years (1991 and 2001). The reach also had a general tendency to gain water during the months typically having low discharges, particularly from July through October in most years (fig. 19). Therefore, enforcing the instream-flow requirement at the siphon during low-flow periods generally resulted in larger flows throughout the reach by virtue of accretion. Conversely,

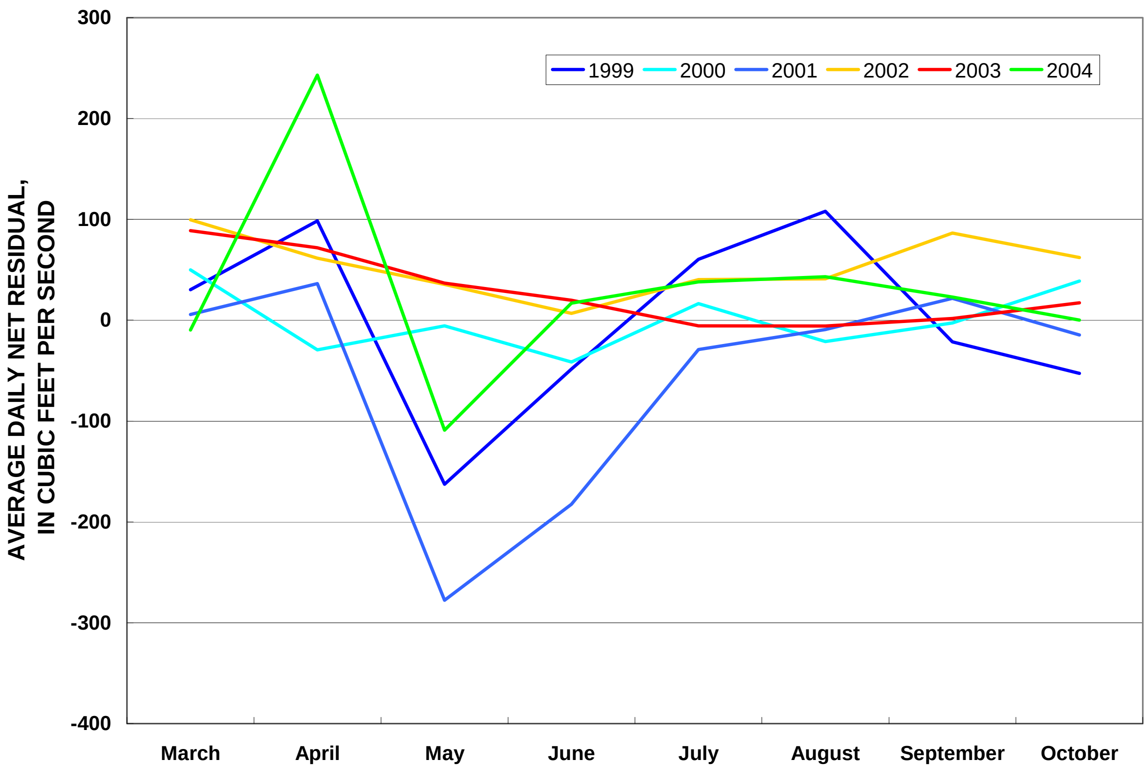
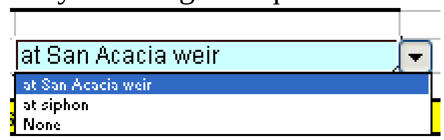


Figure 19. Average daily gains and losses in the Rio Grande between the Lower San Juan Riverside Drain and San Acacia Dam. Color coding grades from red (driest water year) to dark blue (wettest water year) for the period of record.

enforcement at San Acacia Dam resulted in lower flows at the upstream sites because the instream-flow requirements were partly made up by the accretions, thus allowing larger diversions at the siphon.

The third option ("None") reverses the priority of allocation from the instream-flow requirement to the irrigation demand. In essence, this option is the equivalent of giving the first right to the water to the irrigation demand for the siphon. In practice, selecting this option effectively sets all the instream-flow requirements (including those of the Biological Opinion) to zero. By selecting the aqua-colored box in figure 18, a drop-down list appears with the three choices. The enforcement option is selected by clicking on the desired choice. If no option is specifically chosen, the model will use the enforcement location from the previous run.



Changes in the instream-flow requirements can have major influences on water availability for the siphon diversion and on the discharges estimated at the habitat sites. Any of the discharges listed under the heading of "Instream-flow requirements," in figure 18 can be changed on the Parameters page, although the two entries highlighted by pink backgrounds are specified in the Biological Opinion and should not be altered. The column labeled "Instream-flow override" (the tan shaded column in figure 18) was added as an easy mechanism to insert instream-flow requirements that are larger than those specified by the Biological Opinion. In the example shown in figure 18, the instream-flow requirements during wet and average years are dictated by the flows specified in the Biological Opinion. In dry years, the flow specified in the Biological Opinion for the June 16–November 15 time period (0 ft^3/s) would be overridden with a requirement of 10 ft^3/s (to be enforced at San Acacia Dam).

Conditional Formatting Thresholds

Conditional formatting is a feature available with Excel® spreadsheets that allows the background of a cell to change color based on one or more specified conditions. The most common use of conditional formatting in the RGHTS is for scoring the results for state variables on the "Yearly Habitat" and "Composite" scoring pages. In general, if the value of a state variable increases by a specified amount (generally by 10 percent or more), its scoring cell is formatted to change to a green background. If the value of the state variable is reduced by a comparable amount, the cell background is formatted to turn red. This feature was incorporated to provide decisionmakers with a quick visual picture of the overall results of a model run. For example, an alternative resulting in mostly green cells would likely be considered more effective than one where all the cells turned red.

The thresholds at which the cells change color can be specified by the user for two of the RGHTS state variables, siphon deliveries and connectivity. The scoring algorithm for siphon deliveries is based on the ratio between the actual delivery and the demand. The default threshold for this ratio is 75 percent. If the delivery is less than 75 percent of the demand, the scoring cell(s) turn red and if greater than or equal to 75 percent they turn green. The ratio at which the color changes occur (the threshold) can be set on a monthly basis in the appropriate cells on the Parameters page, as shown in figure 18.

The scoring algorithm for connectivity is based on a count of consecutive days under the baseline and the alternative when the connectivity index is less than a specified value. There are two thresholds for the connectivity index. The first specifies a minimally acceptable value for the index. The default value for this threshold is 0.950, but the threshold can be changed to any positive value less than 1.0. Results can be misleading when a value of 1.0 is entered in this field. Excel records numbers to the seventh decimal place, regardless of the number format used to display them. A calculated connectivity index may be 0.9999999 (effectively the same as 1.0) but still counted as a threshold violation. Therefore, the user is advised of the potential to accumulate potentially erroneous results if 1.0 is used as the threshold.

The second user-specified parameter in connectivity index table specifies the number of consecutive days that the threshold may be violated during the year without triggering a warning flag on the scoring summary. The default threshold is 5 days, but the number can be changed to any value between zero and 244 (the total number of days between March 1 and October 31). As the threshold for the minimum connectivity index is decreased or the number of allowable days in violation of the threshold is increased, the number of flagged events for a year will decrease.

San Marcial Deliveries Flag

Owing to the variability associated with the estimates of discharges needed at San Acacia to deliver the specified streamflows at San Marcial, a "leeway" factor was incorporated into the formulas used to score threshold violations for the November–June instream-flow requirements under the Biological Opinion. This accommodation was incorporated to avoid counting days when the flow downstream from San Acacia Dam was slightly lower than the estimated flow requirement. For example, the instream-flow requirement for average and dry years (cells D18 and E18) was estimated to be 200 ft^3/s. Consequently, a discharge of 199 ft^3/s would be counted as a threshold violation. Using the default of 95 percent (cell D25, fig. 18) as the "leeway" factor, a threshold violation would not be recorded unless the daily flow downstream from San Acacia Dam was less than 190 ft^3/s.

Hydroperiods

A hydroperiod is defined as the range of dates to be analyzed for the habitat time series for a species or life stage. Generally, the hydroperiod for a life stage encompasses the time period when a life stage is present, although the hydroperiod may be defined more narrowly to investigate potentially critical periods of the year. These time intervals are defined on the "Hydroperiods" page (fig. 20).

The default hydroperiods for adult *H. amarus* and connectivity extend from March 1 through October 31. Adult *H. amarus* may occupy the study area year-round, so their habitat and connectivity were considered for the entire irrigation season used in the hydrologic synthesis and habitat time-series models. The default starting date for juvenile *H. amarus* was set at May 15, corresponding to a May–June spawning period and short incubation period (Platania and Altenbach, 1998). The ending date for this life stage depends on when the fish have grown sufficiently to be considered adults. The default ending date was set as July 15, but any end date can be entered, provided that it is later than the start date.

The default hydroperiod for nesting *E. t. extimus* extends from June 1 to August 15, but the hydroperiod can be changed in a fashion similar to the hydroperiods for *H. amarus*. Our information suggested that *E. t. extimus* nests sometime in late May or early June (Sogge and others, 1997; Craig and Williams, 1998; Moore, 2005), but specific dates were not available and may vary from year to year. Presumably, the nesting hydroperiod would include the time period between nest building and

		Date Range					Day of Year		Summary Page Display		
		Default		**User Inputs**			(Julian date - do not overwrite)		(Do not overwrite)		
Species	**Season**	Start	End	Start	End		Start	End			
RGSM	Young of Year	5/15	7/15				136	197	May-15	Jul-15	May-15 - Jul-15
	adult	3/1	10/31				60	304	Mar-01	Oct-31	Mar-01 - Oct-31
SWWF	Nesting	6/1	7/15				152	196	Jun-01	Jul-15	Jun-01 - Jul-15
Connectivity		3/1	10/31				60	304	Mar-01	Oct-31	Mar-01 - Oct-31

Figure 20. The "Hydroperiods" page of the Rio Grande habitat time-series workbook.

fledging. The hydroperiod can be extended, however, to include the departure of birds to their winter habitats.

The hydroperiod can also be adjusted to examine specific periods considered to be biologically important or when a target organism might be especially vulnerable to reduced streamflow. For example, to examine the effects of the siphon only during the months of July and August, the starting date would be July 1 and the ending date, August 31. The habitat metrics on the scoring pages would be confined to that 2-month interval.

Starting and ending dates entered into the columns labeled "User Inputs" (indicated by the yellow and tan blocks, respectively, in figure 20) will override the dates in the default cells. The dates used in the habitat time-series analysis for a run are automatically recorded on the scoring summary pages. No information is provided, however, to delineate overridden or default hydroperiods. Hydroperiods are copied automatically to the run archive if that option is used on the Parameters page.

The large grey area to the right of the "User Inputs" (yellow and tan) cells on the Hydroperiods page contains formulas to convert the starting and ending dates to Julian days. These data are used in the habitat time-series computations to determine the number of days in a hydroperiod, to flag days for which a habitat value will be computed, and to eliminate habitat calculations for days that are not applicable to the life stage (see additional discussion in section on the HABTS pages). The fields in this grey area must not be modified because doing so may invalidate the habitat time-series values.

Daily Without Siphon

The "Daily Without Siphon" page (fig. 21) contains the empirical streamflow data (light green cells) from all the stream gages used in the mass balance computations. This page also contains the computation columns for estimating the total irrigation demand at the San Acacia Dam headworks (lesser of *SMCNSA**1.1 or 265), the return flow from the San Francisco Riverside Drain Outfall (Q_{SFRDO}, eq. 6 and 7), the total discharge to the Socorro Main Canal (Q_{SMCD}, eq. 8), and the residual from the mass balance of the gage data (Q_{RES}, eq. 9). Normally, the values and formulas contained on this page would never be amended. The only circumstance justifying a modification of values on this table would be if a different (or longer) period of record were to be used. Years after 2004 could be appended to the bottom of the file but would require extending the period of record for all other computational pages and reformatting the habitat summary pages. Use of pre-1999 data would require adjustments to the measured Belen District drain flows to reflect current conditions.

		ALL VALUES IN FT^3/S											
		GAGE DATA									SFRD	CALCULATIONS	
1999 Calendar Date	1999 Julian Date	SMCNSA	RGFB	BIDB	SFRD	LSJRD	RPB	LFC	RGFSA	Irrigation Demand (Q_{SMCID})	Outfall Estimate (Q_{SFRDO})	Canal Diversion (Q_{SMCD})	Residual (Q_{RES})
03/01/99	60	82 0	894.0	9.6	8.5	52.0	0.01	0.0	870.0	90.2	0	72	5
03/02/99	61	136 0	817.0	9.4	8.5	52 0	0.04	0.0	770.0	149.6	0	132	42
03/03/99	62	178 0	659.0	12.0	10.0	52.0	0.05	0.0	741.0	195.8	0	174	213
03/04/99	63	248 0	526.0	26.0	18.0	53.0	0.05	0.0	492.0	265	1	222	143
03/05/99	64	273 0	461.0	60.0	19.0	54.0	0.04	0.2	422.0	265	2	188	102
03/06/99	65	269 0	422.0	63.0	16.0	56.0	0.05	0.2	386.0	265	2	188	103
03/07/99	66	268 0	482.0	59.0	11.0	72.0	0.05	0.2	397.0	265	1	196	47
03/08/99	67	238 0	519.0	60.0	13.0	136 0	0.05	0.2	460.0	261.8	1	190	3
03/09/99	68	239 0	580.0	23.0	10.0	130 0	0.09	0.3	450.0	262.9	1	231	-21

Figure 21. Portion of the "Daily Without Siphon" page of the Rio Grande habitat time-series workbook.

Daily With Siphon

The "Daily With Siphon" page (fig. 22) contains much of the same information as the "Daily Without Siphon" page in columns D through N. These columns have been hidden in figure 22 to accommodate the new information generated on this page, specifically in column A and columns O through AB.

Column A contains a code that classifies the water year as being wet, average, or dry. The codes reflect the hydrologic conditions for each year, classified according to the definitions of year types contained in the Biological Opinion (U.S. Fish and Wildlife Service, 2003b). Column O contains the estimated discharge in the Rio Grande immediately upstream from San Acacia Dam (Q_{RGASAD}, eq. 10). The potential total demand for the siphon diversion is calculated in column N (Q_{SD}, eq. 13). Columns Q, R, and S contain the various instream-flow requirements for the date (column B) and water year type (column A), copied from the instream-flow requirements table on the "Parameters" page. The "Critical" instream flow demand (column T) is the largest of the values listed in columns Q–S. The total discharge available for diversion at the siphon (Q_{AVS}, eq. 11 or eq. 12) is calculated in column U. The actual siphon diversion (column V) is the lesser of the demand (column P) or the amount available (column U). The portion of the total irrigation demand not met by the siphon diversion must be delivered at the San Acacia Dam headworks and is calculated in column X (Q_{SMC}, eq. 14). The total discharge remaining downstream from San Acacia Dam for delivery to San Marcial to satisfy the conditions of the Biological Opinion (Q_{RGBSAD}, eq. 15) is calculated in column Y. Column Z contains a record of the amount, if any, that the streamflow downstream from San Acacia Dam was less than the Biological Opinion demand. This information is not used directly in the RGHTS, so column Z has been hidden in figure 22. Columns AA and AB contain counts of days under the baseline and the alternative, respectively, when the discharge downstream from San Acacia Dam is less than the Biological Opinion Demand by an amount specified by the "leeway" factor discussed on the "Parameters" page. This information is summarized for each year in the period of record on the "Composite Summary" page.

	A	B	C	O	P	Q	R	S	T	U	V	X	Y	AA	AB
1															
2				ALL VALUES IN FT³/S											
3				CALCULATIONS											
4	Wet, Dry or Avg. Year	1999 Calendar Date	1999 Julian Date	Rio Grande Flow above San Acacia w/o Siphon (QRGASAD)	Potential Siphon Demand (QSD)	Instream Flow Fishery Demand	Bio. Opinion Fishery Demand (Nov-Jun)	Bio. Opinion Fishery Demand (Jun-Nov)	Critical Instream Flow Demand (max of Q, R, S)	Available for Siphon Diversion (QAVS)	Actual Siphon Diversion (QSDIV)	Socorro Main Canal Diversion (QSMC)	Rio Grande Flow below San Acacia (QRGBSAD)	Day Count QRGBSA < Bio Op Demand (Baseline)	Day Count QRGBSA < Bio Op Demand (Alternative)
5	D	03/01/99	60	942	72	0	200	0	200	43	43	29	870	0	0
6	D	03/02/99	61	902	132	0	200	0	200	43	43	89	770	0	0
7	D	03/03/99	62	915	174	0	200	0	200	43	43	131	741	0	0
8	D	03/04/99	63	714	222	0	200	0	200	44	44	178	492	0	0
9	D	03/05/99	64	610	188	0	200	0	200	45	45	143	422	0	0
10	D	03/06/99	65	574	188	0	200	0	200	47	47	141	386	0	0
11	D	03/07/99	66	594	196	0	200	0	200	63	63	133	397	0	0
12	D	03/08/99	67	650	190	0	200	0	200	127	127	63	460	0	0
13	D	03/09/99	68	681	231	0	200	0	200	121	121	110	450	0	0
14	D	03/10/99	69	576	229	0	200	0	200	115	115	114	347	0	0
15	D	03/11/99	70	494	204	0	200	0	200	100	100	104	290	0	0
16	D	03/12/99	71	538	208	0	200	0	200	98	98	110	329	0	0

Figure 22. Portion of the "Daily With Siphon" page of the Rio Grande habitat time-series workbook.

Flows

The "Flows" page (fig. 23) contains a daily listing of the discharges at each of the habitat simulation sites for the baseline (Flow without Siphon) and alternative (Flow with Siphon) condition. Discharges without the siphon (columns C, D, and E) are calculated using equations 16, 17, and 18, respectively, and discharges with the siphon (columns F, G, and H) are calculated using equations 19,

	A	B	C	D	E	F	G	H
3			Flow Without Siphon (cfs)			Flow With Siphon (cfs)		
4	**Calendar Date**	**Julian Day**	Rio Salado Site	Sevilleta Site	Rio Puerco Site	Rio Salado Site	Sevilleta Site	Rio Puerco Site
5	03/01/99	60	941.9	939.5	937.6	898.9	896.5	894.6
6	03/02/99	61	897.5	877.5	862.5	854.5	834.5	819.5
7	03/03/99	62	891.8	789.7	713.1	848.8	746.7	670.1
8	03/04/99	63	698.2	629.5	578.1	654.2	585.5	534.1
9	03/05/99	64	598.5	549.5	512.7	553.5	504.5	467.7
10	03/06/99	65	562.4	512.9	475.8	515.4	465.9	428.8
11	03/07/99	66	588.4	565.8	548.8	525.4	502.8	485.8
12	03/08/99	67	650.2	648.7	647.7	523.2	521.7	520.7
13	03/09/99	68	683.1	693.2	700.7	562.1	572.2	579.7
14	03/10/99	69	579.9	597.1	609.9	464.9	482.1	494.9
15	03/11/99	70	499.6	524.2	542.7	399.6	424.2	442.7
16	03/12/99	71	541.8	560.4	574.4	443.9	462.4	476.4
17	03/13/99	72	620.1	622.4	624.2	498.1	500.4	502.2
18	03/14/99	73	654.5	691.8	719.8	507.5	544.8	572.8
19	03/15/99	74	794.4	746.3	710.2	648.4	600.3	564.2

Figure 23. Portion of the "Flows" page of the Rio Grande habitat time-series workbook.

20, and 21. These are the discharges used in the HABTS pages to calculate the daily habitat time series values.

RGSM_HQ

The "RGSM_HQ" page (fig. 24) contains the lookup tables used along with the discharges from the "Flows" page in the calculation of the habitat time series for each life stage or species. The site to which the lookup table applies is shown in the upper left-hand corner of each table. The term "Normalized" immediately below the site name indicates the type of data (and units) contained in the habitat columns.

There are three basic expressions of habitat areas that can be used in a habitat time series. The first is the total habitat for the site, in units of area (for example, square meters, acres, or hectares), exactly as the data were exported from the GIS application. The second type is a normalized habitat area, where the total habitat area is divided by the length of the site and units are expressed as square meters per kilometer, acres per mile, or hectares per kilometer. Habitat areas are normalized to compensate for sites having different lengths, which has a direct influence on the total wetted surface area from which habitat areas are calculated. Normalization allows for a more direct side by side comparison of the amount of habitat in multiple sites at the same discharges. The third approach is to multiply the normalized habitat area by the length of stream represented by each site to derive a total habitat area for a river segment. We have chosen the second option, normalized habitat area, for all computations associated with the habitat time series discussed in this report.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Rio Puerco		CFS	CFS	RGSM_YOY		RGSM_AD		RGSM_YOY		RGSM_AD		SWWF			
2	Normalized	Min	0			With	LWD			Without	LWD				CONNECTIVITY INDE	
3		Max	11500		3	4	5	6	7	8	9	10	11	12	13	14
4			Upper_LoFl	Upper_HiFl	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
5		CFS	0	5	0	227	0	303	0	13,286	0	13,340	53,163.0	59,706	0.521	0.798
6			5	10	227	325	303	438	13,286	16,540	13,340	16,668	59,706	60,420	0.798	0 995
7			10	20	325	480	438	630	16,540	19,660	16,668	20,037	60,420	61,116.4	0.995	0 994
8			20	40	480	596	630	775	19,660	21,449	20,037	22,493	61,116.4	61,636.5	0.994	0 997
9			40	60	596	636	775	832	21,449	20,576	22,493	23,351	61,636.5	62,050.1	0.997	0 999
10			60	80	636	642	832	863	20,576	18,317	23,351	23,289	62,050.1	62,523.5	0.999	1 000
11			80	100	642	646	863	899	18,317	16,021	23,289	22,740	62,523.5	62,749.5	1.000	1 000
12			100	150	646	656	899	932	16,021	11,575	22,740	20,259	62,749.5	64,092.4	1.000	1 000
13			150	200	656	596	932	860	11,575	9,055	20,259	16,703	64,092.4	64,661.6	1.000	1 000
14			200	300	596	458	860	674	9,055	6,020	16,703	9,516	64,661.6	65,144.7	1.000	1 000
15			300	400	458	318	674	494	6,020	4,542	9,516	6,465	65,144.7	65,507.0	1.000	1 000
16			400	500	318	240	494	376	4,542	3,433	6,465	4,763	65,507.0	65,818.9	1.000	1 000
17			500	600	240	186	376	281	3,433	2,299	4,763	3,360	65,818.9	66,217.5	1.000	1 000
18			600	800	186	95	281	152	2,299	1,557	3,360	1,828	66,217.5	67,307.8	1.000	1 000
19			800	1,000	95	64	152	92	1,557	1,733	1,828	1,804	67,307.8	68,719.5	1.000	1 000
20			1,000	5,000	64	64	92	92	1,733	1,733	1,804	1,804	68,719.5	68,719.5	1.000	1 000
21			5,000		64		92		1,733		1,804		68,719.5		1.000	

Figure 24. Example of a discharge-habitat lookup table (Rio Puerco site) found on the “RGSM_HQ” page of the Rio Grande habitat time-series workbook.

The format of the lookup tables may seem confusing but was designed for computational efficiency in the habitat time-series calculations. The values contained in a column for discharge or habitat for a life stage are offset and repeated in the adjacent column. For example, the discharges contained in the lookup table ranged from 0 to 1,000 ft^3/s as listed in column C. The same discharges are offset (moved up one row) in column D. Normalized habitat areas for juvenile *H. amarus* (with LWD as a habitat component) for the flow range 0–1,000 ft^3/s are contained in column E. These same normalized habitat areas are offset (moved up one row) in column F. This format is repeated for RGSM Adults with LWD (columns G and H), RGSM Juveniles without LWD (columns I and J), RGSM Adults without LWD (columns K and L), *E. t. extimus* (columns M and N), and connectivity index (columns O and P). This design was used to facilitate linear interpolation of habitat areas for discharges in the flow time series that were intermediate to flows recorded in the lookup tables (see discussion of HABTS pages for more details).

A blue background in a lookup table cell indicates that its value was stipulated. For example, the habitat area at 0 ft^3/s was assigned a value of 0 m^2 per km. The rationale for this stipulation is as follows. At zero discharge there would be no velocity in any of the wetted patches. Our criteria (table 2) specified that zero velocity would be unsuitable. Therefore, it follows that suitable habitat area at zero discharge would be zero, and no actual habitat simulations were necessary. Habitat values for *E. t. extimus* habitat and connectivity, however, were based on actual zero-discharge simulation estimates.

The upper limit of discharges entered into the lookup tables was 5,000 ft^3/s. Habitat values for 1,000 ft^3/s were copied to their corresponding locations for 5,000 ft^3/s, but none of these values were used in the habitat time series. Our highest simulated discharge was 1,000 ft^3/s, but many of the flows in the hydrologic series exceeded that value. Rather than extrapolating habitat values for discharges above 1,000 ft^3/s, we confined the habitat time-series analysis to discharges less than or equal to 1,000 ft^3/s. Habitat values for 5,000 ft^3/s were replicated simply to avoid the possibility of returning a #NA# (not applicable) value for the time step.

HABTS_<Site Name>

The RGHTS workbook contains three “HABTS” pages, one for each of the study sites: HABTS_RIO_PUERCO, HABTS_SEVILLETA, and HABTS_RIO_SALADO). As illustrated in figure 25, each page can be divided into three basic types of information: Header information (light green background), Flow data (light blue background, and Habitat computations (tan background).

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	**Rio Grande**					**RGSM_Adult With LWD**							
2	**Rio Puerco Site**						**Inseason**						
3						**Total days**	**244**						
4						**Inseason**	**1**						
5						**Start Day**	**60**						
6						**End day**	**304**						
7	**Date**	**Baseline**	**Scenario**	**Day of Year**	**Base Slope**	**Scen Slope**	**Season**	**Base Norm Area**	**Scenario Norm Area**	**Inseason Base**	**Inseason Scene**	**Base <50% Flag**	**Scen <50% Flag**
8	04/26/99	511.02	415 26	116	0.11	0.15	1	365	476	365	476	na	na
9	04/27/99	576.10	461 50	117	0.76	0 61	1	304	421	304	421	na	na
10	04/28/99	568.43	452 25	118	0.68	0 52	1	311	432	311	432	na	na
11	04/29/99	688.82	581 84	119	0.44	0 82	1	224	298	224	298	1	1
12	04/30/99	619.22	509.44	120	0.10	0 09	1	269	367	269	367	1	na
13	05/01/99	615.76	494 82	121	0.08	0 95	1	271	382	271	382	na	na
14	05/02/99	749.42	622 60	122	0.75	0.11	1	185	267	185	267	1	1
15	05/03/99	1223.87	1115 67	123	0.06	0 03	1	92	92	na	na	na	na
16	05/04/99	2172.50	2076 06	124	0.29	0 27	1	92	92	na	na	na	na
17	05/05/99	2419.81	2308 67	125	0.35	0 33	1	92	92	na	na	na	na
18	05/06/99	2589.89	2477.77	126	0.40	0 37	1	92	92	na	na	na	na

Figure 25. Portion of the "HABTS_RIO_PUERCO" page of the Rio Grande habitat time-series workbook.

Header Information

Header information includes the name of the target species or life stage to which the habitat computations apply and information related to the hydroperiod for the target organism. The start and end days refer to the Julian day of the year and are copied directly from the "Hydroperiods" page. The total days within the hydroperiod are calculated as the difference between the end and start days. The entries labeled "Inseason" and "1" indicate the flag used to mark dates that fall within the hydroperiod for the target organism.

Flow Data

Most of the entries in the "Flow Data" category (light blue highlight in figure 25) are copied directly from the "Flows" page of the RGHTS workbook. These entries include the Date (column A), the daily discharge calculated for the baseline (column B), the daily discharge calculated for the alternative (column C), and the Julian day (column D). The two columns labeled "Base Slope" and "Scen (Scenario) Slope" contain values calculated for linear interpolation of habitat values. The "slopes" are actually ratios representing the linear distance of a discharge in column B or column C from the lower bracket of the flow range of the lookup tables (RGSM_HQ) that would contain the interpolated discharge. For example, the baseline discharge on April 26, 1999, was 511 ft^3/s (cell B8, fig. 25). The flow range in the lookup table containing that discharge would be between 500 ft^3/s and 600 ft^3/s. The "slope" for that discharge is calculated as:

$$Slope = (Q_{INT} – Q_{LB}) / (Q_{UB} – Q_{LB}) \qquad (22)$$

where Q_{INT} is the interpolation discharge, Q_{LB} is the lower bracket of the flow range in the lookup table and Q_{UB} is the upper bracket of the flow range. For our example, the "slope" for a discharge of 511 ft^3/s would be

$$Slope_{Q511} = (511–500)/(600–500) = 0.11 \text{ (the value in cell E8, fig. 25).}$$

Simply stated, this means that a discharge of 511 ft^3/s is 11 percent of the distance between 500 ft^3/s and 600 ft^3/s.

Habitat Computations

The first entry under the category of "Habitat Computations" is located under column G (fig. 25) labeled "Season." In this column, the program tests the Julian day in column D against the start and end days for the hydroperiod. If the Julian day in column D falls between the range of days for the hydroperiod (cells G5 and G6), a value of 1 is recorded for the day. If the Julian day in column D is outside the hydroperiod, a value of 0 is recorded. For example, in figure 25, the “Season” flags for April 26–May 6 are all 1, indicating that the dates are to be included in the adult hydroperiod.

The habitat values corresponding to the daily discharges listed in columns B and C are located in columns H and I, labeled “Base Norm Area” and “Scenario Norm Area” respectively. These habitat values are determined by the following process:

1. The flow range corresponding to the daily discharge for the date is found in the lookup table.
2. The habitat area corresponding to that discharge is calculated as:

$$HA_Q = Slope_Q * (HA_{UB} – HA_{LB}) + HA_{LB} \quad (23)$$

where HA_Q is the habitat area corresponding to the daily discharge, $Slope_Q$ is the slope for the discharge calculated in equation 22, HA_{UB} is the habitat area for the upper bracket of habitat areas from the lookup table (for example, column H in figure 24), and HA_{LB} is the habitat area for the lower bracket (for example, column G in figure 24). Following the example for a discharge of 511 ft^3/s, the habitat area for adult *H. amarus* (with LWD) corresponding to the upper bracket (600 ft^3/s) is 281 m^2/km and 376 m^2/km for the lower bracket (500 ft^3/s). The habitat area associated with a discharge of 511 ft^3/s is calculated as:

HA_{Q511} = 0.11 * (281–376) + 376 = 365 (the value in cell H8, fig. 25).

The cells labeled as “In season Base” and “In season Scene” (for example, columns J and K in figure 25) contain the interpolated habitat values only for the dates that are included in the hydroperiod for the target organism and for discharges less than or equal to 1,000 ft^3/s. If the habitat value falls outside the hydroperiod, or the discharge is greater than 1,000 ft^3/s, a value of “na” (not applicable) is returned for the cell. Otherwise, the values in this column are the same as those in columns H and I.

The scoring algorithms for the habitat-related state variables in the RGHTS model are based on an average of the lowest 50 percent of the habitat areas recorded for a hydroperiod. Several functions are performed simultaneously in the columns labeled “Base <50% Flag” and “Scen <50% Flag” (columns L and M in figure 25):

1. All the numerical values in columns H and I (nothing flagged as “na”) are ranked according to magnitude and the total number of numerical values summed.
2. A probability of exceedance associated with each rank is calculated (Probability = Rank/ n+1).
3. If the value in column H or I has an exceedance probability of 50 percent or higher, the cell in column L or M, respectively is flagged with a “1.” This indicates that the habitat value in column H or I is in the lower 50 percent (below the median) of the values for the hydroperiod.
4. The below-median flags are used to calculate the habitat scoring metric for the hydroperiod, discussed in the “Yearly Habitat” section.

Yearly Habitat

The “Yearly Habitat” page contains an annual compilation of the habitat metrics for each site and target organism and the percentage difference between the metrics for the baseline and alternative (fig. 26). There are three tables of habitat statistics on the “Yearly Habitat” page, one for each study site. Each table contains groupings of habitat values, arrayed by year (column A) and by target organism (for example, YOY with LWD in columns B–D in figure 26). The hydroperiod used in the habitat calculations for each target organism is listed immediately below the target organism label. This feature was added to assist users in distinguishing otherwise identical runs that differed only by the hydroperiod used in the analysis.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1																			
2		YOY with LWD			Adult with LWD			YOY without LWD			Adult without LWD			ectivity (Consecutive days below thre			SWWFC		
3	Rio Puerco Site	15-May	through	15-Jul	1-Mar	through	31-Oct	15-May	through	15-Jul	1-Mar	through	31-Oct	1-Mar	through	31-Oct	1-Jun	through	15-Jul
4	Water Year	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (Days)	Alternative (Days)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)
5	1999	85.1	112.7	32.45%	170.7	209.4	22.63%	1,618.9	1,746.1	7.85%	2,208.1	2,622.9	18.79%	0	0	0%	66,983.2	66,423.1	-0.84%
6	2000	181.6	221.0	21.67%	287.1	344.9	20.11%	2,406.5	3,041.0	26.37%	3,560.4	4,383.1	23.11%	0	0	0%	65,685.5	65,488.3	-0.30%
7	2001	199.8	222.3	11.27%	329.4	377.6	14.62%	1,640.1	1,729.6	5.46%	4,249.6	5,045.3	18.73%	0	0	0%	65,308.7	65,004.3	-0.47%
8	2002	504.3	543.5	7.79%	678.7	697.7	2.81%	7,368.9	9,198.6	24.83%	11,640.3	14,411.1	23.80%	0	0	0%	63,163.8	62,202.6	-1.52%
9	2003	444.9	415.8	-6.55%	645.1	458.1	-29.00%	8,022.7	8,681.8	8.22%	12,936.8	10,824.2	-16.33%	0	16	1600%	61,913.0	61,448.7	-0.75%
10	2004	447.3	434.3	-2.90%	408.9	257.0	-37.17%	3,860.1	4,560.7	18.15%	7,559.9	5,582.4	-26.16%	1	20	1900%	62,841.3	61,792.2	-1.67%
11																			
12		YOY with LWD			Adult with LWD			YOY without LWD			Adult without LWD			ectivity (Consecutive days below thre			SWWFC		
13	Sevilleta Site	15-May	through	15-Jul	1-Mar	through	31-Oct	15-May	through	15-Jul	1-Mar	through	31-Oct	1-Mar	through	31-Oct	1-Jun	through	0-Jan
14	Water Year	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (Days)	Alternative (Days)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)
15	1999	54.5	52.8	-3.00%	80.6	83.2	3.33%	3,750.7	3,847.5	2.58%	5,051.2	5,641.1	11.68%	0	0	0%	28,588.8	28,374.2	-0.75%
16	2000	55.1	64.2	16.57%	92.8	111.3	19.91%	4,795.9	5,467.5	14.00%	6,943.1	8,527.3	22.82%	0	0	0%	28,235.9	28,184.3	-0.18%
17	2001	62.7	73.0	16.39%	112.8	133.1	17.96%	5,106.8	5,570.8	9.09%	8,242.2	9,370.1	13.68%	0	0	0%	27,880.6	27,441.1	-1.58%
18	2002	180.6	182.2	0.85%	222.0	218.6	-1.53%	10,275.9	11,668.8	13.56%	15,489.9	17,186.4	10.95%	0	0	0%	25,691.2	24,778.8	-3.55%
19	2003	139.1	137.0	-1.51%	198.5	187.3	-5.64%	10,162.4	10,553.8	3.85%	16,084.5	14,349.8	-10.79%	0	4	400%	24,369.9	24,019.4	-1.44%
20	2004	156.9	147.1	-6.27%	137.9	138.5	0.42%	9,428.5	10,336.4	9.63%	10,878.2	10,314.6	-5.18%	0	2	200%	25,562.8	24,592.9	-3.79%
21																			
22		YOY with LWD			Adult with LWD			YOY without LWD			Adult without LWD			ectivity (Consecutive days below thre			SWWFC		
23	Rio Salado Site	15-May	through	15-Jul	1-Mar	through	31-Oct	15-May	through	15-Jul	1-Mar	through	31-Oct	1-Mar	through	31-Oct	1-Jun	through	0-Jan
24	Water Year	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (Days)	Alternative (Days)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)
25	1999	64.3	64.5	0.24%	97.7	101.5	3.88%	4,512.4	4,513.2	0.02%	5,481.7	5,543.5	1.13%	0	0	0%	35,052.8	34,854.5	-0.57%
26	2000	78.8	88.9	12.80%	114.7	129.6	13.04%	4,491.6	4,634.5	3.18%	5,775.3	6,153.3	6.55%	0	0	0%	34,214.6	34,058.4	-0.46%
27	2001	84.4	86.2	2.12%	127.6	137.3	7.61%	4,661.2	4,811.4	3.22%	6,149.5	6,420.8	4.41%	0	0	0%	33,753.4	33,485.0	-0.80%
28	2002	138.5	155.9	12.59%	196.6	225.4	14.67%	6,550.9	7,404.1	13.02%	8,276.8	9,572.8	15.66%	0	0	0%	32,704.2	32,282.6	-1.29%
29	2003	139.9	145.8	4.21%	218.0	206.8	-5.16%	6,955.1	7,328.9	5.38%	9,423.4	9,198.9	-2.38%	0	6	600%	31,982.2	31,769.4	-0.67%
30	2004	124.1	137.2	10.59%	154.5	167.0	8.07%	6,063.6	6,637.0	9.46%	7,154.3	7,817.1	9.26%	0	0	0%	32,746.2	32,282.8	-1.41%

Figure 26. The "Yearly Habitat" scoring summary page in the Rio Grande habitat time-series model.

The habitat areas associated with the baseline and alternative for a target organism are recorded in the columns labeled "Base (m^2/km)" and "Alternative (m^2/km)," illustrated in columns B and C (fig. 26). These habitat areas were normalized according to reach length with units of square meters per kilometer and represent the average of the lowest 50 percent of the "In season" values for each year. The average of the lowest 50 percent of the habitat areas is one of several metrics that could have been used to define potentially limiting habitat events. A number of studies relating fish populations to habitat dynamics (Nehring and Anderson, 1993; Bovee and others, 1994; Bowen, 1996; Freeman and others, 2001: Bowen and others, 2003; Capra and others, 2003) found that fish population responses were more highly associated to the lowest habitat areas occurring in the time series than they were to other statistical metrics (for example, the average of all events in the series). By definition, the lowest habitat events in a time series are those occurring below the median and this metric has been the standard for many instream flow studies (Bovee and others, 2007; Bovee and others, 2008).

The percent change from the baseline condition is calculated as

$$\Delta(\%) = (HA_{ALT} – HA_{BASE}) / HA_{BASE} \quad (24)$$

where $\Delta(\%)$ is the percentage change in habitat area from the baseline, HA_{ALT} is the (normalized) habitat area for the alternative, and HA_{BASE} is the (normalized) habitat area for the baseline. The percent change in each habitat metric is listed annually under the columns labeled "Δ(%)" (Columns D, G, J, M, and S in figure 26).

Scoring of the connectivity index (columns N, O, and P in figure 26) was based on the maximum number of consecutive days during the year that the index was lower than a user-specified threshold entered on the Parameters page. In this case, the change from the baseline condition was calculated as the percent change in the number of days below the threshold and is recorded in column P. The calculation of "Δ(%)" for connectivity differs somewhat from its counterparts for habitat area, stemming primarily from the potential of dividing by zero. If the number of days below the threshold for both the baseline and alternative is zero, "Δ(%)" is set to zero. If the number of days below the threshold is zero under the baseline, but nonzero under the alternative, "Δ(%)" is calculated simply as:

$$\Delta(\%) = (DBT_{ALT} – DBT_{BASE}) / 1 \quad (25)$$

where DBT_{ALT} and DBT_{BASE} are Days Below Threshold for the alternative and baseline respectively, expressed as a percentage. For example, in 2003 at the Rio Puerco site there were no threshold violations under the baseline, but 16 days were below the threshold under the alternative, resulting in a recorded 1,600 percent increase (Cell P9, fig. 26).

Cells under the "Δ(%)" columns for the habitat metrics were conditionally formatted to highlight potentially significant changes from the baseline condition. If the alternative results in an increase in habitat area of 10 percent or more, the background of the cell turns green. If the alternative results in a comparable decrease in habitat area, the background of the cell turns red. Owing to uncertainties associated with data-collection errors and modeling simplifications, changes of less than 10 percent in either direction are not color coded.

Conditional formatting for the "Δ(%)" for the connectivity index is the opposite of that for the habitat area metrics because it is based on threshold violations rather than habitat areas. If the number of connectivity threshold violations increases by more than 10 percent, the background of the "Δ(%)" column will turn red. In addition, if the number of days below threshold in columns N or O exceed the number of allowable days recorded on the Parameters page, those cell background will turn red as well. As with the conditional formatting protocols for the other state variables in the RGHTS, this color coding was designed to assist the decisionmakers by providing a quick visual summary of the results of a model run.

Composite Summary

The "Composite Summary" page (fig. 27) consists of scoring metrics that are an aggregate of all the pertinent state variables related to the entire study area. The upper table on this page contains aggregated habitat values for all three sites, combined as length-weighted averages of the corresponding values from the "Yearly Habitat" summary. The metrics for connectivity on this page represent the "worst case" scenario, found as the maximum number of consecutive days below the threshold among the three sites (for example, the maximum of cells O9, O19, and O29 in figure 26).

Two state variables that were not included on the Yearly Habitat page were added to the Composite Summary. The first is a comparison of siphon demands and deliveries for each year. The acceptable ratios between demands and deliveries were entered as threshold values on the Parameters page. If the amount of water delivered by the siphon exceeds the specified threshold, the background of the cell is formatted to turn green. In years when the siphon delivery is less than the demand by the ratio expressed as the threshold, the cell background turns red.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	All Site	RGSM YOY with LWD			RGSM Adult with LWD			RGSM YOY without LWD			RGSM Adult without LWD			Connectivity (Consecutive days below threshold)			SWWFC		
2	Composite Scores	15-May	through	15-Jul	1-Mar	through	31-Oct	15-May	through	15-Jul	1-Mar	through	31-Oct	1-Mar	through	31-Oct	1-Jun	through	0-Jan
3	Water Year	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)	Base (Days)	Alternative (Days)	Δ (%)	Base (m^2/km)	Alternative (m^2/km)	Δ (%)
4	1999	66.6	73.7	10.73%	111.9	125.0	11.69%	3,437.1	3,507.2	2.04%	4,418.9	4,767.0	7.88%	0	0	0%	41,618	41,313	-0.73%
5	2000	98.9	116.8	18.07%	154.8	182.9	18.15%	4,020.9	4,488.8	11.64%	5,576.3	6,507.9	16.71%	0	0	0%	40,825	40,695	-0.32%
6	2001	108.7	119.3	9.72%	178.4	202.6	13.54%	3,980.9	4,226.1	6.16%	6,367.8	7,090.1	11.34%	0	0	0%	40,425	40,086	-0.84%
7	2002	255.1	273.0	6.99%	339.5	354.2	4.31%	8,106.0	9,422.9	16.25%	11,782.4	13,630.9	15.69%	0	0	0%	38,665	37,919	-1.93%
8	2003	224.4	217.7	-2.98%	329.7	269.7	-18.22%	8,395.0	8,854.3	5.47%	12,773.9	11,486.6	-10.08%	0	16	1600%	37,583	37,251	-0.88%
9	2004	225.6	223.3	-1.02%	219.3	181.8	-17.08%	6,651.0	7,379.0	10.95%	8,594.5	8,086.7	-5.91%	1	20	950%	38,545	37,739	-2.09%
10																			
11	Siphon Deliveries	ANNUAL SUM IN AF			Flows below San Acacia Dam			Discharge < Biological Opinion Threshold (Days)											
12	Water Year	Demand (AF)	Delivery (AF)	Δ (%)			Water Year	Base (Days)	Alternative (Days)	Δ (%)									
13	1999	63,059	51,889	82.29%			1999	0	0	0%									
14	2000	32,917	31,468	95.60%			2000	0	0	0%									
15	2001	36,776	36,215	98.48%			2001	0	0	0%									
16	2002	24,243	24,082	99.34%			2002	0	0	0%									
17	2003	15,114	12,341	81.66%			2003	0	0	0%									
18	2004	22,926	16,042	69.98%			2004	0	0	0%									

Figure 27. The "Composite Summary" scoring page in the Rio Grande habitat time-series model.

The second addition to the Composite Summary page is a table tracking the days when the discharge downstream from San Acacia Dam is less than the amount estimated to be necessary to provide the streamflow at San Marcial as directed by the Biological Opinion. The values listed in columns H and I in figure 27 are annual counts of the days when San Acacia discharges were smaller than the Biological Opinion thresholds. Conditional formatting of the “Δ(%)” column (J) is the same as that used for the connectivity index.

Graphics

Three pages of the RGHTS workbook contain plots of the daily flow and habitat time series for each site: Rio_Puerco_Plots, Sevilleta_Plots, and Rio_Salado_Plots. Examples of the displays provided on these pages are shown in figure 28. The primary purpose of these graphs is to preserve the chronological sequence of events in the habitat time series. Chronology is not preserved in the summary scoring tables and may be important for investigating seasonal effects of discharge and habitat. The charts contained on these pages are transient and will change as soon as a new model run is formulated. Therefore, the plots for individual runs can be saved only by printing to hard copy or saving them electronically. The plots cannot be used directly to quantify the effects of an alternative on discharges or habitat areas. They may be useful, however, in the interpretation of cause and effect mechanisms occurring in the time series or for identifying potential critical periods for closer examination by narrowing the hydroperiod.

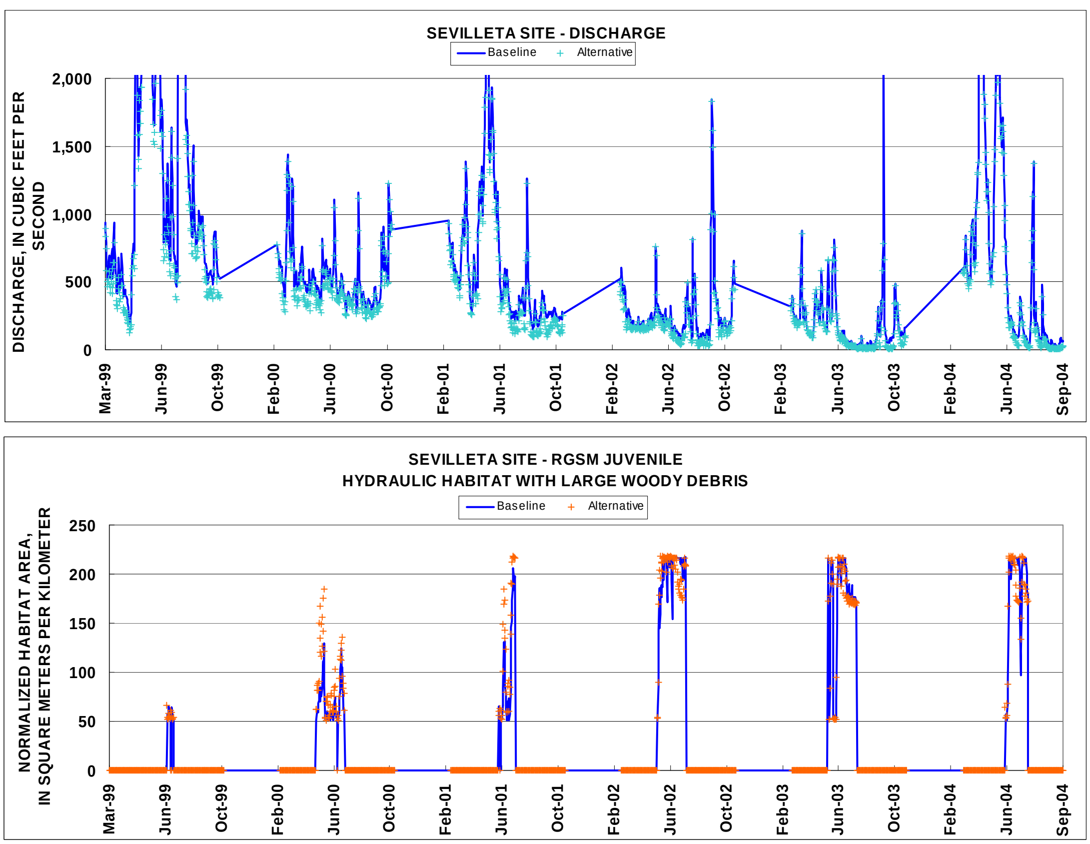


Figure 28. Examples of time-series plots available on the “<Site Name>_Plots” pages of the RGHTS workbook.

Results Archive

It takes less than a minute to set up and run an alternative through the RGHTS, but it can take hours to manually compile the operational rules and results of multiple runs for cross-comparison. The light green control bar labeled “Archive Run Results” on the Parameters page is designed to capture the scoring metrics from the scoring pages and compile them, along with pertinent details of the run setup into an archive file. When the “Archive Run Results” button is activated, the program queries the user as to whether to start a new archive. For the first run a new archive file is created, and on subsequent runs the previously created file is appended with additional results. Up to five individual runs can be compiled into a single archive file. The number of compiled runs was limited to five in order to ensure that the results from all the runs could be viewed on a single page with a minimum of scrolling.

The archive file contains three pages of information. The first page, labeled “Scenarios,” is designed to assist in run documentation. This page lists the scenarios sequentially as they are run and saved to the archive file. Pertinent information about the run includes the sequential scenario number, the run date, the instream-flow enforcement location, the instream-flow targets, and siphon delivery and minimum connectivity flags (refer to figure 42).

The second page in the archive file is entitled “Yearly_Summary” (refer to figure 43). This page contains a side-by-side summary of the run results for each study site as recorded on the “Yearly Habitat” page of the RGHTS workbook. The archive contains only the “Δ%” columns for each state variable; the actual habitat metrics are omitted to conserve space but can be retrieved from the original “Yearly Habitat” pages manually, if necessary. Each scenario is cross-referenced, by number, to the run parameters on the “Scenarios” page. The hydroperiods used for each target organism in each run are also recorded under the scenario number. This feature was added to assist users in differentiating runs where the only change from previous runs was the hydroperiod.

The third page in the archive file is the “Composite Summary” (refer to figure 44) and is organized similarly to the “Yearly Summary” page. There are two primary differences, however, between the composite and yearly summaries. First, the habitat scoring metrics are composite values for all three sites from the Composite Summary page. Second, the “Composite Summary” includes the scoring tables for siphon deliveries and San Marcial instream-flow requirements, neither of which is included on the “Yearly Summary” page.

Results

Habitat maps for all the target species, life stages, sites, and simulated discharges are contained in Appendixes 4–6. Appendix 4 contains the maps for adult and juvenile *H. amarus*. Appendix 5 contains habitat connectivity maps for discharges between 0 and 100 ft^3/s (100 percent connectivity occurred at all discharges greater than 100 ft^3/s), and Appendix 6 contains maps of the vegetation/water surface buffer intersections for *E. t. extimus*.

Habitat as a Function of Discharge

Rio Grande Silvery Minnow

Two types of habitat–discharge functions were developed for *H. amarus* from the GIS mapping exercise. The first type, termed “hydraulic habitat,” was based solely on the areas of patches having suitable depths and velocities for adults and juveniles. The second type, “hydraulic habitat with LWD,” included areas having suitable depths and velocities within the specified buffer distances from deposits of large woody debris (0.25 m for juveniles and 0.5 m for adults). Figures 29 and 30 show the relations between normalized hydraulic habitat area and discharge for *H. amarus* adults and juveniles, respectively. Figures 31 and 32 illustrate these relations for hydraulic habitat with LWD.

The normalized areas of hydraulic habitat tended to increase rapidly between 0 ft^3/s and 20 ft^3/s for adult and juvenile *H. amarus* at all three sites. Overall, the area of suitable hydraulic habitat for adults reached its maximum values at roughly the same range of discharges (40 ft^3/s to 80 ft^3/s), although the absolute peaks varied from site to site (fig. 29). Maximum hydraulic habitat area for adults was attained at 40 ft^3/s at the Rio Salado site, at 60 ft^3/s at the Rio Puerco site, and at 80 ft^3/s at the Sevilleta site. The maximum for the composite of all three sites occurred at 60 ft^3/s.

At discharges less than 150 ft^3/s, the Rio Puerco and Sevilleta sites had comparable areas of suitable hydraulic habitat for adults, but the area of this habitat type was considerably lower in the same flow range at the Rio Salado site (fig. 29). At discharges larger than 150 ft^3/s, the area of suitable hydraulic habitat for adults declined rapidly at all three sites, owing largely to increased areas having velocities in excess of the suitable range for adult *H. amarus*. Decreases in habitat area between 150 ft^3/s to 1,000 ft^3/s were most notable at the Rio Puerco site. The area of suitable hydraulic habitat for adults at the Rio Salado site tended to level off at discharges greater than 500 ft^3/s, resulting in this site having the largest area of the three at 1,000 ft^3/s.

Similar patterns in the hydraulic habitat–discharge functions for juvenile *H. amarus* were observed at the three sites. For juveniles, the optimum flow range (the flows producing the most habitat area) was narrower than for the adults and tended to be more consistent from site to site (fig. 30). This phenomenon reflected the narrower criteria range for velocities considered suitable for juveniles. Maximum habitat areas for juvenile *H. amarus* were attained at 20 ft^3/s at the Rio Salado site and at 40 ft^3/s at the Rio Puerco and Sevilleta sites. Similar to the adult curves, hydraulic habitat for juveniles declined rapidly at discharges higher than the optimum flow, but in this case, the habitat reductions started at around 60 ft^3/s. Habitat area for juveniles also tended to level off between 500 and 1,000 ft^3/s at the Rio Salado site. Unlike the adult curves, however, hydraulic habitat for juveniles increased slightly over the discharge range from 800 to 1,000 ft^3/s at the Rio Puerco site. This increase was probably related to the shallow inundation of point bars along the channel margin at these higher discharges.

When habitat areas were based on hydraulic habitat in association with large woody debris, the habitat–discharge curves differed from those for hydraulic habitat alone in several aspects (figs. 31 and 32). First, habitat areas associated with large woody debris were much smaller than for hydraulic habitat area alone. This result was expected because the habitat calculations for the former were confined to the buffered patches surrounding the debris deposits. The areas occupied by debris piles were a much smaller subset of the total wetted area of the stream, so this was a logical result. The second notable difference between the two habitat definitions was related to the shapes of the habitat–discharge functions. The hydraulic habitat–discharge curves (figs. 29 and 30) were fairly similar in shape among the sites, reflecting similarities in channel structure and hydraulics. The shapes of the habitat–discharge curves with the inclusion of LWD (figs. 31 and 32) were markedly different from site to site and commonly peaked over a different range of flows than the curves for hydraulic habitat alone. For example, the optimum flow range for adult hydraulic habitat was between 40 and 150 ft^3/s at the Rio Puerco site, with a peak at 60 ft^3/s (fig. 29). When LWD was incorporated into the habitat definition, the optimum flow range at the Rio Puerco site was between 60 and 200 ft^3/s with a peak at 150 ft^3/s (fig. 31). Similar results were obtained at the other sites and for juvenile *H. amarus* (table 5).

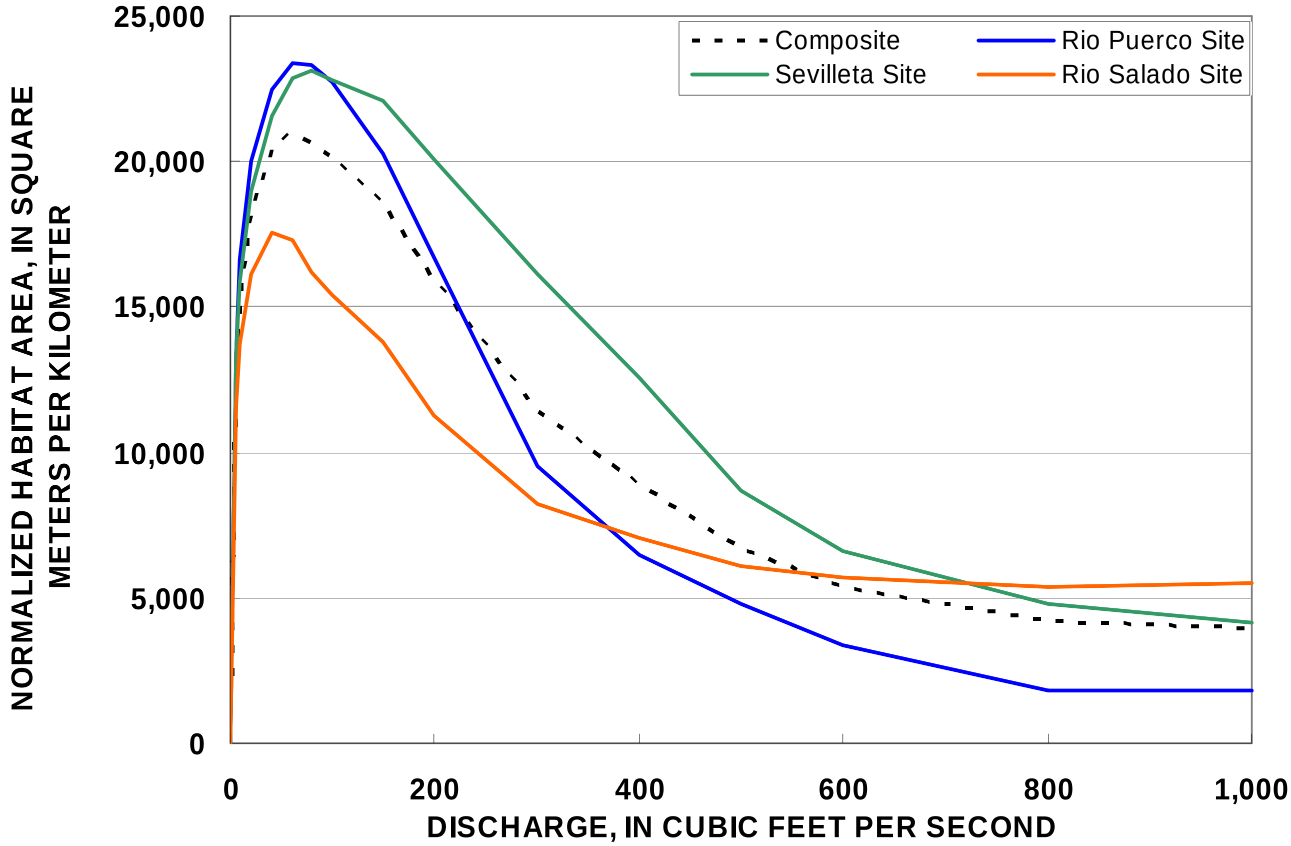


Figure 29. Normalized hydraulic habitat area as a function of discharge for adult *H. amarus*.

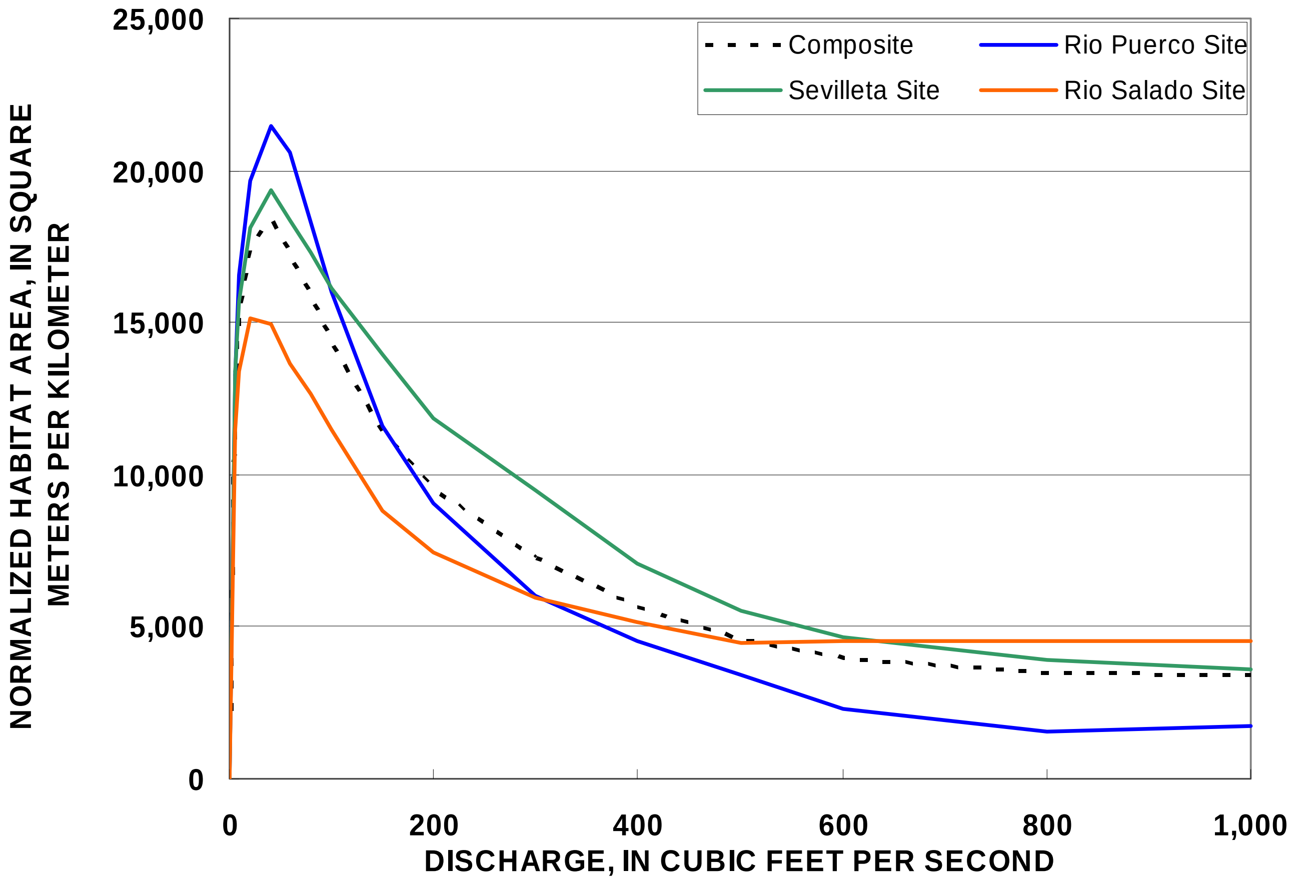


Figure 30. Normalized hydraulic habitat area as a function of discharge for juvenile *H. amarus*.

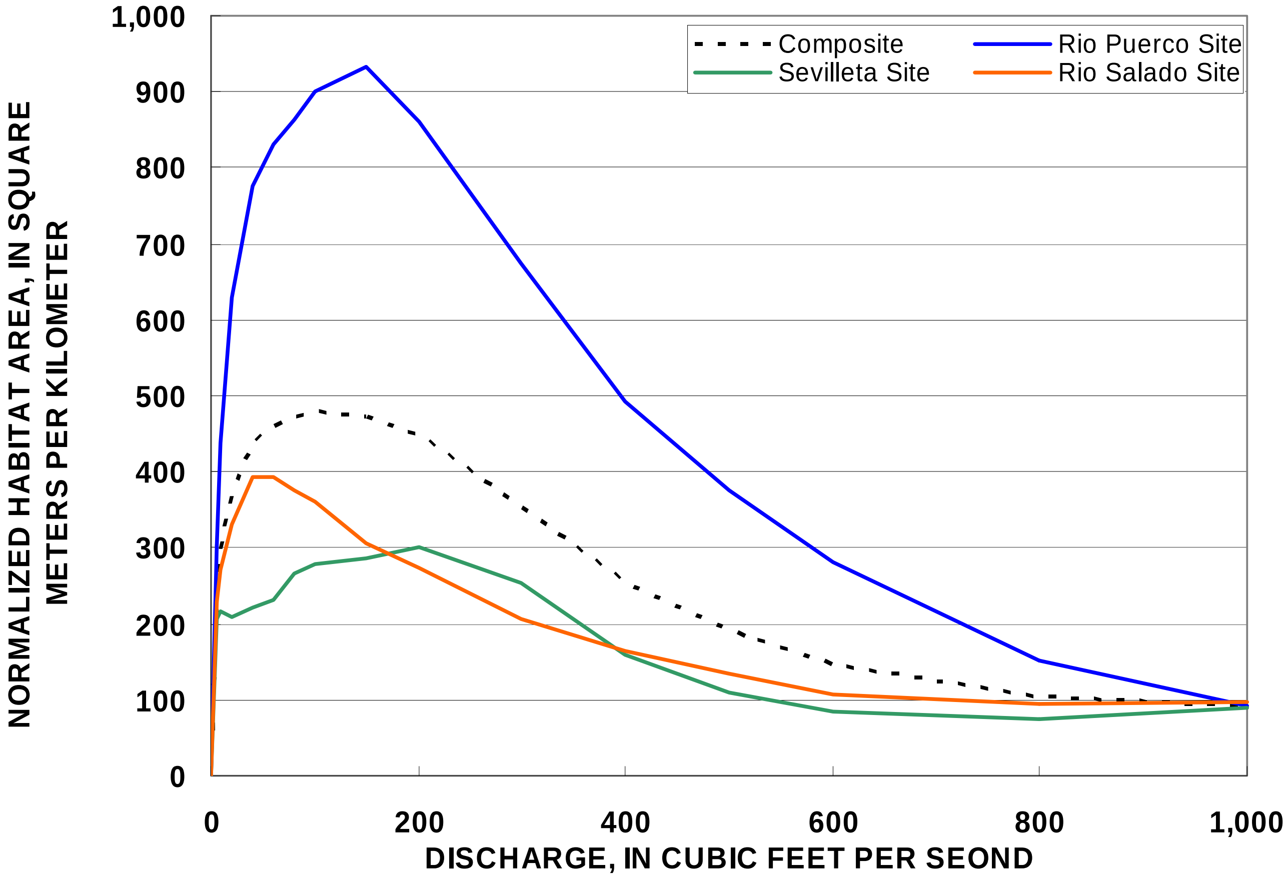


Figure 31. Normalized hydraulic habitat area with large woody debris as a function of discharge for adult *H. amarus*.

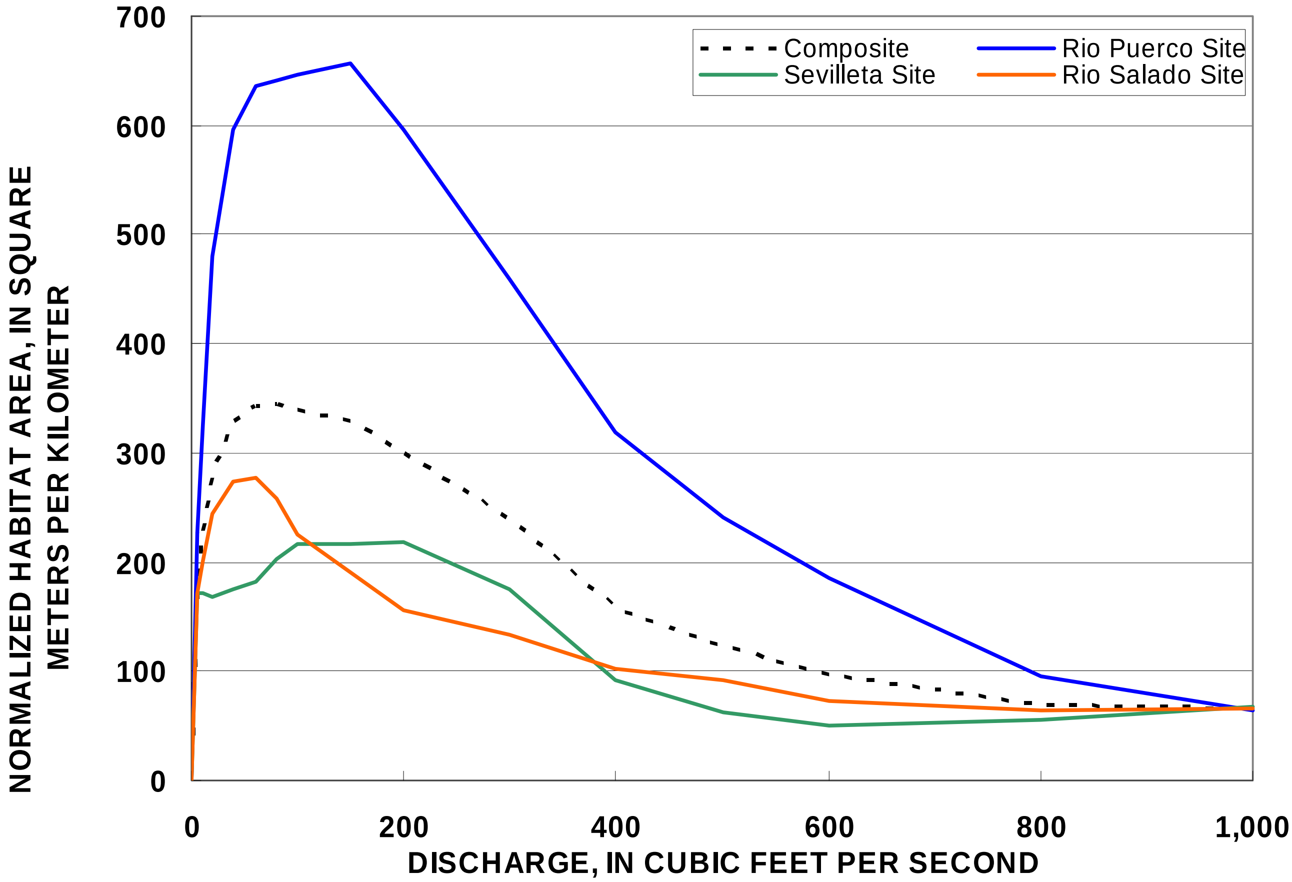


Figure 32. Normalized hydraulic habitat area with large woody debris as a function of discharge for juvenile *H. amarus*.

Table 5. Comparison of optimum flow ranges for *H. amarus* based on hydraulic habitat alone and on hydraulic habitat in association with large woody debris. Discharge in cubic feet per second associated with maximum habitat indicated in parentheses.

Site	*H. amarus* adult		*H. amarus* juvenile	
	Optimum flow range without LWD	Optimum flow range with LWD	Optimum flow range without LWD	Optimum flow range with LWD
Rio Puerco	40–150 (60)	60–200 (150)	20–80 (40)	60–150 (150)
Sevilleta	40–200 (80)	80–300 (200)	20–80 (40)	60–200 (200)
Rio Salado	20–100 (60)	40–100 (40,60)	20–40 (20)	40–80 (60)
Composite	40–100 (60)	40–200 (100)	20–60 (40)	40–150 (80)

The reason that the maximum areas of suitable habitat occurred at a higher range of discharges when LWD was incorporated as a habitat variable is illustrated in figure 33. Deposits of LWD tended to be concentrated along shorelines and on higher elevation mid-channel bars at all three sites. At low discharges, many of these deposits were located above the water line. As discharges increased, more of the deposits were inundated, thus increasing the available pool of LWD patches to be included in the habitat class. Therefore, even though the areas of suitable hydraulic habitat were larger at relatively low discharges, suitable habitat incorporating LWD was typically maximized at considerably higher flows.

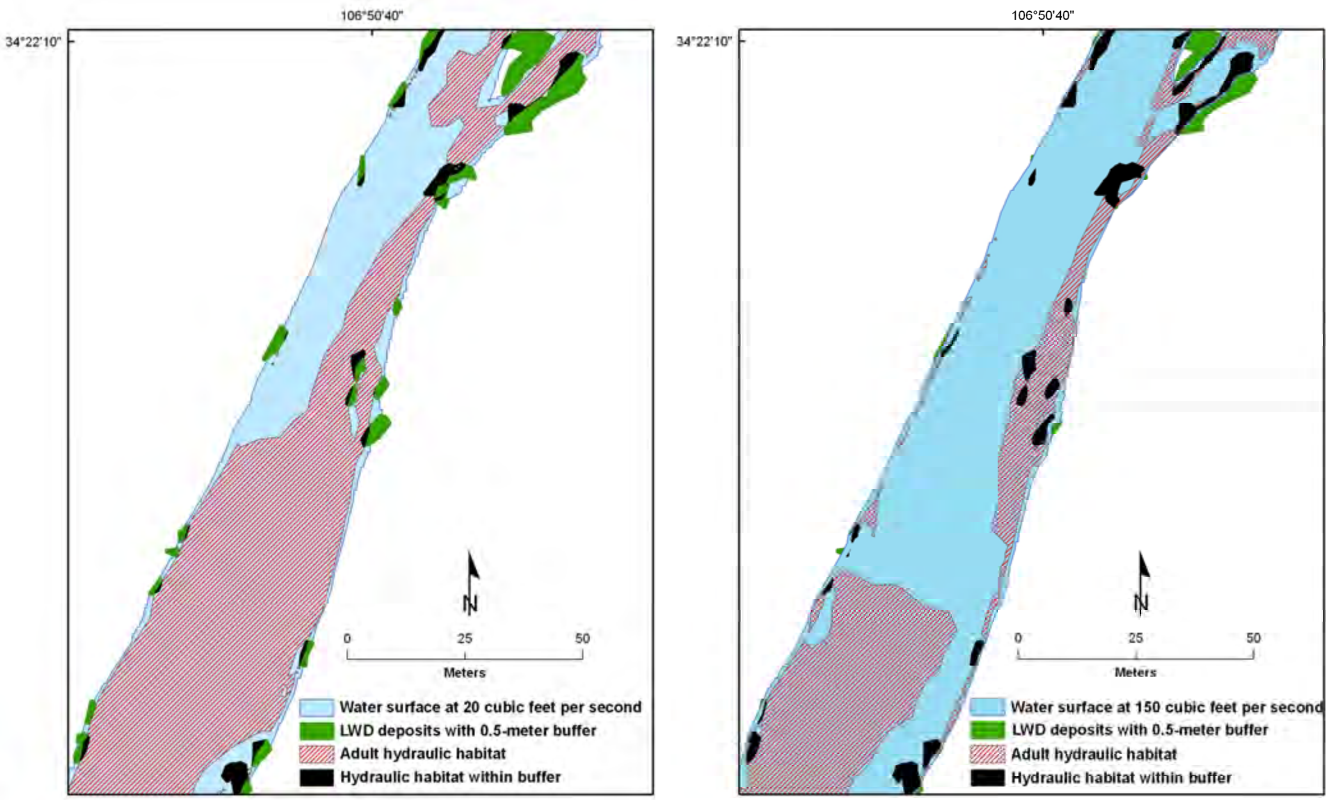


Figure 33. Juxtaposition of large woody debris deposits and suitable hydraulic habitat for adult *H. amarus* in a portion of the Rio Puerco site at 20 cubic feet per second and at 150 cubic feet per second.

Connectivity

Connectivity increased rapidly over the discharge range from 0 to 10 ft^3/s at all three sites (fig. 34). Total (100 percent) connectivity was achieved at the Rio Puerco and Rio Salado sites at 80 ft^3/s and at 150 ft^3/s in the Sevilleta site. Between 10 ft^3/s and 80 ft^3/s or 150 ft^3/s at these sites, respectively, the main channel area was contiguous, but each site contained a few disconnected patches (fig. 35, for example). Connectivity less than 100 percent may be a concern if there is a potential for stranding in isolated pools for extended periods of time. It is for this reason that the scoring metric for connectivity is based on the maximum number of consecutive days that the connectivity index is below its user-specified threshold. If stranding in isolated pools is not a concern for *H. amarus*, the threshold connectivity index on the Parameters page can be set to a lower value, using the connectivity maps in Appendix 5 as a guide.

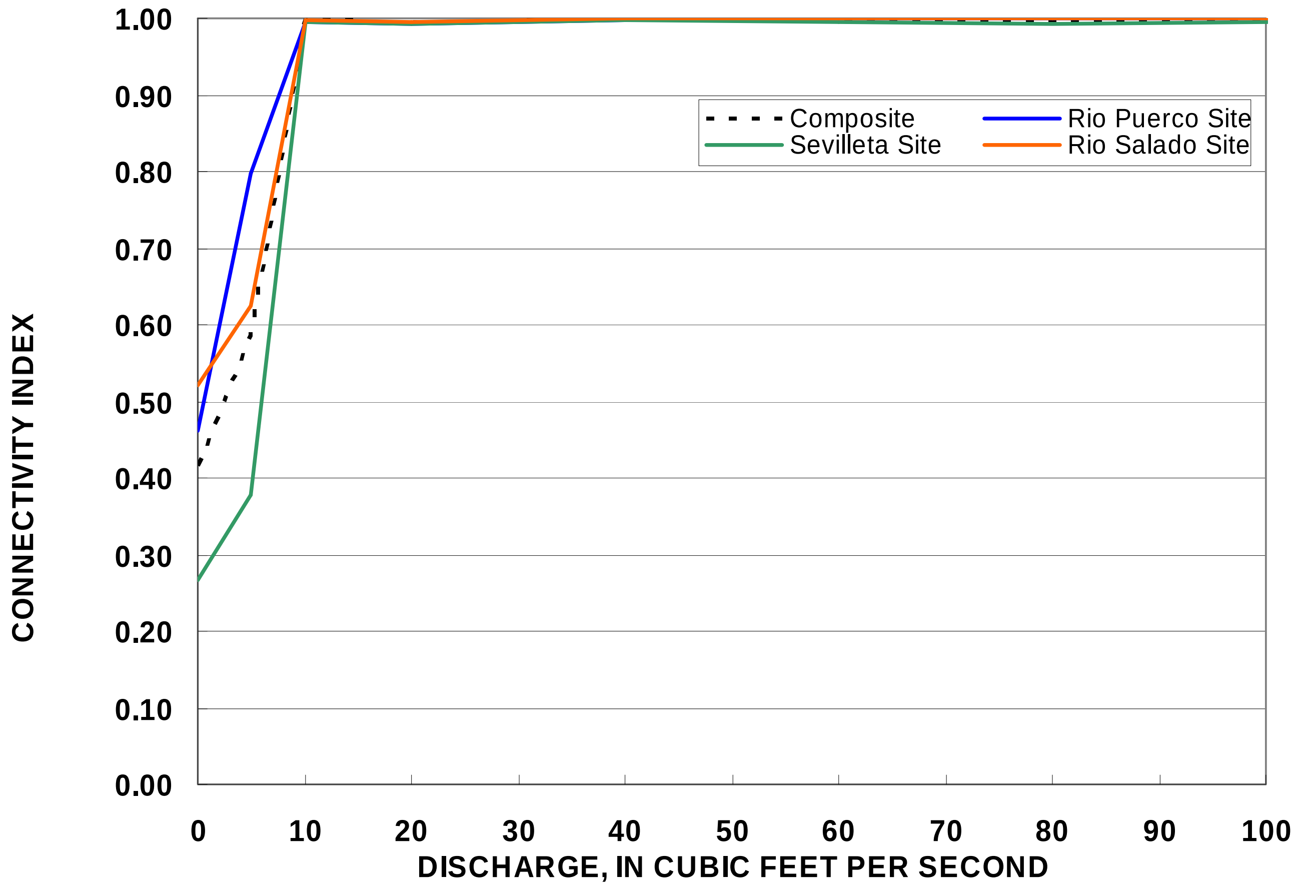


Figure 34. Habitat connectivity index as a function of discharge. X-axis truncated at 100 cubic feet per second to accentuate index at low flows.

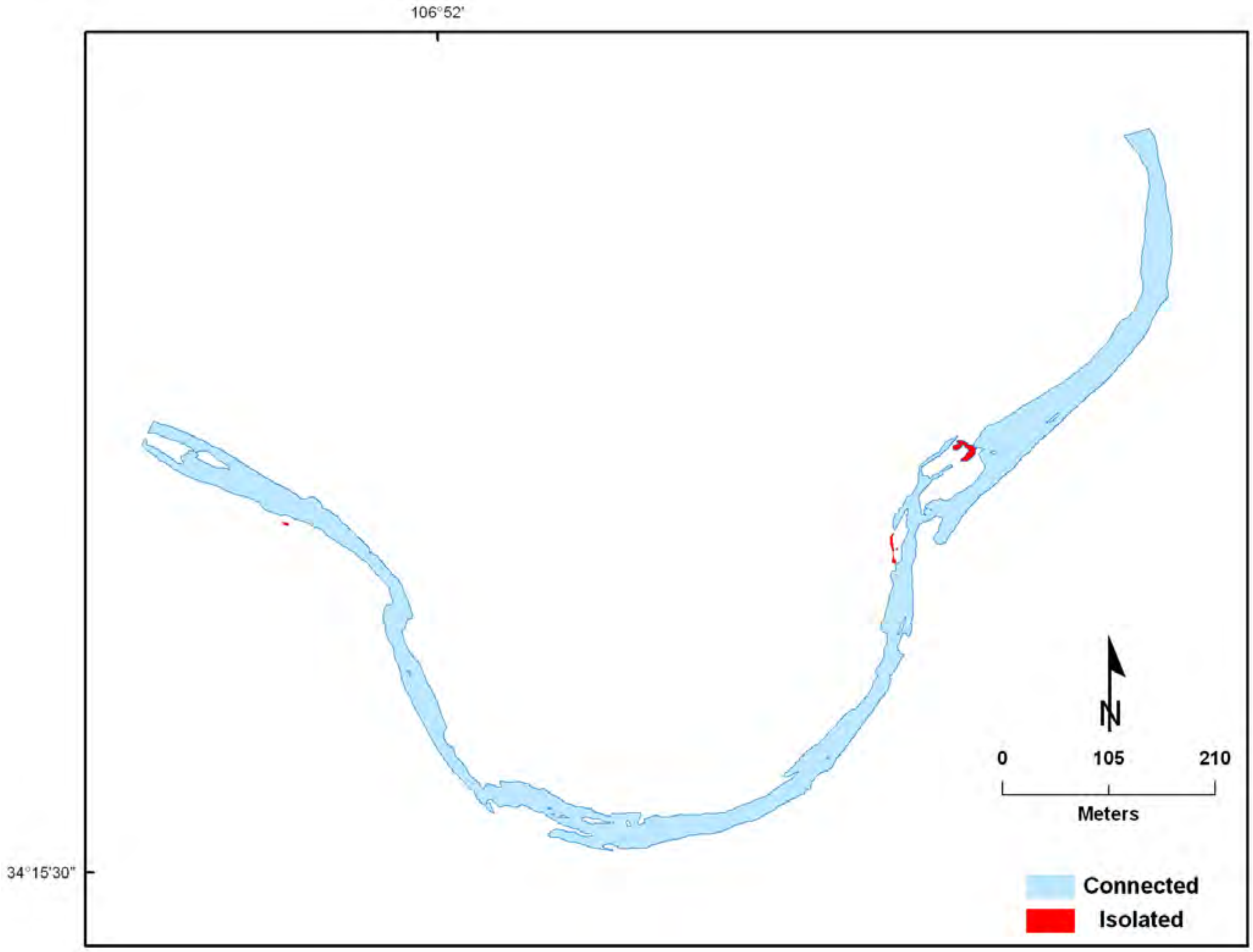


Figure 35. Habitat connectivity map of the Rio Salado site at 20 cubic feet per second, illustrating contiguity of the main channel and presence of disconnected pools.

Southwestern Willow Flycatcher

Nesting habitat area for *E. t. extimus*, as defined for this study, proved to be relatively unresponsive to discharges larger than 5 ft^3/s (fig. 36). Habitat areas increased monotonically at discharges larger than 5 ft^3/s but decreased rapidly below that flow.

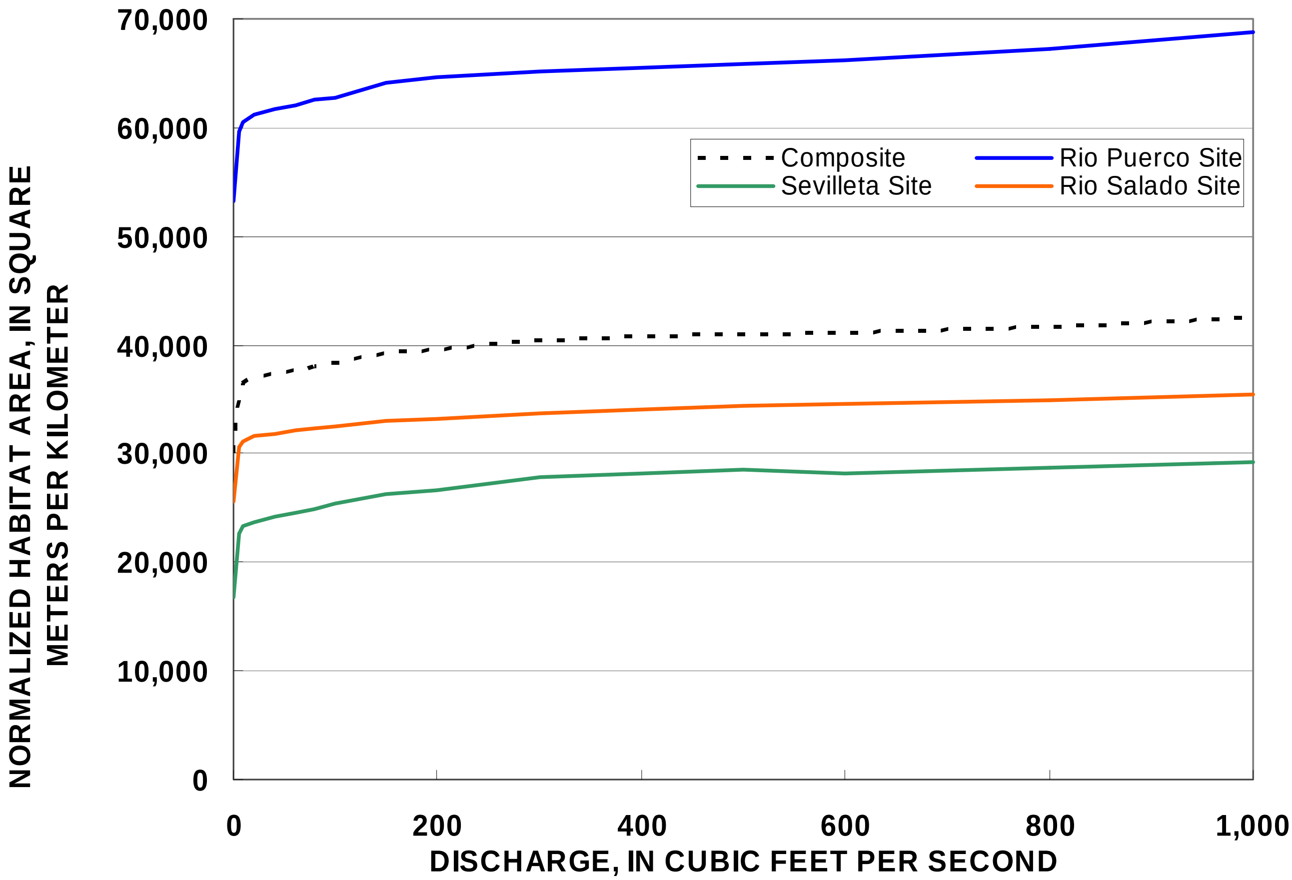


Figure 36. Habitat area as a function of discharge for *E. t. extimus*.

Habitat Time Series–RGHTS Beta-Test Runs

We ran five scenarios with the RGHTS model to test model algorithms, options, and archiving functions. The scenarios differed from one another by the instream-flow requirement imposed and by the location at which the instream flow rule was enforced.

Scenario 1: Unrestricted Siphon Diversion

Scenario 1 was formulated to examine the effects of siphon withdrawals with no instream flow enforcement. In this case, all the instream-flow requirements, including those in compliance with the Biological Opinion, were set to zero. As a result, the volume of water available for diversion at the siphon was unrestricted, amounting to the total flow from the Lower San Juan Riverside Drain, the capacity of the Drain Unit 7 canal, or the total siphon demand, whichever was the smallest. Scenario 1 resulted in a general reduction in streamflow for the entire period of record (fig. 37), although the proportion of the total discharge diverted became relatively small at flows above 2,000 ft^3/s. Under the baseline condition, discharges less than 10 ft^3/s occurred at this site only 0.07 percent of the time. Under Scenario 1, however, discharges less than 10 ft^3/s occurred approximately 2.0 percent of the time, with several occasions when the discharge approached zero.

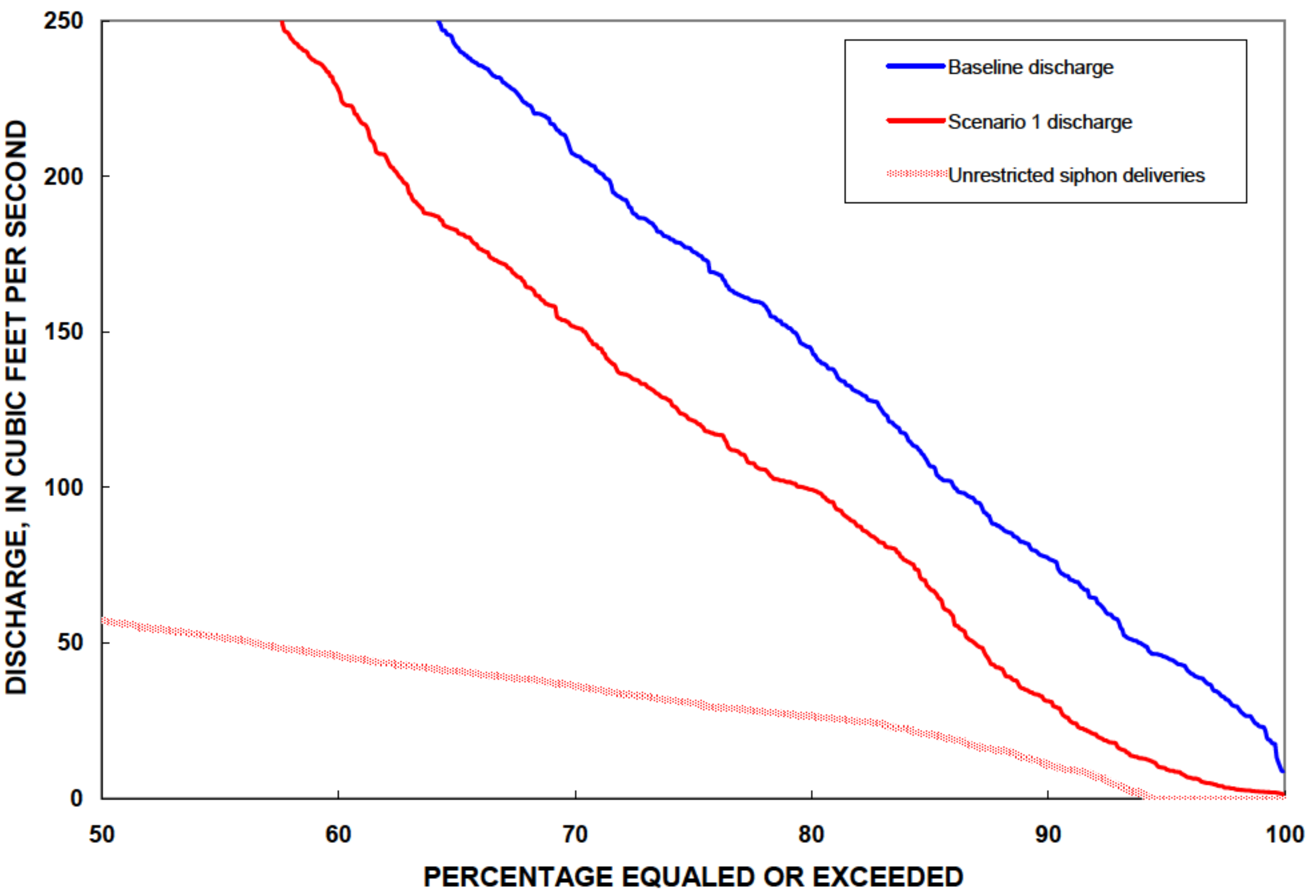


Figure 37. Flow and siphon delivery duration curves for the Rio Puerco site resulting from imposition of Scenario 1 in the RGHTS model. Values above median have been trimmed to accentuate low-flow events.

Scenario 2: Biological Opinion Instream-Flow Requirements

Scenario 2 consisted of enforcing the existing instream-flow requirements from the Biological Opinion at San Acacia Dam. No augmentation of instream flows during dry years was imposed on the system (the Instream-flow override was set to zero). Compared to Scenario 1 (no restrictions), this scenario reduced siphon deliveries over the period of record by 2.42 percent (fig. 38). In most years, the reduction in siphon deliveries was less than that, but in 2002 the overall reduction in siphon deliveries compared to Scenario 1 was 14 percent. Furthermore, reductions of more than 50 percent occurred on 35 days during the 2002 irrigation season. Most of the reductions happened in April and June, reflecting the more stringent instream flow demands of the Biological Opinion during the November 16–June 15 window.

The effects of Scenario 2 on streamflows at the Rio Puerco site (fig. 38) were similar to those of Scenario 1. In fact, the distributions of discharges less than 60 ft^3/s under Scenarios 1 and 2 were identical. This result originated from two sources. First, flows less than 60 ft^3/s occurred only during the June 16–November 15 window, when the instream-flow requirements under the Biological Opinion were set to zero during dry years. Second, all years but one (2001) were classified as dry for our modeled hydrologic record. Consequently, the effect of the Biological Opinion instream-flow requirement during the summer months was the same as the unrestricted diversion scenario in 5 of the 6 years we modeled.

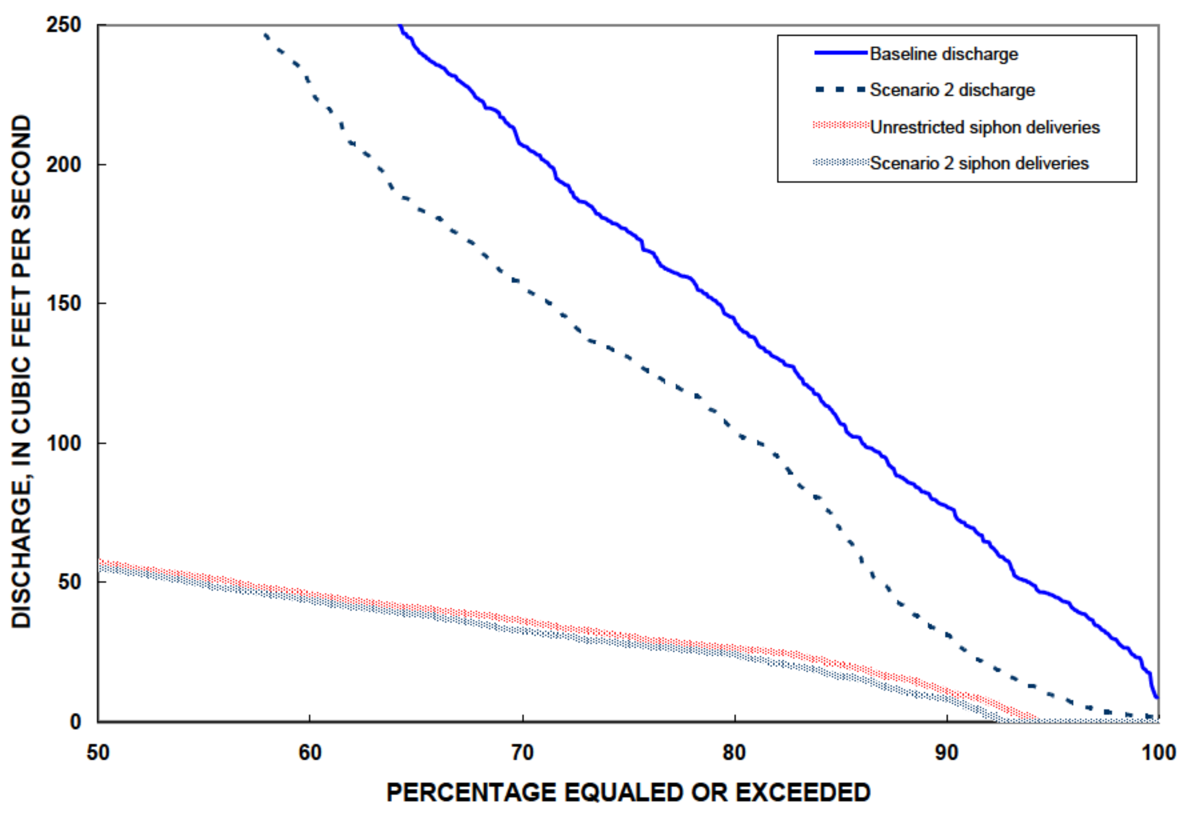


Figure 38. Flow and siphon delivery duration curves for the Rio Puerco site resulting from imposition of Scenario 2 in the RGHTS model. Values above median have been trimmed to accentuate low-flow events.

Scenario 3: Biological Opinion With 10-Cubic Foot per Second Override at San Acacia Dam

Scenario 3 was similar to Scenario 2, except that a 10-ft^3/s instream-flow override was specified for the June 16–November 15 period. Under Scenario 3, the instream-flow requirements were established according to the Biological Opinion from November 16 to June 15 in all years and by the instream-flow override from June 16 to November 15 in all years except 2001. That year was classified as average, so the instream-flow requirement for the June–November window was set at 50 ft^3/s by the Biological Opinion. All instream-flow requirements were enforced at San Acacia Dam.

Siphon deliveries under Scenario 3 were slightly lower than for Scenario 2. Compared to unrestricted availability (Scenario 1), overall deliveries were reduced by 2.58 percent under Scenario 3 fig. 39). The pattern of delivery reductions observed under Scenario 3 was identical to Scenario 2, except that the incidence of large reductions (50 percent or more) increased slightly in 2003 with Scenario 3. Changes in discharge under Scenario 3 relative to the baseline were nearly identical to those observed under Scenario 2 (fig. 39). The 10-ft^3/s instream-flow override was enforced only a few times during the period of record, and its main effect was to slightly elevate the very low flows (1–2 ft^3/s) observed under Scenarios 1 and 2.

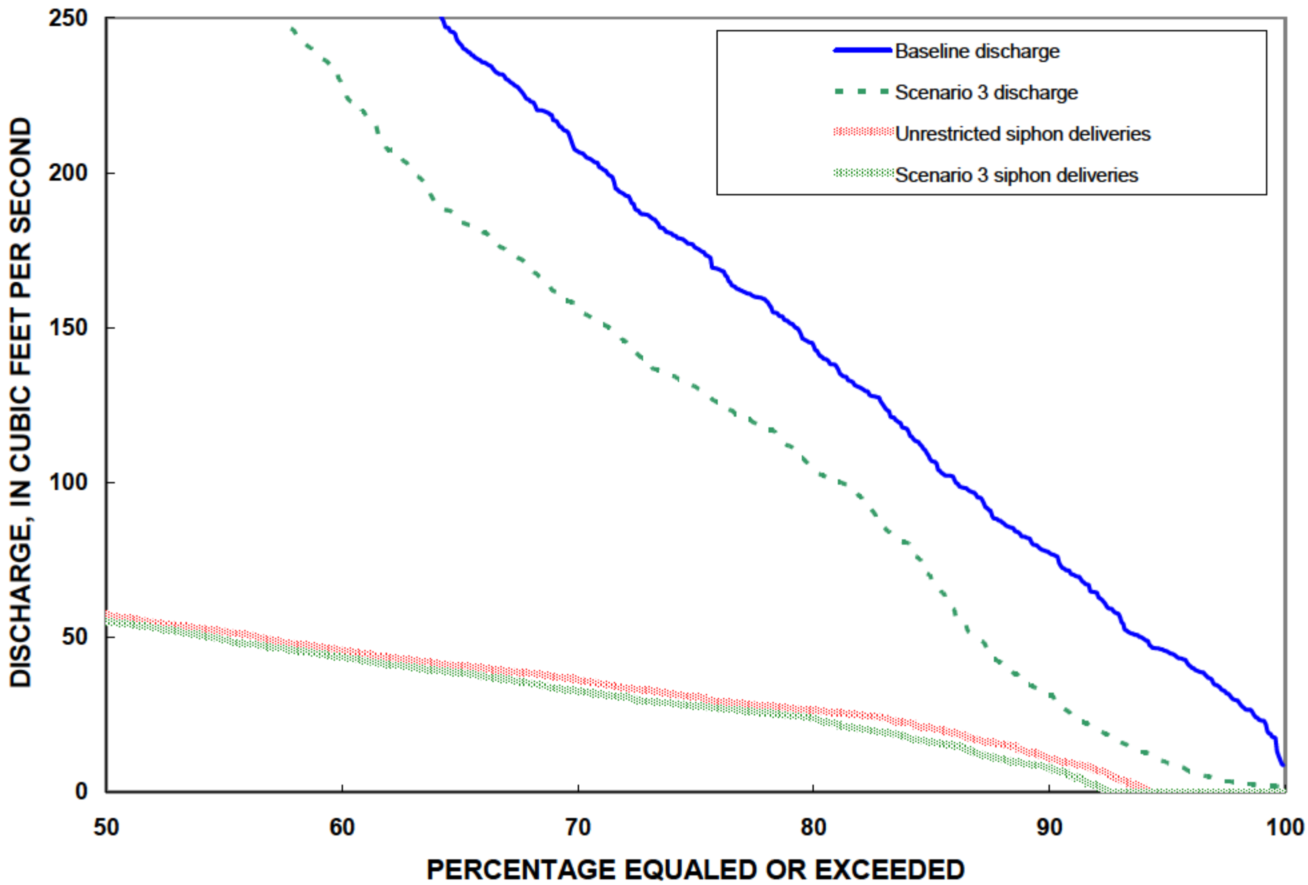


Figure 39. Flow and siphon delivery duration curves for the Rio Puerco site resulting from imposition of Scenario 3 in the RGHTS model. Values above median have been trimmed to accentuate low-flow events.

Scenario 4: Biological Opinion With 10-Cubic Foot per Second Override at Bernardo Siphon

Scenario 4 differed from Scenario 3 only in the location of enforcement of the instream-flow requirements. The magnitudes of the instream-flow requirements for Scenarios 3 and 4 were identical. The only difference was that the instream-flow requirements under Scenario 4 were enforced at the siphon location rather than at San Acacia Dam (Scenario 3). As minor as this difference might seem, the effects on siphon deliveries and downstream flows were considerable (fig. 40). Overall siphon deliveries were 5.8 percent lower than Scenario 1, and in 2002 they were nearly 28 percent lower. The other major difference was that the lowest discharges at the Rio Puerco site rarely fell below 10 ft^3/s during the entire period of record (2 days at 9 ft^3/s) under Scenario 4. The enforcement location made a major difference because of accretions occurring between the Lower San Juan Riverside Drain and San Acacia Dam that dominated the driest years and months of our modeling period (fig. 19). An instream-flow requirement of 10 ft^3/s at San Acacia Dam could be achieved with a considerably lower streamflow at the siphon location. In contrast, enforcing the 10 ft^3/s instream-flow requirement at the siphon typically resulted in discharges in excess of 10 ft^3/s at San Acacia Dam.

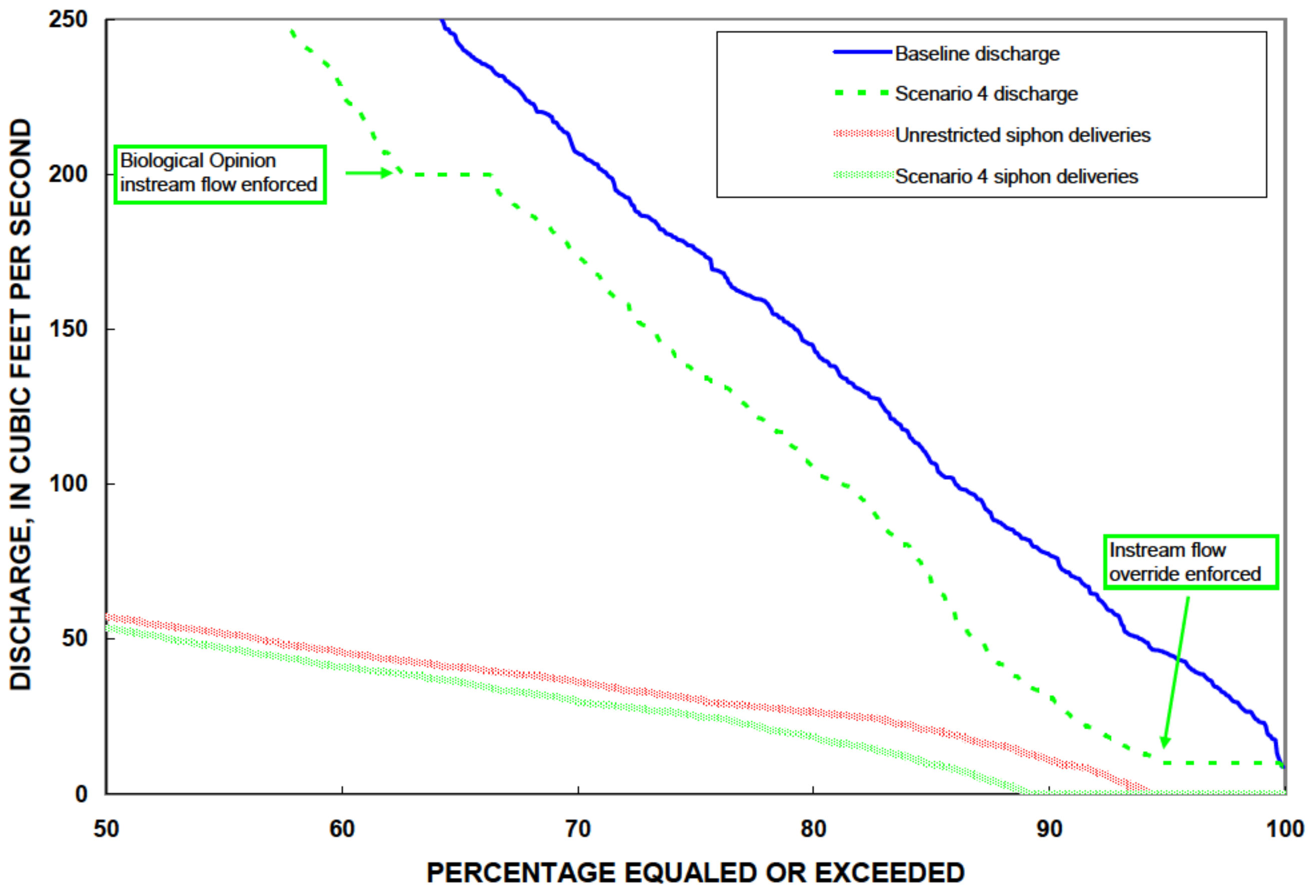


Figure 40. Flow and siphon delivery duration curves for the Rio Puerco site resulting from imposition of Scenario 4 in the RGHTS model. Note knick points where instream flow rules take effect.

Scenario 5: Biological Opinion With 100-Cubic Foot per Second Override at Bernardo Siphon

Scenario 5 was designed to provide optimum streamflow conditions for adult *H. amarus* throughout the LSJRD–San Acacia Dam study area. This scenario was set up by establishing the instream-flow override value at 100 ft^3/s (the peak of the composite curve in figure 31) and enforcing the instream-flow requirement at the Bernardo siphon location. As might be expected, Scenario 5 produced the largest changes in siphon deliveries and low flows of any of the scenarios we tested (fig. 41). Siphon deliveries were reduced by approximately 15.5 percent for the period of record compared to Scenario 1. During 2002, 2003, and 2004, however, the reductions in siphon deliveries compared to Scenario 1 were 44.83 percent, 65.38 percent, and 41.54 percent, respectively. As shown in figure 41, siphon deliveries would have been shut off for approximately 25 percent of the days during the period of record under Scenario 5 (mostly in 2002–2004). The other major effect of Scenario 5 was to the streamflows downstream from the siphon location. The Biological Opinion instream-flow requirement under Scenario 5 had the same effect as Scenario 4, but the instream-flow override essentially resulted in the same flows as the baseline whenever the total inflow was less than 100 ft^3/s (fig. 41).

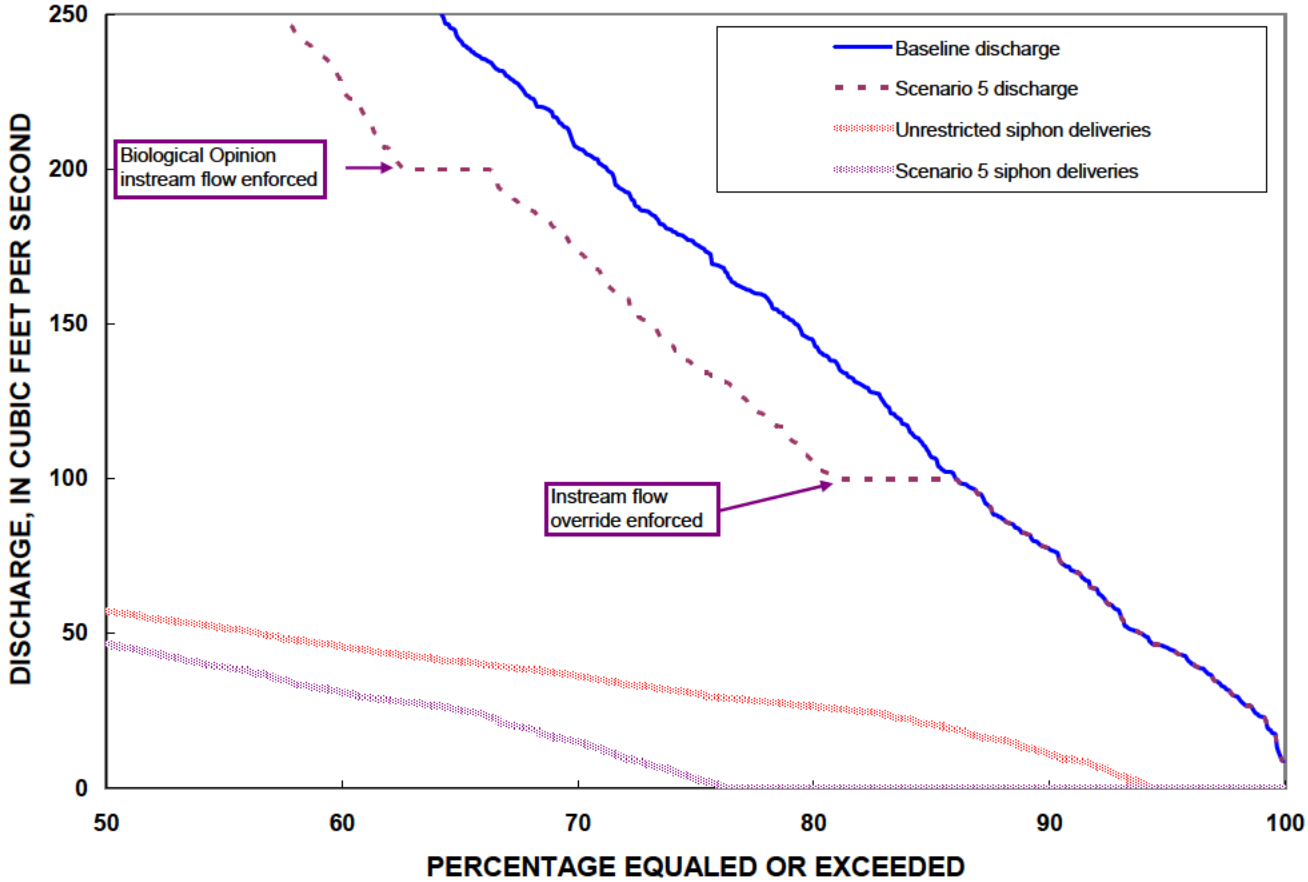


Figure 41. Flow and siphon delivery duration curves for the Rio Puerco site resulting from imposition of Scenario 5 in the RGHTS model. Note knick points where instream flow rules take effect.

Side By Side Comparisons of Run Results

The rules and conditions for the five scenario runs are summarized on the “Scenarios” page of the archive file (fig. 42), and side-by-side comparisons of the results of these runs are shown in figures 43 and 44.

Rio Grande Silvery Minnow Habitat

One of the more interesting results from the RGHTS runs was that diversions to the Bernardo siphon resulted in substantial increases to suitable habitat for both life stages of *H. amarus* in several years (figs. 43 and 44). Habitat increases were particularly evident during the first 3 years of our simulation period, 1999–2001, the wettest of the 6-year period in terms of total water supply (table 6).

Another noteworthy result was that the changes in habitat area that occurred at each site during 1999–2001, in particular, were identical regardless of the scenario treatment (figs. 43 and 44). This outcome implied that habitat limitations during those years were not related to low-flow events because:

1. Habitat areas were reduced from their maxima when discharges exceeded 200 ft^3/s (figs. 29–32).
2. Discharges larger than 200 ft^3/s were not affected by any of the instream flow rules imposed under the five scenarios. The flow-duration curves for the two most disparate scenarios (1 and 5) were identical in water years 1999–2001, reinforcing the premise that the instream flow rules had no effect on downstream discharges or siphon deliveries during those years (fig. 45).
3. Most of the lowest flows in water years 1999–2001 were higher than 200 ft^3/s, and in 2000 the discharge was never less than 200 ft^3/s.
4. All of the scenarios resulted in discharges that were less than or equal to the flows observed under the baseline.
5. From this evidence, the increases in suitable habitat area observed in figures 43 and 44 were attributable to flow reductions when baseline discharges were larger than 200 ft^3/s.

Scenario Number	Run Date	IFR Enforcement location	Instream Flow Requirement (Nov–June)	Instream Flow Requirement (June–Nov)	Siphon Delivery Flag	Connectivity Index Flag
1	3/11/2008	None	0	0	0.75	0.95
2	3/11/2008	at San Acacia dam	0 or Bio. Opinion, whichever is greater	0 or Bio. Opinion, whichever is greater	0.75	0.95
3	3/11/2008	at San Acacia dam	0 or Bio. Opinion, whichever is greater	10 or Bio. Opinion, whichever is greater	0.75	0.95
4	3/11/2008	at Bernardo siphon	0 or Bio. Opinion, whichever is greater	10 or Bio. Opinion, whichever is greater	0.75	0.95
5	3/11/2008	at Bernardo siphon	0 or Bio. Opinion, whichever is greater	100 or Bio. Opinion, whichever is greater	0.75	0.95

Figure 42. The “Scenarios” page from the run archive file summarizing the five scenarios examined during the beta test runs of the RGHTS model.

Location	Year	5/15 through 7/15	5/15 through 7/15	5/15 through 7/15	5/15 through 7/15	5/15 through 7/15	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31
	1999	32.5%	32.5%	32.5%	32.5%	32.5%	22.6%	22.6%	22.6%	22.6%	22.6%
	2000	21.7%	21.7%	21.7%	21.7%	21.7%	20.1%	20.1%	20.1%	20.1%	20.1%
Rio Puerco Site	2001	11.3%	11.3%	11.3%	11.3%	11.3%	14.6%	14.6%	14.6%	14.6%	14.6%
	2002	7.8%	6.6%	6.6%	5.9%	8.6%	2.8%	2.6%	2.6%	-0.9%	8.3%
	2003	-6.5%	-6.5%	-6.5%	-6.5%	2.0%	-29.0%	-29.0%	-24.5%	-20.1%	2.2%
	2004	-2.9%	-3.0%	-3.0%	-2.9%	9.1%	-37.2%	-37.2%	-37.2%	-34.3%	4.0%
	1999	-3.0%	-3.0%	-3.0%	-3.0%	-3.0%	3.3%	3.3%	3.3%	3.3%	3.3%
	2000	16.6%	16.6%	16.6%	16.6%	16.6%	19.9%	19.9%	19.9%	19.9%	19.9%
Sevilleta Site	2001	16.4%	16.4%	16.4%	16.4%	16.4%	18.0%	18.0%	18.0%	18.0%	18.0%
	2002	0.8%	0.7%	0.7%	0.8%	7.3%	-1.5%	-1.4%	-1.4%	-1.4%	5.3%
	2003	-1.5%	-1.5%	-1.5%	-1.5%	1.3%	-5.6%	-5.6%	-3.1%	-2.7%	2.1%
	2004	-6.3%	-6.3%	-6.3%	-6.3%	5.0%	0.4%	0.4%	0.4%	0.2%	2.8%
	1999	0.2%	0.2%	0.2%	0.2%	0.2%	3.9%	3.9%	3.9%	3.9%	3.9%
	2000	12.8%	12.8%	12.8%	12.8%	12.8%	13.0%	13.0%	13.0%	13.0%	13.0%
Rio Salado Site	2001	2.1%	2.1%	2.1%	2.1%	2.1%	7.6%	7.6%	7.6%	7.6%	7.6%
	2002	12.6%	7.8%	7.8%	7.3%	7.3%	14.7%	13.4%	13.4%	8.5%	8.3%
	2003	4.2%	4.1%	4.1%	4.1%	2.4%	-5.2%	-5.2%	0.4%	-2.8%	2.8%
	2004	10.6%	6.5%	6.5%	5.4%	5.2%	8.1%	7.1%	7.1%	7.5%	6.9%

Location	Year	YOY without LWD					Adult without LWD				
	1999	7.9%	7.9%	7.9%	7.9%	7.9%	18.8%	18.8%	18.8%	18.8%	18.8%
	2000	26.3%	26.3%	26.3%	26.3%	26.3%	23.1%	23.1%	23.1%	23.1%	23.1%
Rio Puerco Site	2001	0.4%	0.4%	0.4%	0.4%	0.4%	18.7%	18.7%	18.7%	18.7%	18.7%
	2002	24.8%	18.7%	18.7%	14.2%	14.2%	23.8%	21.2%	21.2%	15.7%	16.0%
	2003	8.2%	8.0%	8.0%	8.0%	6.5%	-16.3%	-16.4%	-11.0%	-2.5%	5.0%
	2004	17.7%	14.6%	14.6%	13.3%	13.3%	-26.2%	-26.2%	-26.2%	-26.3%	9.9%
	1999	2.6%	2.6%	2.6%	2.6%	2.6%	11.7%	11.7%	11.7%	11.7%	11.7%
	2000	14.0%	14.0%	14.0%	14.0%	14.0%	22.8%	22.8%	22.8%	22.8%	22.8%
Sevilleta Site	2001	9.1%	9.1%	9.1%	9.1%	9.1%	13.7%	13.7%	13.7%	13.7%	13.7%
	2002	13.6%	10.1%	10.1%	8.1%	8.1%	11.0%	10.0%	10.0%	7.6%	7.6%
	2003	3.9%	3.8%	3.8%	3.8%	2.9%	-10.8%	-10.8%	-6.5%	-5.8%	2.4%
	2004	9.6%	6.3%	6.3%	4.3%	4.3%	-5.2%	-5.2%	-5.2%	0.4%	4.9%
	1999	0.0%	0.0%	0.0%	0.0%	0.0%	1.1%	1.1%	1.1%	1.1%	1.1%
	2000	3.2%	3.2%	3.2%	3.2%	3.2%	6.5%	6.5%	6.5%	6.5%	6.5%
Rio Salado Site	2001	3.2%	3.2%	3.2%	3.2%	3.2%	4.4%	4.4%	4.4%	4.4%	4.4%
	2002	13.0%	8.8%	8.8%	7.7%	7.7%	15.7%	13.4%	13.4%	7.9%	7.7%
	2003	5.4%	5.3%	5.3%	5.3%	3.0%	-2.4%	-2.6%	3.2%	-0.5%	2.9%
	2004	9.5%	6.2%	6.2%	4.9%	4.8%	9.3%	7.6%	7.6%	7.1%	6.3%

		Connectivity (days below threshold) Hydroperiod					SWWFC Hydroperiod				
		3/1 through 10/31	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31	6/1 through 7/15	6/1 through 7/15	6/1 through 7/15	6/1 through 7/15	6/1 through 7/15
	1999	0%	0%	0%	0%	0%	-0.8%	-0.8%	-0.8%	-0.8%	-0.8%
	2000	0%	0%	0%	0%	0%	-0.3%	-0.3%	-0.3%	-0.3%	-0.3%
Rio Puerco Site	2001	0%	0%	0%	0%	0%	-0.5%	-0.5%	-0.5%	-0.5%	-0.5%
	2002	0%	0%	0%	0%	0%	-1.5%	-1.5%	-1.5%	-1.5%	-0.8%
	2003	1600%	1600%	900%	0%	0%	-0.7%	-0.7%	-0.7%	-0.7%	0.0%
	2004	1900%	1900%	1900%	0%	0%	-1.7%	-1.7%	-1.7%	-1.7%	-0.4%
	1999	0%	0%	0%	0%	0%	-0.8%	-0.8%	-0.8%	-0.8%	-0.8%
	2000	0%	0%	0%	0%	0%	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%
Sevilleta Site	2001	0%	0%	0%	0%	0%	-1.6%	-1.6%	-1.6%	-1.6%	-1.6%
	2002	0%	0%	0%	0%	0%	-3.6%	-3.5%	-3.5%	-3.5%	-1.4%
	2003	400%	400%	300%	200%	0%	-1.4%	-1.4%	-1.4%	-1.4%	0.0%
	2004	200%	200%	200%	0%	0%	-3.8%	-3.8%	-3.8%	-3.8%	-0.6%
	1999	0%	0%	0%	0%	0%	-0.6%	-0.6%	-0.6%	-0.6%	-0.6%
	2000	0%	0%	0%	0%	0%	-0.5%	-0.5%	-0.5%	-0.5%	-0.5%
Rio Salado Site	2001	0%	0%	0%	0%	0%	-0.8%	-0.8%	-0.8%	-0.8%	-0.8%
	2002	0%	0%	0%	0%	0%	-1.3%	-1.3%	-1.3%	-1.3%	-0.6%
	2003	600%	600%	0%	300%	0%	-0.7%	-0.7%	-0.7%	-0.7%	0.0%
	2004	0%	0%	0%	0%	0%	-1.4%	-1.4%	-1.4%	-1.4%	-0.2%

Figure 43. The "Annual Summary" page from the run archive file for the five scenarios examined during the beta test runs of the RGHTS model.

Location	Year	RGSM YOY with LWD					RGSM Adult with LWD				
		Scenario					Scenario				
		1	2	3	4	5	1	2	3	4	5
		Hydroperiods					Hydroperiods				
		5/15 through 7/15	5/15 through 7/15	5/15 through 7/15	5/15 through 7/15	5/15 through 7/15	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31
Composite	1999	10.7%	10.7%	10.7%	10.7%	10.7%	11.7%	11.7%	11.7%	11.7%	11.7%
	2000	18.1%	18.1%	18.1%	18.1%	18.1%	18.2%	18.2%	18.2%	18.2%	18.2%
	2001	9.7%	9.7%	9.7%	9.7%	9.7%	13.5%	13.5%	13.5%	13.5%	13.5%
	2002	7.0%	5.4%	5.4%	4.9%	8.0%	4.3%	3.9%	3.9%	1.0%	7.6%
	2003	-3.0%	-3.0%	-3.0%	-3.0%	1.9%	-18.2%	-18.2%	-13.9%	-12.2%	2.3%
	2004	-1.0%	-1.9%	-1.9%	-2.1%	7.3%	-17.1%	-17.3%	-17.3%	-15.8%	4.5%

Location	Year	RGSM YOY without LWD					RGSM Adult without LWD				
		Scenario					Scenario				
		1	2	3	4	5	1	2	3	4	5
		Hydroperiods					Hydroperiods				
		5/15 through 7/15	5/15 through 7/15	5/15 through 7/15	5/15 through 7/15	5/15 through 7/15	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31
Composite	1999	2.0%	2.0%	2.0%	2.0%	2.0%	7.9%	7.9%	7.9%	7.9%	7.9%
	2000	11.6%	11.6%	11.6%	11.6%	11.6%	16.7%	16.7%	16.7%	16.7%	16.7%
	2001	5.5%	5.5%	5.5%	5.5%	5.5%	11.3%	11.3%	11.3%	11.3%	11.3%
	2002	16.2%	11.9%	11.9%	9.5%	9.5%	15.7%	13.9%	13.9%	9.9%	9.9%
	2003	5.5%	5.4%	5.4%	5.4%	3.9%	-10.1%	-10.2%	-5.1%	-3.4%	3.3%
	2004	10.9%	7.7%	7.7%	6.0%	6.0%	-5.9%	-6.4%	-6.4%	-4.1%	6.6%

Location	Year	Connectivity (days below threshold)					SWWFC				
		Scenario					Scenario				
		1	2	3	4	5	1	2	3	4	5
		Hydroperiods					Hydroperiods				
		3/1 through 10/31	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31	3/1 through 10/31	6/1 through 7/15	6/1 through 7/15	6/1 through 7/15	6/1 through 7/15	6/1 through 7/15
Composite	1999	0%	0%	0%	0%	0%	-0.7%	-0.7%	-0.7%	-0.7%	-0.7%
	2000	0%	0%	0%	0%	0%	-0.3%	-0.3%	-0.3%	-0.3%	-0.3%
	2001	0%	0%	0%	0%	0%	-0.8%	-0.8%	-0.8%	-0.8%	-0.8%
	2002	0%	0%	0%	0%	0%	-1.9%	-1.9%	-1.9%	-1.9%	-0.9%
	2003	1600%	1600%	900%	300%	0%	-0.9%	-0.9%	-0.9%	-0.9%	0.0%
	2004	950%	950%	950%	0%	0%	-2.1%	-2.1%	-2.1%	-2.1%	-0.4%

Location	Year	Siphon Deliveries ANNUAL SUM IN AF					Discharge < Biological Opinion Threshold (Days)				
		Scenario					Scenario				
		1	2	3	4	5	1	2	3	4	5
Composite	1999	82.3%	81.9%	81.9%	80.7%	80.7%	0%	0%	0%	0%	0%
	2000	95.6%	95.6%	95.6%	95.6%	95.6%	0%	0%	0%	0%	0%
	2001	98.5%	98.5%	98.5%	98.5%	98.2%	0%	0%	0%	0%	0%
	2002	99.3%	85.4%	85.4%	71.7%	54.8%	0%	0%	0%	0%	0%
	2003	81.7%	80.7%	78.9%	73.3%	28.3%	0%	0%	0%	0%	0%
	2004	70.0%	68.3%	68.3%	65.5%	40.9%	0%	0%	0%	0%	0%

Figure 44. The "Composite Summary" page from the run archive file for the five scenarios examined during the beta test runs of the RGHTS model.

Table 6. Ranking of water years from wettest to driest according to total water supply calculated at the Rio Salado site.

Water year	Total water supply in acre-feet	Rank
1999	679,581	1
2001	292,202	2
2000	262,835	3
2004	165,741	4
2002	139,557	5
2003	101,615	6

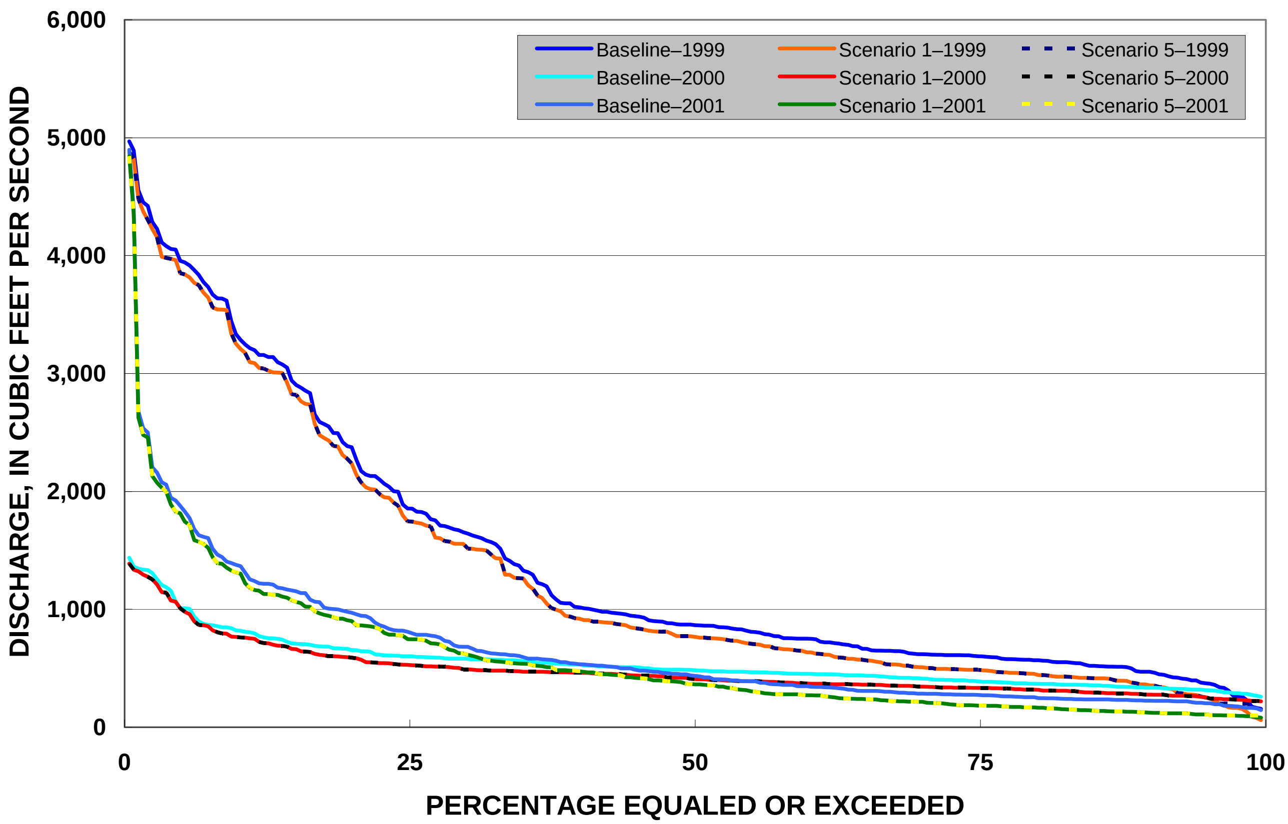


Figure 45. Flow-duration curves for the Rio Puerco site, water years 1999–2001, for the baseline condition and Scenarios 1 and 5.

In 2003 and 2004, there was a generalized reduction in habitat area at the Rio Puerco and Sevilleta sites under all scenarios except Scenario 5, which resulted in modest habitat increases (figs. 43 and 44). Habitat changes varied as a function of the interactions between the operating rules, the overall water supply, groundwater accretions or losses between the siphon and San Acacia Dam, and the timing and intensity of monsoons. Water years 2002 and 2003 were the driest for the period of record in terms of total water supply (table 6), but the lowest baseline discharges occurred in 2003 and 2004 (fig. 46). In 2002 and 2004, the study reach tended to gain flow by groundwater accretions from June through October, but in 2003 there were no major gains or losses during the summer months (fig. 19). Large monsoon-related discharges also occurred during August of 2002 and 2003 (fig. 47).

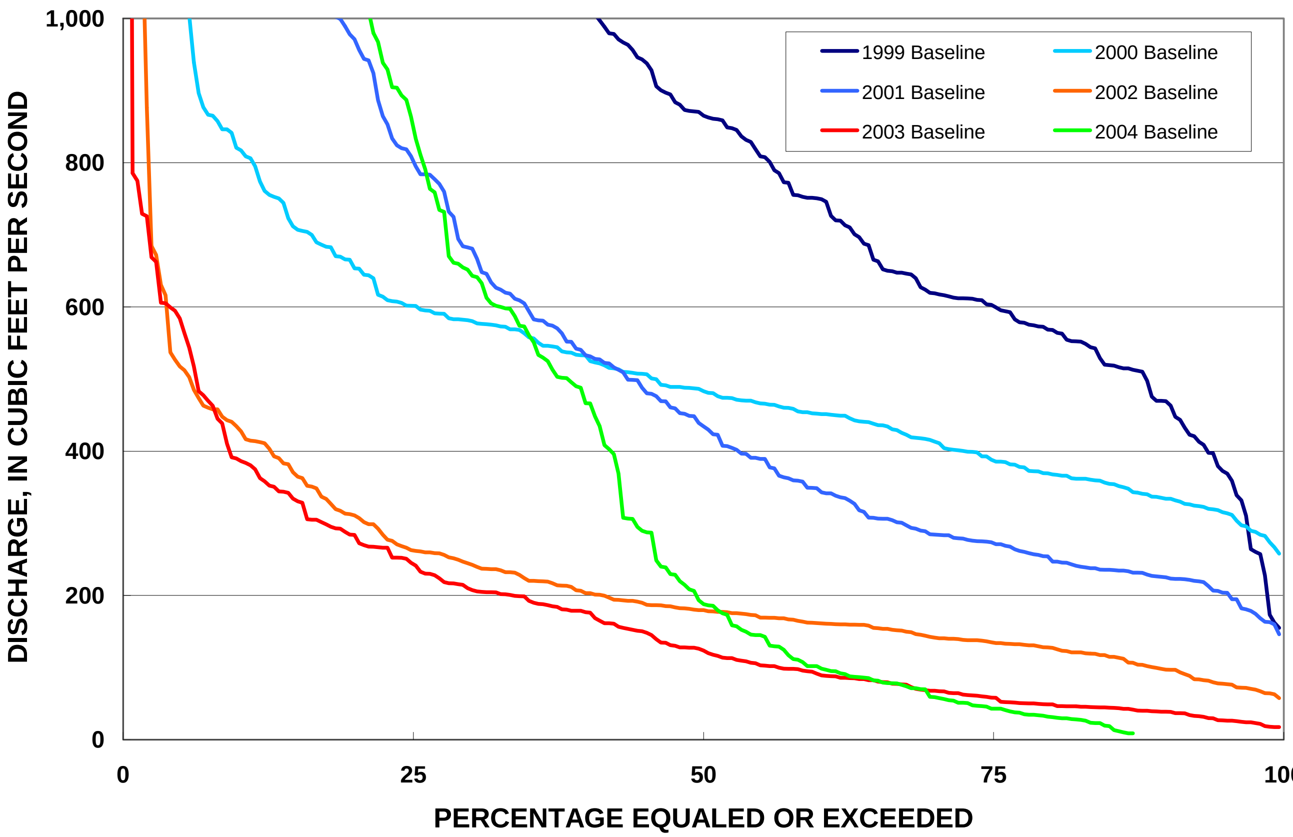


Figure 46. Annual baseline flow-duration curves for the Rio Puerco site, water years 1999–2004. Y-axis truncated at 1,000 cubic feet per second to accentuate low flow ranges.

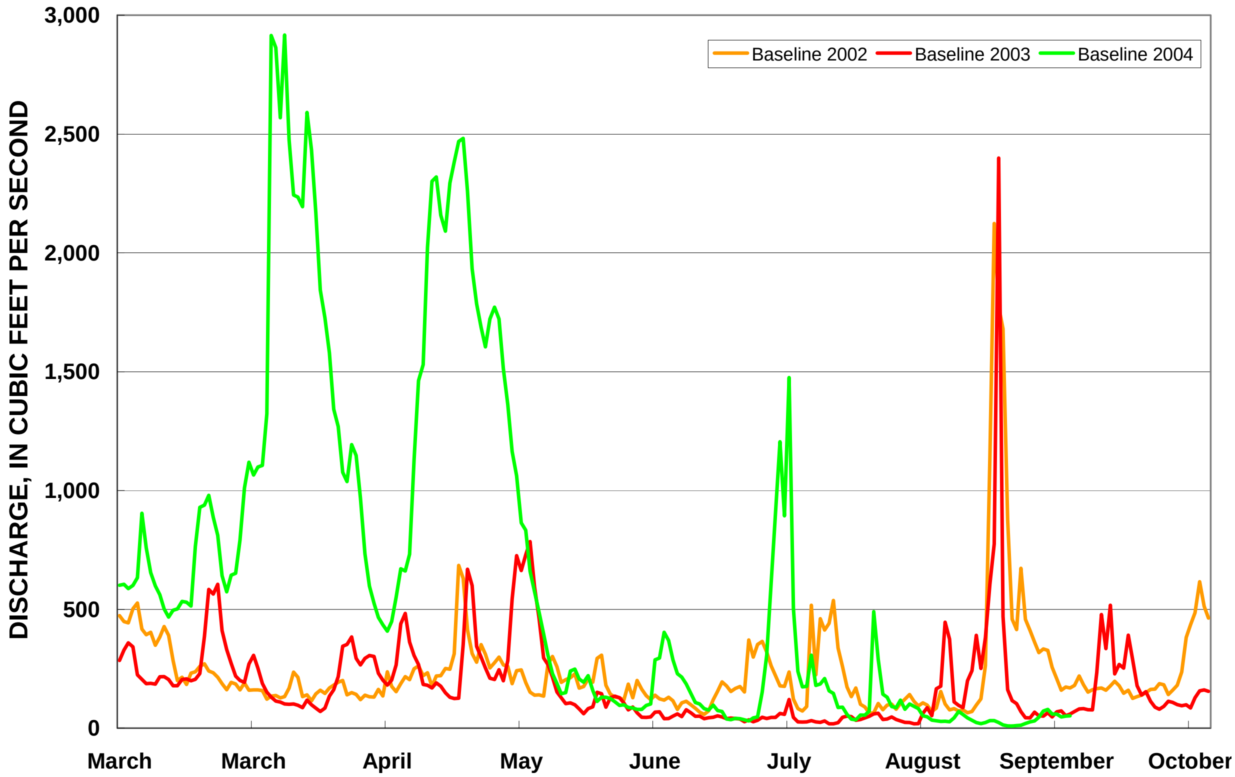


Figure 47. Annual baseline flow time-series for the Rio Puerco site, water years 2002–2004.

During 2003 and 2004, the largest habitat reductions were reported for adult *H. amarus* under Scenarios 1 and 2 (figs. 43 and 44), which provided the fewest restrictions on siphon diversions during low-flow periods. Scenarios 3 and 4 resulted in smaller habitat reductions, reflecting the effects of the instream-flow requirements and the enforcement location. As the instream-flow requirements provided increasingly stringent constraints on siphon diversions, the habitat losses became progressively smaller. In contrast to Scenarios 1–4, Scenario 5 resulted in small but positive increases in *H. amarus* habitat 2002, 2003, and 2004. The mechanism involved in this reversal of outcomes can be explained as follows:

1. Habitat losses generally occurred when discharges smaller than 100 ft^3/s were further reduced by siphon diversions.
2. Scenarios that increasingly limited siphon diversions resulted in progressively higher discharges downstream from the siphon. Low flows were still smaller than baseline levels, however, resulting in habitat areas that were reduced, but to a lesser degree than under unrestricted diversion. The habitat reduction associated with Scenario 3 is smaller than Scenarios 1 and 2 because it provided a 10-ft^3/s minimum flow at San Acacia Dam. The habitat reduction under Scenario 4 is less than Scenario 3 because the 10-ft^3/s instream flow was enforced at the siphon location.
3. Under Scenario 5, the instream-flow requirements were sufficiently high that siphon deliveries were cut off much sooner, resulting in a low-flow regime that was identical to the baseline for discharges less than 100 ft^3/s. Because the low flows for the scenario and baseline were essentially the same, the limiting habitat effects were switched from the low flows to the higher flows that occurred in the spring of 2004 and in August of 2002 and 2003. In this case, reducing the high flows by way of

siphon diversions resulted in net habitat increases in a manner similar to that observed in the 1999–2001 period.

The habitat responses to the scenario treatments at the Rio Salado site differed somewhat from the two upstream sites, particularly during 2004. Whereas habitat reductions were commonplace in the Rio Puerco and Sevilleta sites for all treatments except scenario 5, habitat increases dominated at the Rio Salado site under all scenarios. As the instream-flow requirements at this site became progressively more restrictive from Scenario 1 to Scenario 5, the increases in habitat area at the Rio Salado site decreased accordingly. For example, the largest increases in habitat area were observed under Scenario 1 and the smallest under Scenario 5. Several factors contributed to this result:

1. Habitat areas for juvenile and adult *H. amarus* were maximized at considerably lower discharges at this site than at the two upstream sites (table 5). Consequently, habitat increases occurred when baseline discharges over about 60 ft^3/s were reduced by siphon diversions, compared to 150–200 ft^3/s at the upstream sites.
2. The five scenarios resulted in progressively smaller flow reductions from the baseline, with Scenario 1 producing the largest reductions and Scenario 5 the smallest. Therefore, habitat increases occurred under all the scenarios but varied according to the flow reduction.
3. Even though Scenario 1 caused a reduction in the lowest baseline discharges in 2004, a larger proportion of the resultant discharges were in the optimum flow range (20–60 ft^3/s) for the Rio Salado site (fig. 48).

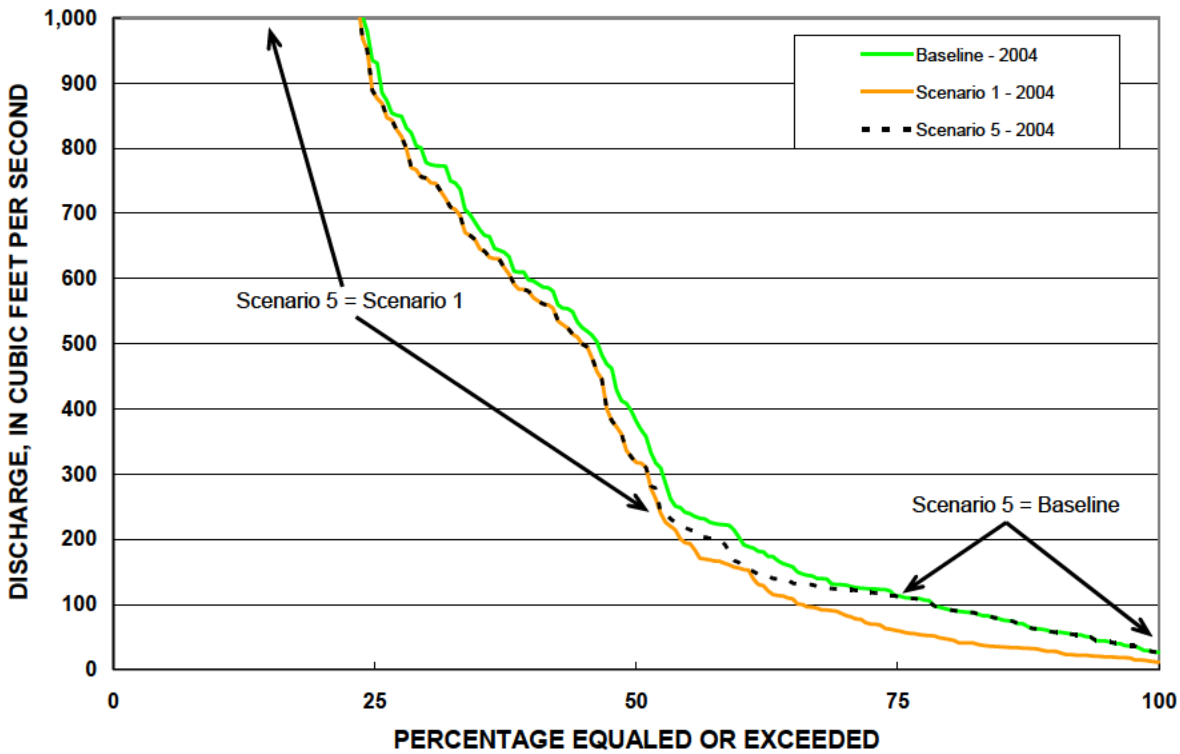


Figure 48. Flow-duration curves for the Rio Salado site, water year 2004, for the baseline condition and Scenarios 1 and 5.

Connectivity

The relations between the various scenarios and their effects on connectivity were much simpler to interpret than the effects on *H. amarus* habitat. Unlike the habitat metrics for *H. amarus*, connectivity was strictly a low-flow issue. Specifically, with the connectivity index threshold set at 0.95 as it was for all five scenario runs, threshold violations were recorded only when the discharge was less than 10 ft^3/s at any of the sites (see fig. 34). Therefore, the scenarios that allowed the largest increases in the frequency of very low flows (Scenarios 1 and 2) were flagged more often than the scenarios that reduced low flows less frequently (Scenarios 3 and 4) or not at all (Scenario 5).

Southwestern Willow Flycatcher Nesting Habitat

Nesting habitat for *E. t. extimus* was slightly reduced at all sites and under all scenarios. This result was in keeping with the nature of the scenarios and the monotonic relation between nesting habitat and discharge. In this sense, the response of this habitat type was similar to connectivity in that relatively large habitat losses occurred only in the lowest ranges of discharges. The response of SWWFC habitat was different from connectivity and *H. amarus* habitat because the habitat areas continually increased as a function of discharge. Therefore, all the scenarios resulted in discharge reductions which in turn resulted in habitat reductions. Another difference in the response of SWWFC habitat was that its hydroperiod tended to correspond to periods of higher discharge in the Rio Grande. As previously discussed, most of the scenarios had little or no effect on siphon operations when baseline discharges were larger than 200 ft^3/s. Consequently, many of the habitat changes shown in figures 43 and 44 are identical across all the scenarios. The only exceptions occurred under Scenario 5, which limited the minimum flow to 100 ft^3/s or the total inflow during the last month of the SWWFC hydroperiod. Habitat areas were still reduced under Scenario 5, but not as much as under the other scenarios.

Discussion

Sand-bed rivers such as the Rio Grande can pose daunting problems for data collection and hydraulic simulations. The complexity of modeling such channels arises from a continually changing topography. Large-scale changes were discovered when we compared the extent of our July 2007 survey at the Rio Salado site with an aerial photograph taken in January 2006 (fig. 49). A channel-forming event occurred in September 2006 when monsoon storms produced a maximum discharge of 7,610 ft^3/s at the San Acacia gage. This episode also included a 7-day period having average daily discharges ranging from 3,400 ft^3/s to 4,600 ft^3/s. Channel changes of lesser scale also occurred at lower discharges, the scale of the change being directly related to streamflow.

The entire streambed can become mobilized at sufficiently high discharges in alluvial channels, effectively lowering the elevation of the active channel. Such channel scouring is typically accompanied by a comparable reduction in the water-surface elevation. Consequently, the actual water-surface elevation will be lower than the elevation predicted from a rating curve that was developed at lower flows. In extreme cases, the stage at very high discharges can actually be lower than it was at more moderate discharges (Leopold and others, 1964).

Our depiction of the topography of the Rio Grande channel was based on measurements taken at discharges ranging from approximately 180 to 320 ft^3/s. The original objective of the study was to examine habitat–discharge relations at low flows, specifically those below 500 ft^3/s. After concluding the hydrologic analysis, however, we found that flows exceeded that discharge quite frequently. In order to estimate the habitat response over a wider range of flows, we simulated discharges as high as 1,000 ft^3/s. We were aware that streambed scour sufficient to affect the rating curve might occur at discharges greater than 500 ft^3/s and would become more significant as flows increased to more than 1,000 ft^3/s.

Nonetheless, the trends in the habitat response functions were consistent with our experiences in similar channels elsewhere. Estimates of habitat areas between 500 and 1,000 ft^3/s may be not be as accurate as those for lower flows, but we believe that the trend is correct.

We anticipate that the trajectories for habitat areas at discharges in excess of 1,000 ft^3/s, however, will deviate sharply from those observed between 500 and 1,000 ft^3/s. There are numerous secondary channels along the river that will become inundated at some higher discharge, forming connected backwaters and flowing channels (fig. 50). When these secondary channels are inundated, we expect that the downward trend in habitat area for *H. amarus* observed between 500 and 1,000 ft^3/s (figs. 29–32) would be reversed and would begin to increase. The relations between discharge and *H. amarus* habitat areas for discharges in excess of 1,000 ft^3/s remain unknown, however, owing to our uncertainties regarding channel scour and its effects on the rating curves for each site.

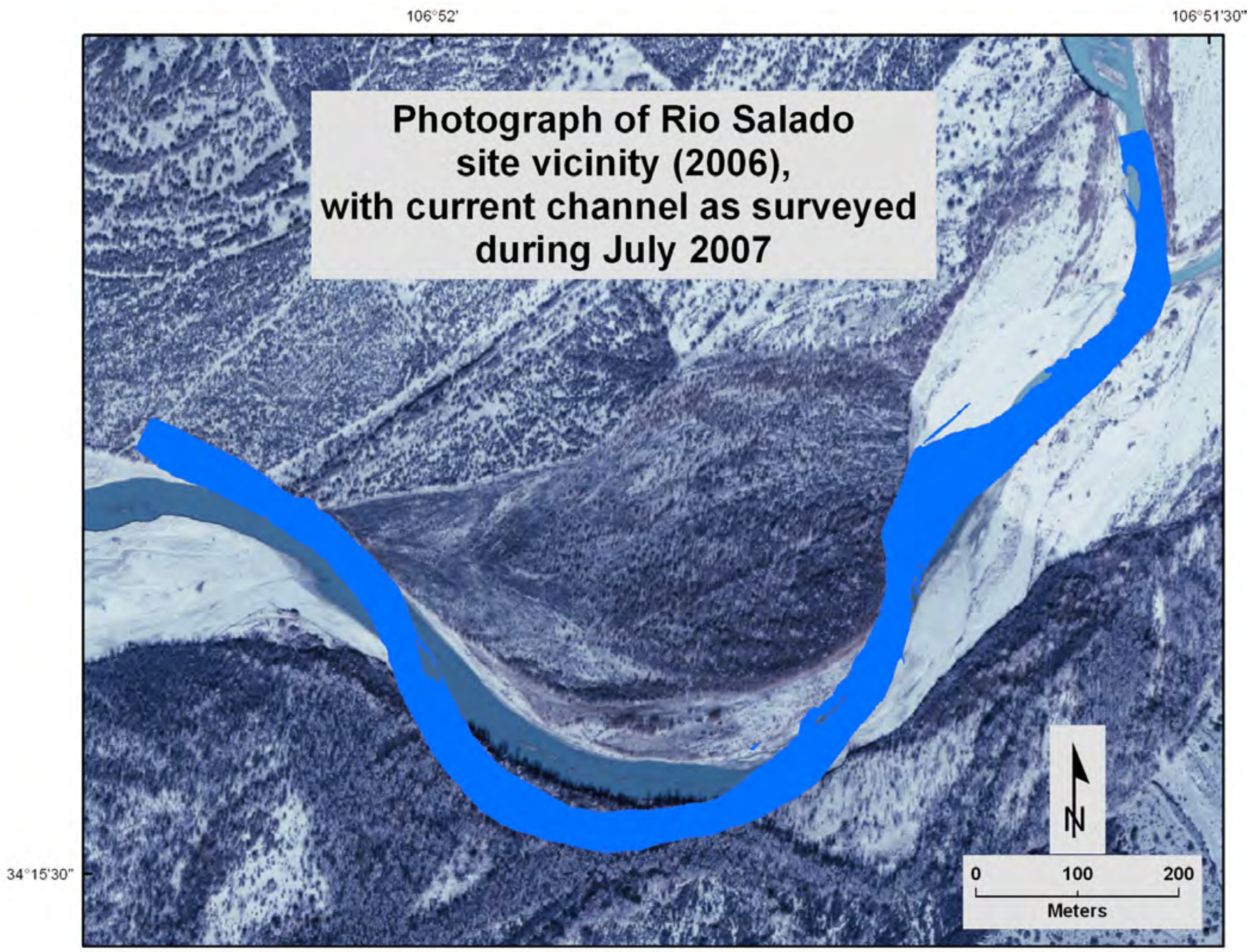


Figure 49. Overlay of the July 2007 survey extent and an aerial photograph of the Rio Salado study site taken in January 2006. Observed channel migration was assumed to be in response to monsoon discharges that occurred in September 2006. Photograph credit–1: 4,800 orthorectified color infrared aerial photography by U.S. Fish and Wildlife Service, January 2006.

Figure 50. Aerial photograph of the Sevilleta site on the Rio Grande, showing subsidiary channels that would contain flowing water at discharges higher than those simulated in the present study.

There may be similar concerns over the effects of potential channel changes at very low discharges. Remshardt and Tashjian (U.S. Fish and Wildlife Service, written commun. February 2008) noted that the Rio Grande within our study area was vulnerable to channel narrowing and vegetation encroachment during extended periods of very low discharge. During extended low-flow periods, the river could excavate a narrower and deeper single-thread thalweg within the bank-to-bank conveyance area we surveyed. If such a process occurred, the wetted surface area at low discharges would be considerably smaller than those depicted in our study, potentially resulting in habitat areas smaller than those shown in figures 29–32. Although this is a reasonable hypothesis, our data were insufficient to confirm or reject it. At discharges smaller than 20 ft^3/s, however, the stream power would be very low, and these conditions would probably need to persist for fairly long (duration unknown) periods in order for this type of scour to take place.

It appears that the overriding issue is not so much one of the instability of the channel, but rather the potential instability of the discharge–habitat relations we developed for this study. Channel changes occur in the Rio Grande over a variety of spatial and temporal scales. Our surveys were essentially snapshots of the Rio Grande channel during a short period in 2007. The magnitude and persistence of channel changes sufficient to cause a fundamental shift in the shapes of the habitat–discharge functions are unknown. The only reliable way to test the stability of these relations would be to repeat this study at various intervals, particularly following known channel-forming events. In the absence of such replication, we must assume that the basic shapes of the habitat–discharge functions developed in this study are representative and persistent.

The environmental effects of the siphon with regard to *H. amarus* habitat will depend largely on the rules affecting its operation. The scenario runs we used as examples in this report can provide some insights for further experimentation by the stakeholders. Although the scenario runs did not cover the entire range of possible operating alternatives, several lessons can be taken from them.

1. The instream flow rules had little or no effect on siphon withdrawals when the total inflow exceeded 200 ft^3/s.
2. Siphon diversions appeared to have a beneficial effect on *H. amarus* habitat when the total inflow discharge was between 200 ft^3/s and 1,000 ft^3/s.
3. This tendency may not hold when total inflows are larger than 1,000 ft^3/s. If the effects of diversions at discharges larger than 1,000 ft^3/s are at issue, the channel should be resurveyed during a high-flow period and the data used to expand the range of the hydraulic and habitat simulations.
4. During periods of low discharge, the magnitude and enforcement location of the instream-flow requirement can be a major factor in determining the habitat effects of a scenario.

Scenarios 1 (unrestricted siphon diversions) and 5 (requiring the habitat optimizing discharge as the instream flow) might be viewed as practical operational boundaries for future experimentation. The combinations of instream-flow requirements and enforcement locations are numerous, but from a practical standpoint, not infinite. Some combinations will produce comparable results, and their relative values can be judged by feasibility and ease of implementation. For example, an instream-flow requirement of 120 ft^3/s enforced at San Acacia Dam has approximately the same effect as enforcing a 100-ft^3/s instream flow at the siphon location. Skeptics are invited to make this run with the RGHTS to test the veracity of our assertion. More specifically, the RGHTS is public domain software, so all stakeholders should have access to it. We encourage collaborative gaming with the model to determine whether mutually acceptable operating rules with mutually acceptable consequences can be defined. If such a solution can be found, then the RGHTS will have served its purpose.

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Appendix 1. Rating Tables as Received from the New Mexico Water Science Center

Table 1-1. Rating table for the Rio Grande at the Rio Puerco site.

U.S. DEPARTMENT OF THE INTERIOR - U.S. GEOLOGICAL SURVEY - WATER RESOURCES

Rio Grande BRD Rio Puerco site
Date Processed: 2007-08-02 14:03 By lkmiller
Rating for Discharge, IN cfs
RATING ID: 0000 TYPE: stage-discharge EXPANSION: logarithmic STATUS: working

Remarks:

OFFSET: 30.00

EXPANDED RATING TABLE

UNSP	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09	DIFF IN Q PER .1 UNITS
			Discharge IN cfs			(STANDARD PRECISION)					
31.70						105*	106	108	110	111	16.0
31.80	113	114	116	118	119	121	123*	125	127	128	17.0
31.90	130	132	134	136	138	140	142	144*	146	148	20.0
32.00	150	152	153	155	157	159	161	163	165	167	19.0
32.10	169*	171	173	175	178	180	182	184	187	189	22.0
32.20	191	193	196	198*	200	203	205	208	210	212	24.0
32.30	215	217	220	222	225	227	230	232*	235	238	26.0
32.40	241	243	246	249	252	255	258	261	263	266	28.0
32.50	269	272*	275	278	281	284	287	290	292	295	29.0
32.60	298	301	304	307	310	313	316	319*	323	326	31.0
32.70	329	332	335	338	341	345	348	351	354	358	32.0
32.80	361	364	368	371	375*	378	381	385	388	392	34.0
32.90	395	399	403	406	410	413	417	421	424	428	37.0
33.00	432	435	439*								

"*" indicates a rating descriptor point

Table 1-2. Rating table for the Rio Grande at the Sevilleta site.

U.S. DEPARTMENT OF THE INTERIOR - U.S. GEOLOGICAL SURVEY - WATER RESOURCES

Rio Grande BRD Sevilleta site
Date Processed: 2007-08-03 10:26 By lkmiller
Rating for Discharge, IN cfs
RATING ID: 0001 TYPE: stage-discharge EXPANSION: logarithmic STATUS: working
Created by lkmiller on 08-03-2007 @ 10:17:23 MDT, Updated by lkmiller on 08-03-2007 @ 10:17:23 MDT
Remarks:

OFFSET: 27.00

EXPANDED RATING TABLE

			Discharge IN cfs			(STANDARD PRECISION)					DIFF IN Q PER
UNSP	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09	.1 UNITS
27.80									138*	140	20.0
27.90	142	144	147	149	151	153	156	158	160	162	23.0
28.00	165	167	169	171	174	176	178	181	183	185	23.0
28.10	188	190	192	195	197	200	202	204	207	209	24.0
28.20	212	214	217	219	222	224	227	229	231	234	24.0
28.30	236	239	242	244	247	249	252	254	257	259	26.0
28.40	262	265	267	270	272	275	278	280	283	286	26.0
28.50	288	291	294	296	299	302	304	307	310	312	27.0
28.60	315	318	321	323	326	329	332	334	337	340	28.0
28.70	343	345	348	351	354	357	359	362	365	368	28.0
28.80	371	374	377	379	382	385	388	391	394	397	29.0
28.90	400	402	405	408	411	414	417	420	423	426	29.0
29.00	429	432	435	438	441	444	447*				

"*" indicates a rating descriptor point

Table 1-3. Rating table for the Rio Grande at the Rio Salado site.

U.S. DEPARTMENT OF THE INTERIOR - U.S. GEOLOGICAL SURVEY - WATER RESOURCES

Rio Grande BRD Rio Salado site
Date Processed: 2007-08-03 10:38 By lkmiller
Rating for Discharge, IN cfs
RATING ID: 0002 TYPE: stage-discharge EXPANSION: logarithmic STATUS: working
Created by lkmiller on 08-03-2007 @ 10:37:58 MDT, Updated by lkmiller on 08-03-2007 @ 10:37:58 MDT
Remarks:

OFFSET: 20.00

EXPANDED RATING TABLE

	Discharge IN cfs				(STANDARD PRECISION)						DIFF IN Q PER
UNSP	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09	.1 UNITS
21.60							106*	107	109	111	17.5
21.70	113	115	117	119	121	123	125	127	129	131	20.0
21.80	133	135	138	140	142	144	146	149	151	153	23.0
21.90	156	158	160	163	165	168	170	173	175	178	24.0
22.00	180	183	185	188	191	193	196	199	202	205	27.0
22.10	207	210	213	216	219	222	225	228	231	234	30.0
22.20	237	240	243	246	249	253	256	259	262	266	32.0
22.30	269	273	276	279	283	286	290	293	297	300	35.0
22.40	304	308	311	315	319	323	326	330	334	338	38.0
22.50	342	346	350	354	358	362	366	370	374	378	41.0
22.60	383	387	391	395	400	404	408	413	417	422	43.0
22.70	426	431	435	440	445	449	454	459	464*		

"*" indicates a rating descriptor point

Appendix 2. Control Section Elevations for Range of Simulated Flows

Table 2-1. Control section elevations for discharges simulated at the three Rio Grande study sites.

		Control Water-surface elevation (m)		
Discharge, in cubic feet per second	**Discharge, in cubic meters per second**	**Rio Puerco Site**	**Sevilleta Site**	**Rio Salado Site**
5	0.142	1,433.691	1,429.888	1,423.526
10	0.283	1,433.742	1,429.904	1,423.574
20	0.566	1,433.807	1,429.930	1,423.635
40	1.133	1,433.893	1,429.973	1,423.712
60	1.699	1,433.955	1,430.010	1,423.767
80	2.265	1,434.005	1,430.044	1,423.811
100	2.832	1,434.047	1,430.076	1,423.848
150	4.248	1,434.135	1,430.149	1,423.924
200	5.663	1,434.205	1,430.215	1,423.984
300	8.495	1,434.319	1,430.334	1,424.080
400	11.327	1,434.411	1,430.443	1,424.157
500	14.158	1,434.490	1,430.545	1,424.222
600	16.990	1,434.559	1,430.641	1,424.279
800	22.653	1,434.679	1,430.820	1,424.377
1,000	28.317	1,434.781	1,430.988	1,424.459

Appendix 3. River2D Calibration Statistics

Table 3-1. Calibration statistics for Rio Grande Rio Puerco site.

Point number	Observation coordinates Easting (meters)	Northing (meters)	Observed water-surface elevation (meters)	Steady flow water-surface elevation [1] (metes)	Simulated water-surface elevation (meters)	Delta (meters)
1	330,230.000	3,804,119.700	1,434.305	1,434.311	1,434.297	–0.01467
2	330,307.685	3,804,261.885	1,434.366	1,434.369	1,434.369	–0.00016
3	330,330.909	3,804,330.593	1,434.367	1,434.370	1,434.401	0.03128
4	330,321.876	3,804,475.707	1,434.454	1,434.454	1,434.453	–0.00060
5	330,400.802	3,804,572.741	1,434.468	1,434.465	1,434.490	0.02503
6	330,472.946	3,804,708.701	1,434.540	1,434.535	1,434.540	0.00463
7	330,574.858	3,804,885.842	1,434.656	1,434.649	1,434.637	–0.01210
8	330,619.061	3,804,911.572	1,434.703	1,434.695	1,434.696	0.00037
9	330,686.082	3,804,969.681	1,434.731	1,434.722	1,434.718	–0.00397
10	330,746.173	3,805,029.952	1,434.777	1,434.766	1,434.767	0.00087
11	330,836.192	3,805,112.652	1,434.901	1,434.889	1,434.824	–0.06492
				Mean error excluding upstream point		0.00307
				Mean error including upstream point		–0.00311

[1] Water-surface elevations adjusted to reflect steady flow conditions.

Table 3-2. Calibration statistics for Rio Grande Sevilleta site.

Point number	Observation coordinates Easting (meters)	Northing (meters)	Observed water-surface elevation (meters)	Simulated water surface elevation (meters)	Delta (meters)
1	329,444.603	3,798,352.362	1,430.242	1,430.249	0.007
2	329,364.031	3,798,483.074	1,430.291	1,430.302	0.011
3	329,347.956	3,798,564.854	1,430.346	1,430.335	–0.012
4	329,360.425	3,798,658.813	1,430.420	1,430.424	0.004
5	329,401.570	3,798,796.010	1,430.493	1,430.500	0.007
6	329,380.797	3,798,917.977	1,430.608	1,430.599	–0.009
7	329,366.517	3,799,069.642	1,430.690	1,430.692	0.002
8	329,371.468	3,799,142.607	1,430.698	1,430.708	0.010
9	329,348.170	3,799,227.940	1,430.747	1,430.751	0.004
10	329,316.332	3,799,347.975	1,430.824	1,430.821	–0.003
11	329,310.568	3,799,405.377	1,430.871	1,430.876	0.005
12	329,297.744	3,799,493.676	1,430.917	1,430.921	0.004
13	329,287.554	3,799,563.495	1,430.972	1,430.963	–0.009
14	329,255.864	3,799,651.114	1,431.032	1,431.052	0.020
15	329,181.840	3,799,812.250	1,431.185	1,431.164	–0.021
		Mean error			0.001

Table 3-3. Calibration statistics for Rio Grande Rio Salado site.

Point number	Observation coordinates: Easting (meters)	Observation coordinates: Northing (meters)	Observed water-surface elevation (meters)	Simulated water-surface elevation (meters)	Delta (meters)
1	327,868.117	3,792,832.822	1,423.947	1,423.951	0.0043
2	328,037.117	3,792,714.047	1,424.020	1,424.013	–0.0071
3	328,178.821	3,792,510.397	1,424.150	1,424.140	–0.0104
4	328,429.303	3,792,450.521	1,424.365	1,424.370	0.0053
5	328,487.027	3,792,488.448	1,424.419	1,424.421	0.0017
6	328,567.281	3,792,568.035	1,424.492	1,424.490	–0.0021
7	328,611.275	3,792,609.649	1,424.549	1,424.540	–0.0094
8	328,614.701	3,792,685.016	1,424.612	1,424.602	–0.0104
9	328,668.631	3,792,798.460	1,424.795	1,424.802	0.0071
10	328,744.586	3,792,856.065	1,424.816	1,424.836	0.0198
11	328,839.527	3,792,963.500	1,424.875	1,424.873	–0.0023
12	328,825.149	3,793,104.101	1,424.907	1,424.912	0.0053
				Mean error	0.00015

Appendix 4. Habitat Maps for Rio Grande Silvery Minnows

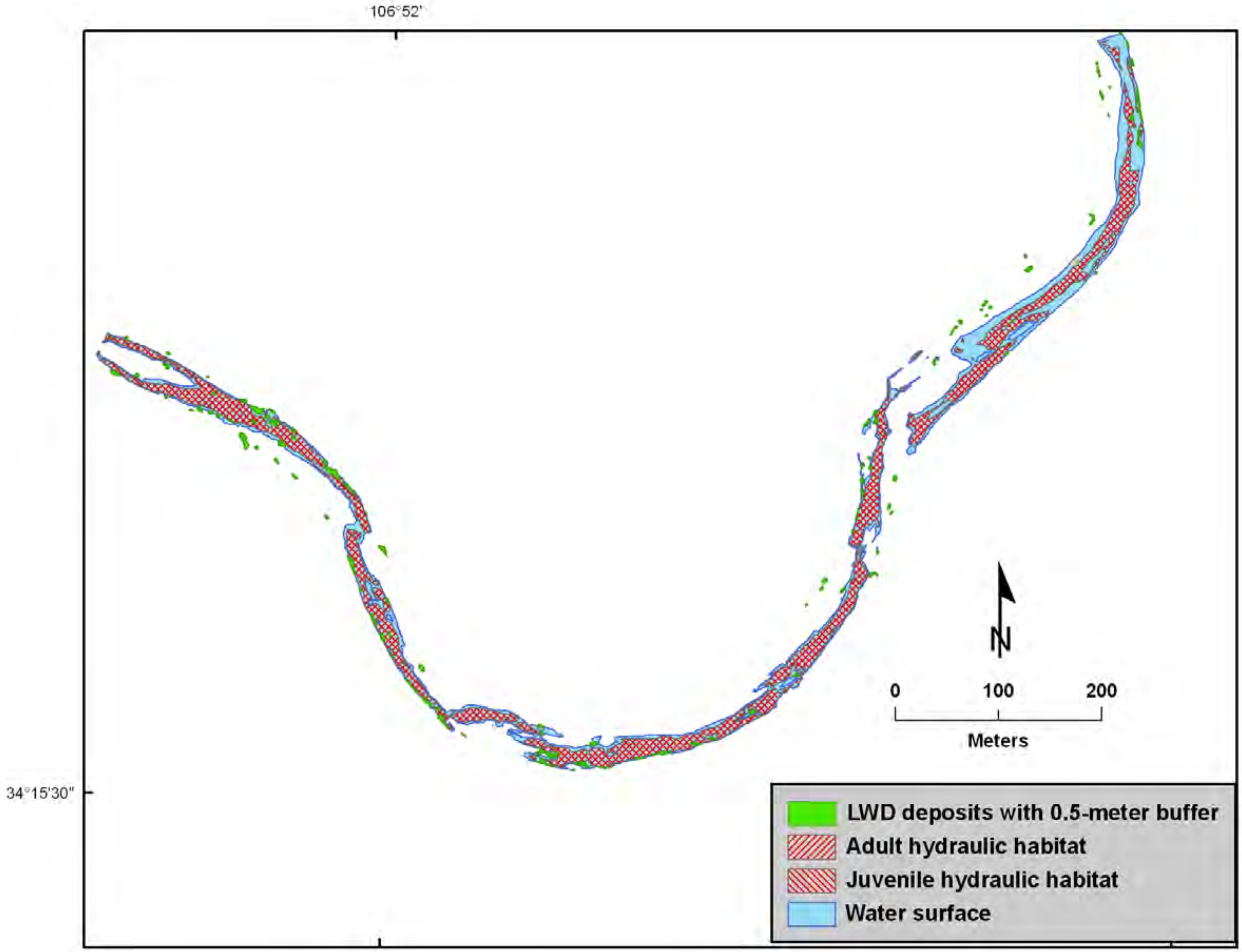

Figure 4-1. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 5 cubic feet per second.

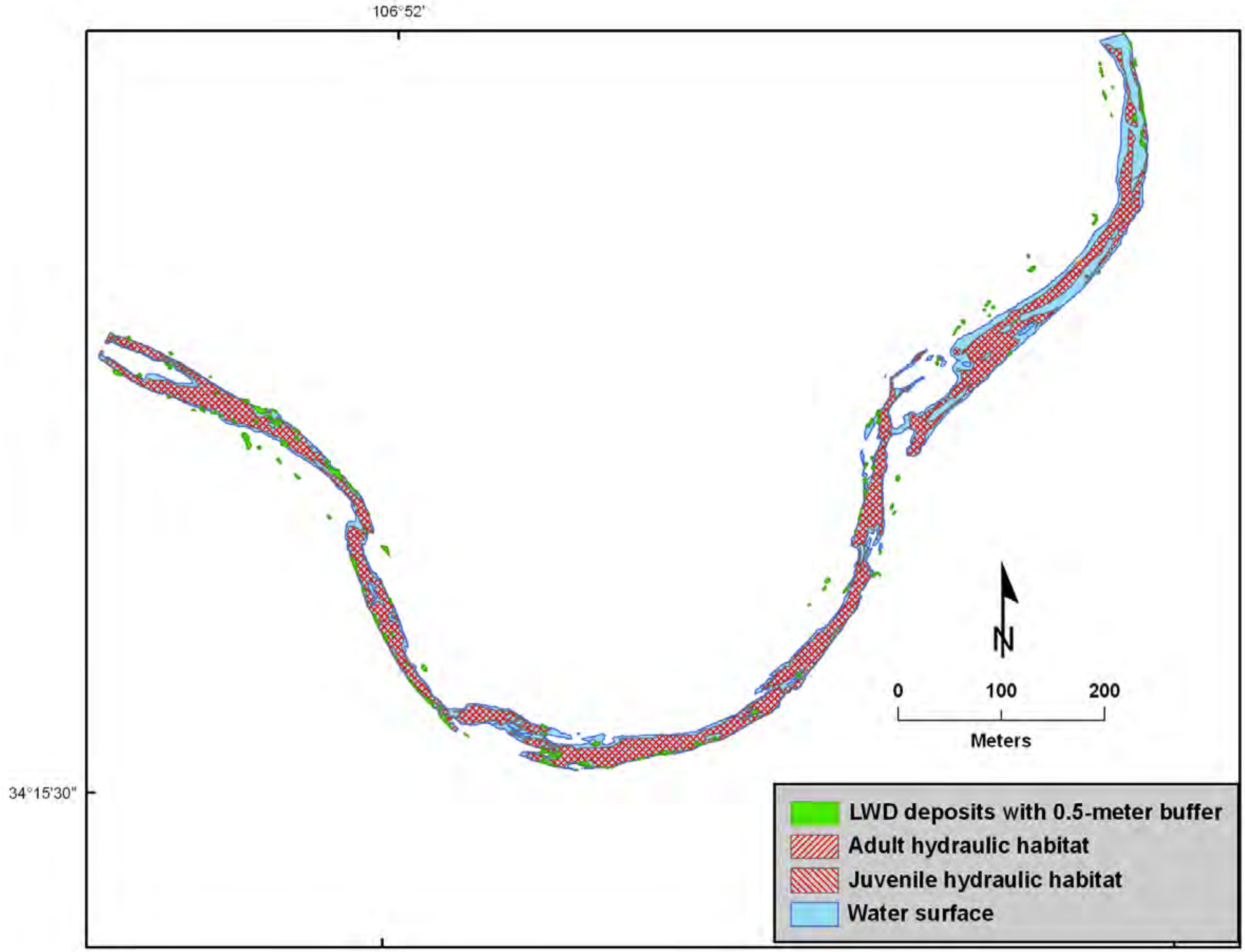

Figure 4-2. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 10 cubic feet per second.

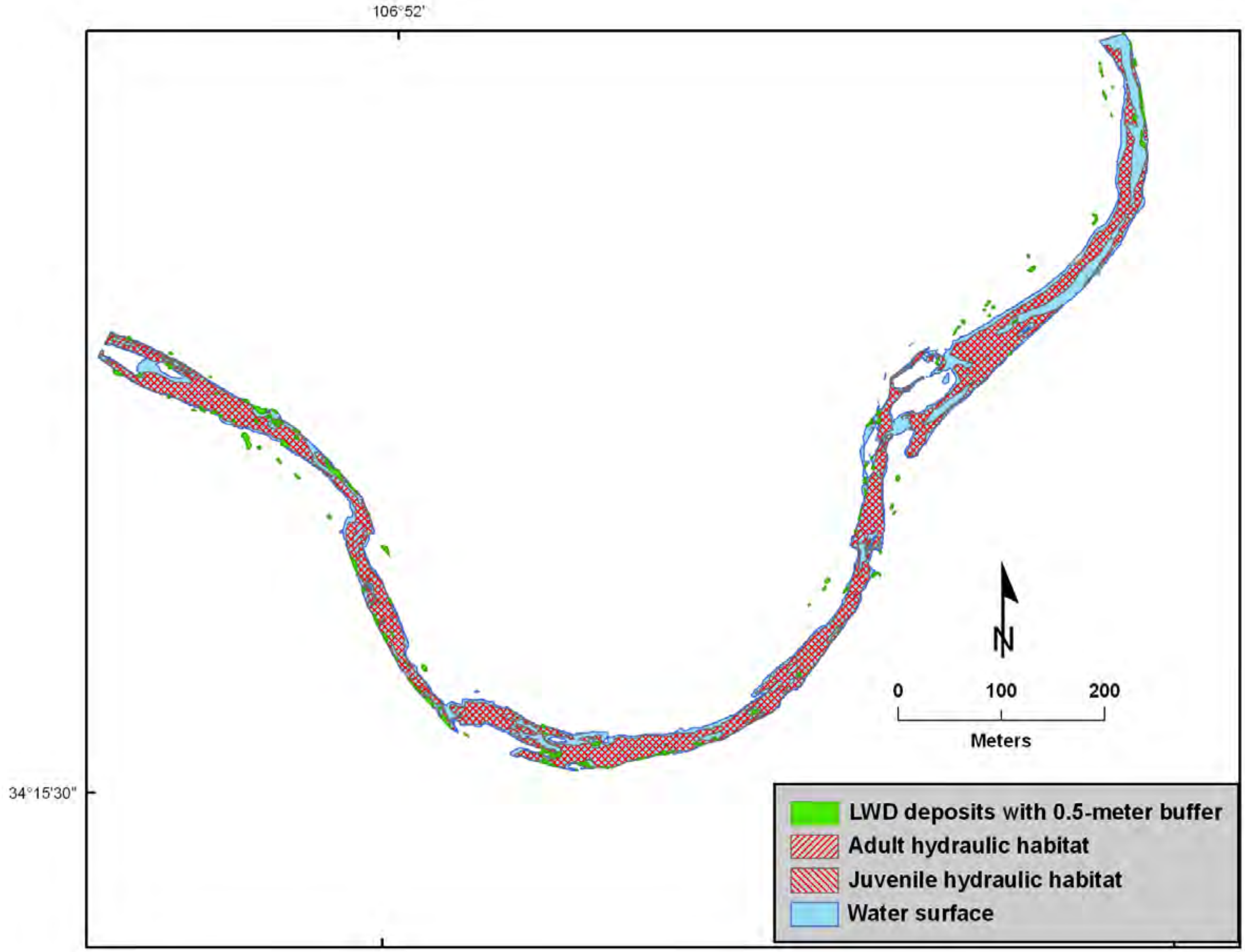

Figure 4-3. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 20 cubic feet per second.

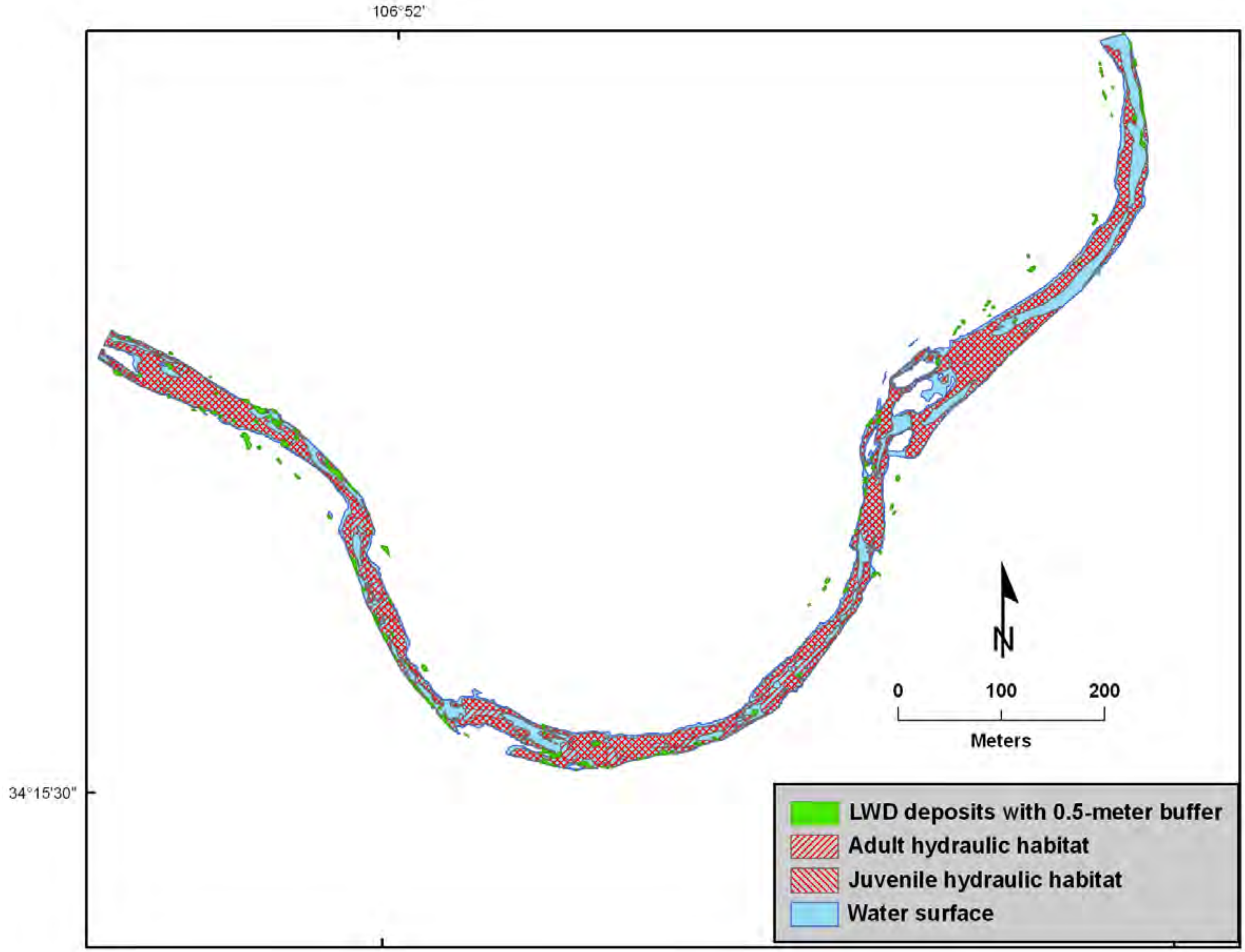

Figure 4-4. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 40 cubic feet per second.

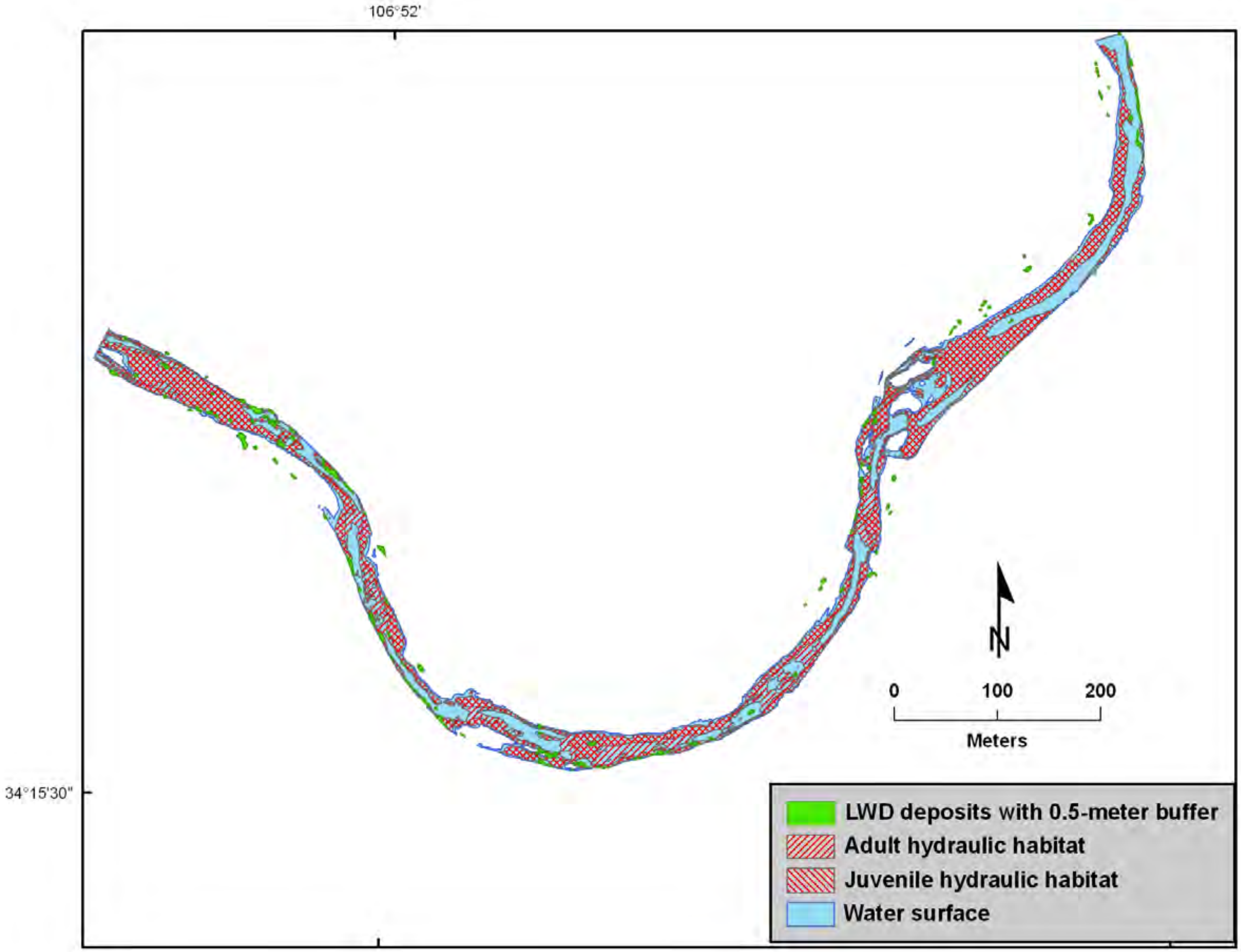

Figure 4-5. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 60 cubic feet per second.

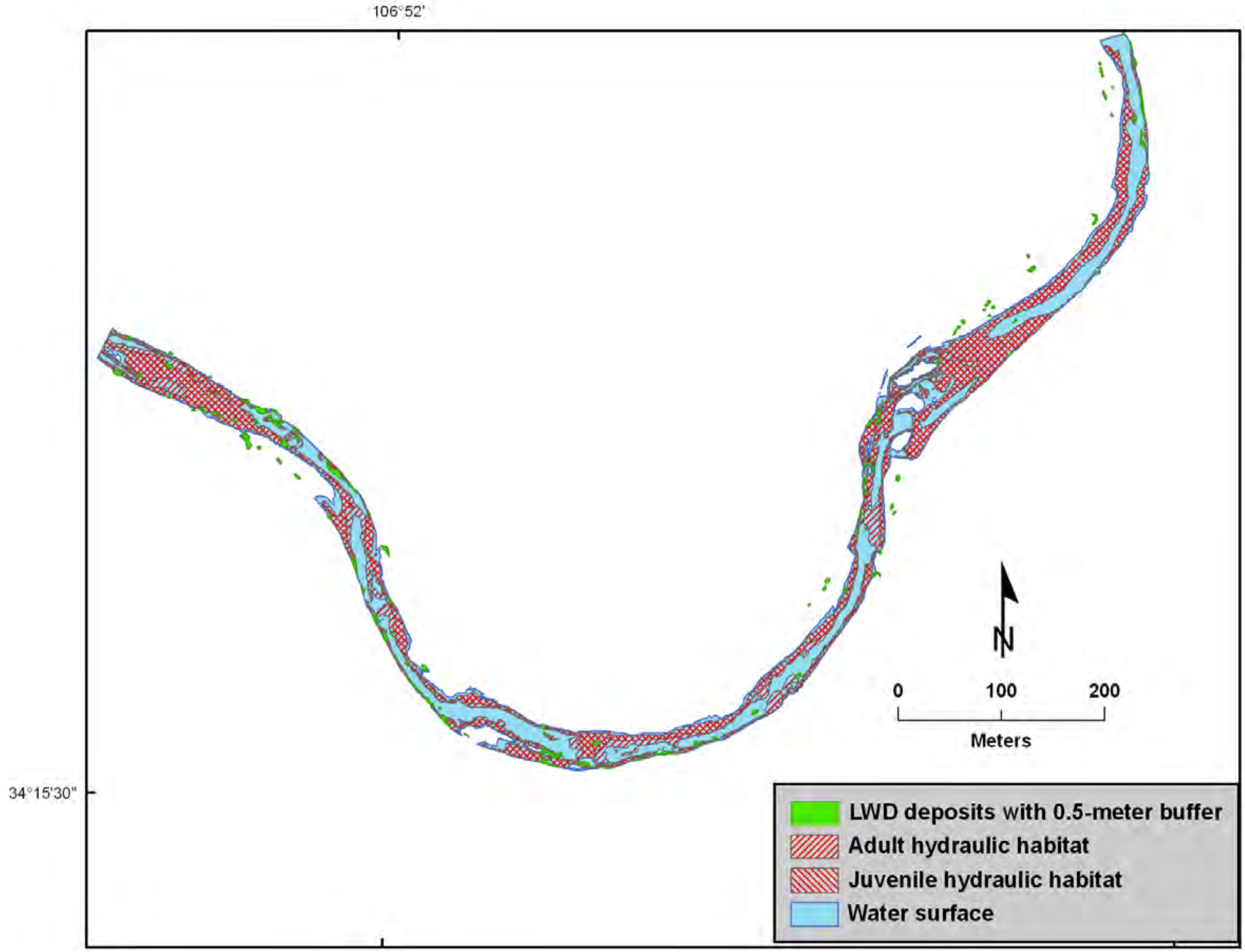

Figure 4-6. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 80 cubic feet per second.

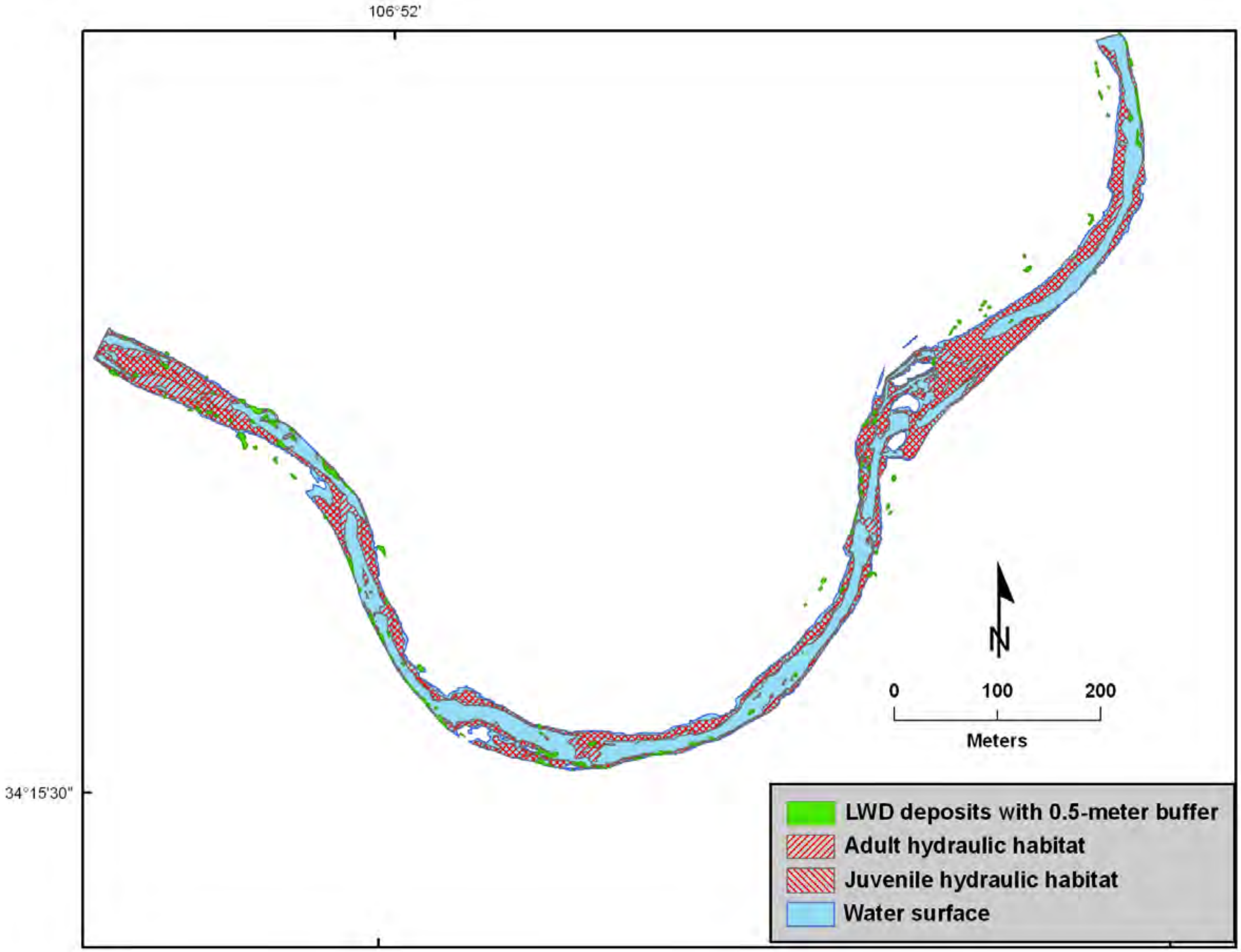

Figure 4-7. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 100 cubic feet per second.

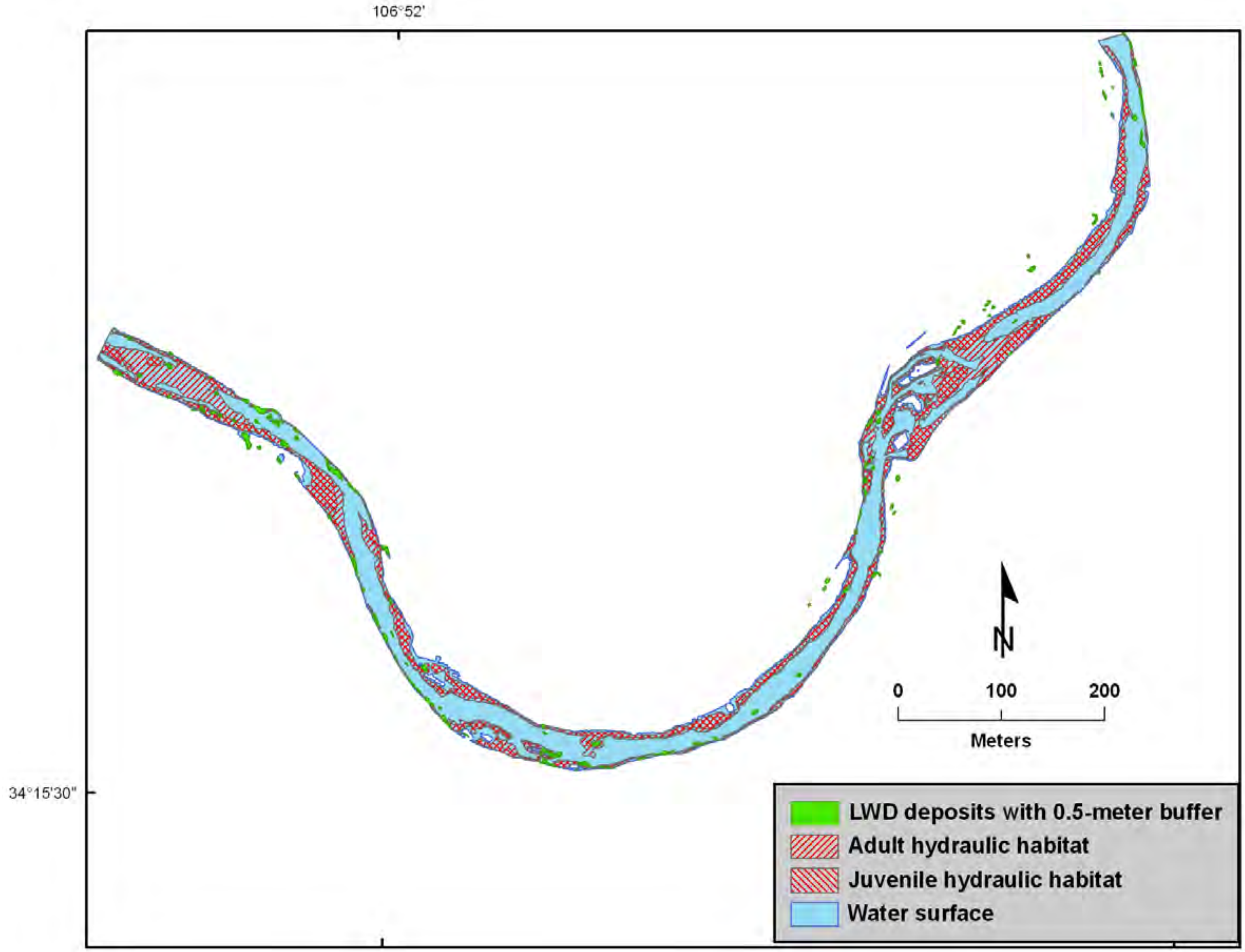

Figure 4-8. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 150 cubic feet per second.

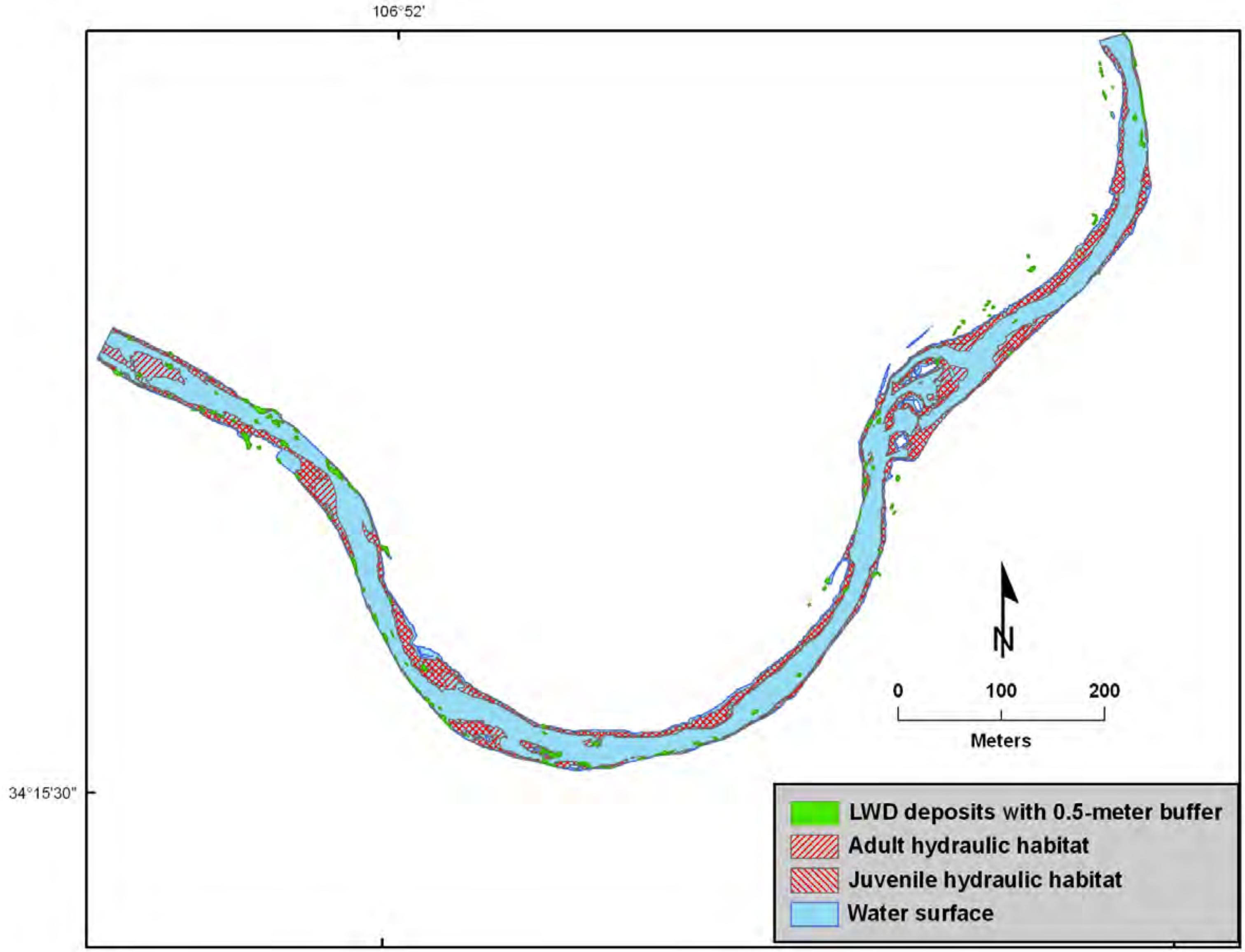

Figure 4-9. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 200 cubic feet per second.

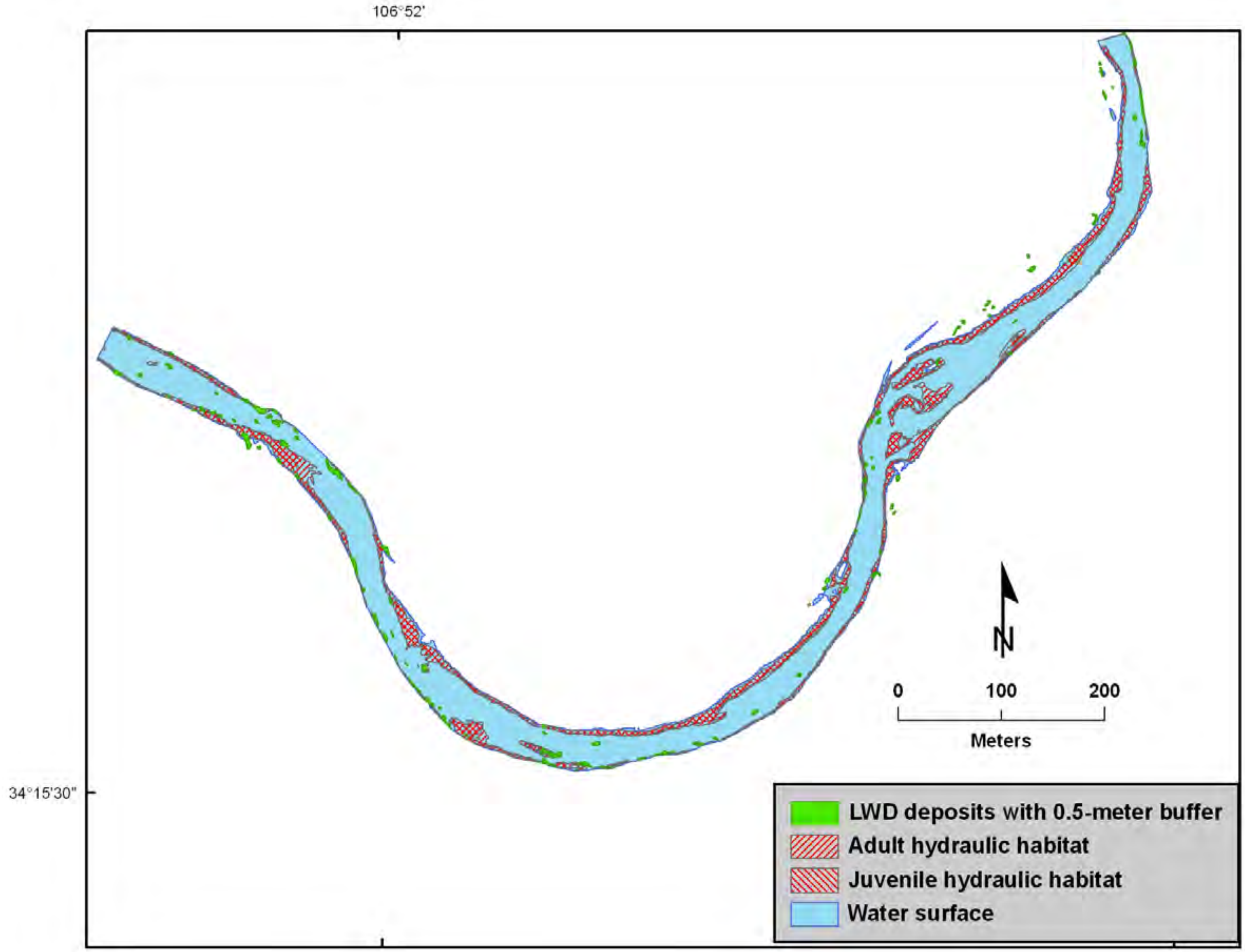

Figure 4-10. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 300 cubic feet per second.

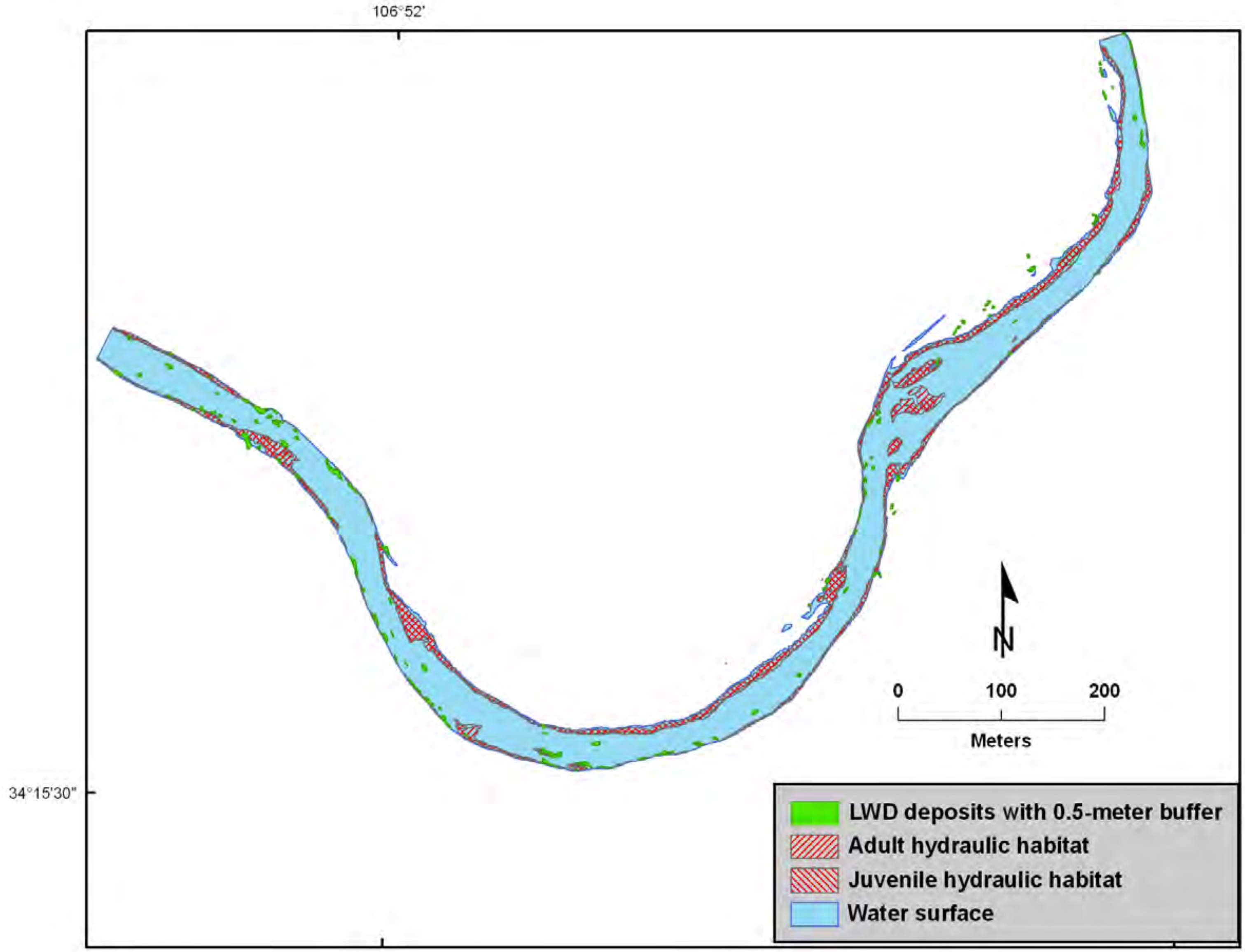

Figure 4-11. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 400 cubic feet per second.

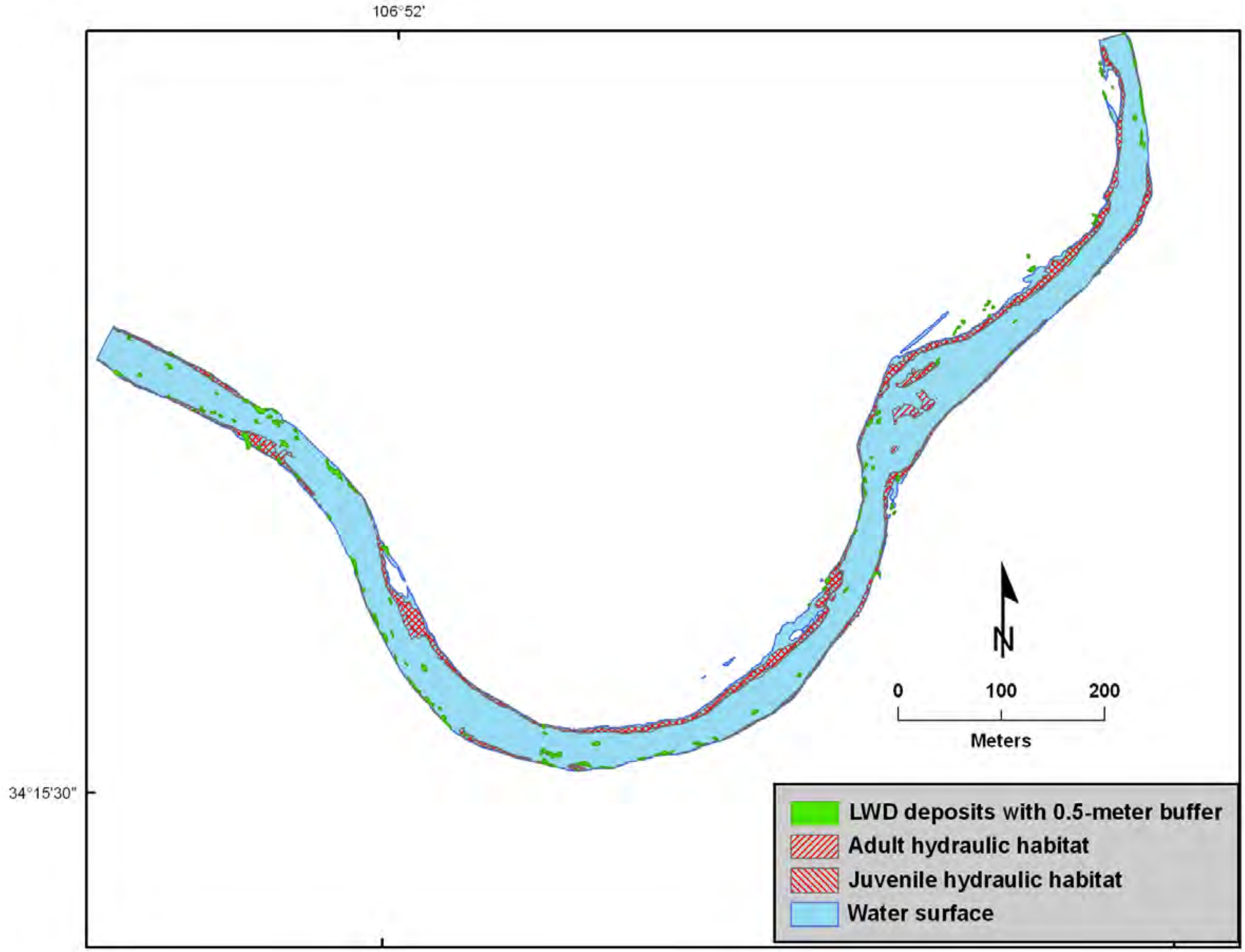

Figure 4-12. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 500 cubic feet per second.

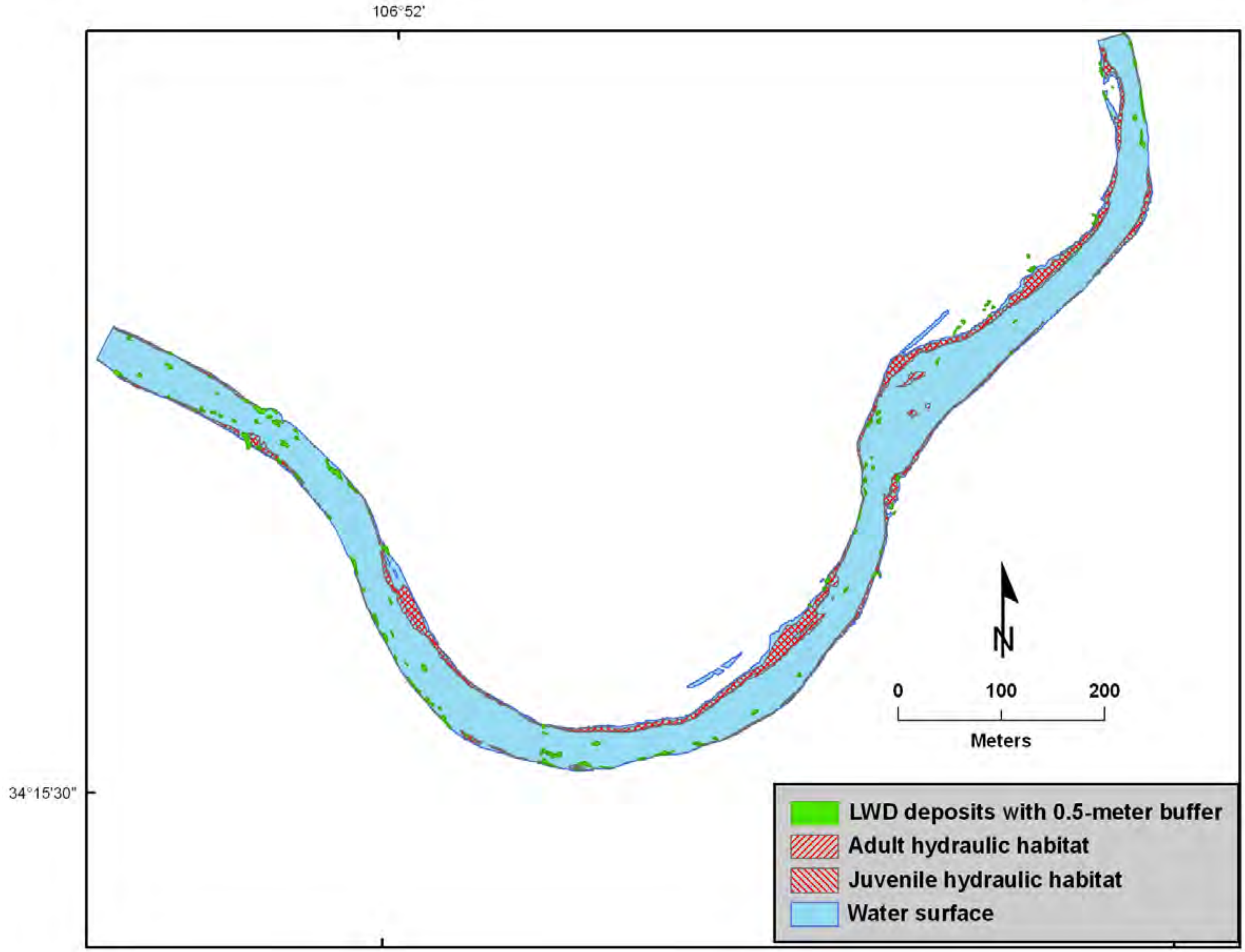

Figure 4-13. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 600 cubic feet per second.

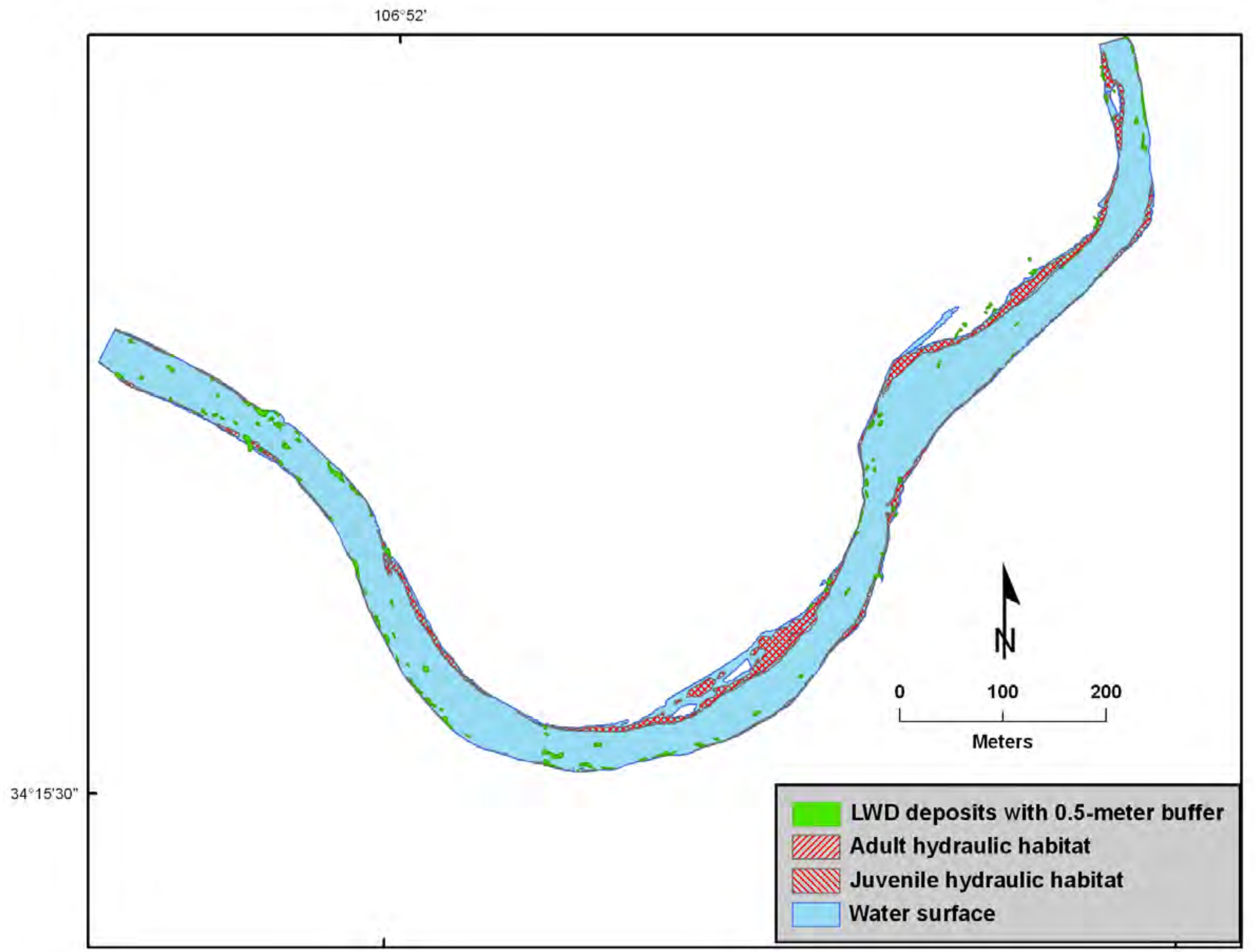

Figure 4-14. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 800 cubic feet per second.

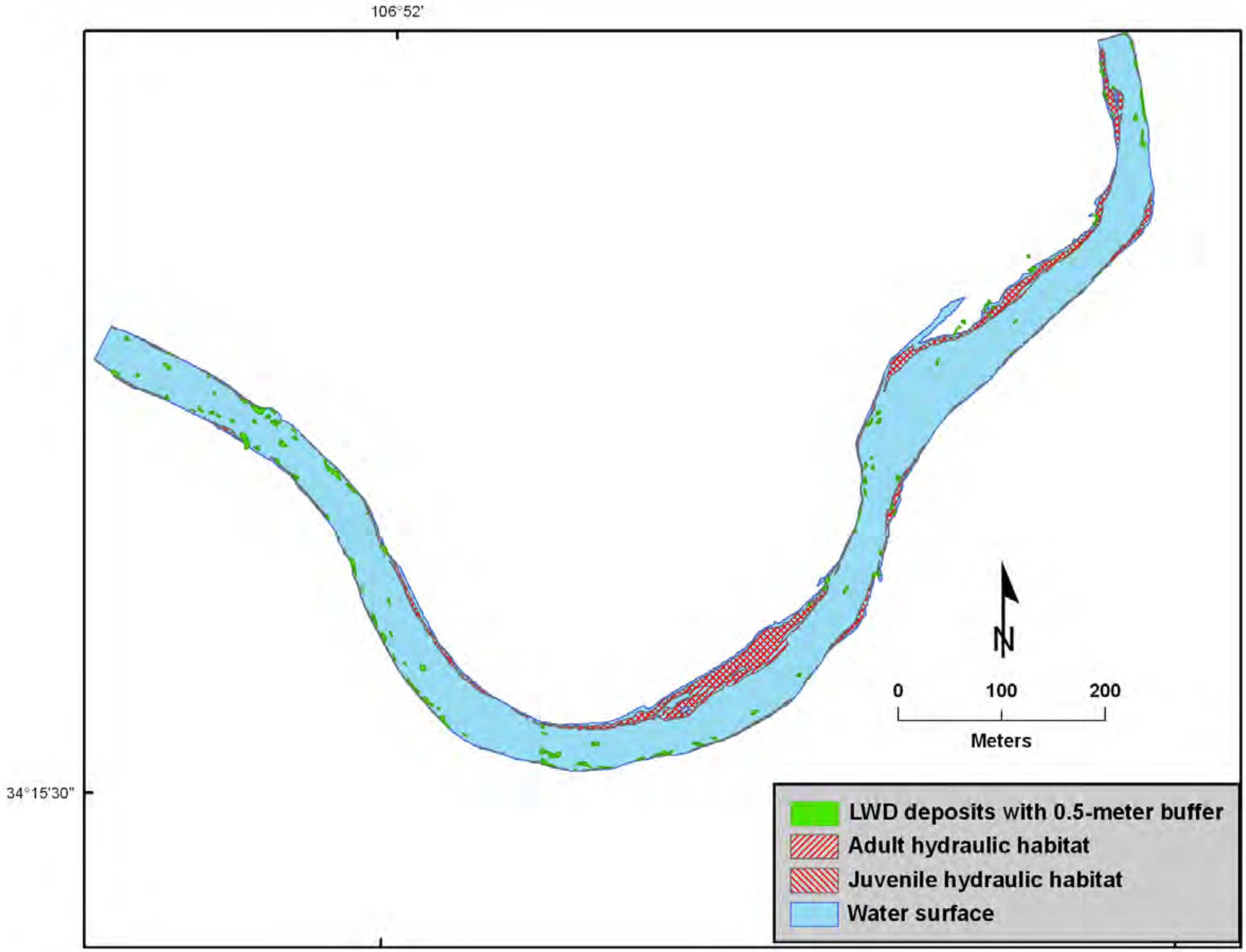

Figure 4-15. Habitat for adult and juvenile *H. amarus*, Rio Salado site, at 1,000 cubic feet per second.

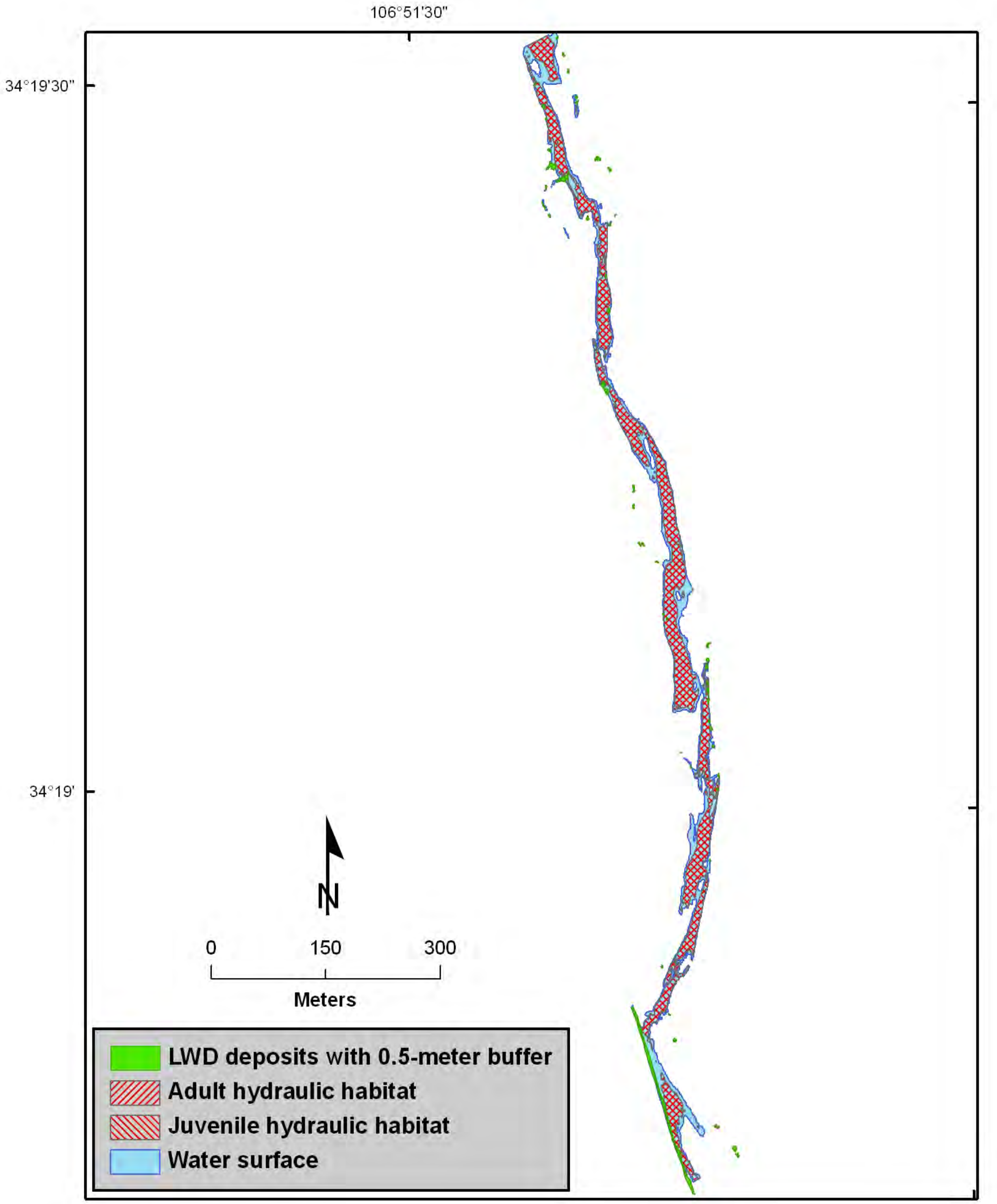

Figure 4-16. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 5 cubic feet per second.

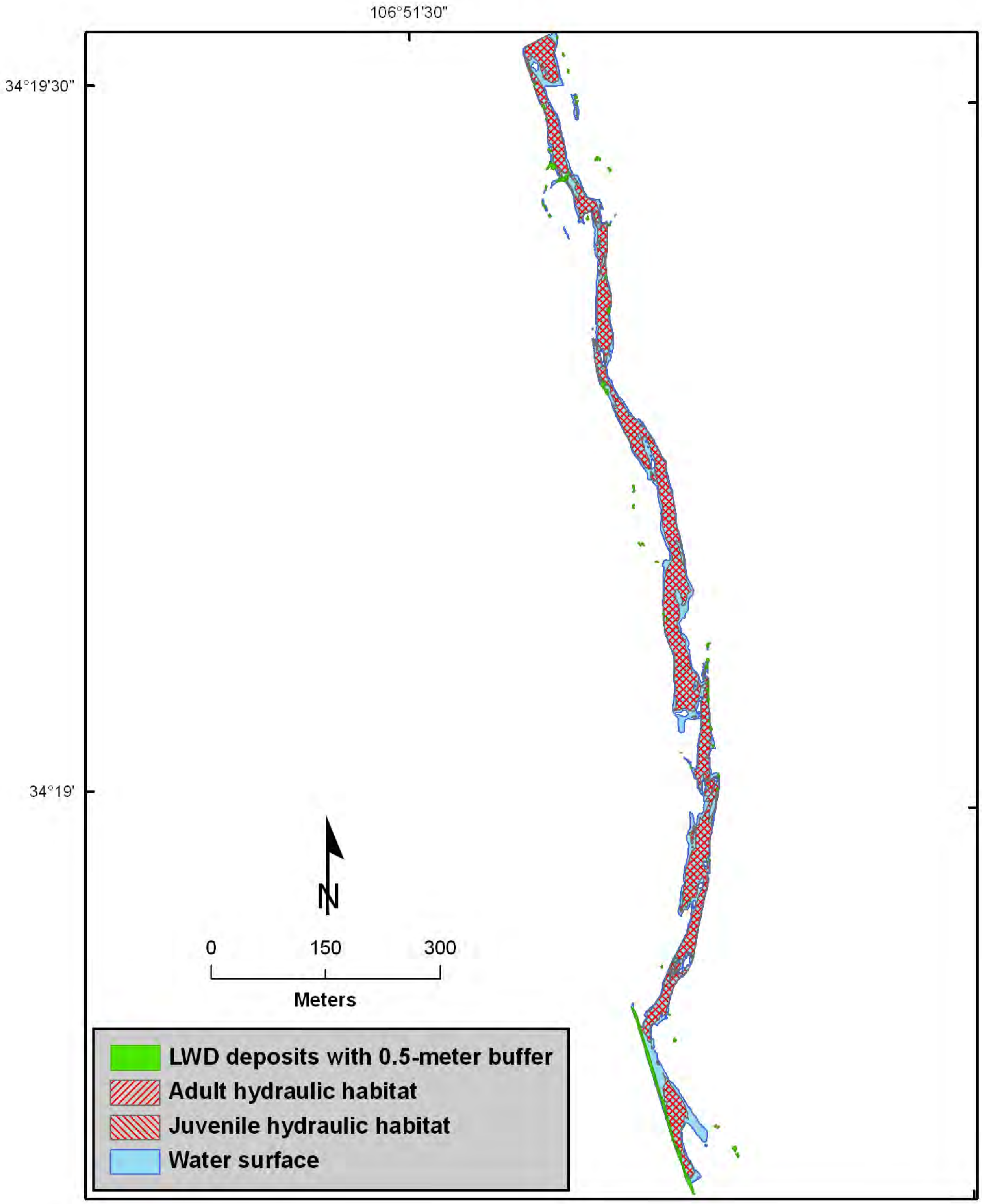

Figure 4-17. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 10 cubic feet per second.

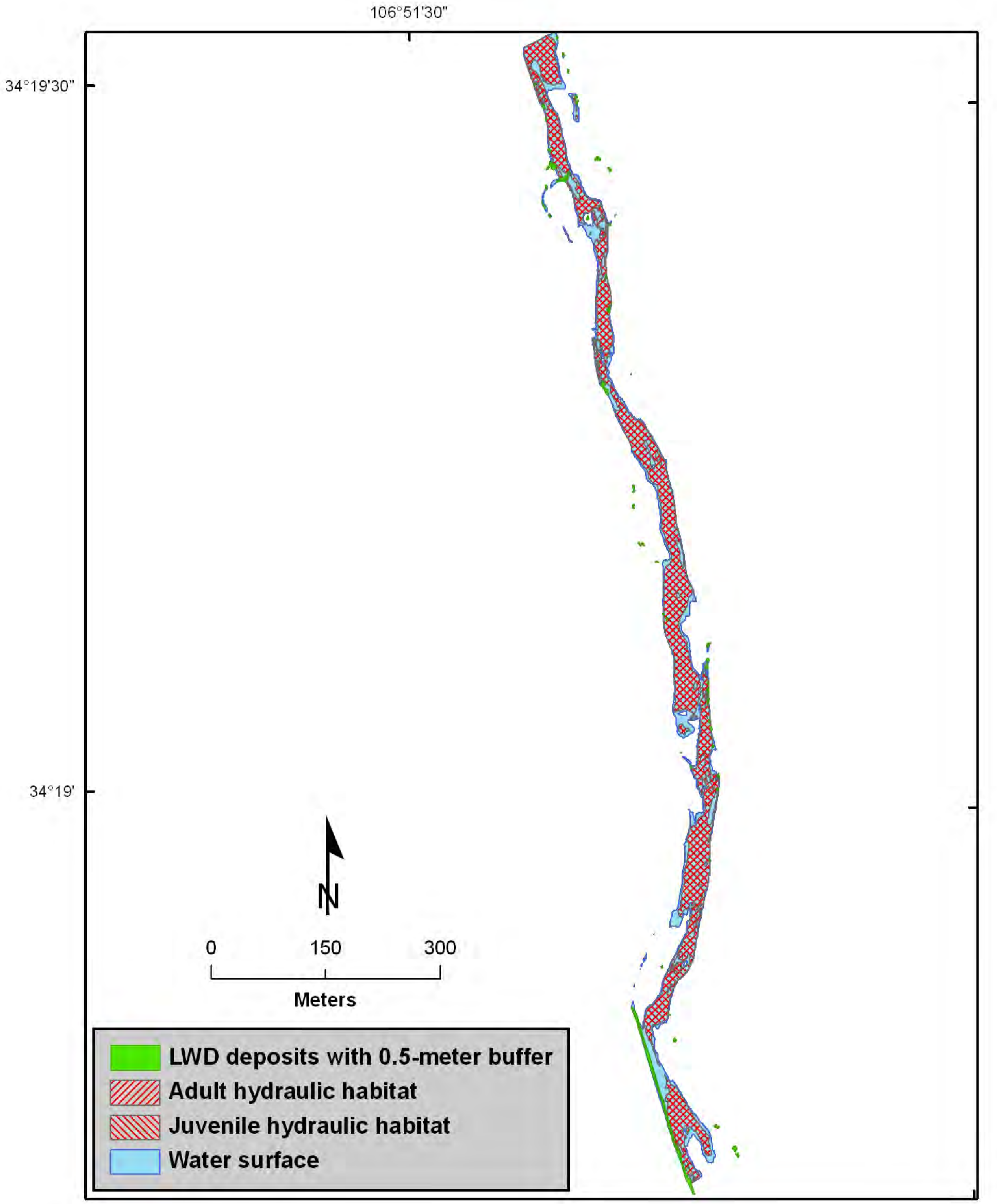

Figure 4-18. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 20 cubic feet per second.

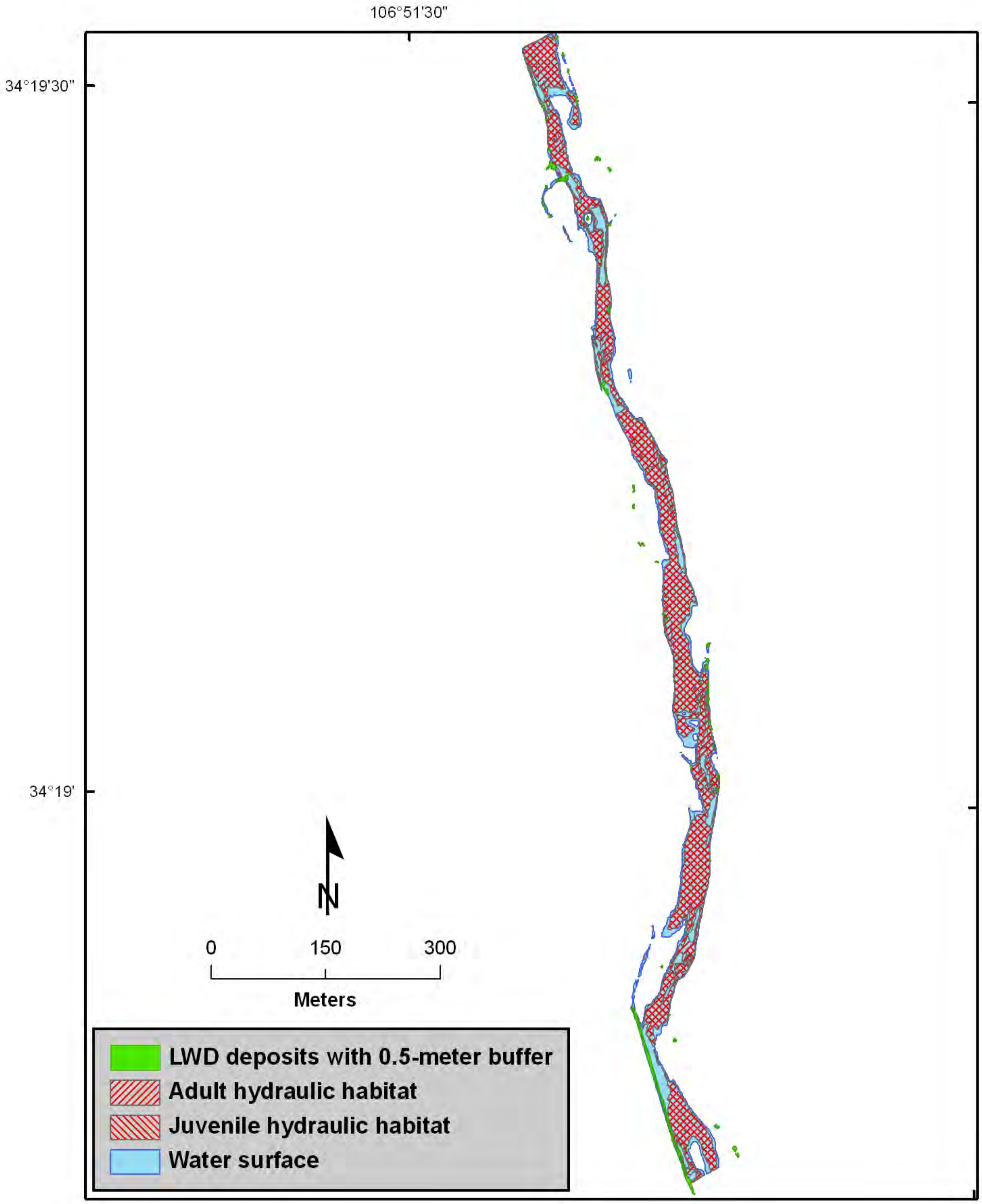

Figure 4-19. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 40 cubic feet per second.

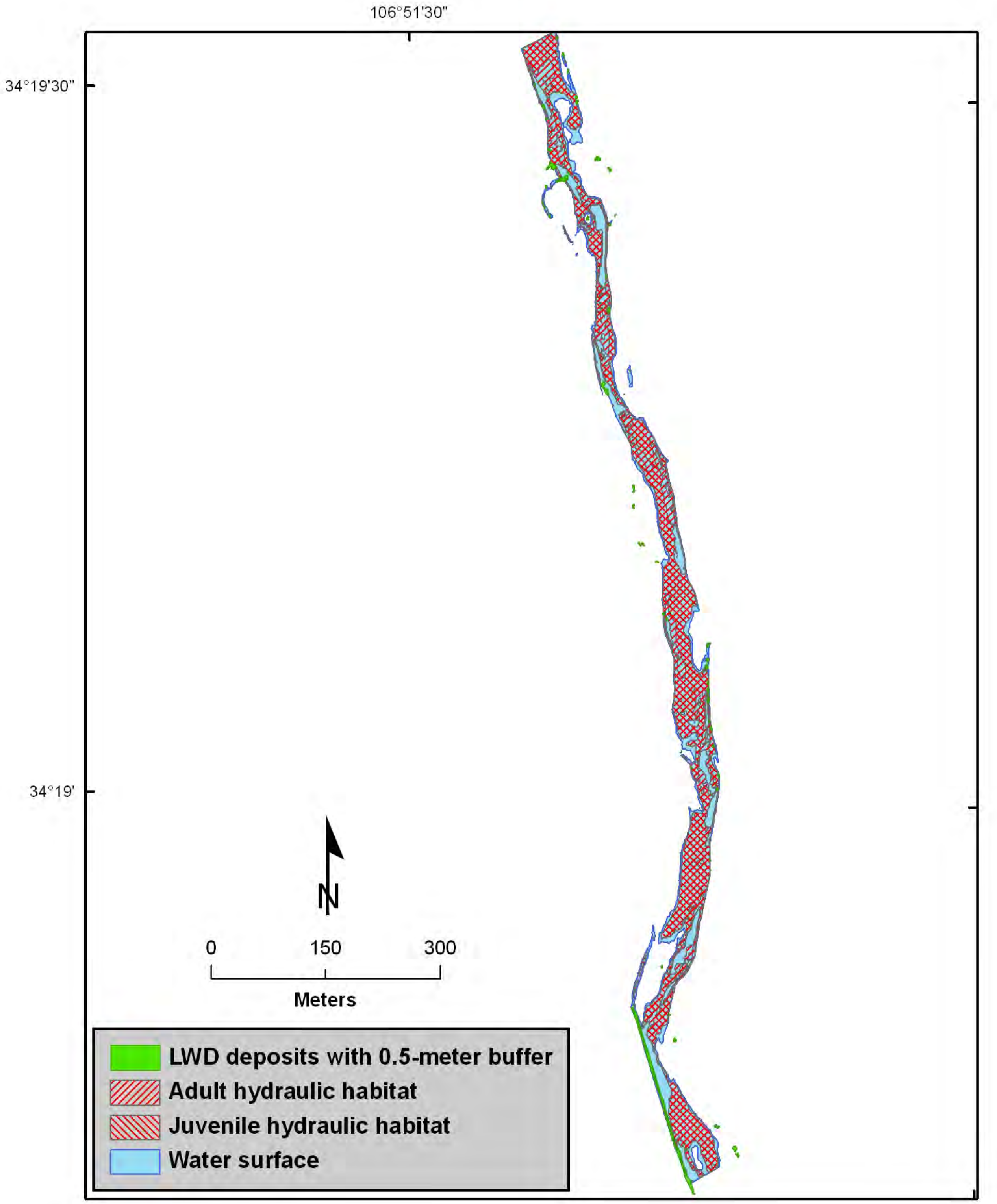

Figure 4-20. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 60 cubic feet per second.

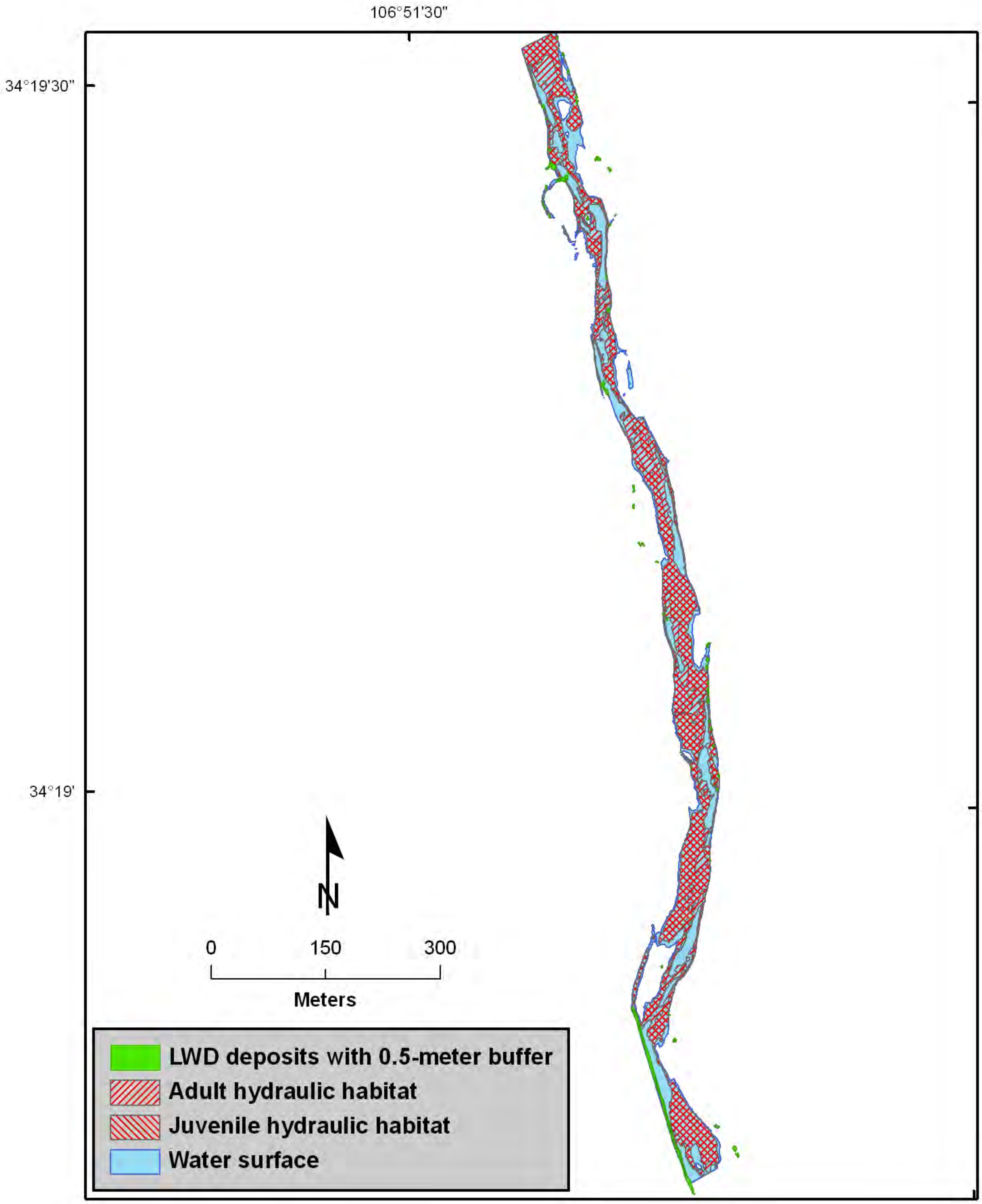

Figure 4-21. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 80 cubic feet per second.

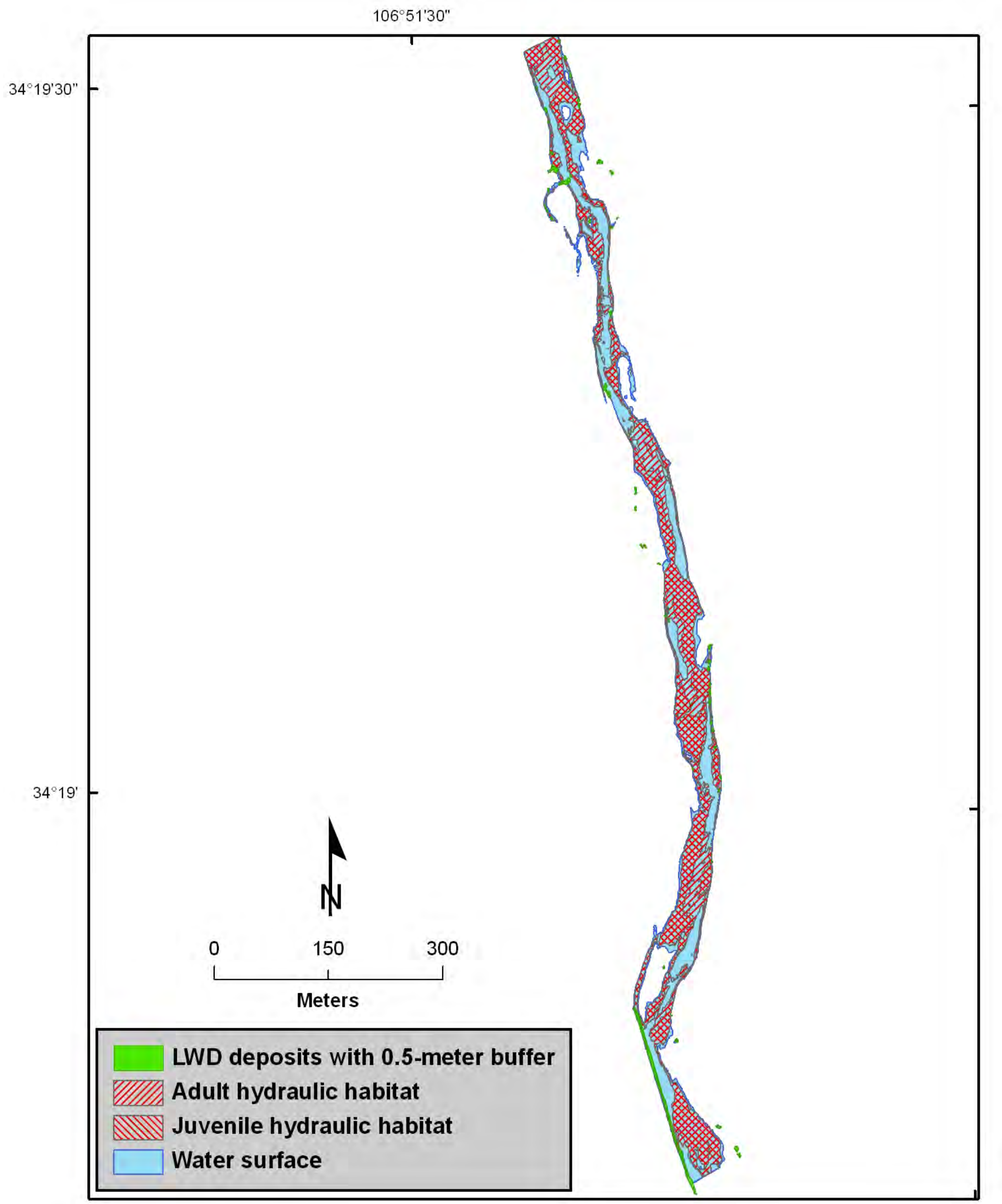

Figure 4-22. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 100 cubic feet per second.

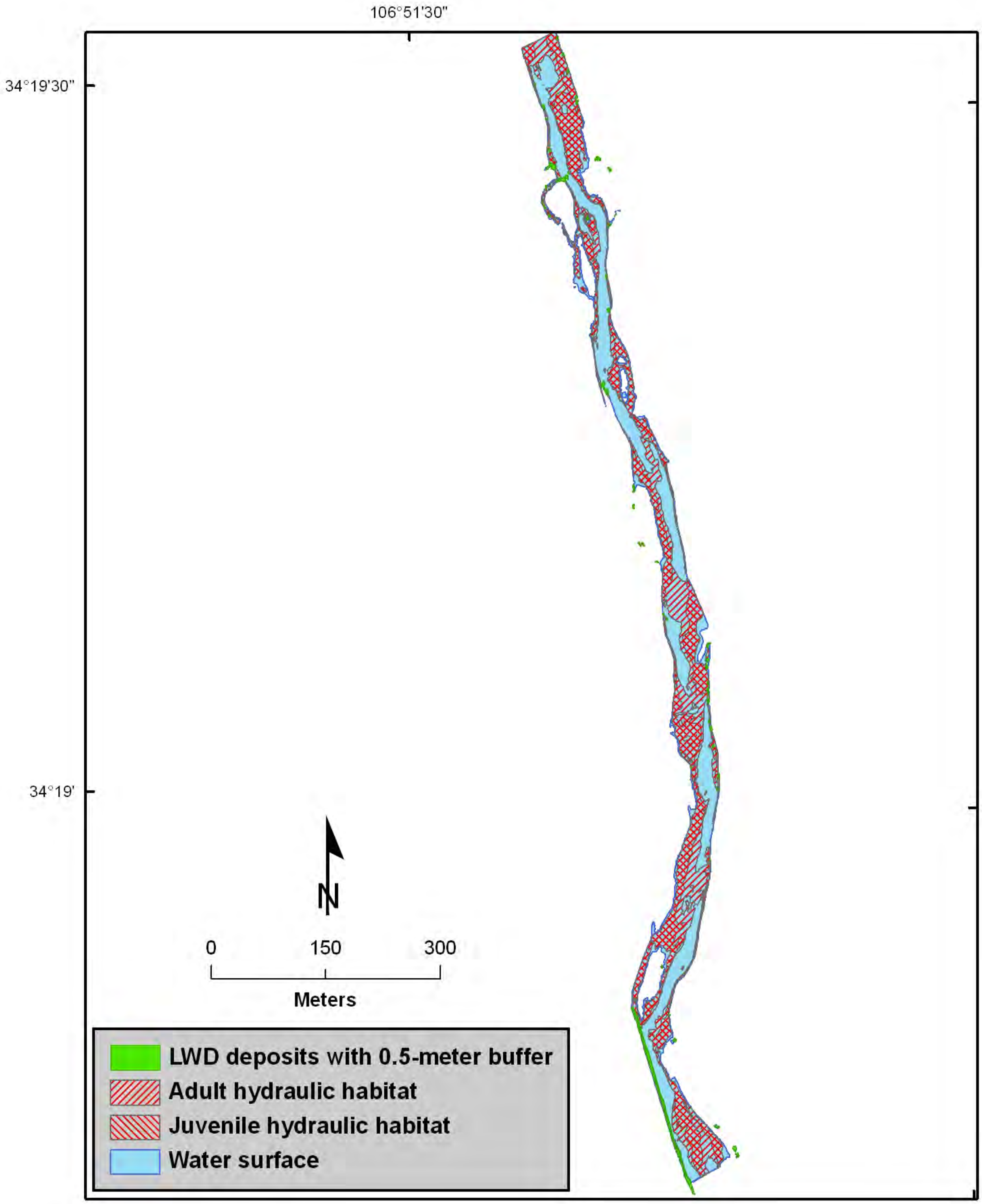

Figure 4-23. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 150 cubic feet per second.

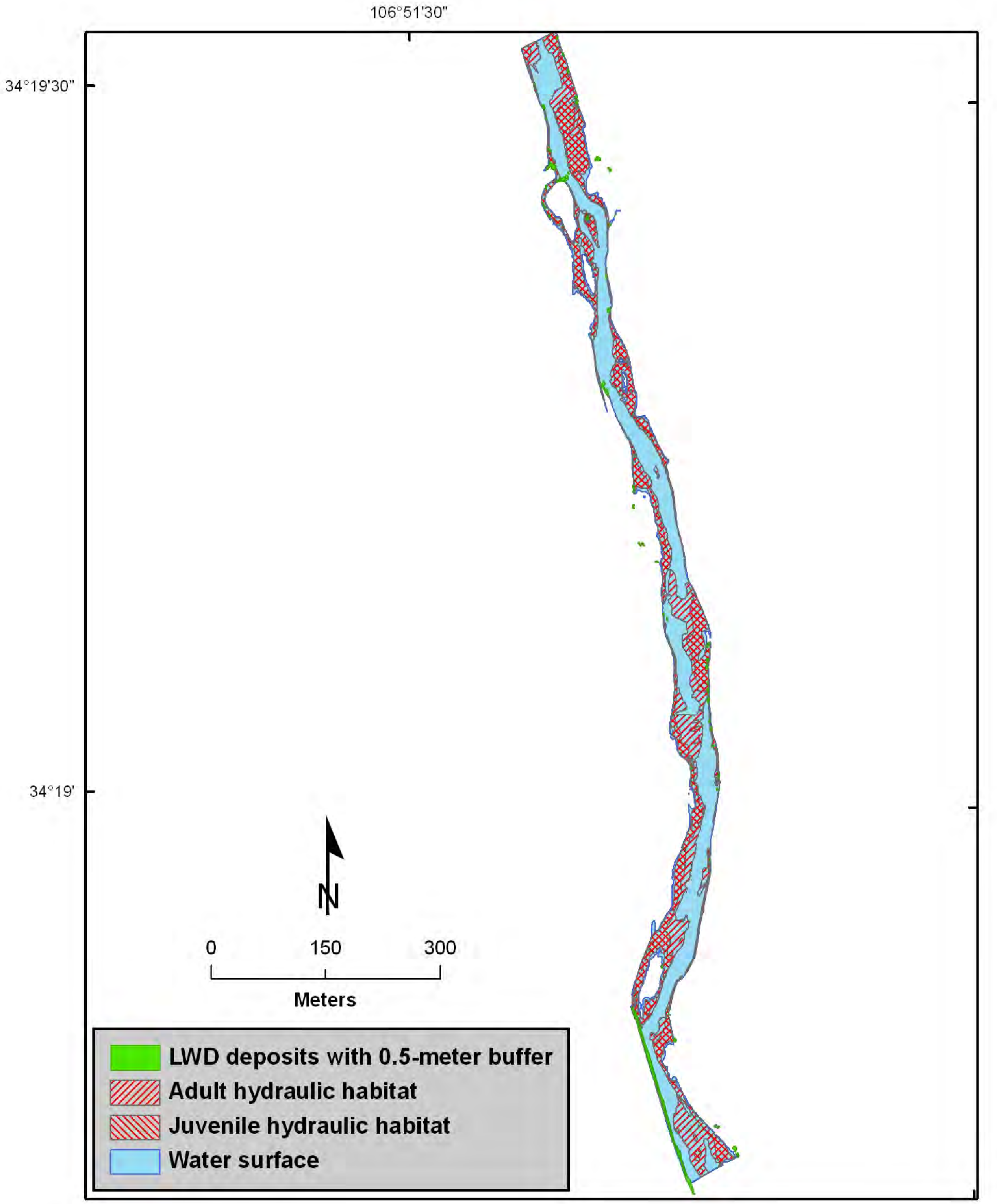

Figure 4-24. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 200 cubic feet per second.

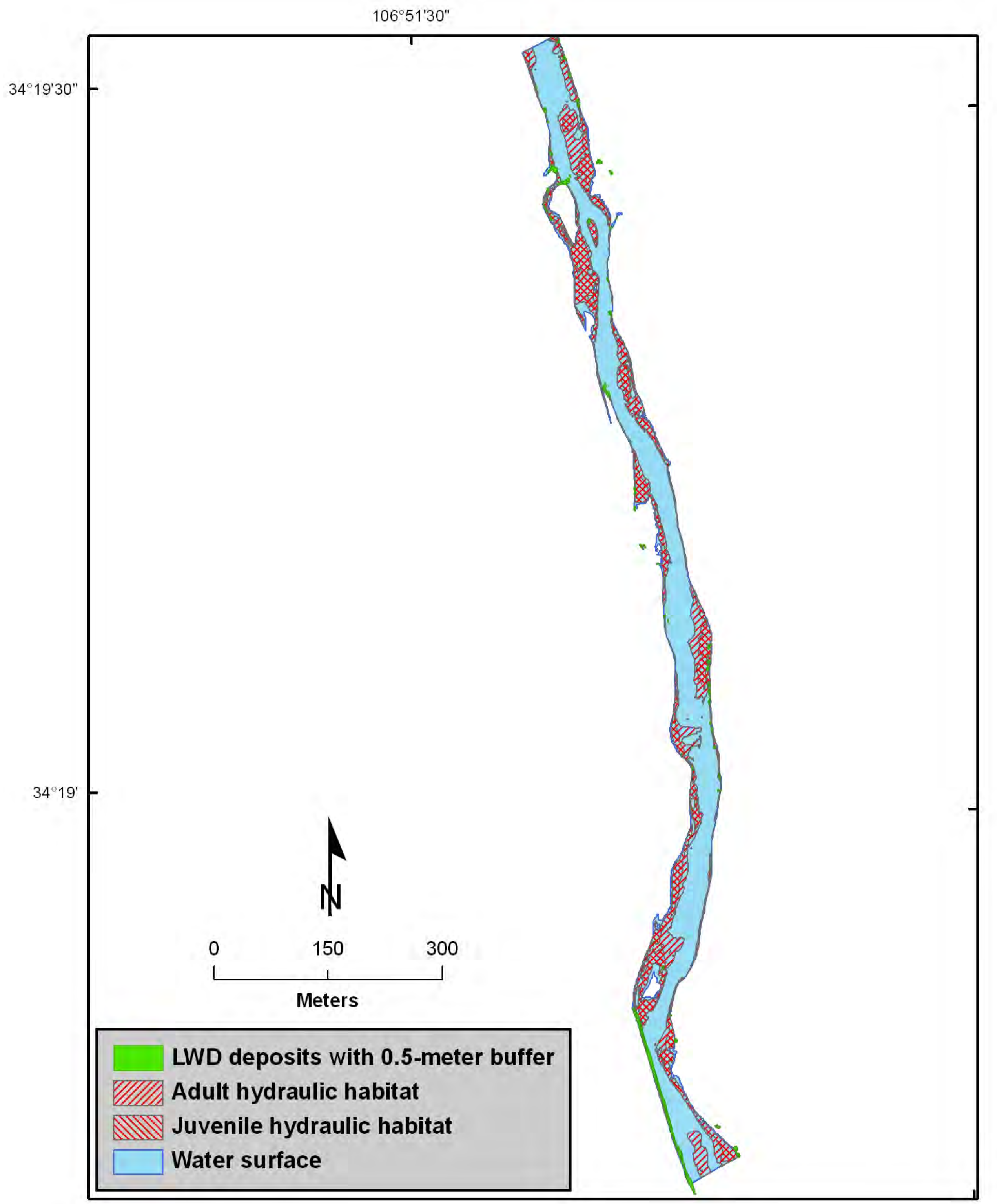

Figure 4-25. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 300 cubic feet per second.

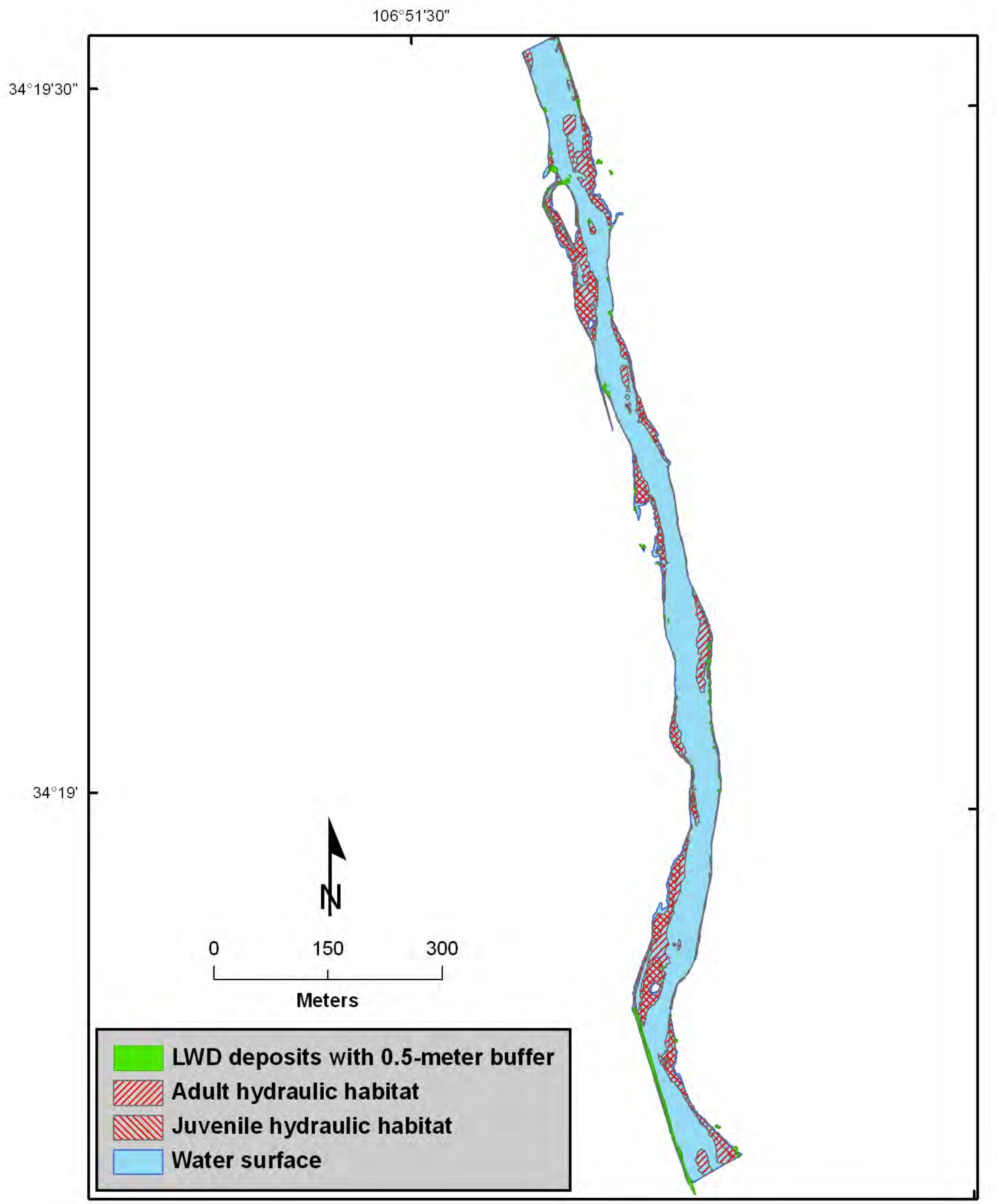

Figure 4-26. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 400 cubic feet per second.

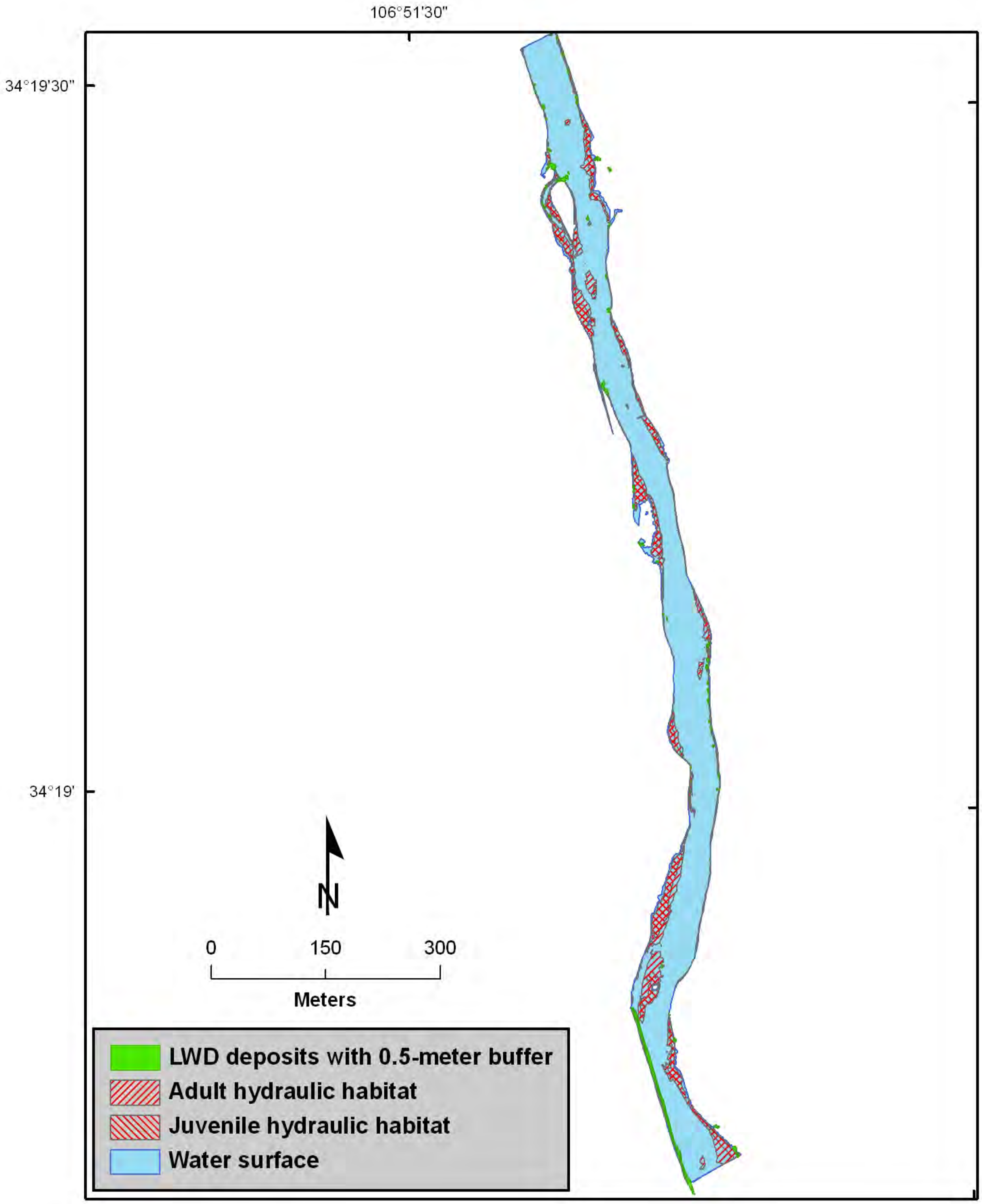

Figure 4-27. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 500 cubic feet per second.

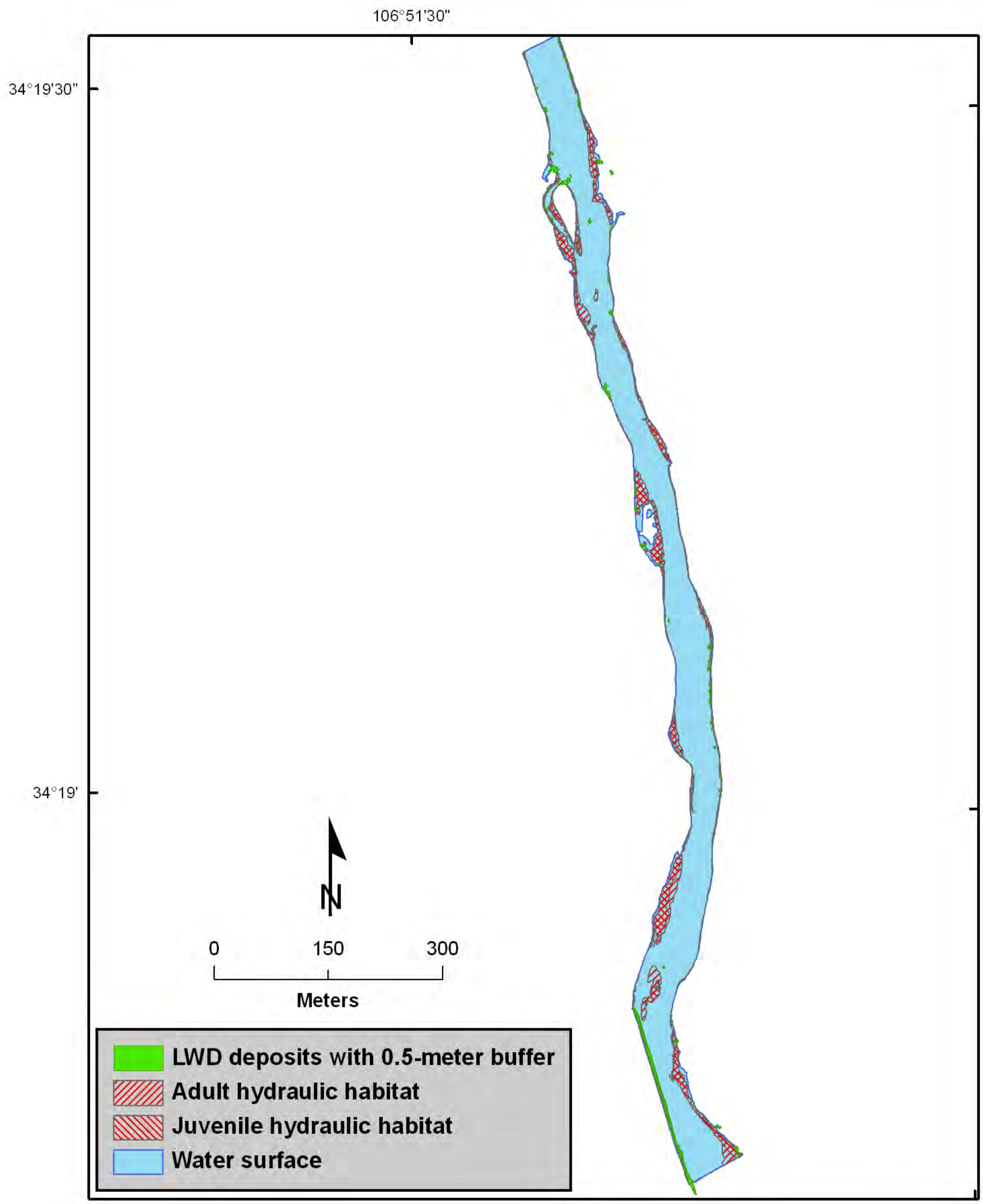

Figure 4-28. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 600 cubic feet per second.

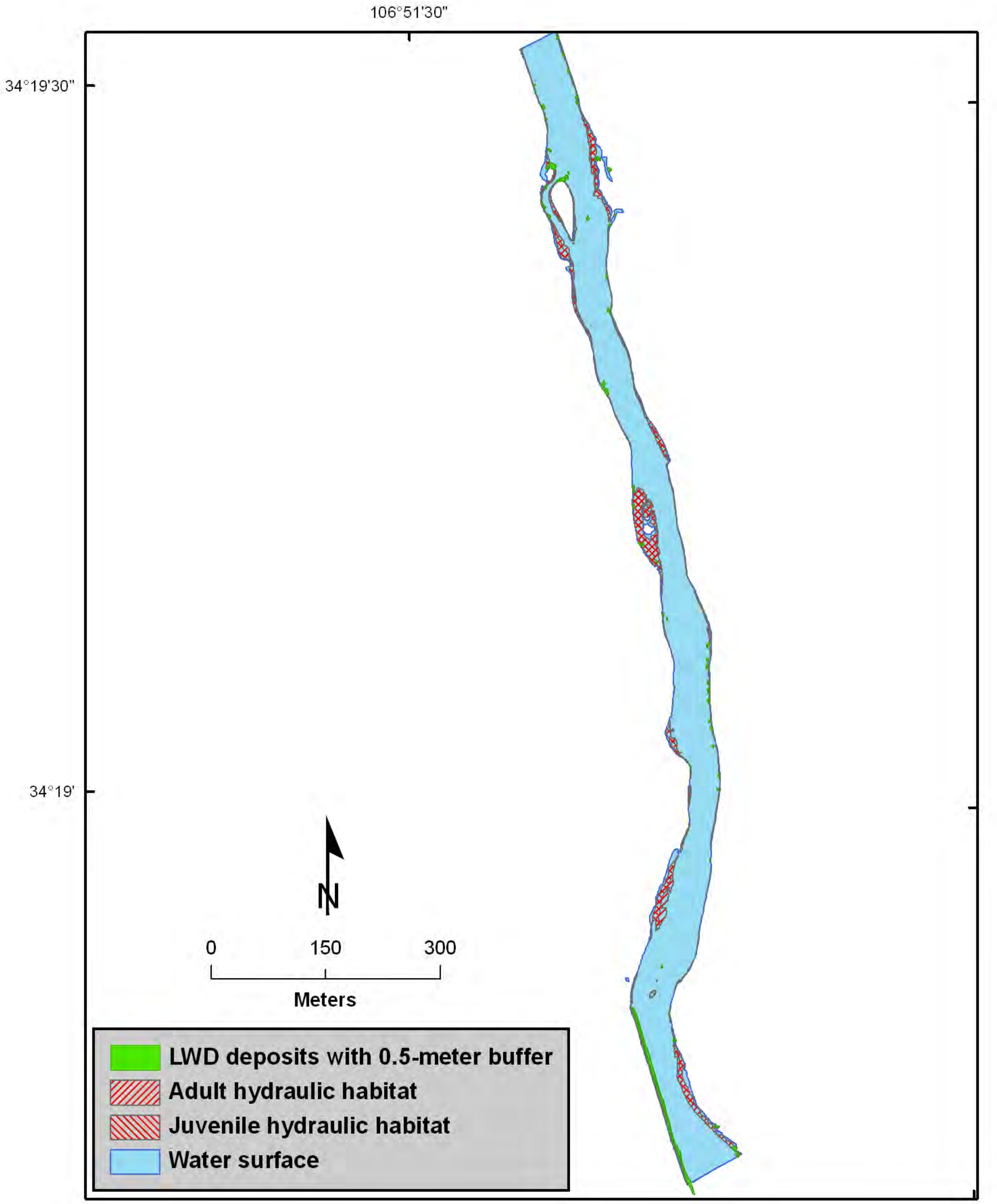

Figure 4-29. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 800 cubic feet per second.

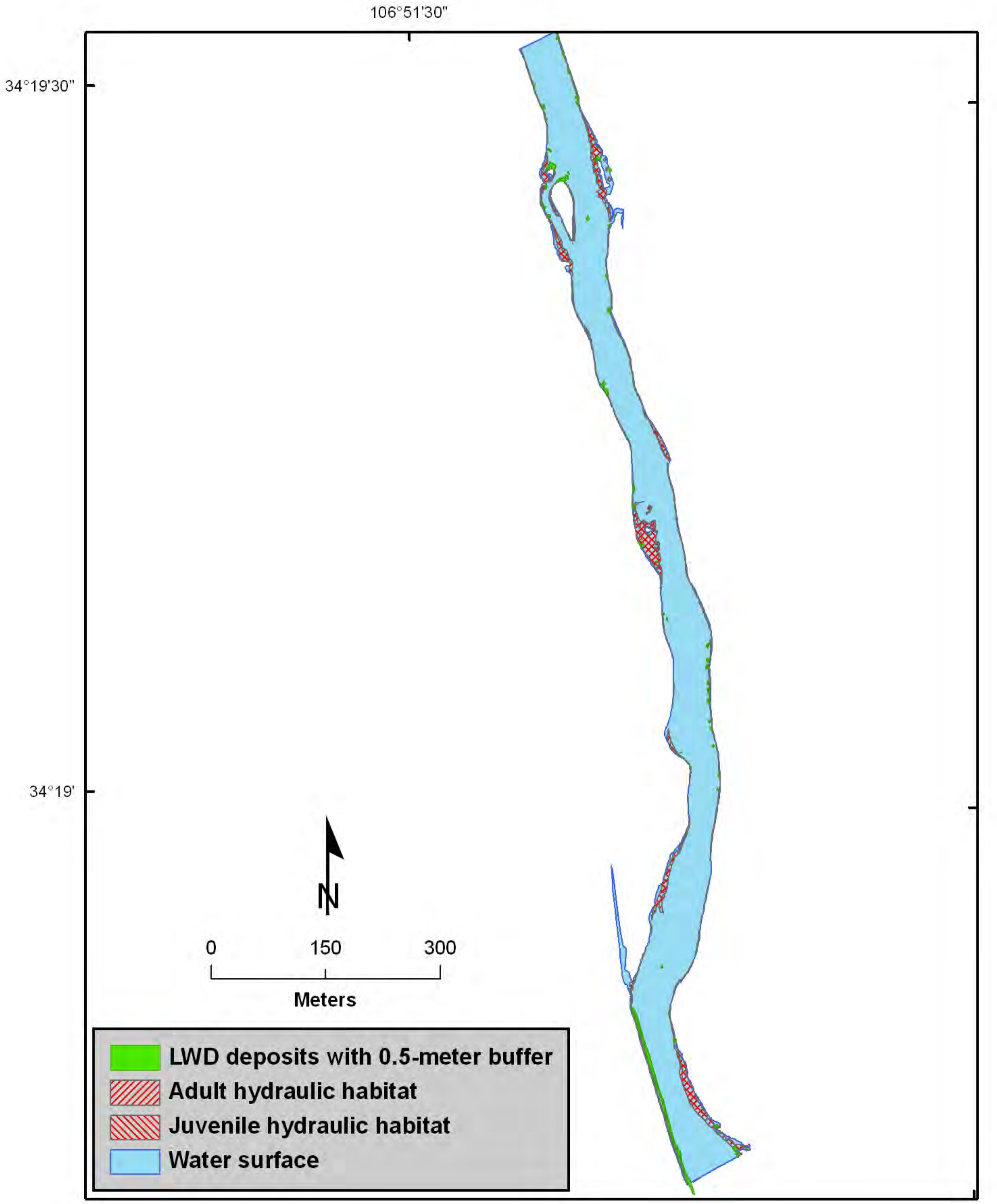

Figure 4-30. Habitat for adult and juvenile *H. amarus*, Sevilleta site, at 1,000 cubic feet per second.

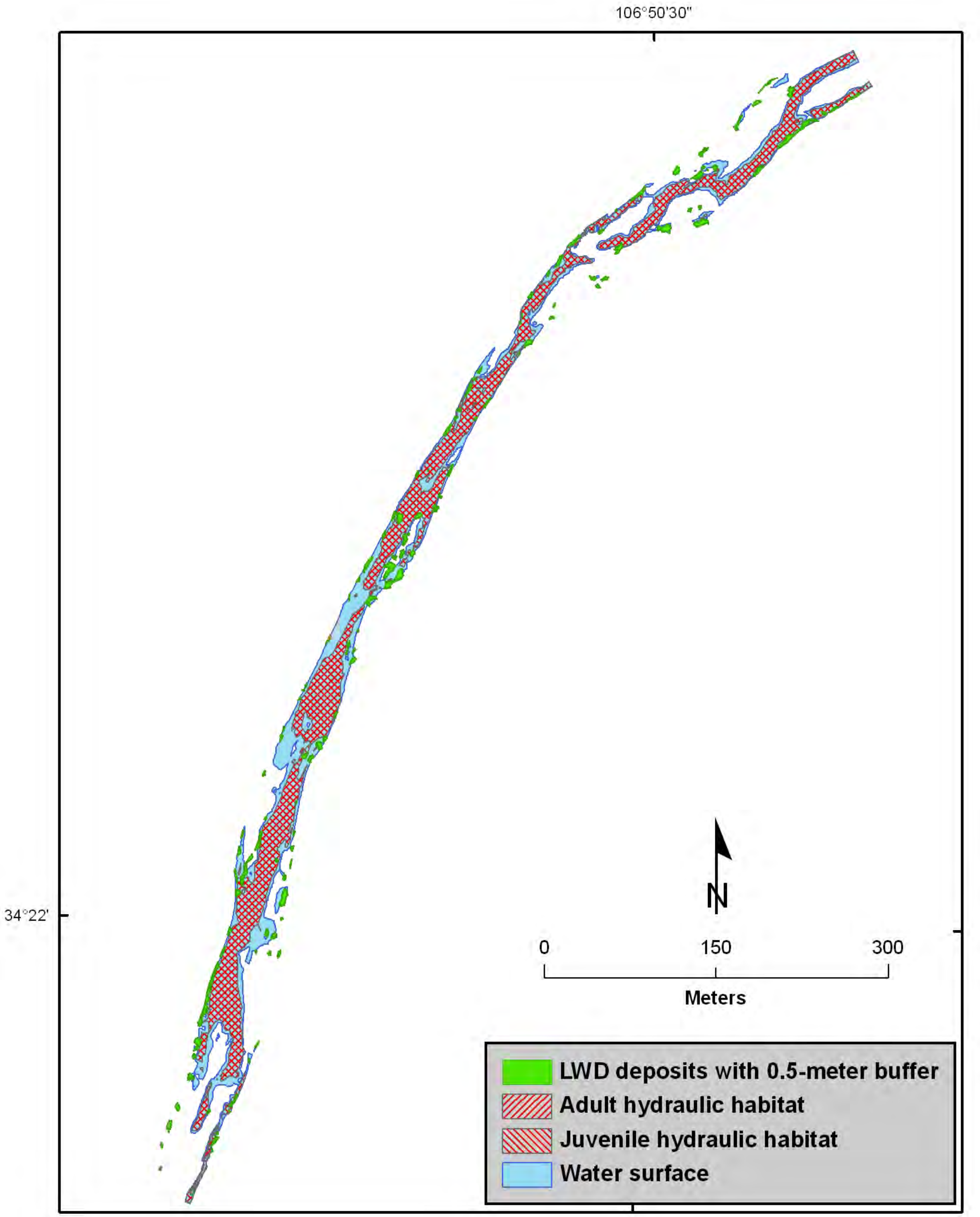

Figure 4-31. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 5 cubic feet per second.

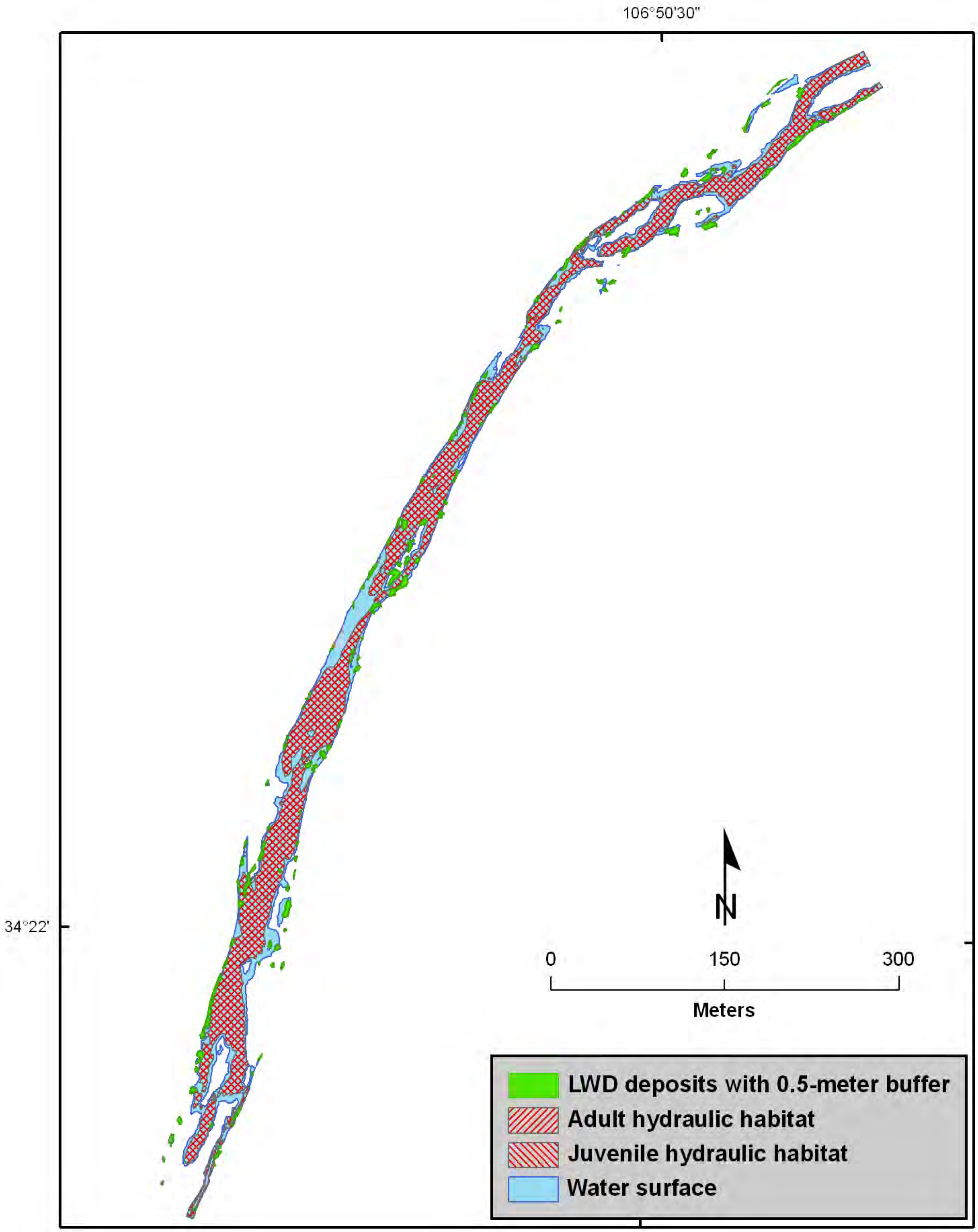

Figure 4-32. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 10 cubic feet per second.

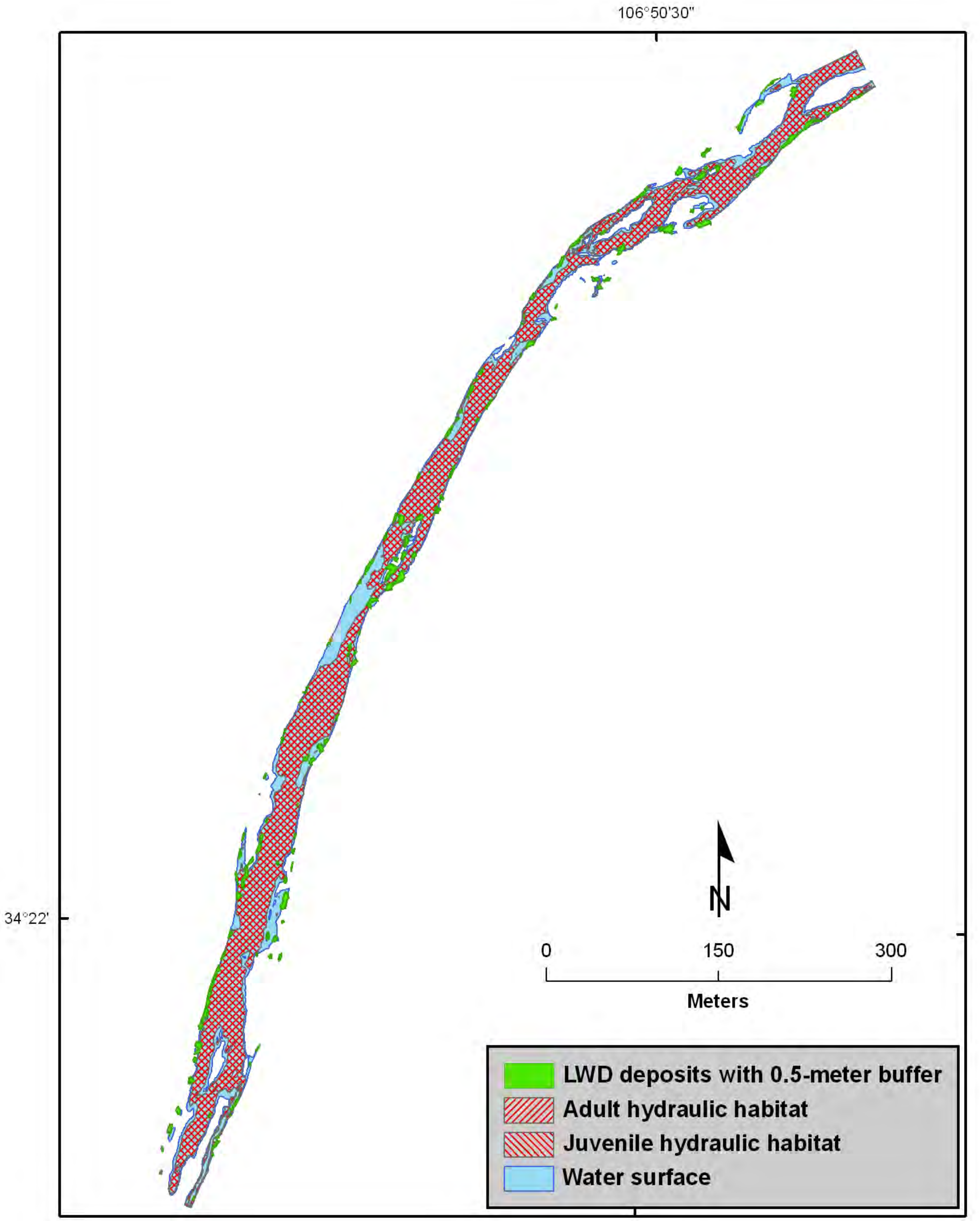

Figure 4-33. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 20 cubic feet per second.

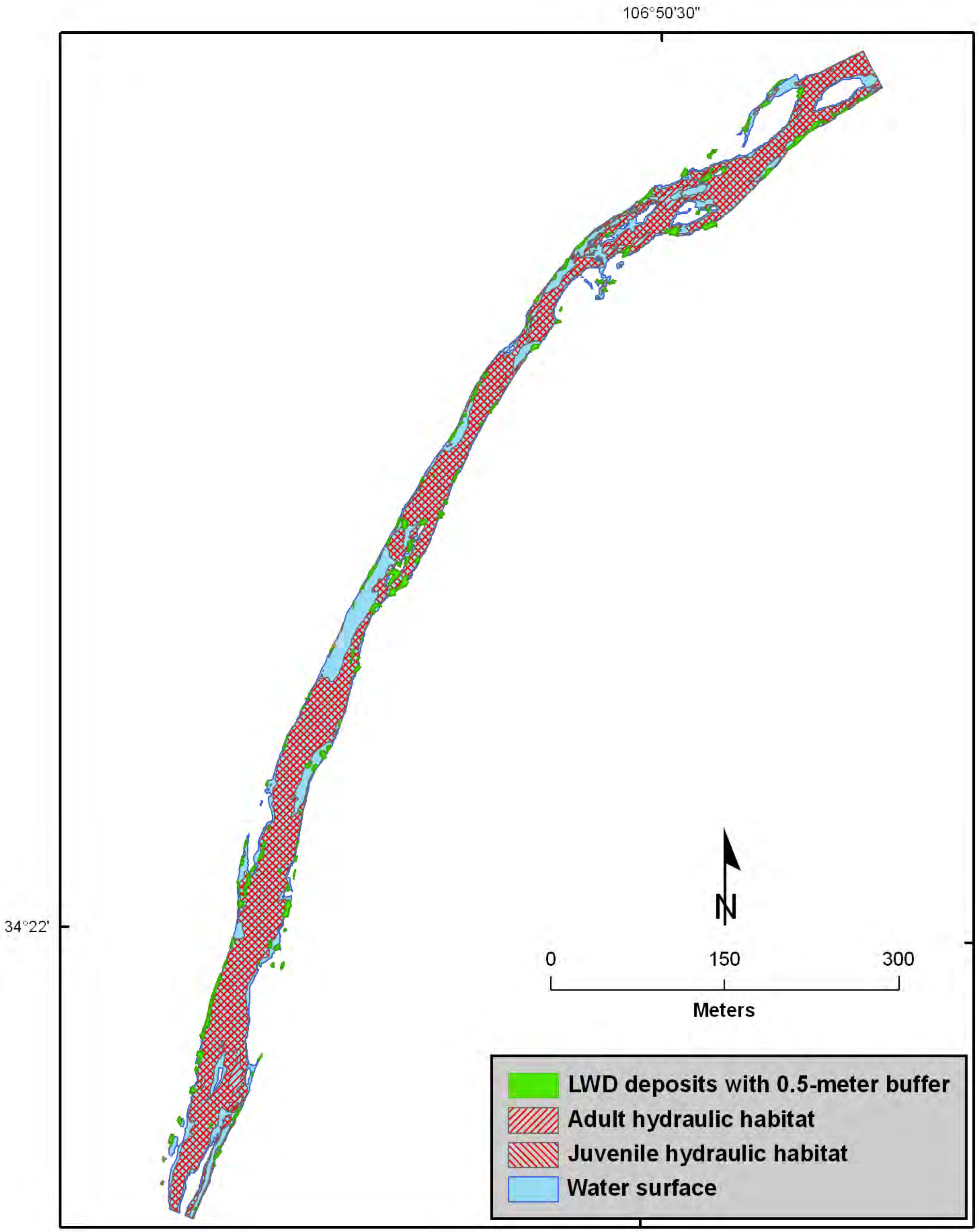

Figure 4-34. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 40 cubic feet per second.

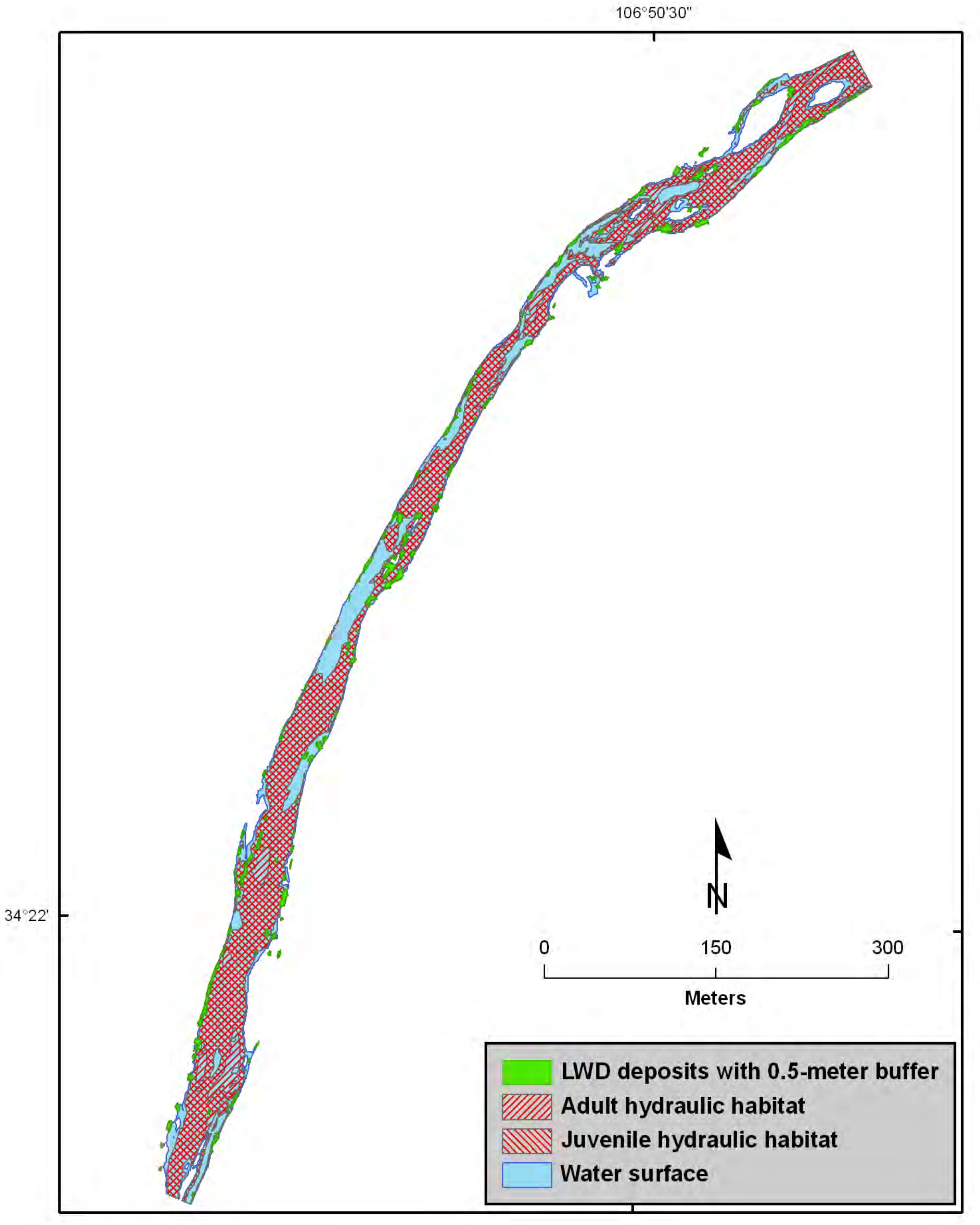

Figure 4-35. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 60 cubic feet per second.

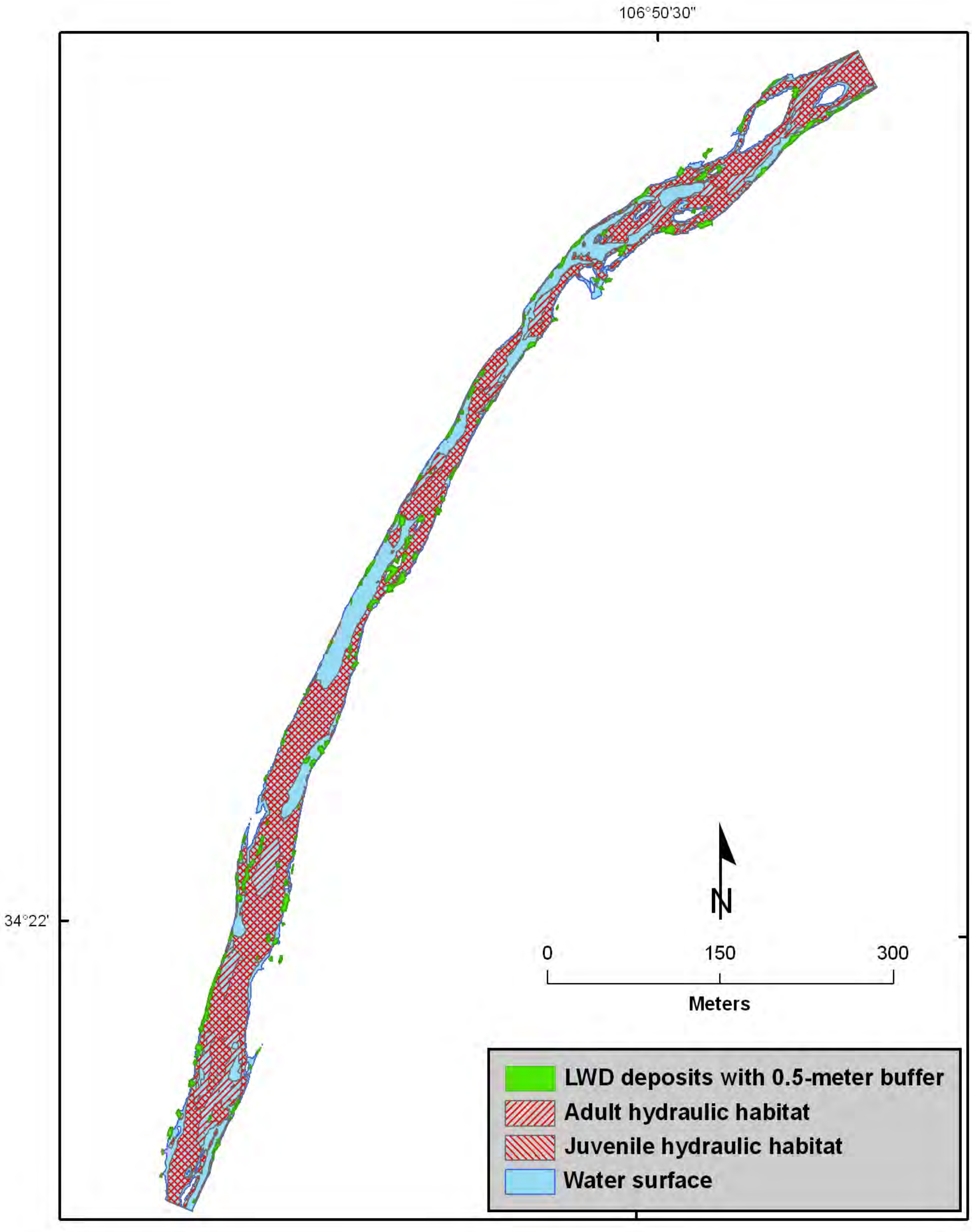

Figure 4-36. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 80 cubic feet per second.

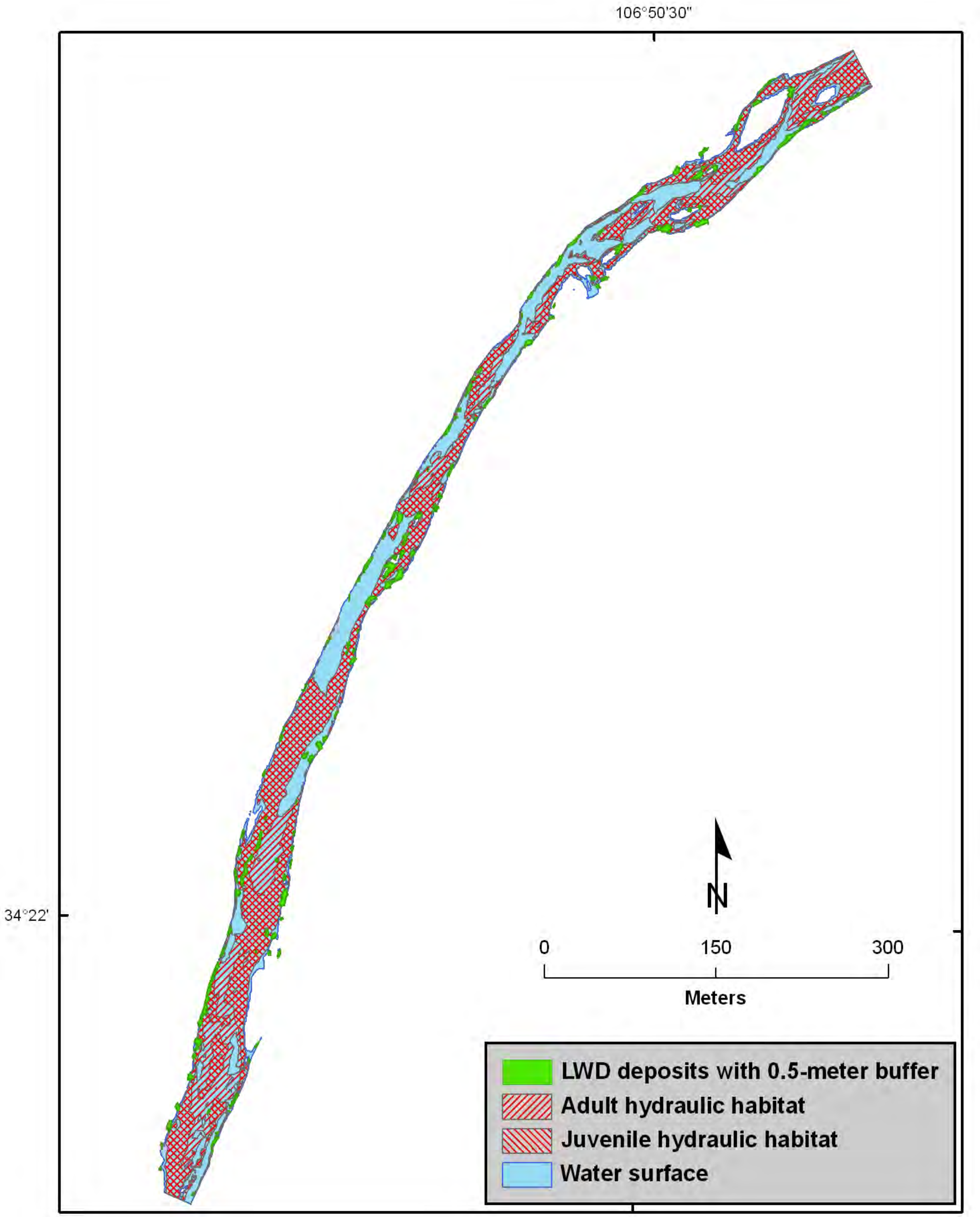

Figure 4-37. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 100 cubic feet per second.

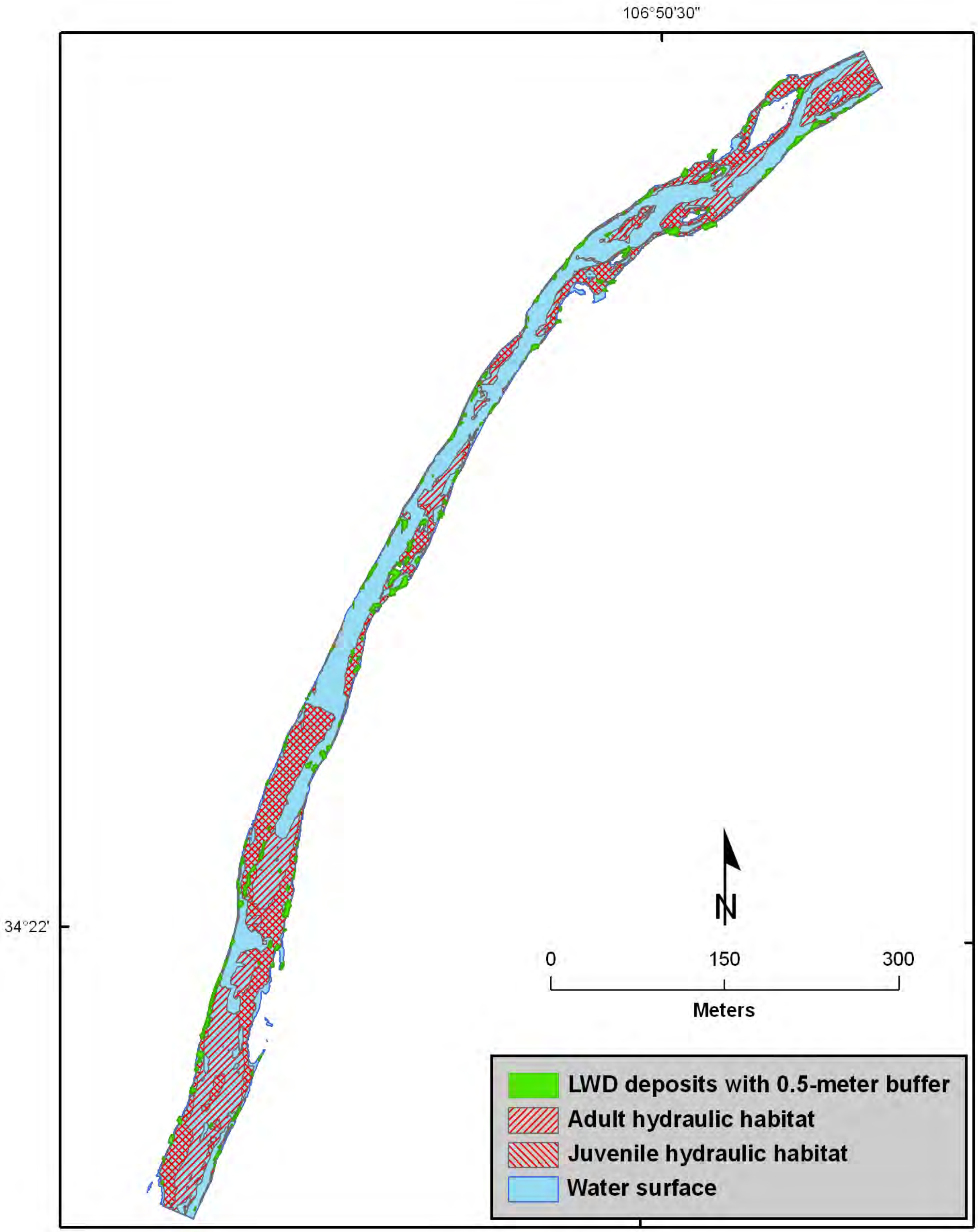

Figure 4-38. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 150 cubic feet per second.

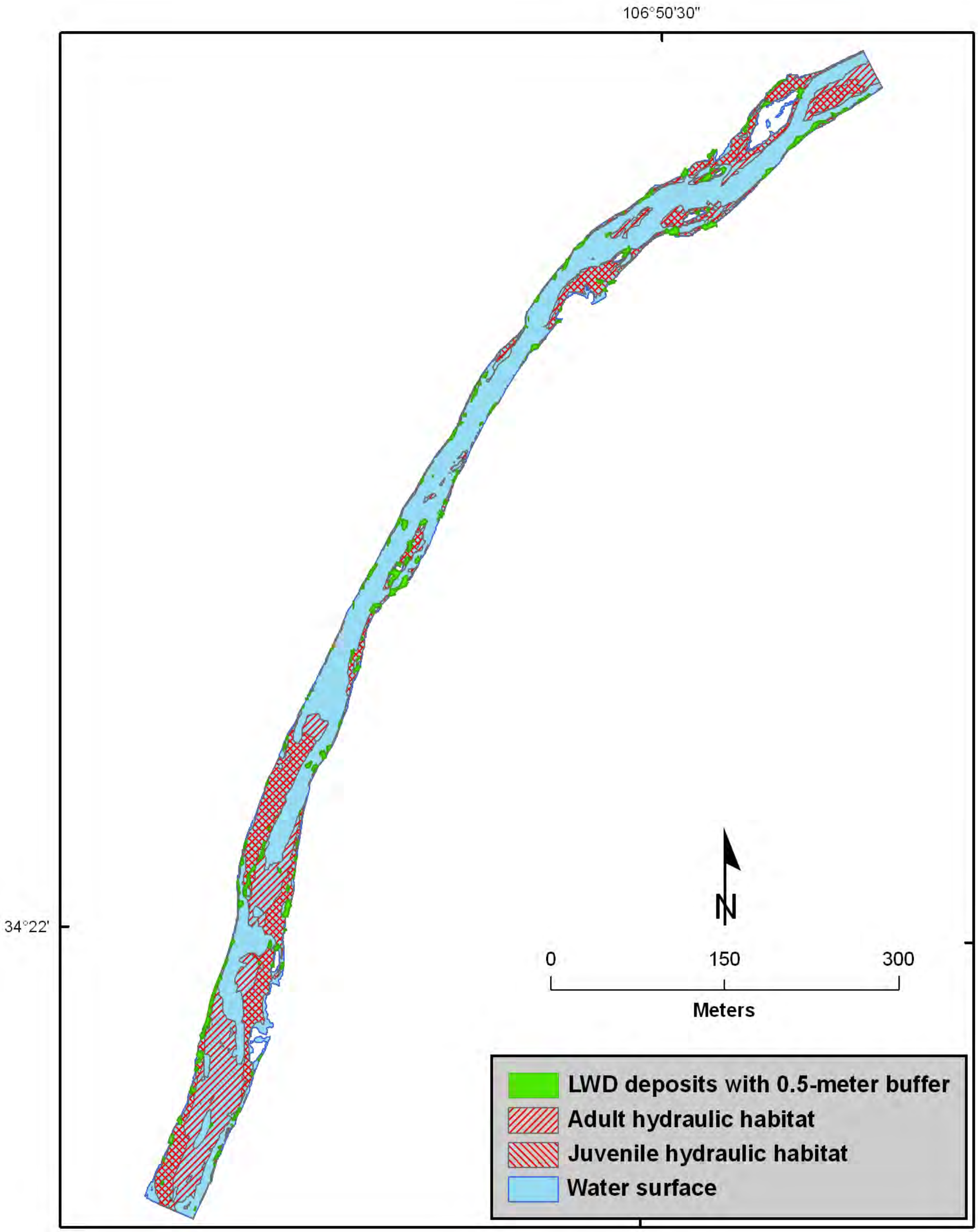

Figure 4-39. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 200 cubic feet per second.

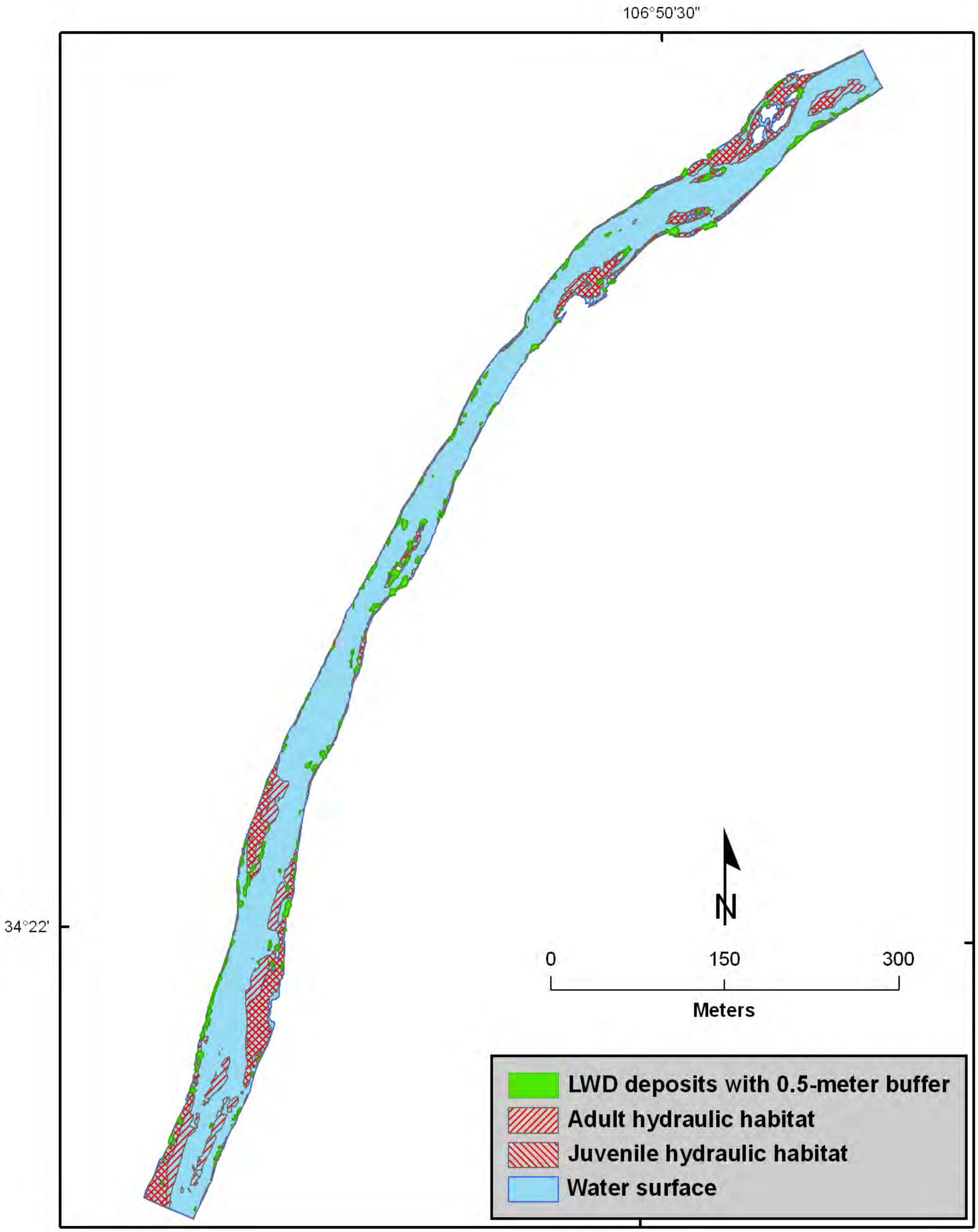

Figure 4-40. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 300 cubic feet per second.

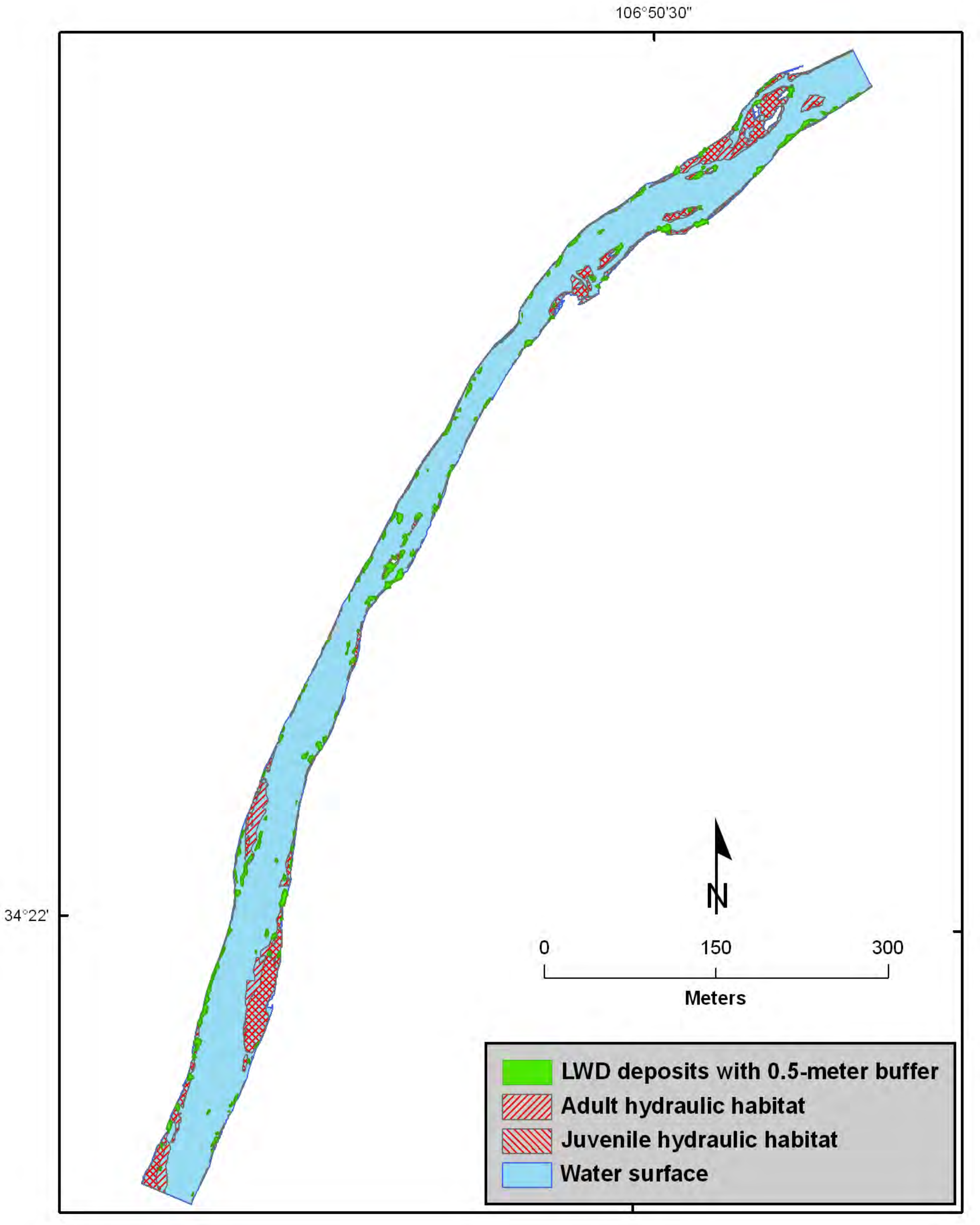

Figure 4-41. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 400 cubic feet per second.

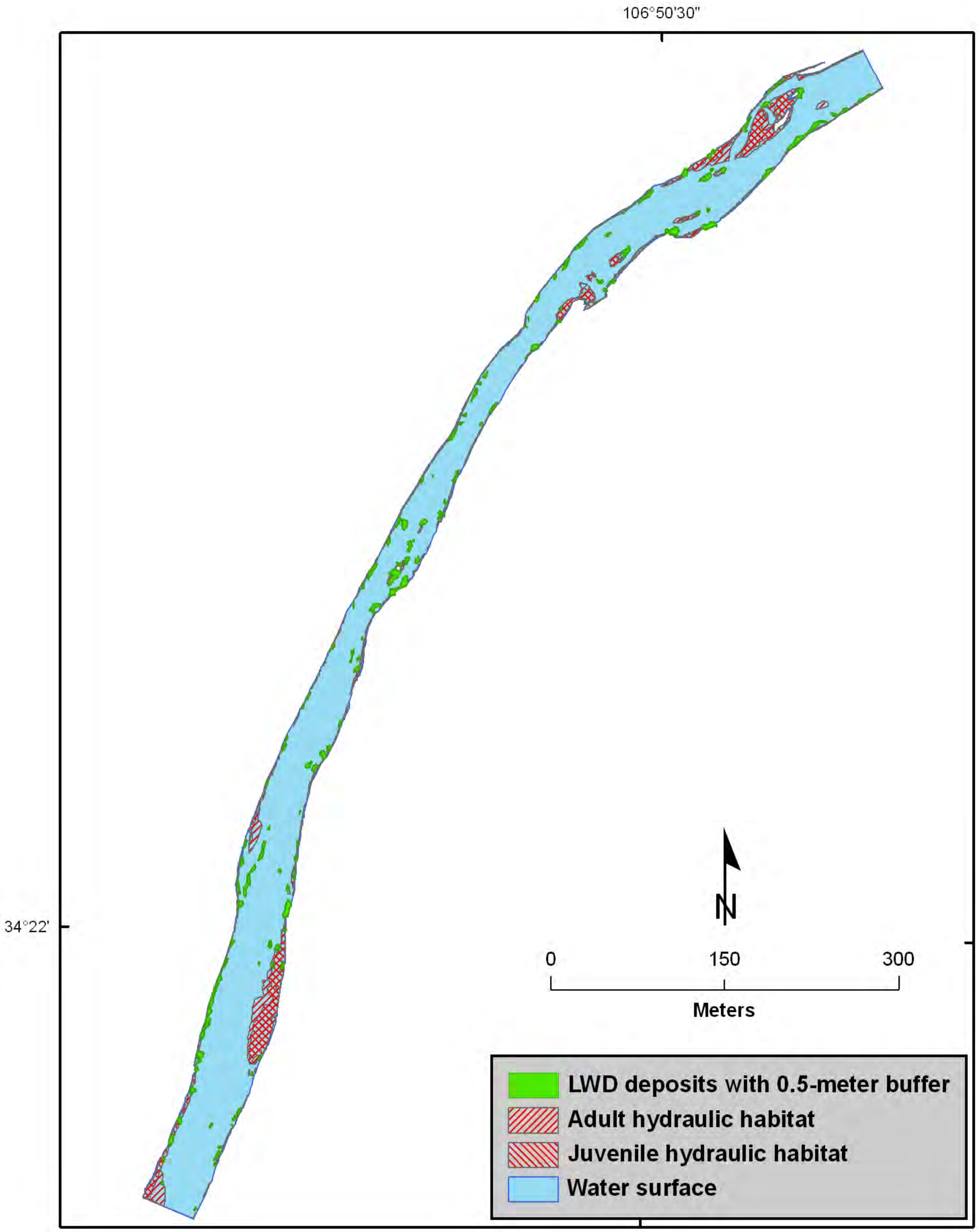

Figure 4-42. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 500 cubic feet per second.

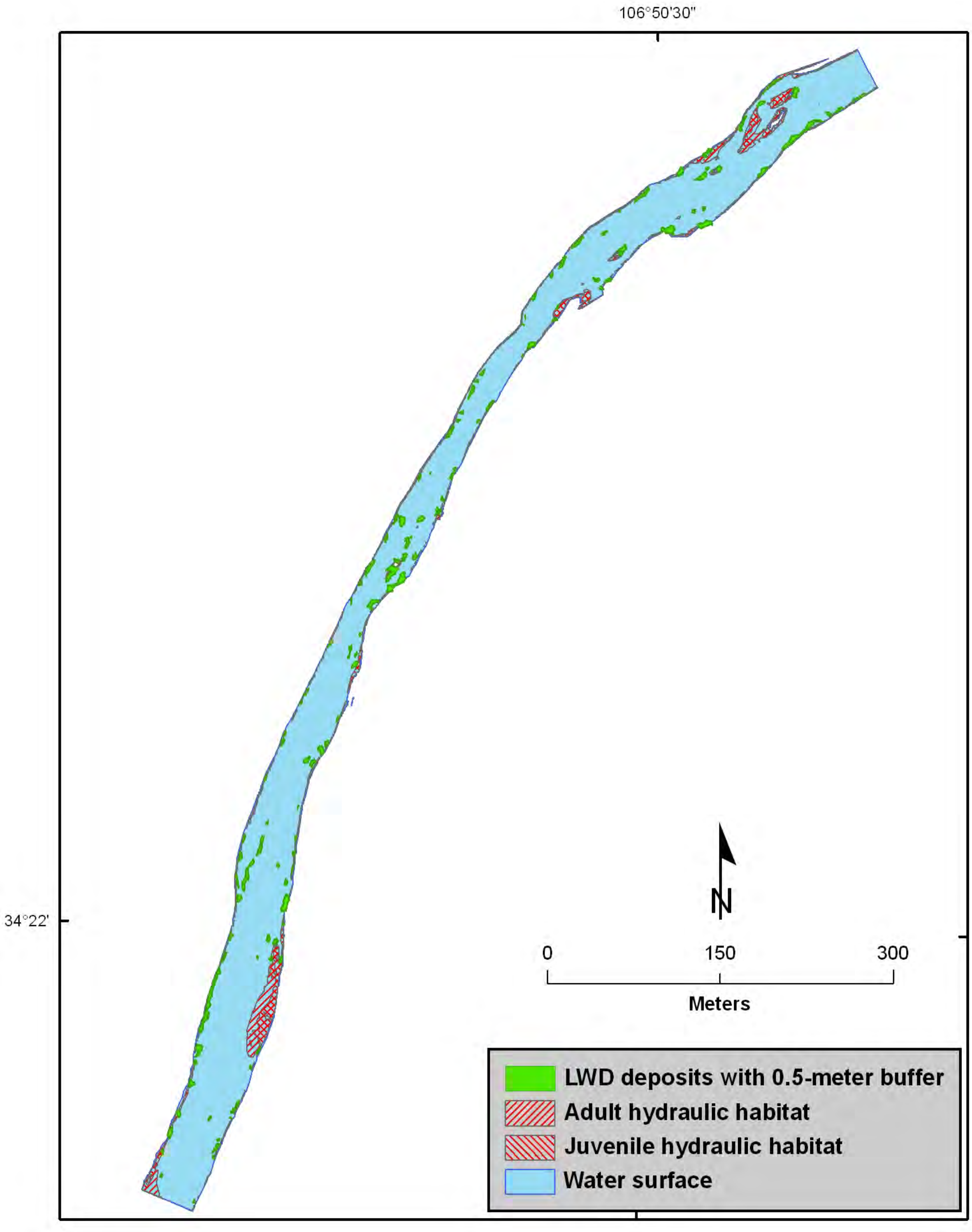

Figure 4-43. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 600 cubic feet per second.

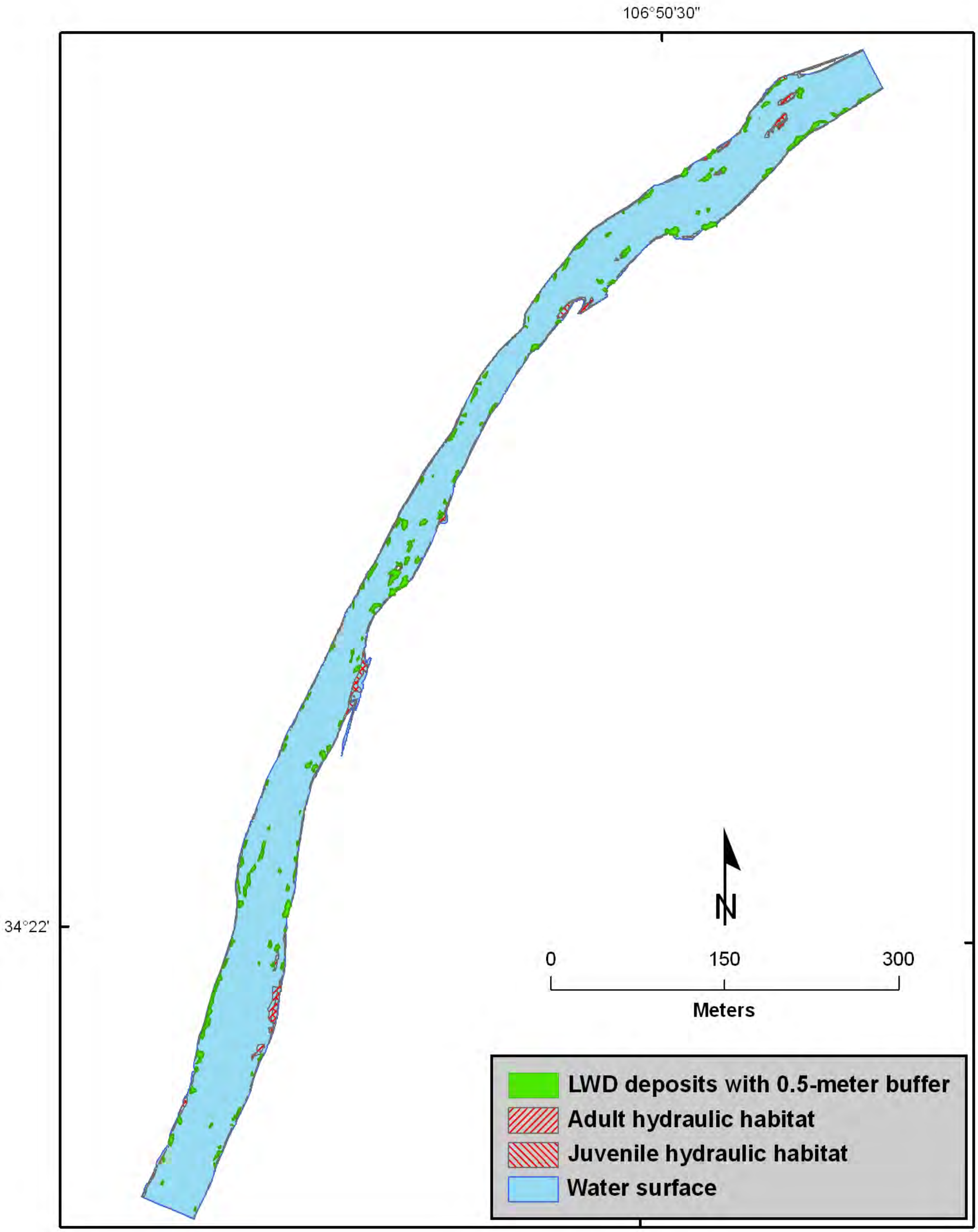

Figure 4-44. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 800 cubic feet per second.

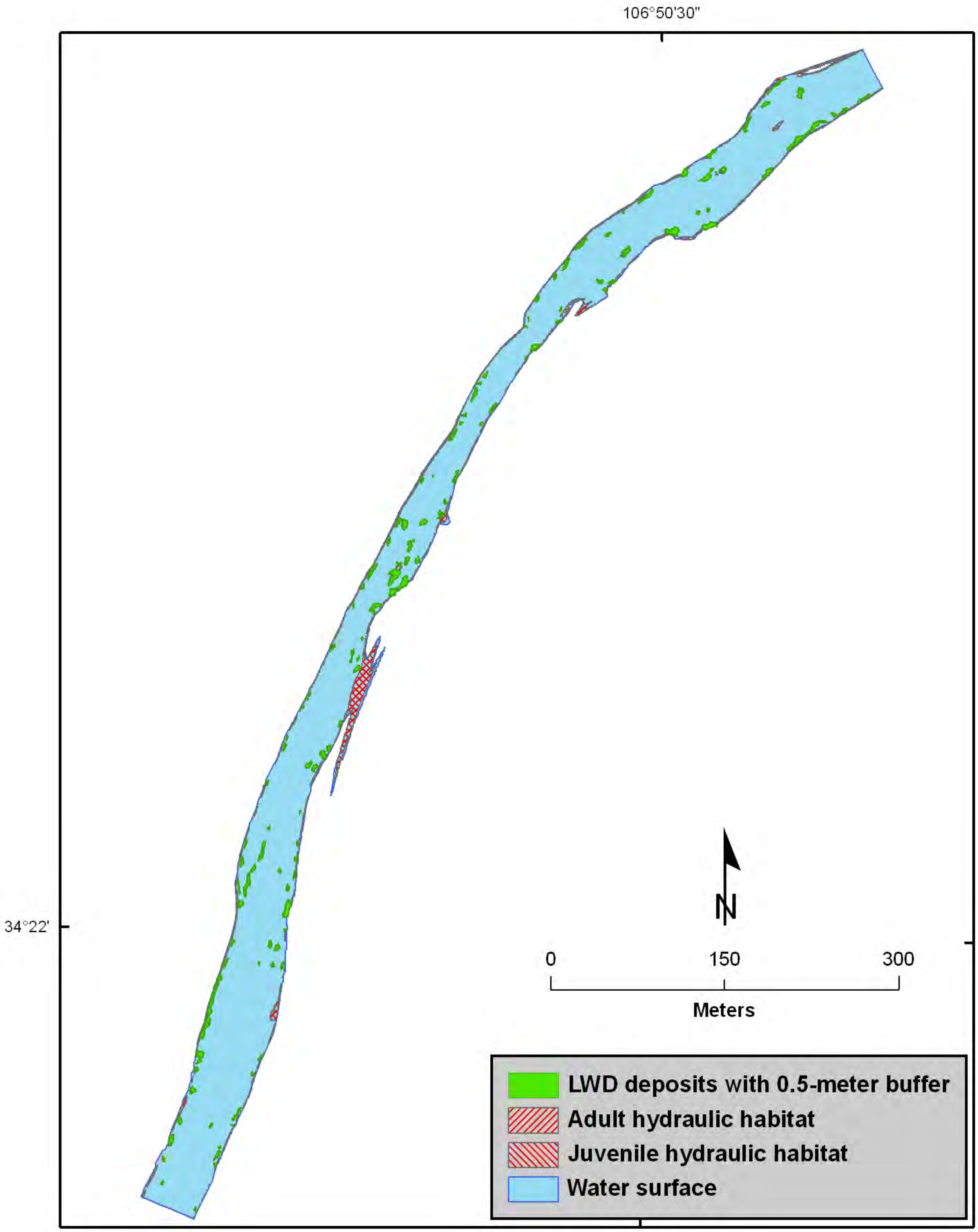

Figure 4-45. Habitat for adult and juvenile *H. amarus*, Rio Puerco site, at 1,000 cubic feet per second.

Appendix 5. Habitat Connectivity Maps for Rio Grande Silvery Minnows at Flows with Less Than 100-Percent Connectivity

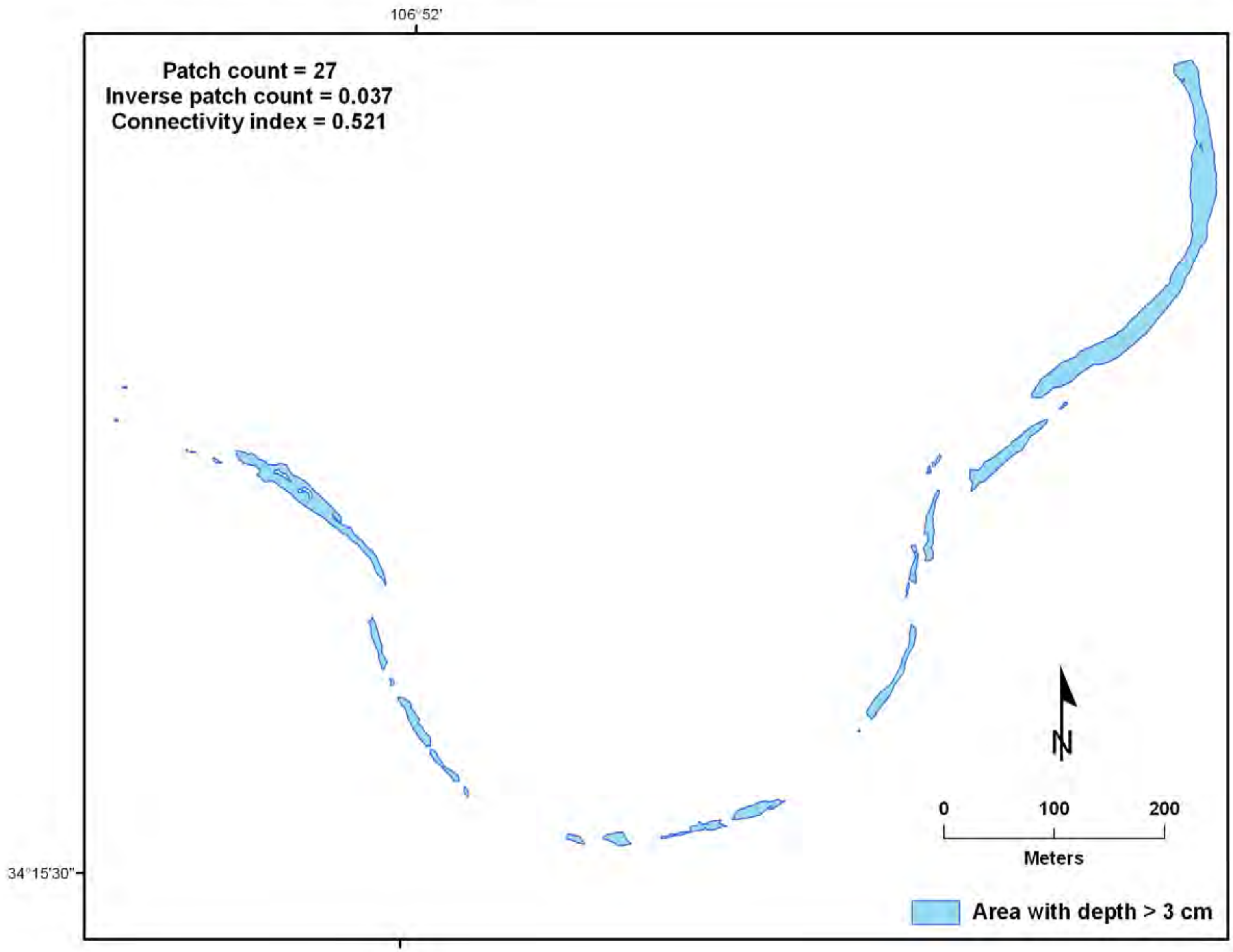

Figure 5-1. Habitat connectivity, Rio Salado site, at 0 cubic feet per second.

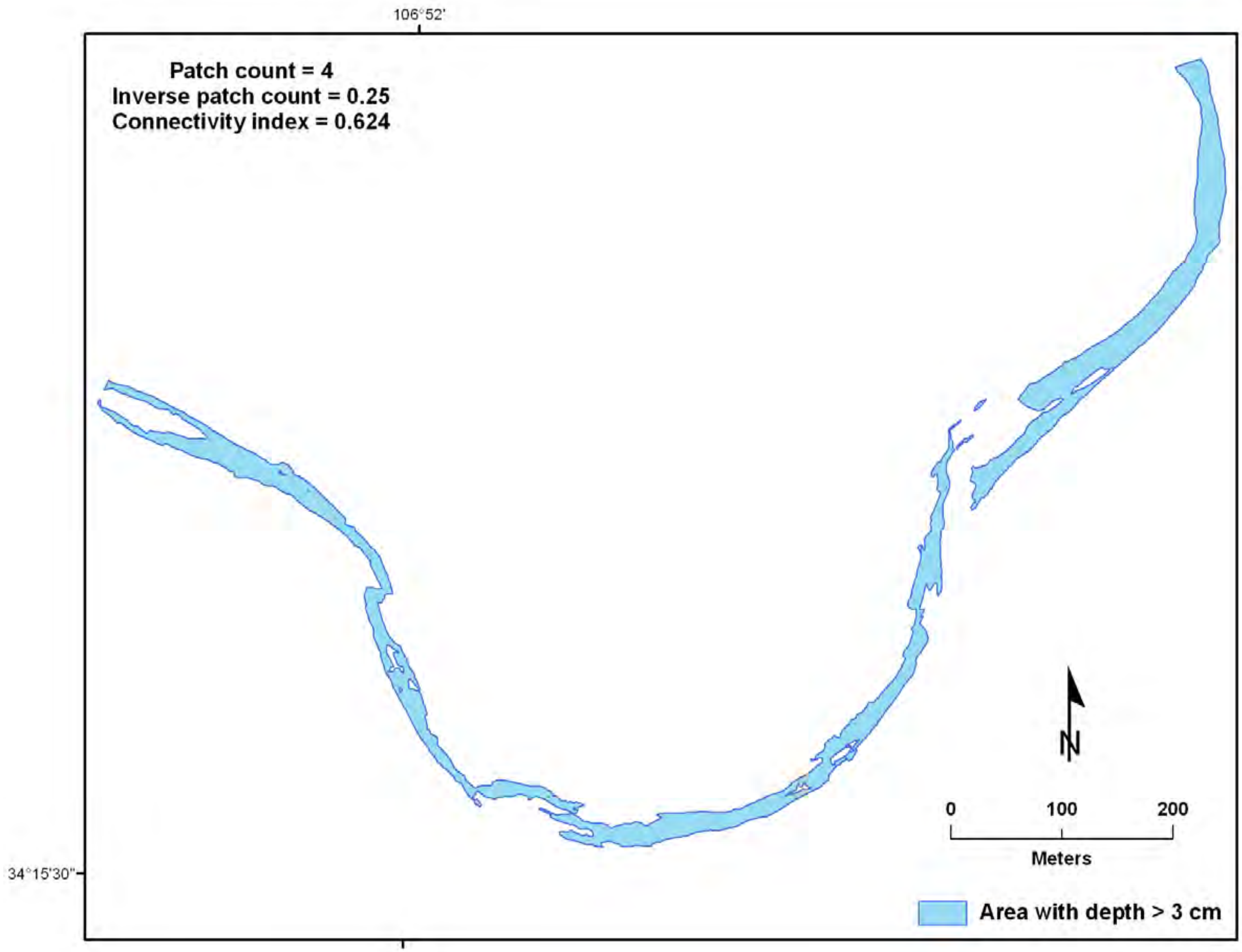

Figure 5-2. Habitat connectivity, Rio Salado site, at 5 cubic feet per second.

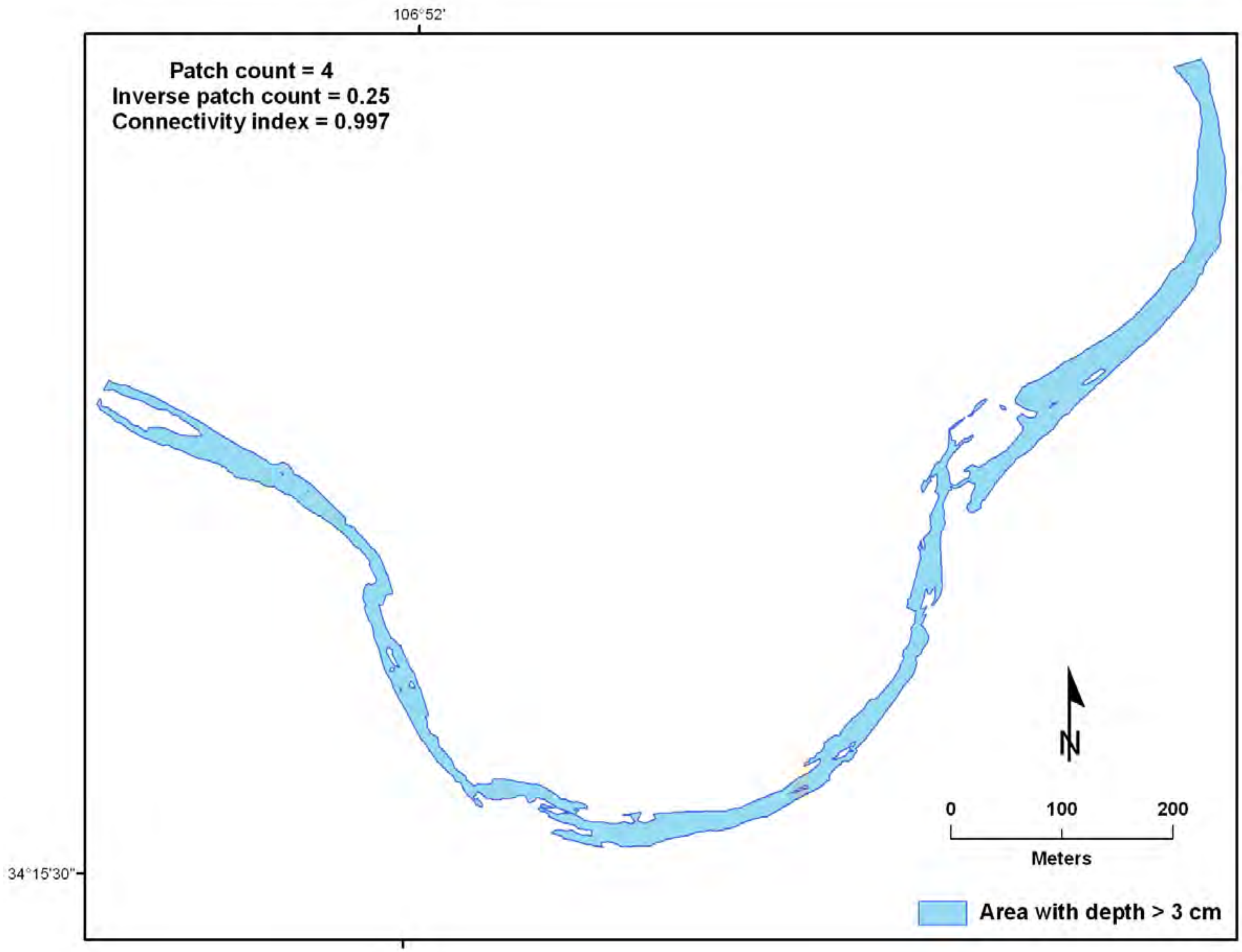

Figure 5-3. Habitat connectivity, Rio Salado site, at 10 cubic feet per second.

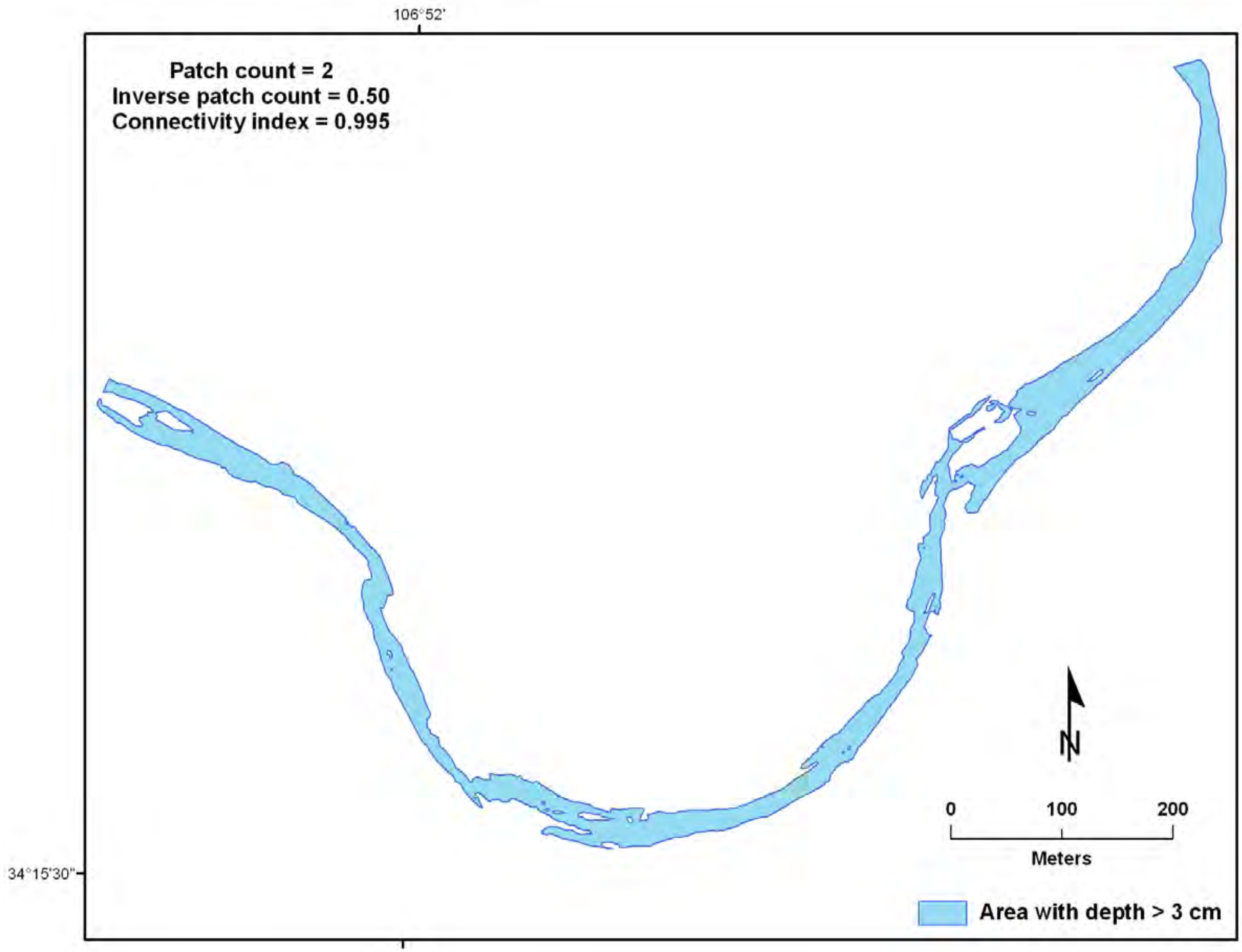

Figure 5-4. Habitat connectivity, Rio Salado site, at 20 cubic feet per second.

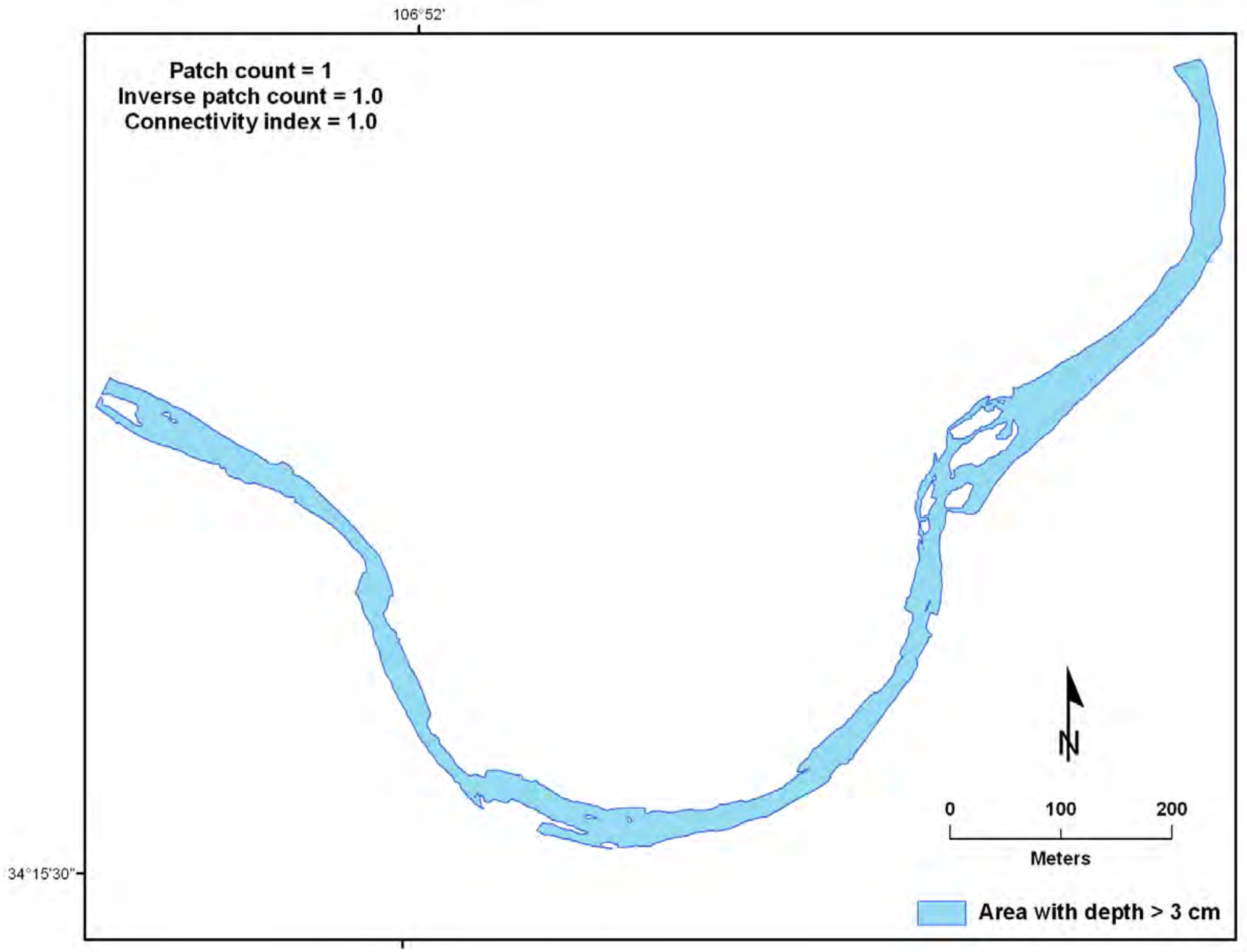

Figure 5-5. Habitat connectivity, Rio Salado site, at 40 cubic feet per second.

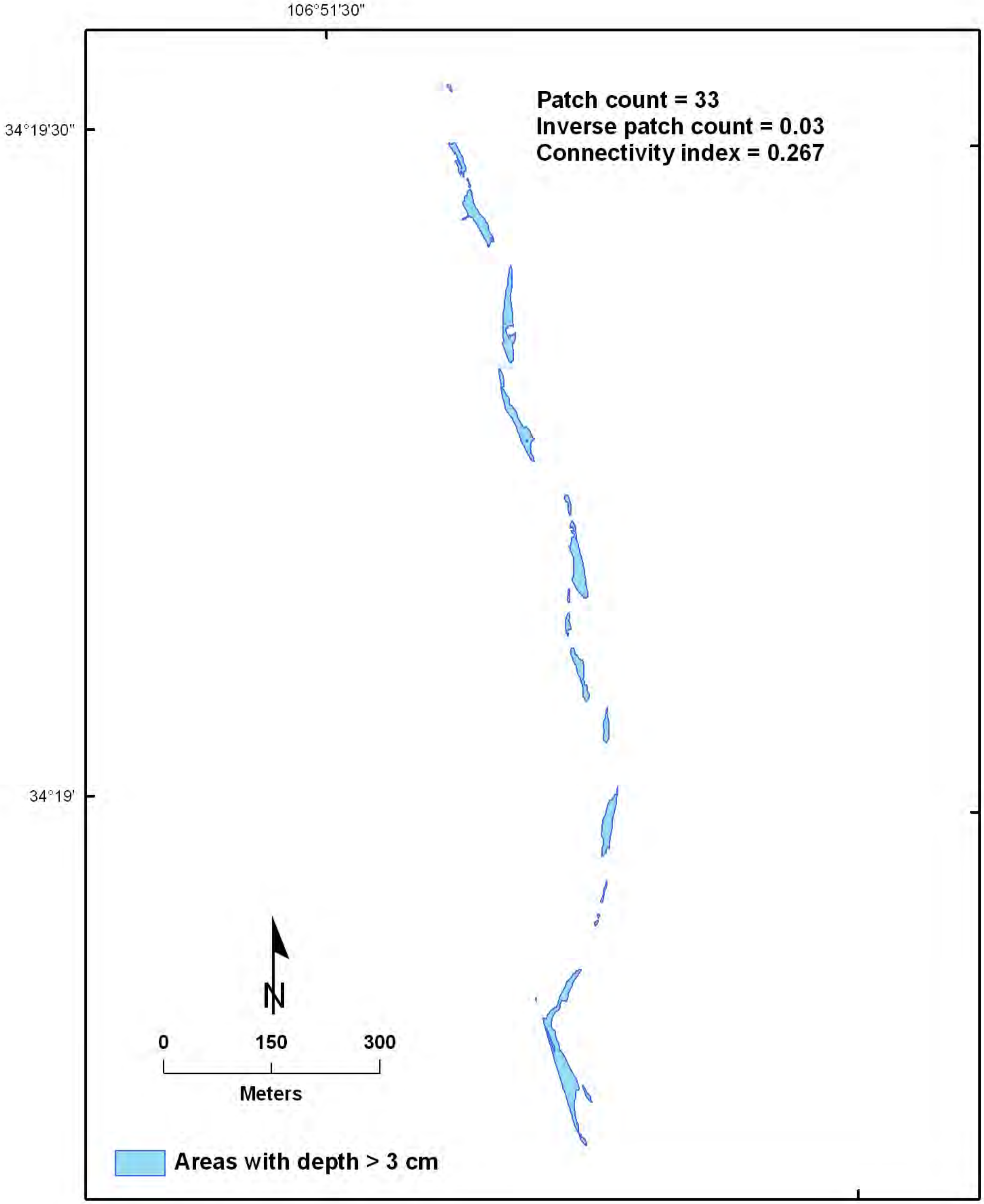

Figure 5-6. Habitat connectivity, Sevilleta site, at 0 cubic feet per second.

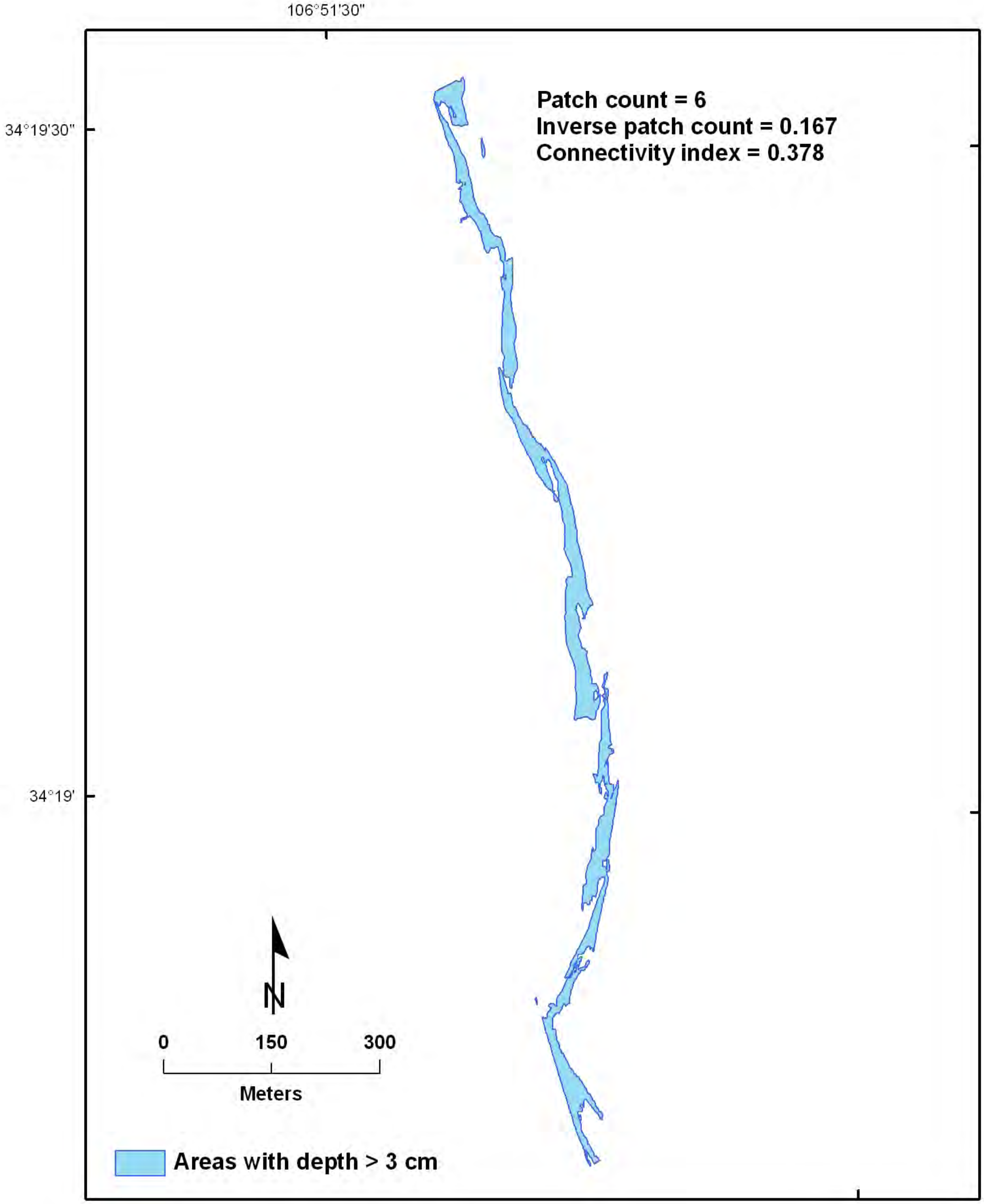

Figure 5-7. Habitat connectivity, Sevilleta site, at 5 cubic feet per second.

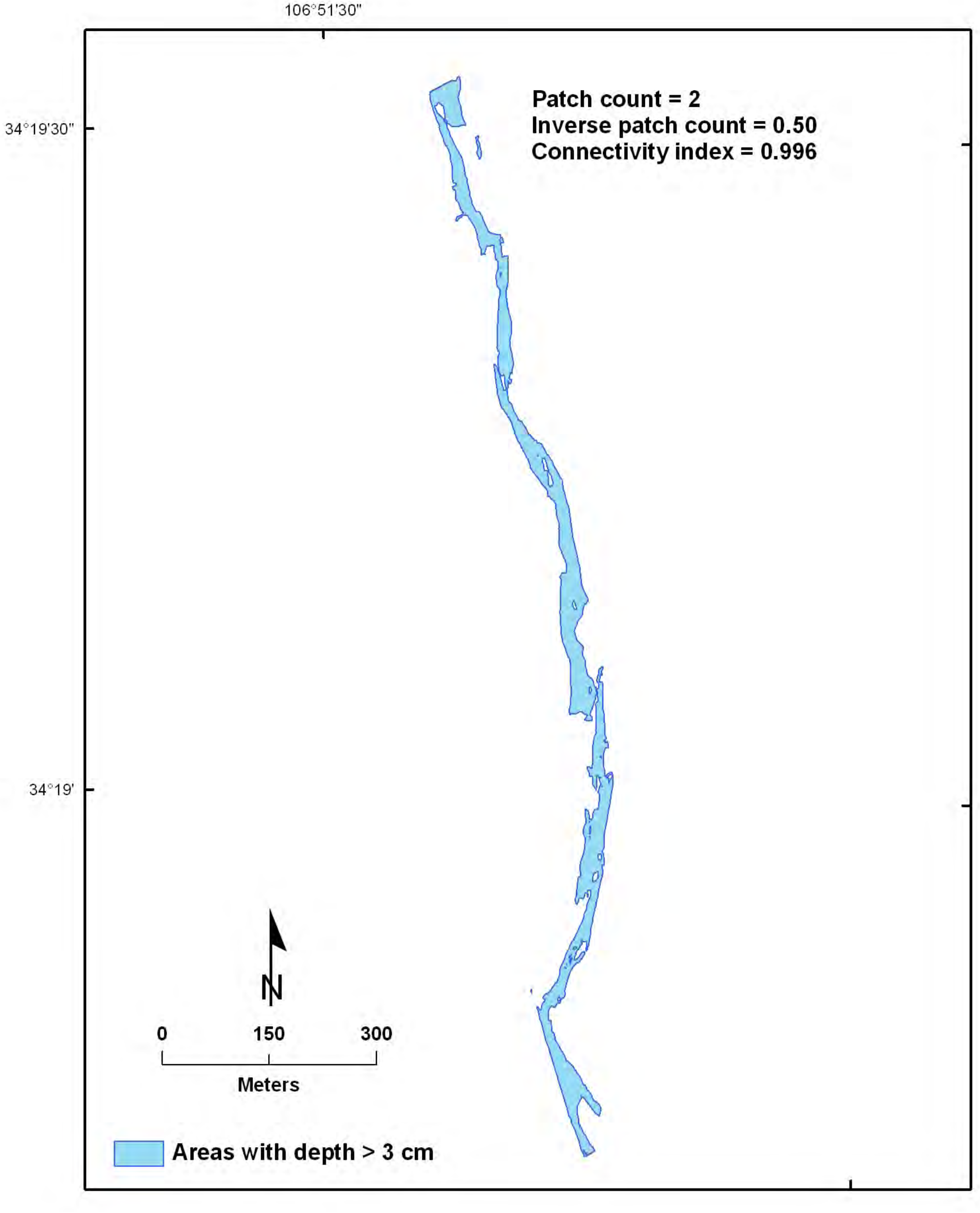

Figure 5-8. Habitat connectivity, Sevilleta site, at 10 cubic feet per second.

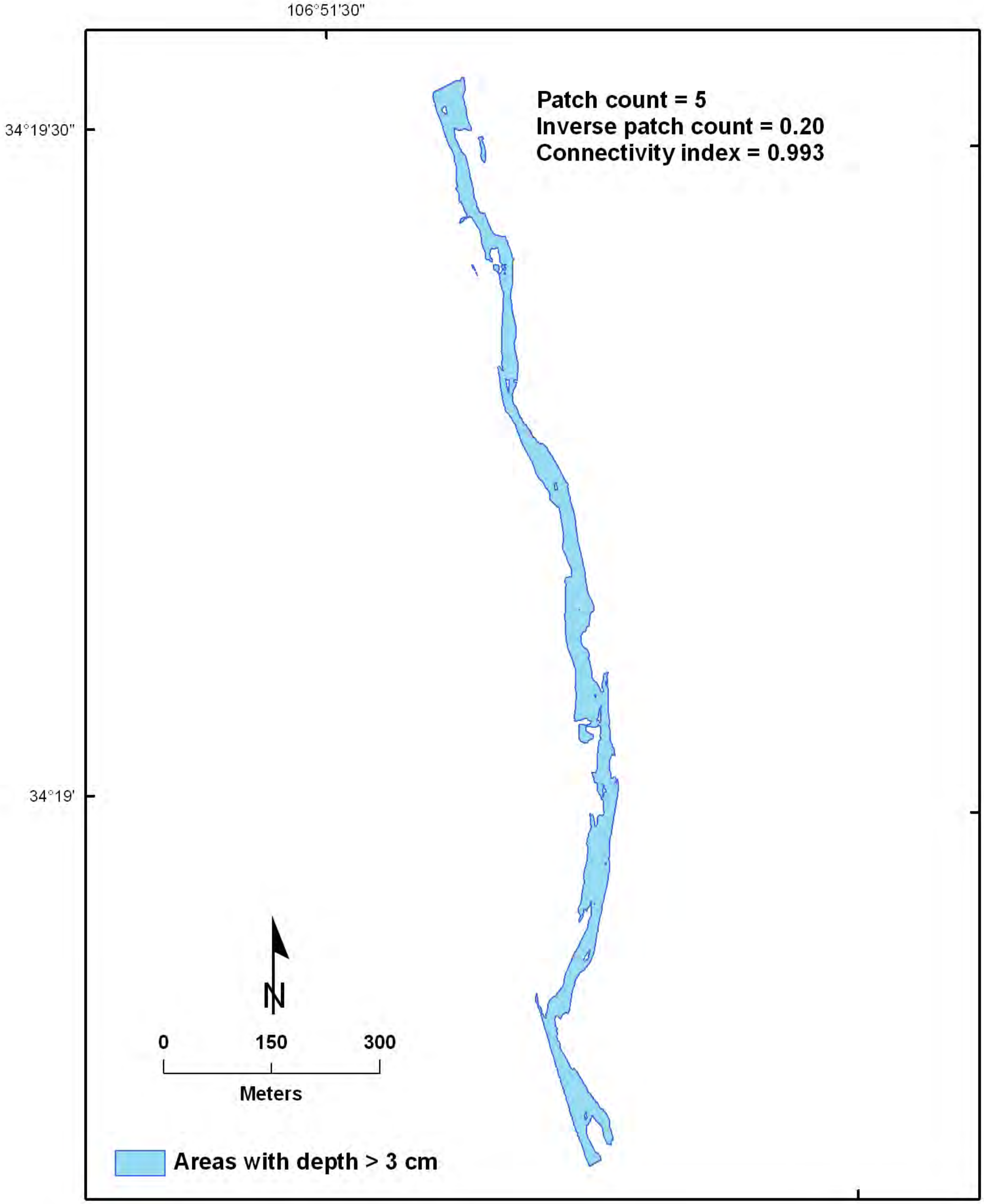

Figure 5-9. Habitat connectivity, Sevilleta site, at 20 cubic feet per second.

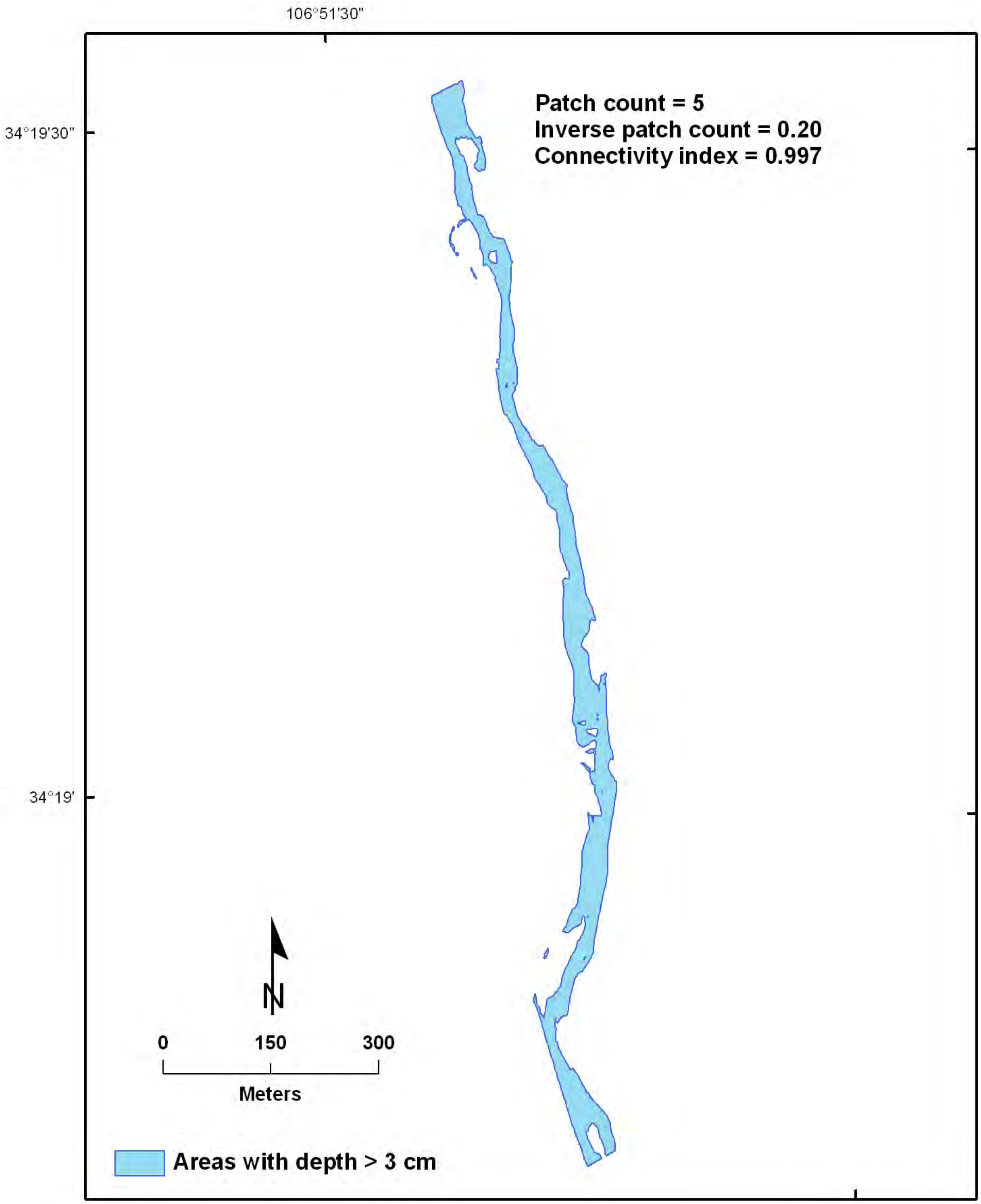

Figure 5-10. Habitat connectivity, Sevilleta site, at 40 cubic feet per second.

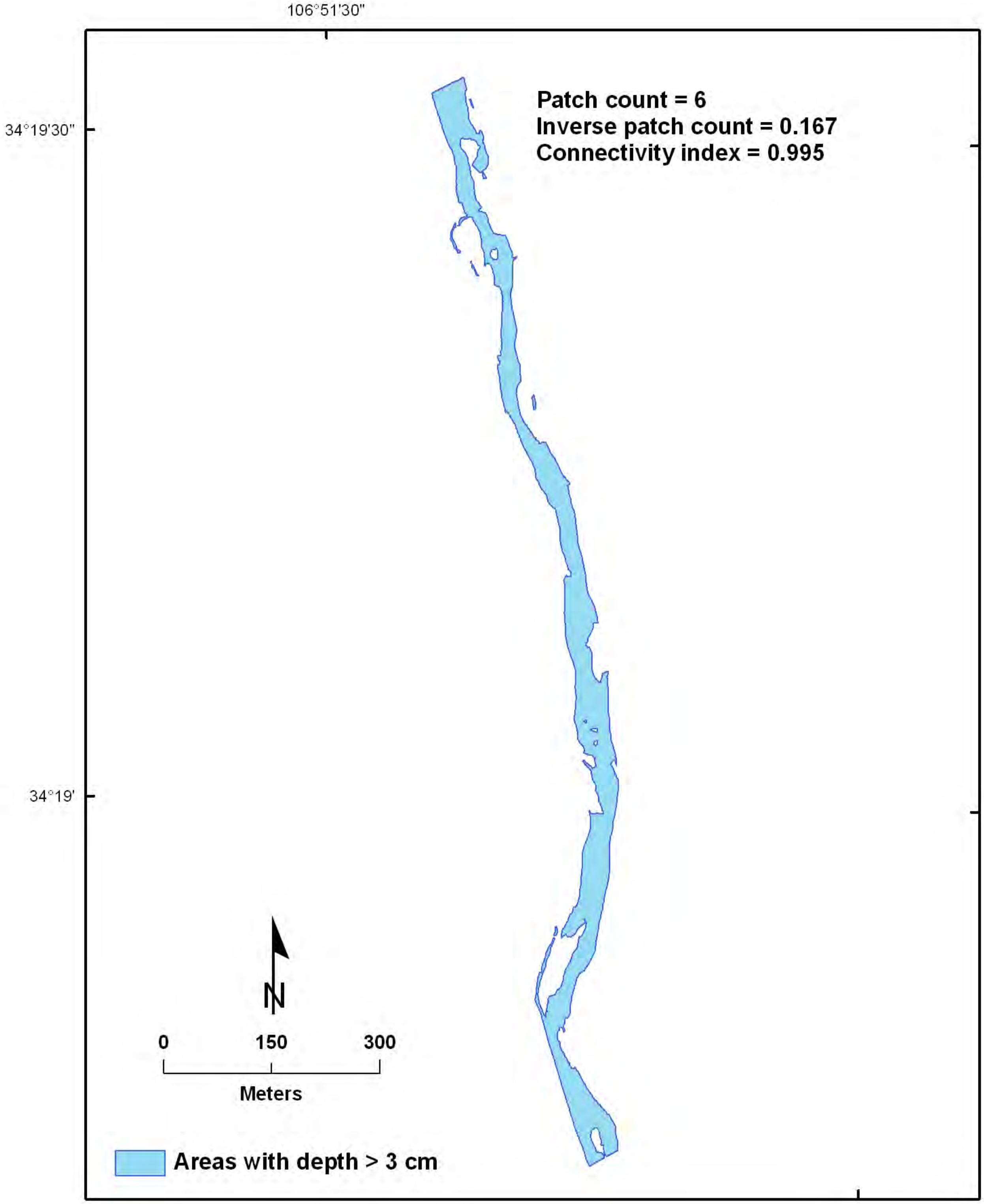

Figure 5-11. Habitat connectivity, Sevilleta site, at 60 cubic feet per second.

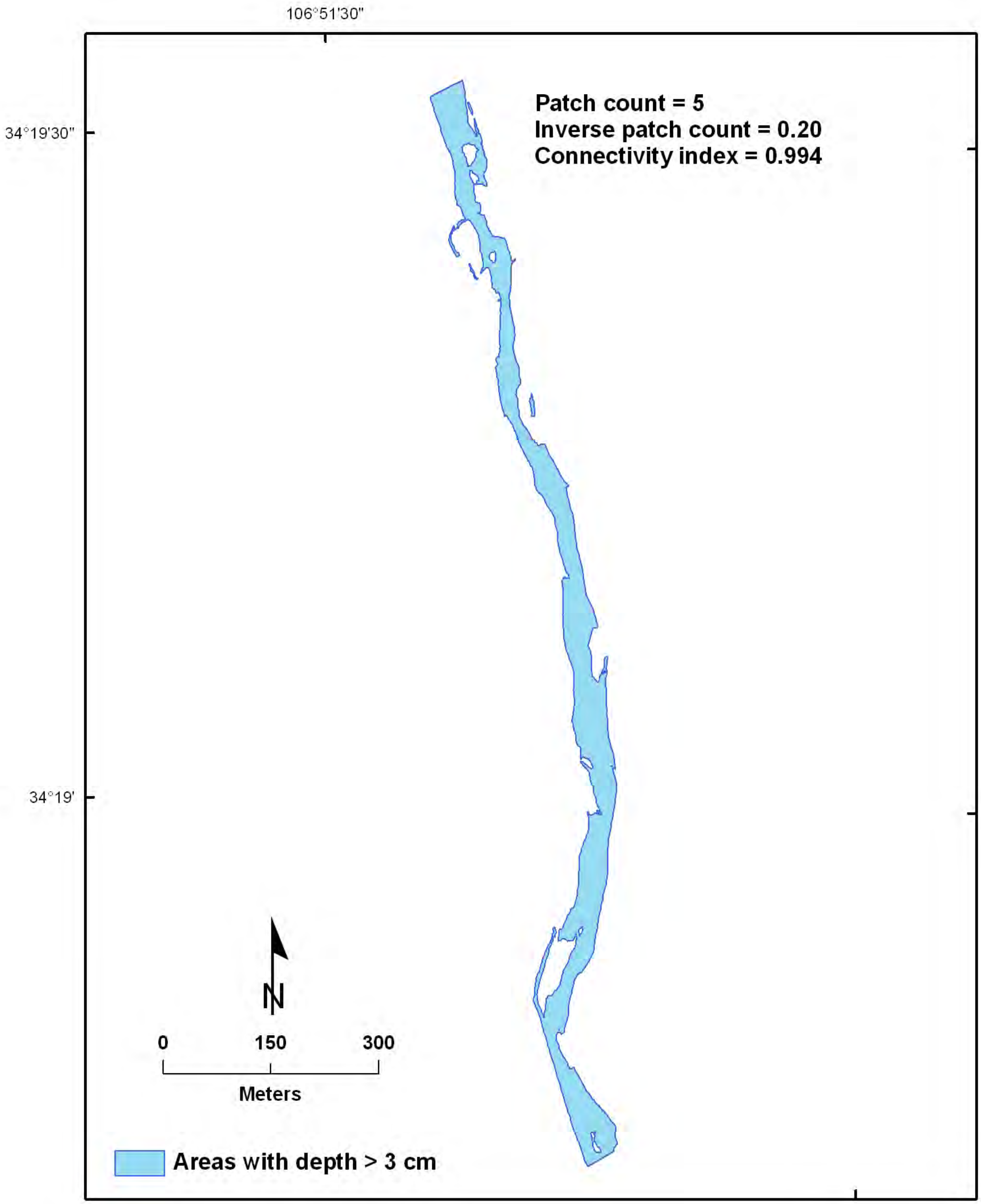

Figure 5-12. Habitat connectivity, Sevilleta site, at 80 cubic feet per second.

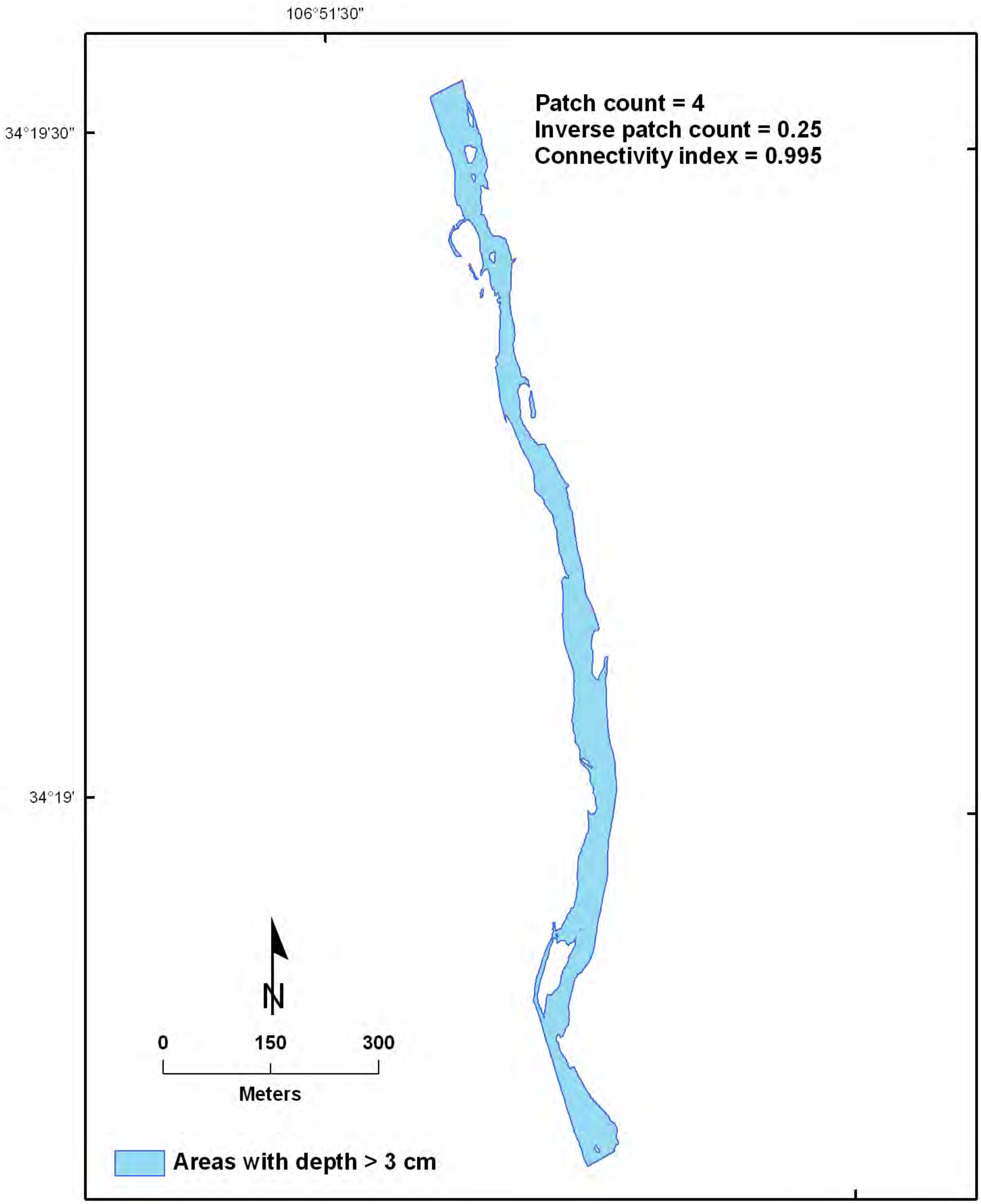

Figure 5-13. Habitat connectivity, Sevilleta site, at 100 cubic feet per second.

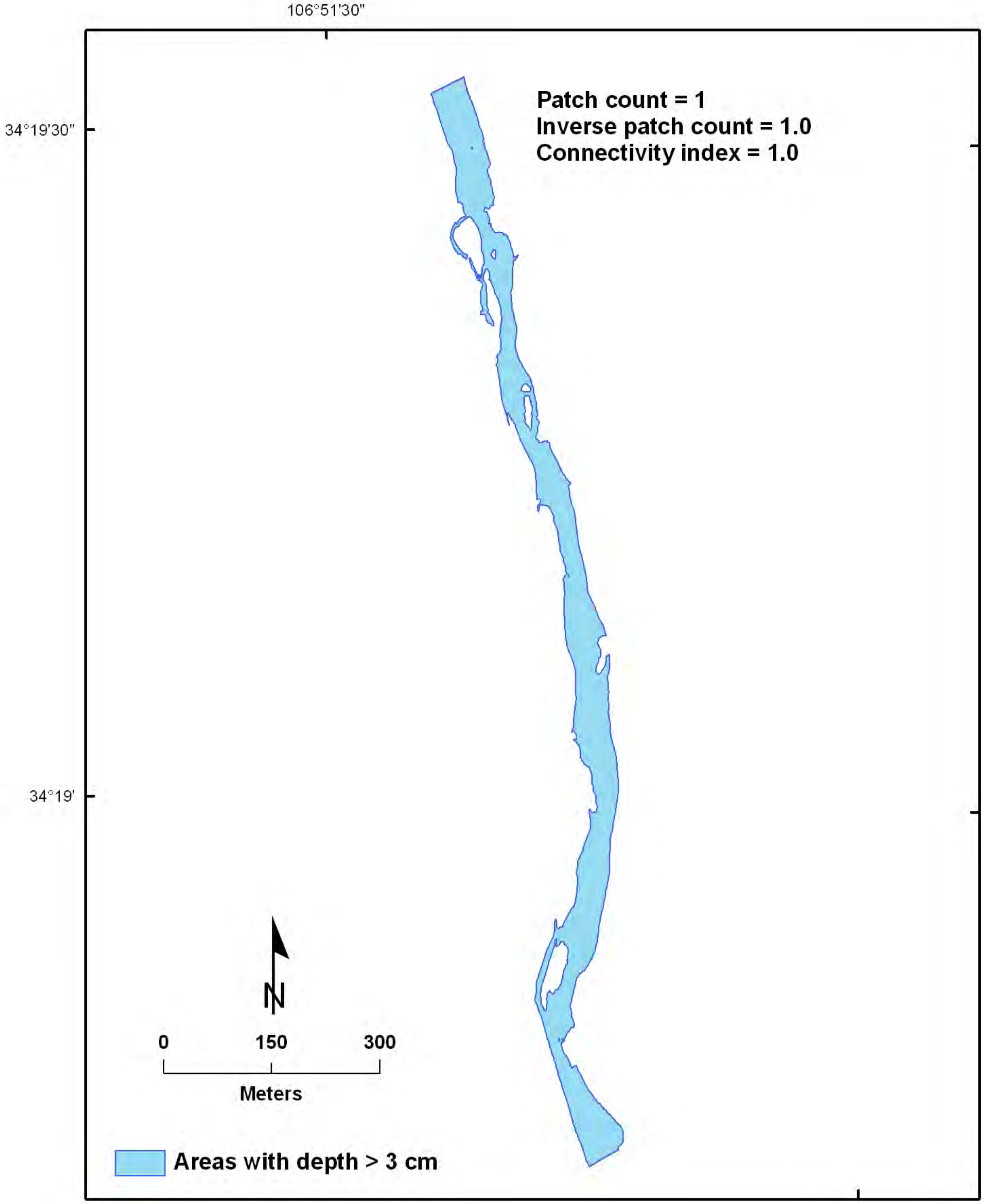

Figure 5-14. Habitat connectivity, Sevilleta site, at 150 cubic feet per second.

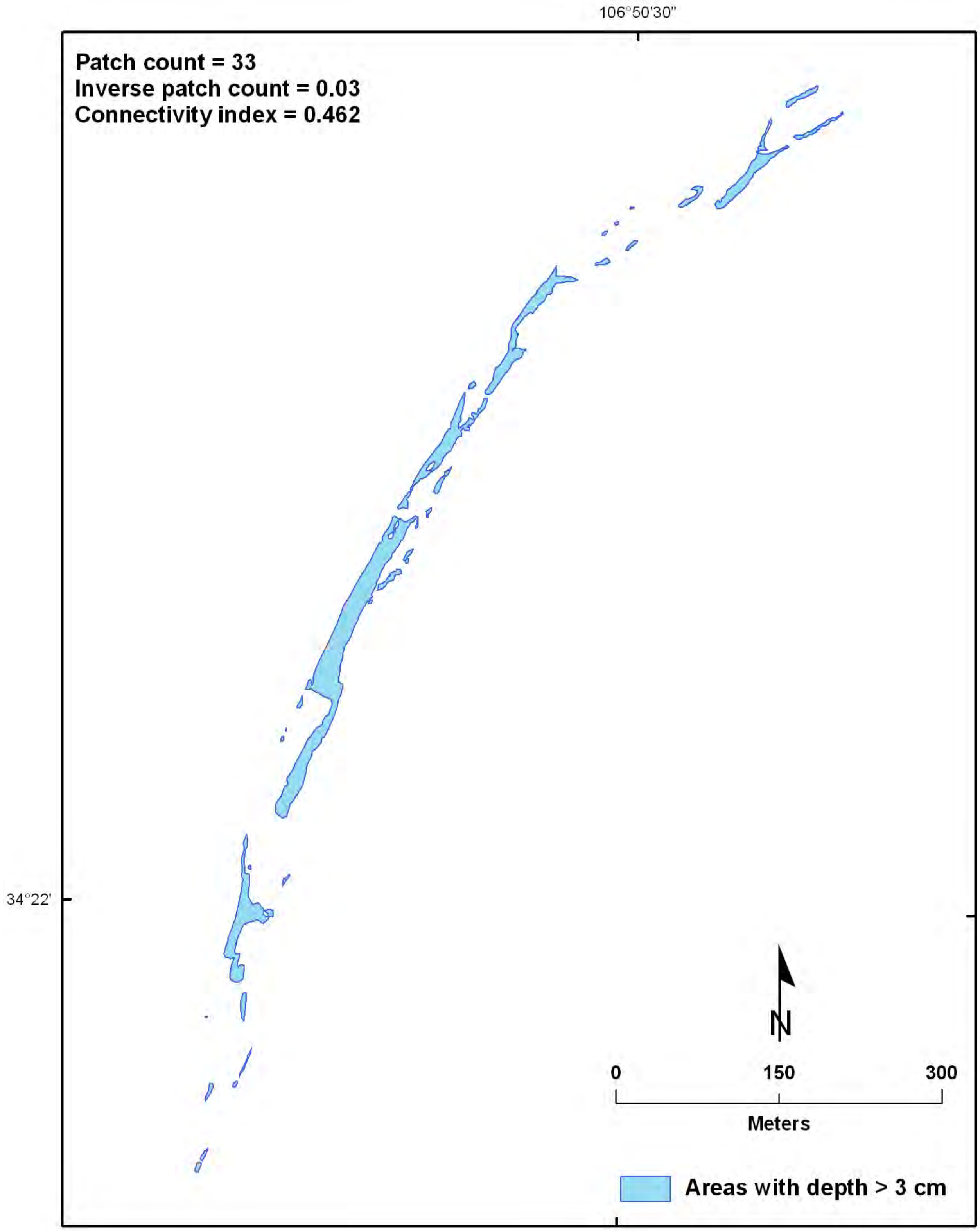

Figure 5-15. Habitat connectivity, Rio Puerco site, at 0 cubic feet per second.

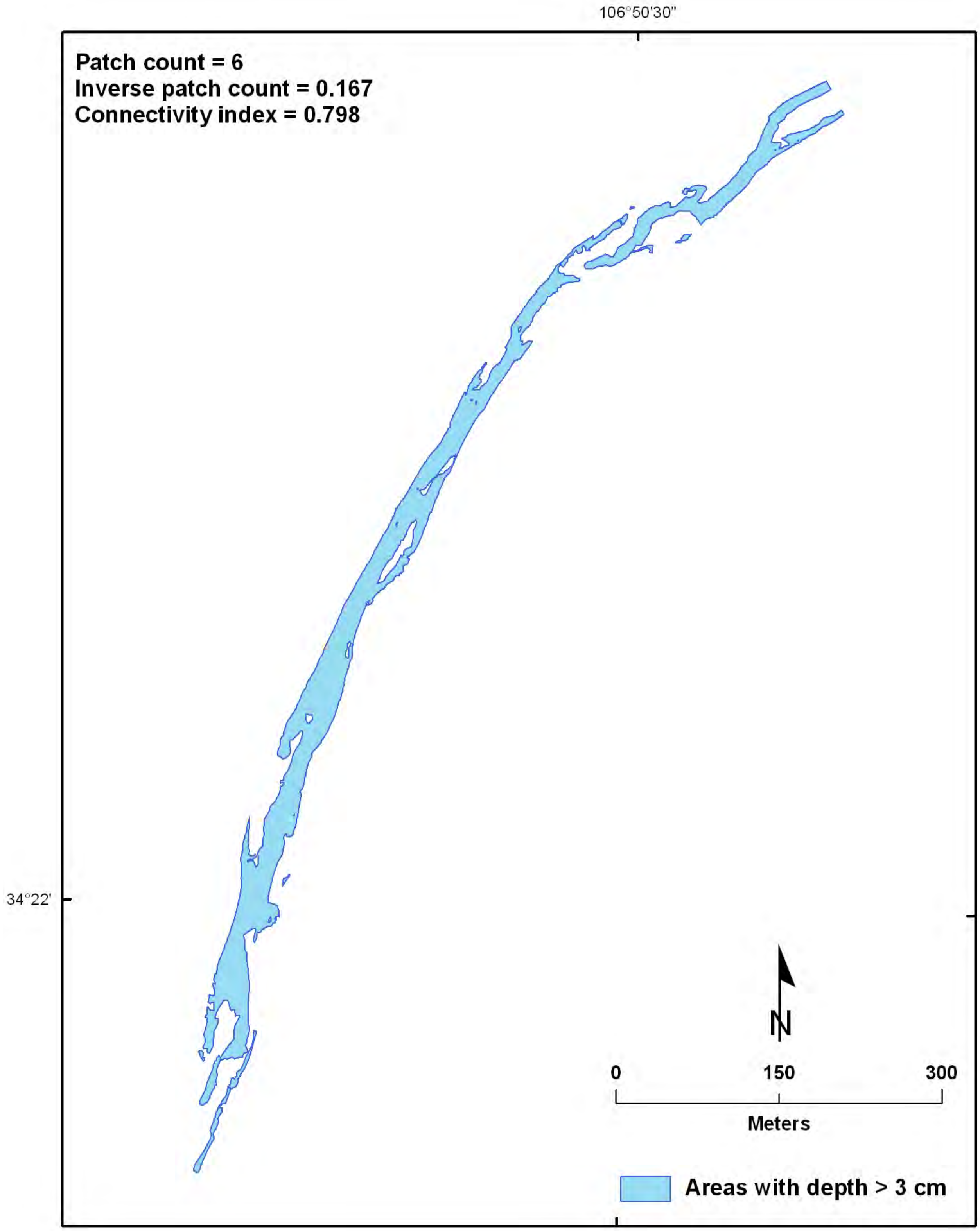

Figure 5-16. Habitat connectivity, Rio Puerco site, at 5 cubic feet per second.

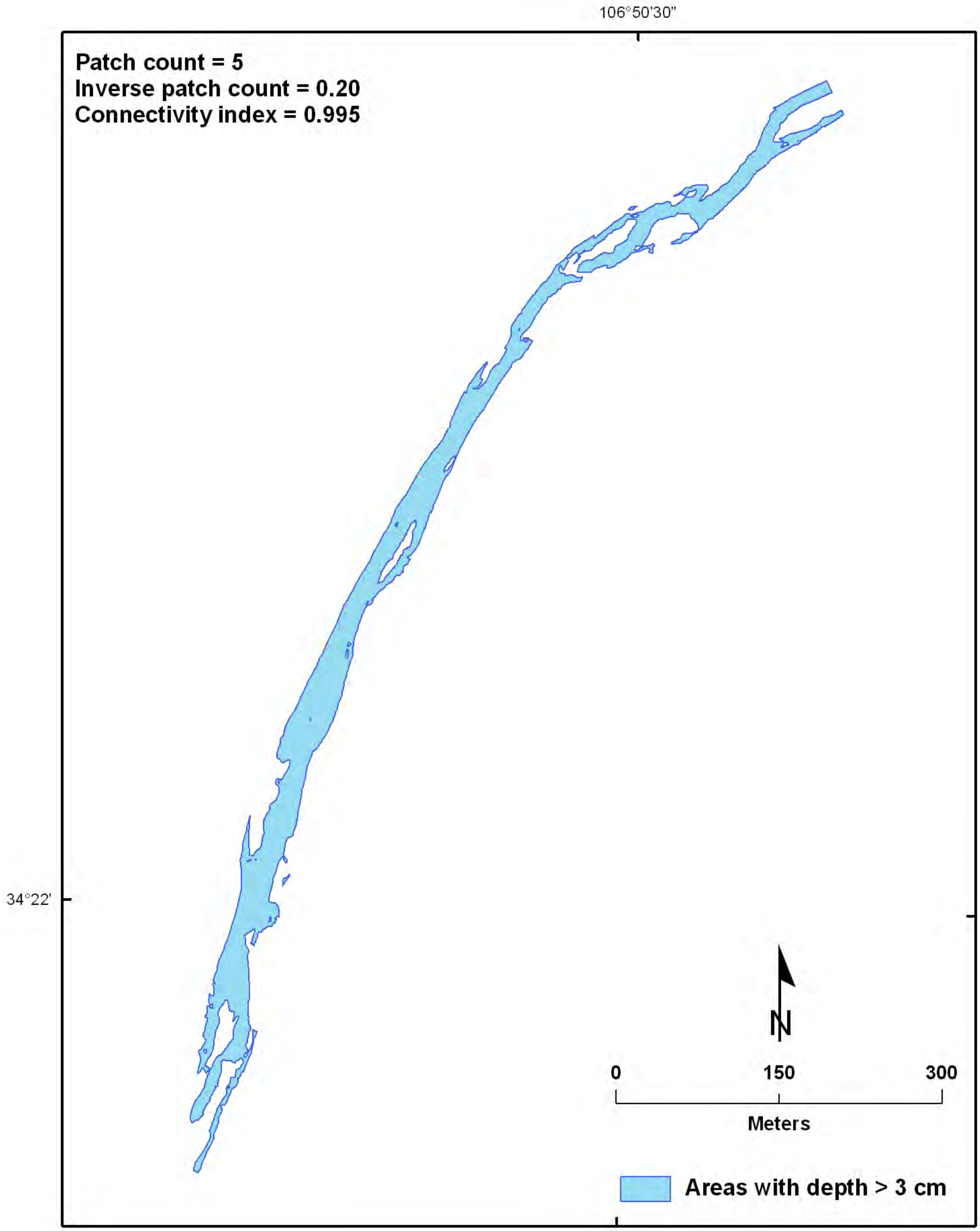

Figure 5-17. Habitat connectivity, Rio Puerco site, at 10 cubic feet per second.

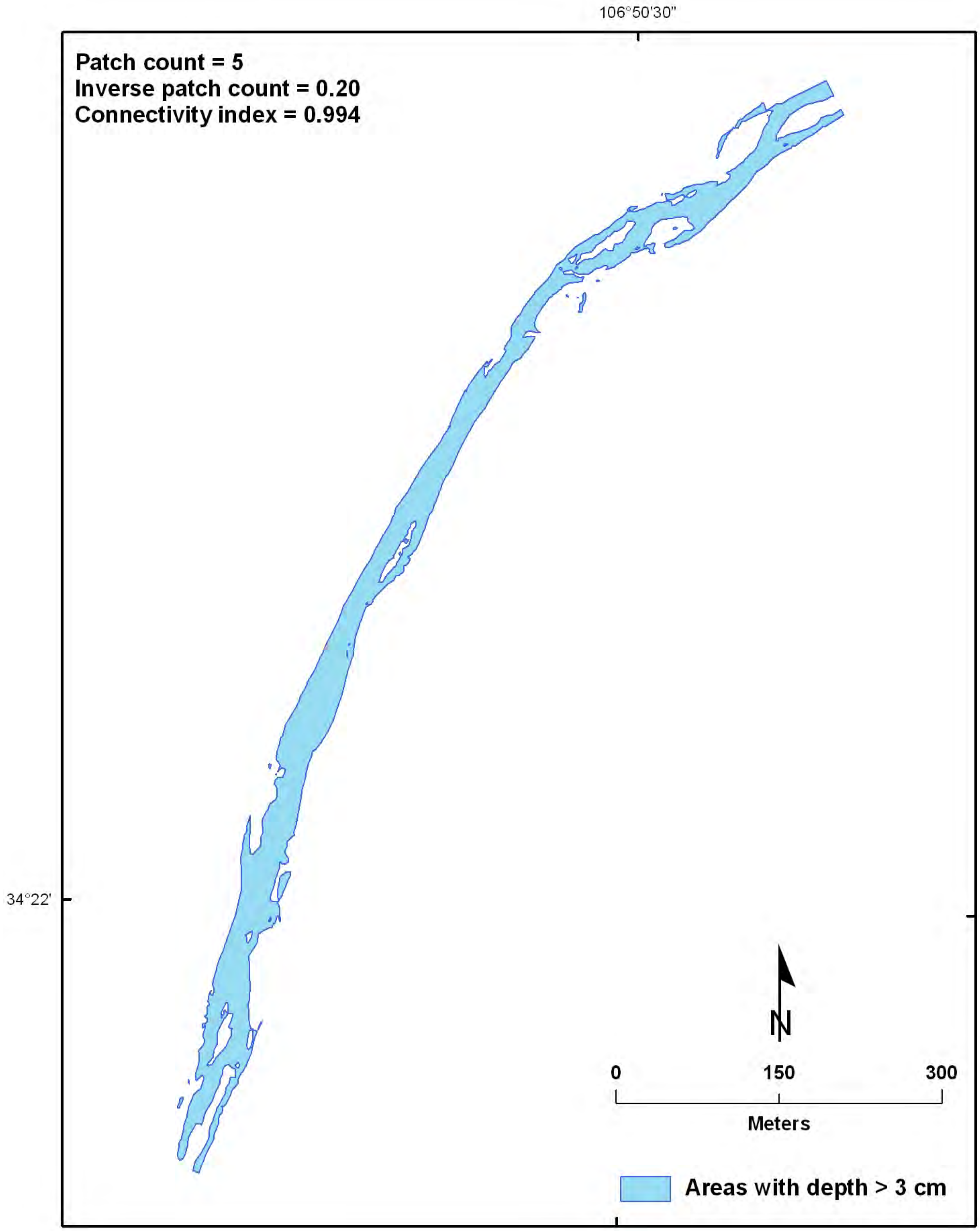

Figure 5-18. Habitat connectivity, Rio Puerco site, at 20 cubic feet per second.

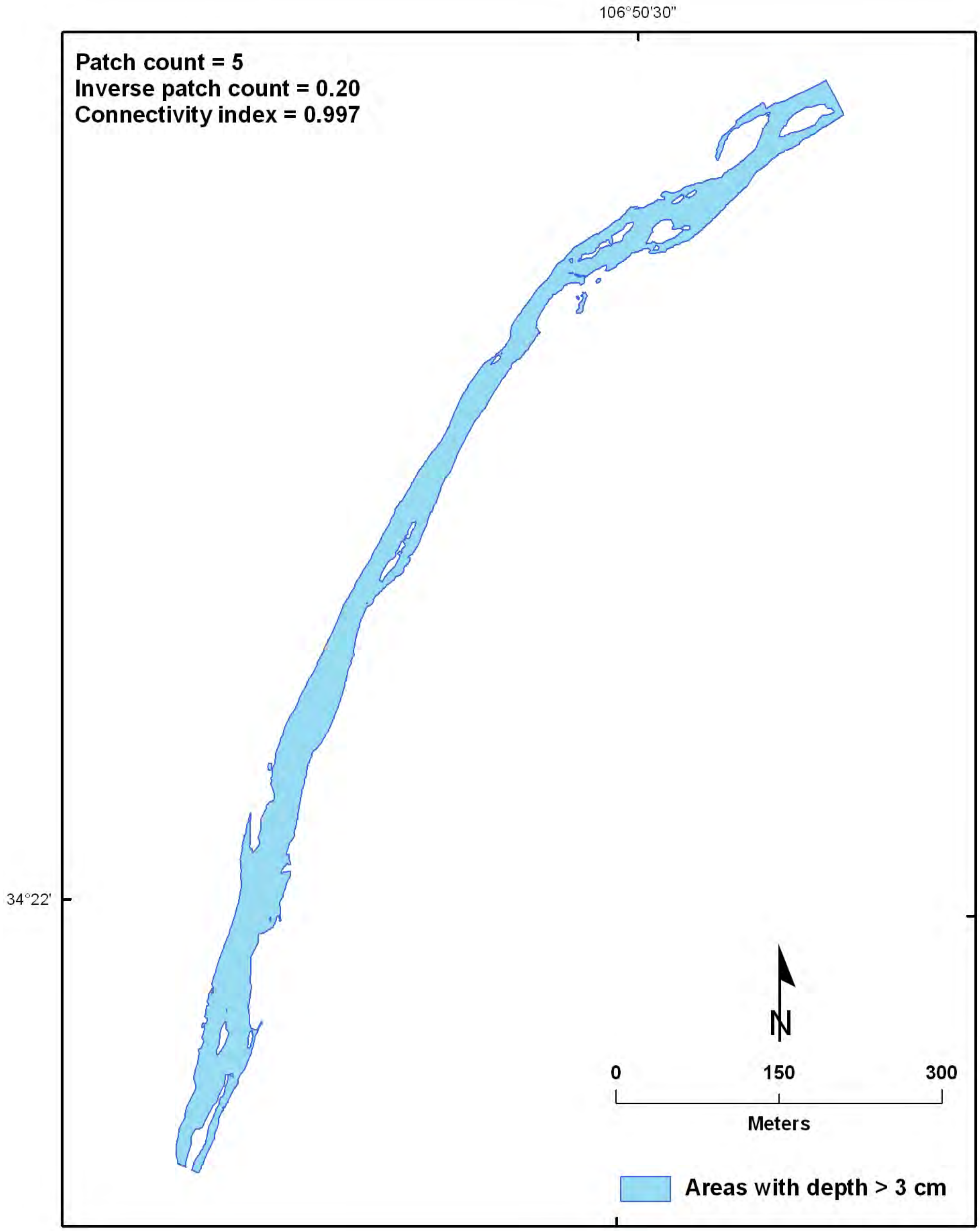

Figure 5-19. Habitat connectivity, Rio Puerco site, at 40 cubic feet per second.

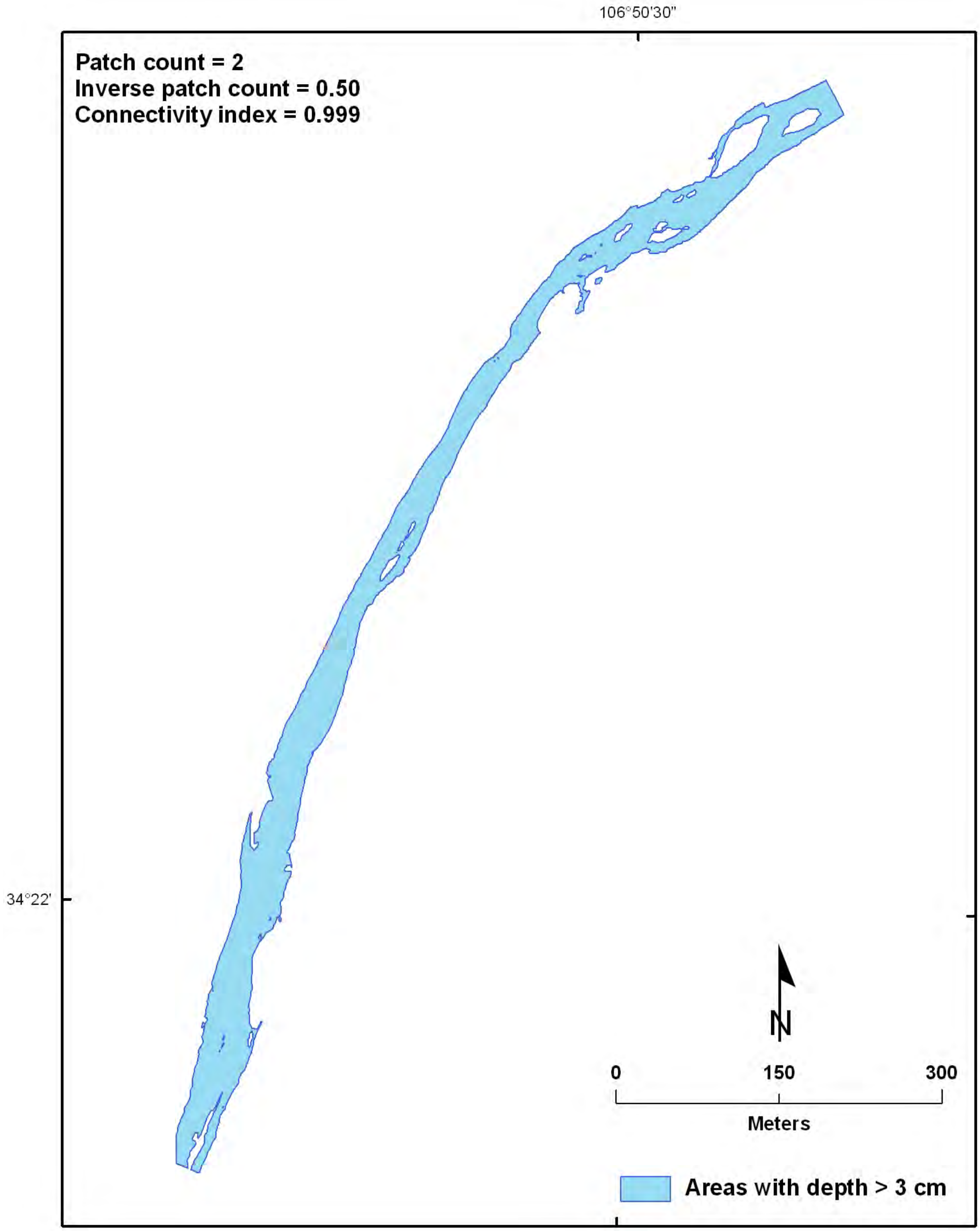

Figure 5-20. Habitat connectivity, Rio Puerco site, at 60 cubic feet per second.

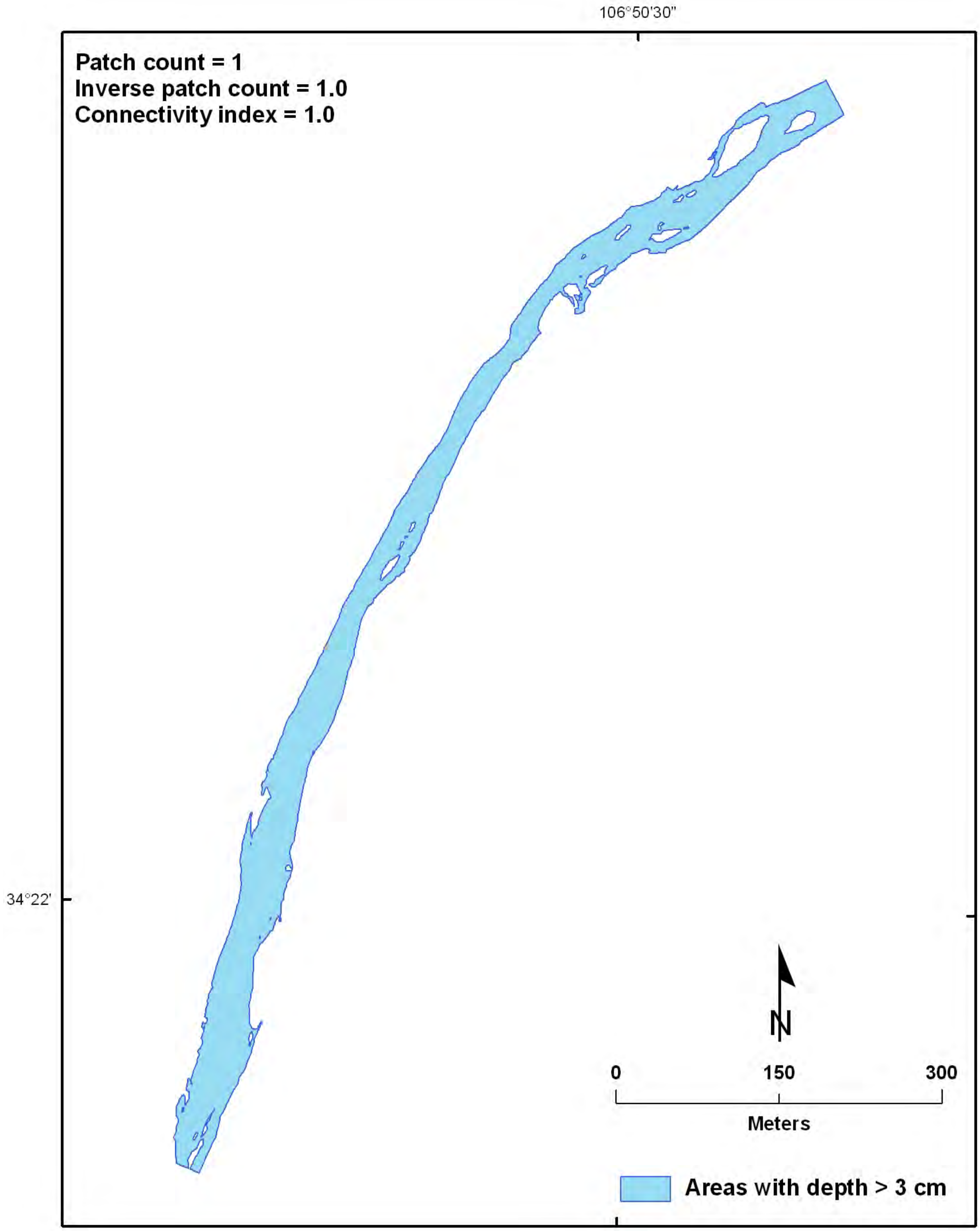

Figure 5-21. Habitat connectivity, Rio Puerco site, at 80 cubic feet per second.

Appendix 6. Habitat Maps for Southwestern Willow Flycatchers

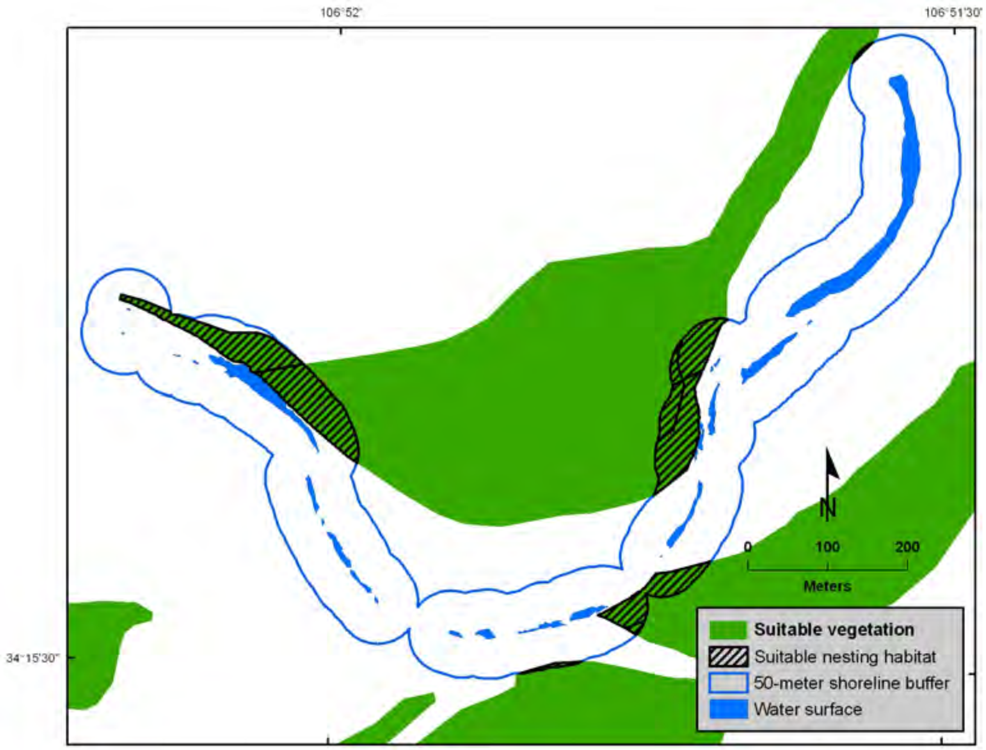

Figure 6-1. Nesting habitat for *E. t. extimus*, Rio Salado site, at 0 cubic feet per second.

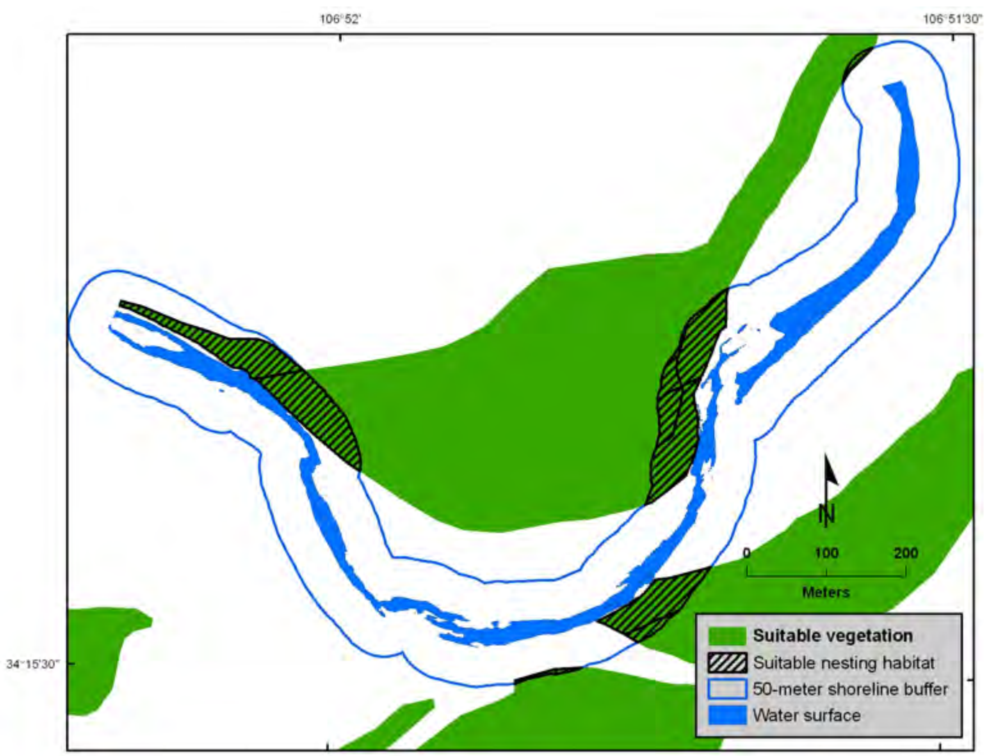

Figure 6-2. Nesting habitat for *E. t. extimus*, Rio Salado site, at 5 cubic feet per second.

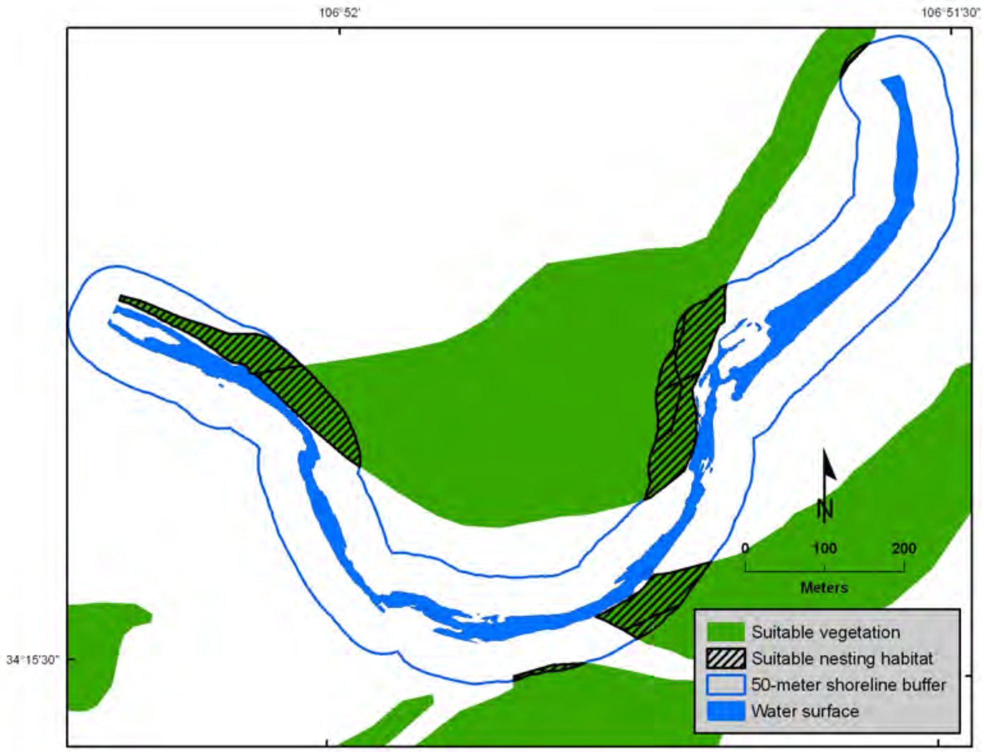

Figure 6-3. Nesting habitat for *E. t. extimus*, Rio Salado site, at 10 cubic feet per second.

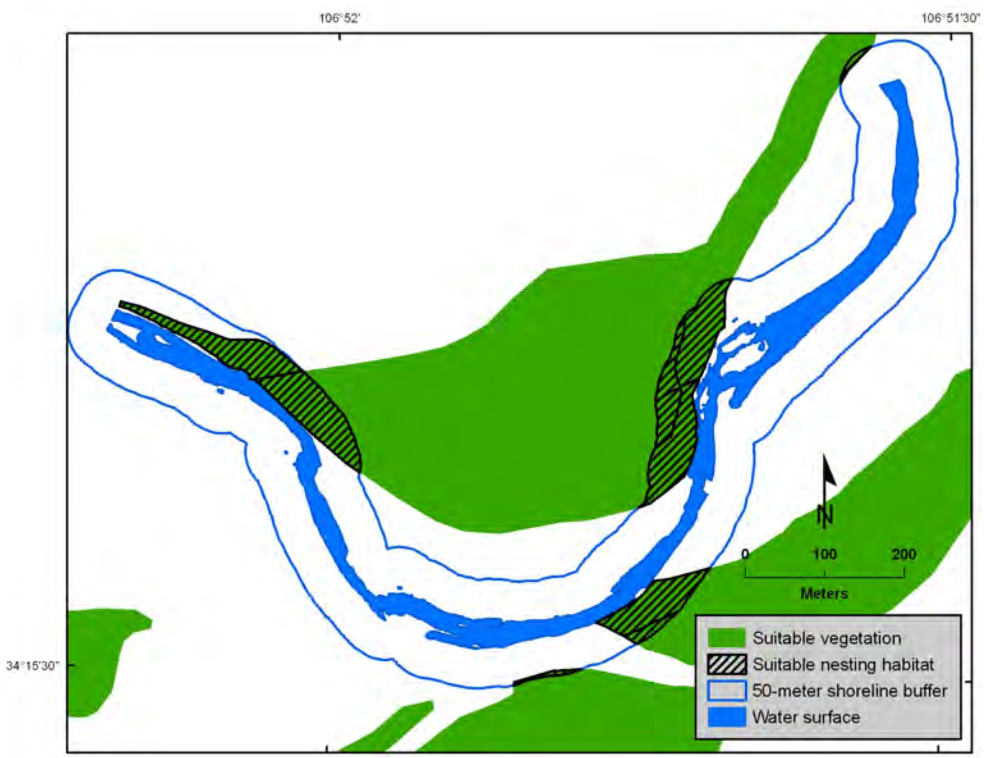

Figure 6-4. Nesting habitat for *E. t. extimus*, Rio Salado site, at 20 cubic feet per second.

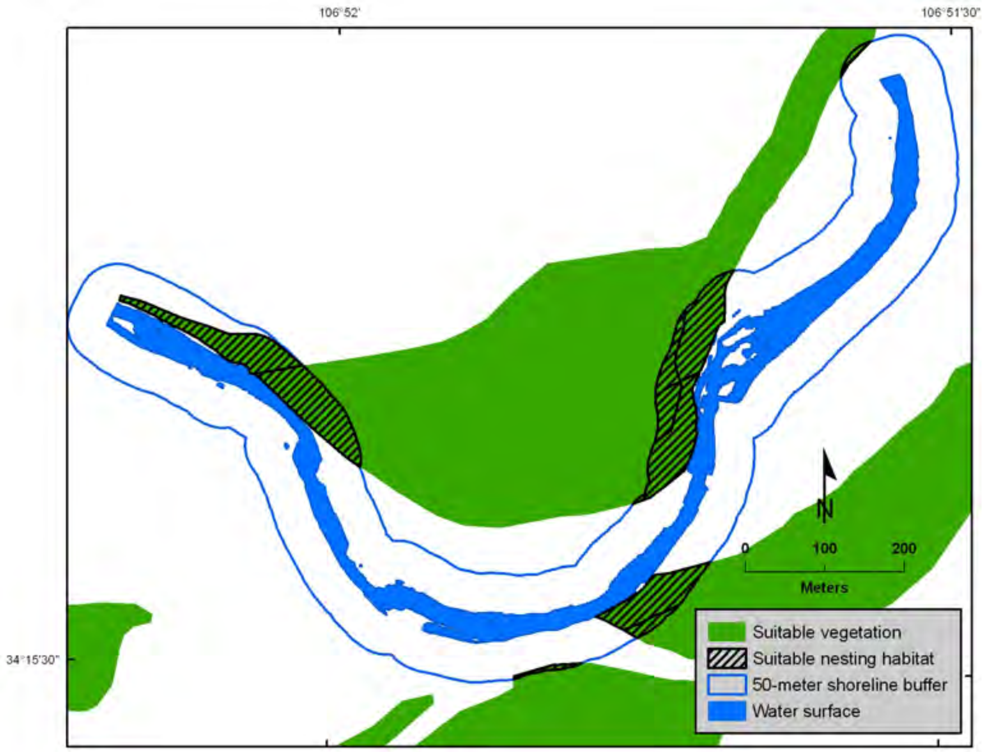

Figure 6-5. Nesting habitat for *E. t. extimus*, Rio Salado site, at 40 cubic feet per second.

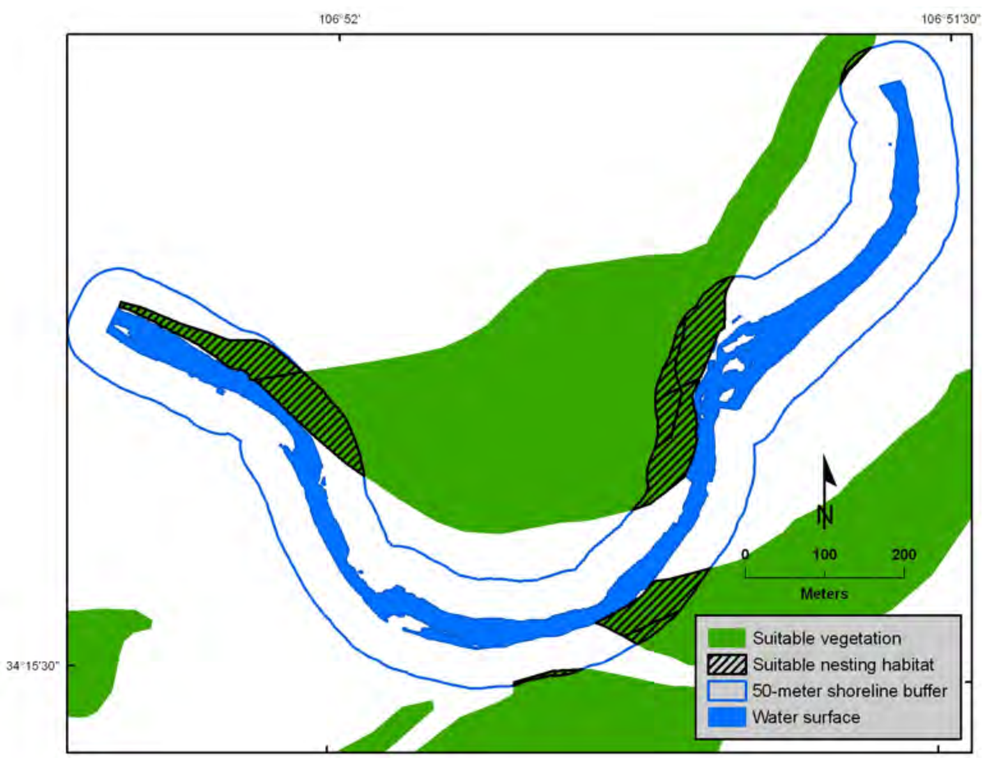

Figure 6-6. Nesting habitat for *E. t. extimus*, Rio Salado site, at 60 cubic feet per second.

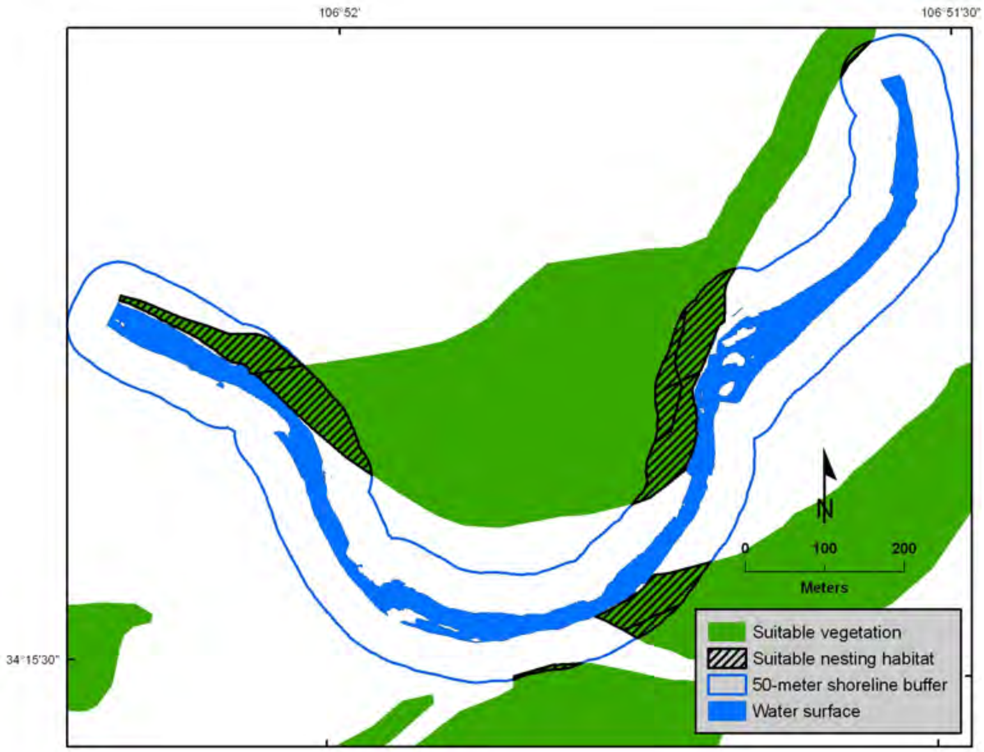

Figure 6-7. Nesting habitat for *E. t. extimus*, Rio Salado site, at 80 cubic feet per second.

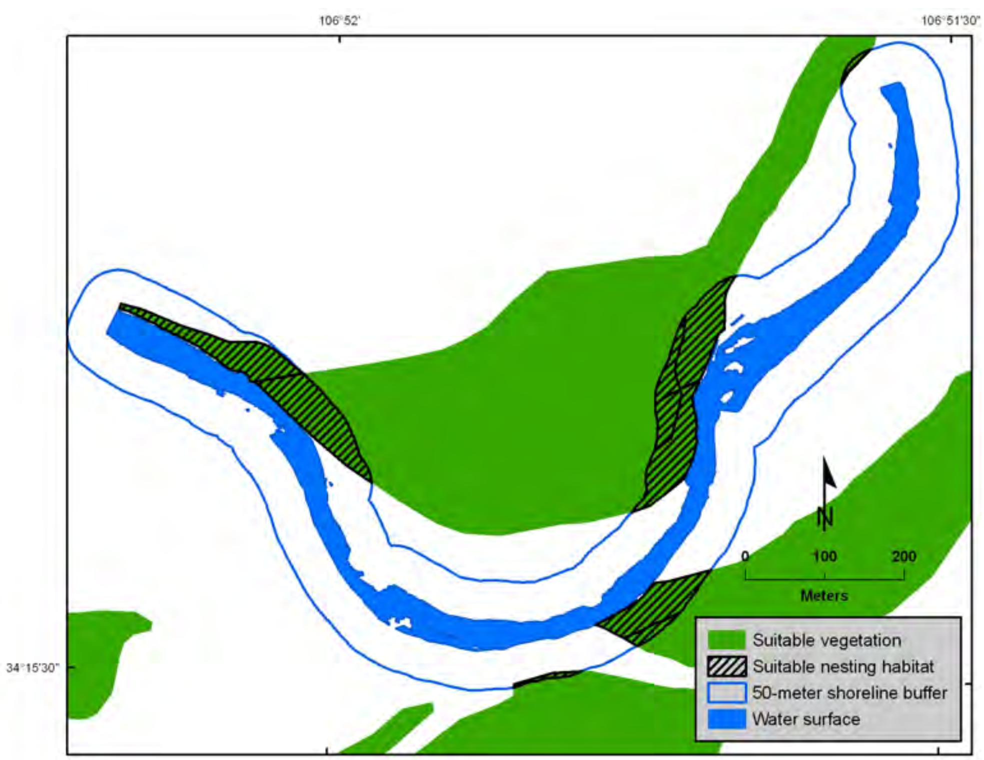

Figure 6-8. Nesting habitat for *E. t. extimus*, Rio Salado site, at 100 cubic feet per second.

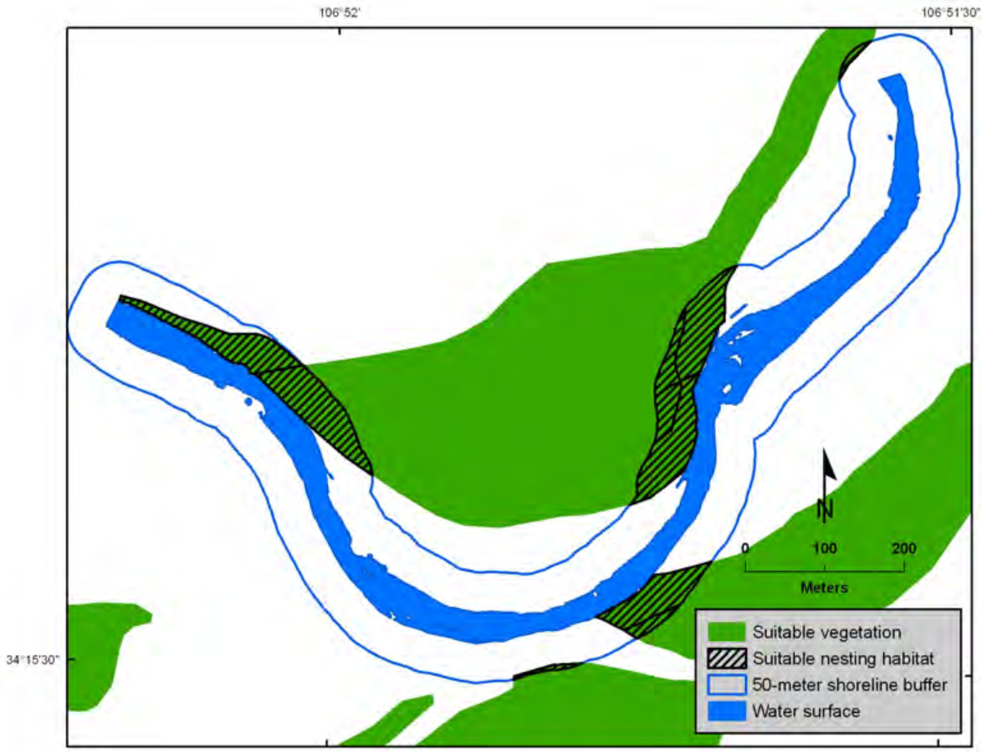

Figure 6-9. Nesting habitat for *E. t. extimus*, Rio Salado site, at 150 cubic feet per second.

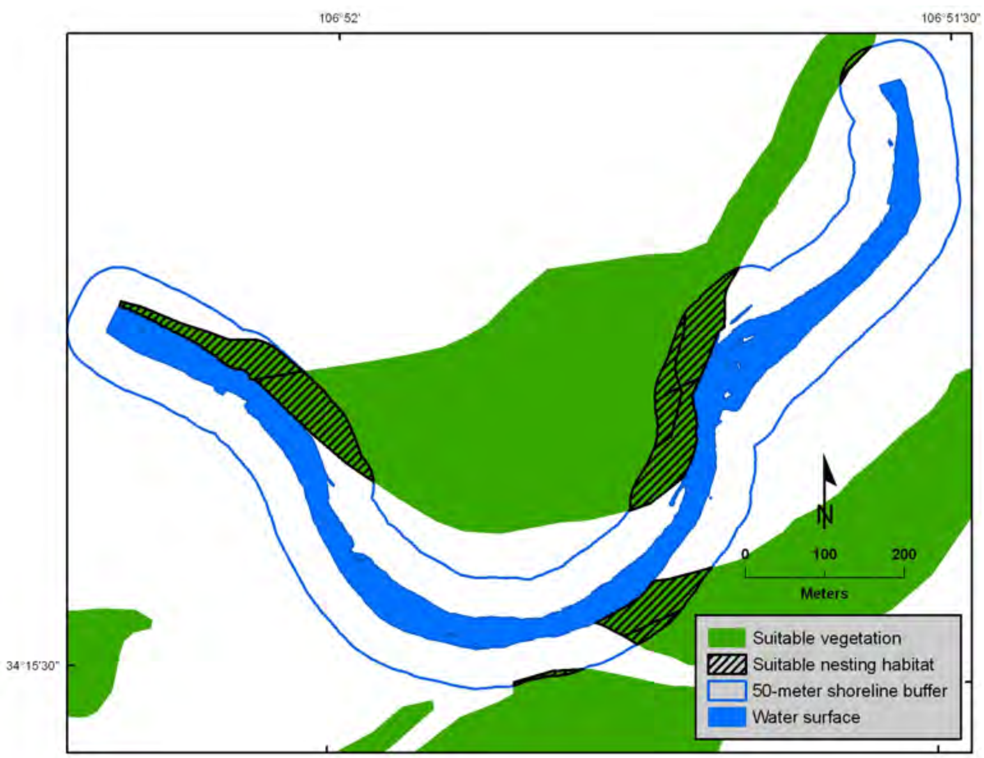

Figure 6-10. Nesting habitat for *E. t. extimus*, Rio Salado site, at 200 cubic feet per second.

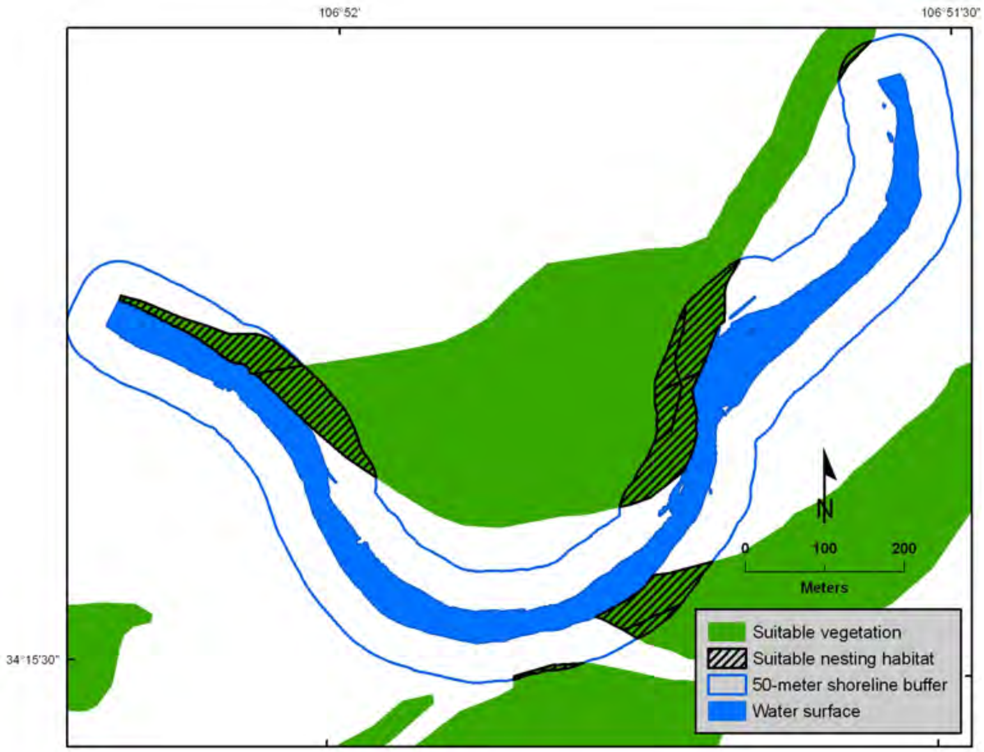

Figure 6-11. Nesting habitat for *E. t. extimus*, Rio Salado site, at 300 cubic feet per second.

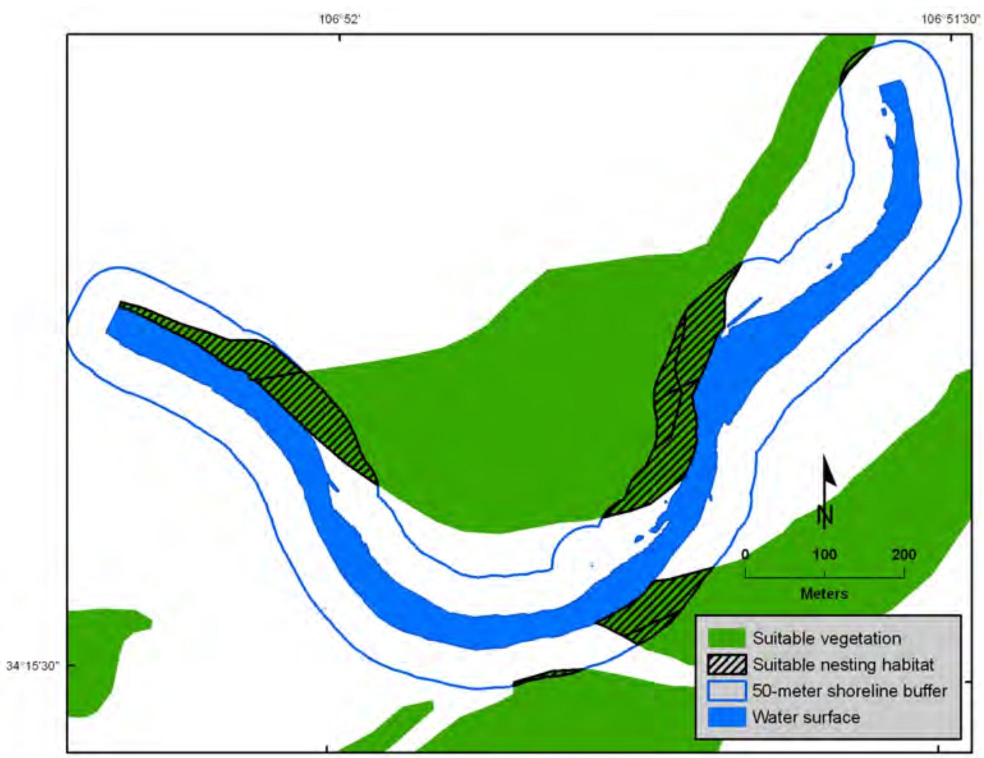

Figure 6-12. Nesting habitat for *E. t. extimus*, Rio Salado site, at 400 cubic feet per second.

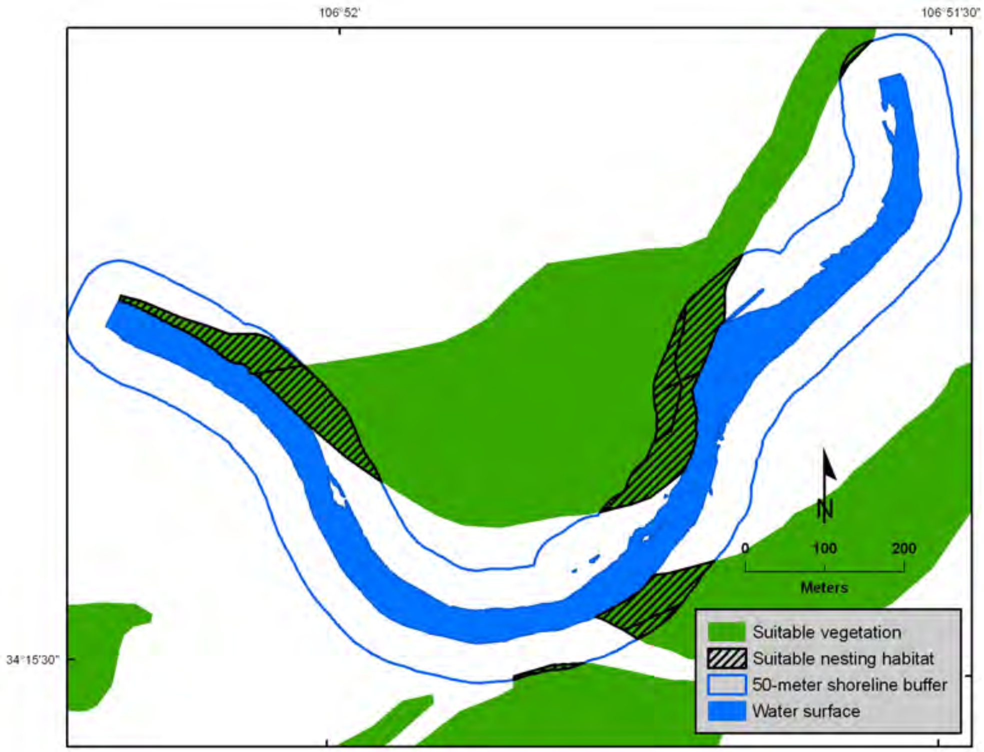

Figure 6-13. Nesting habitat for *E. t. extimus*, Rio Salado site, at 500 cubic feet per second.

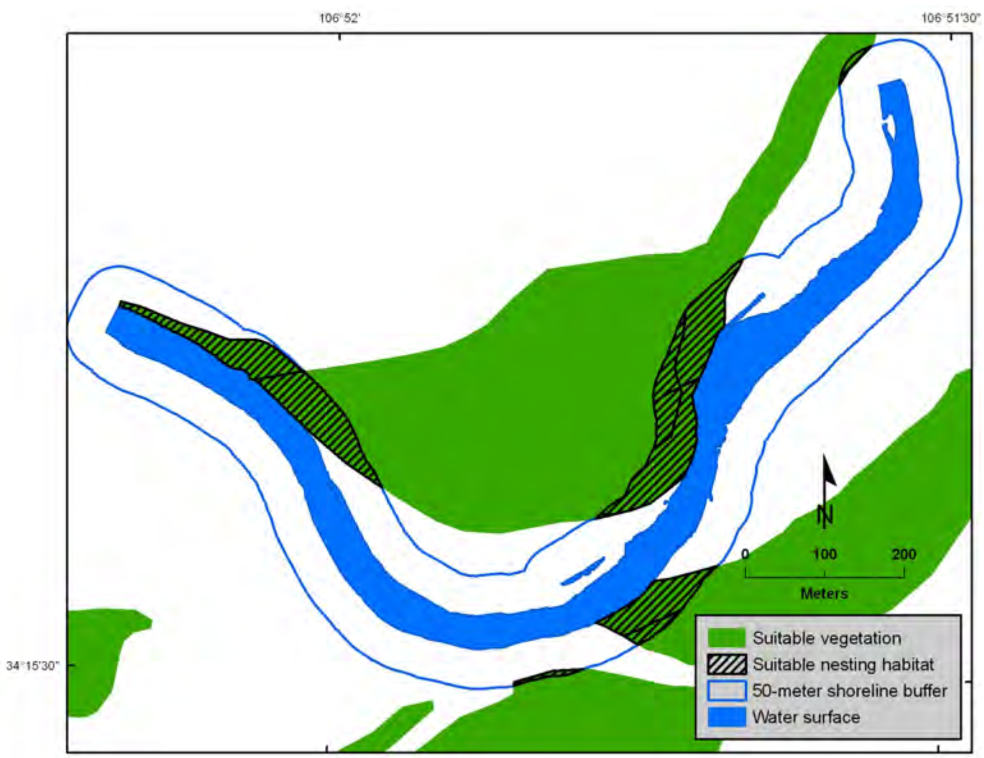

Figure 6-14. Nesting habitat for *E. t. extimus*, Rio Salado site, at 600 cubic feet per second.

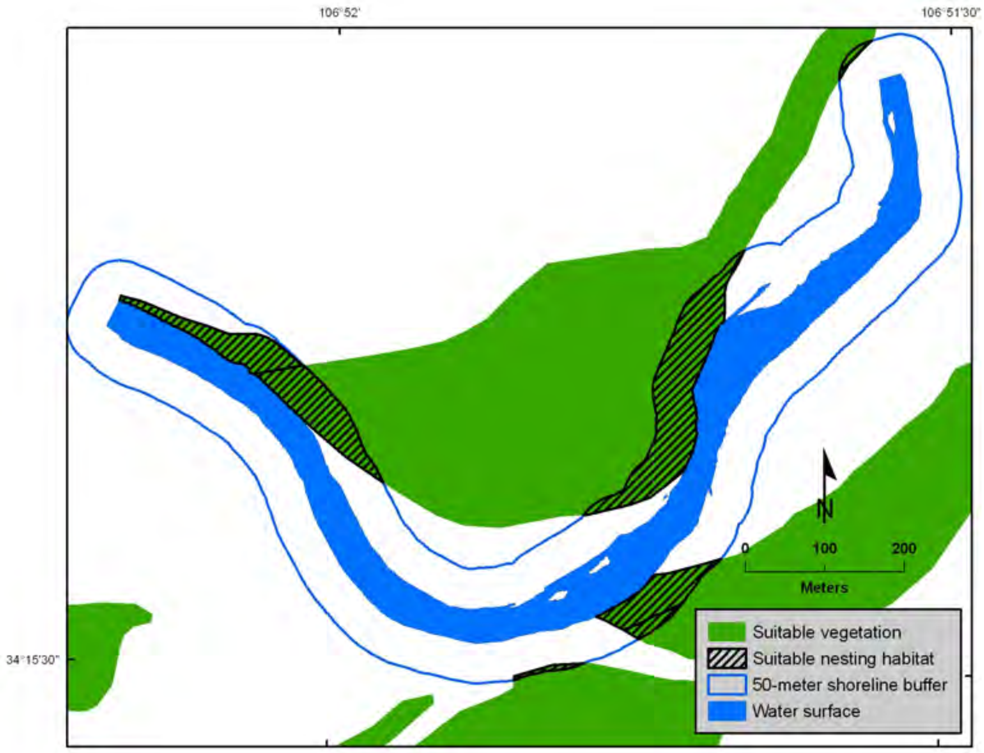

Figure 6-15. Nesting habitat for *E. t. extimus*, Rio Salado site, at 800 cubic feet per second.

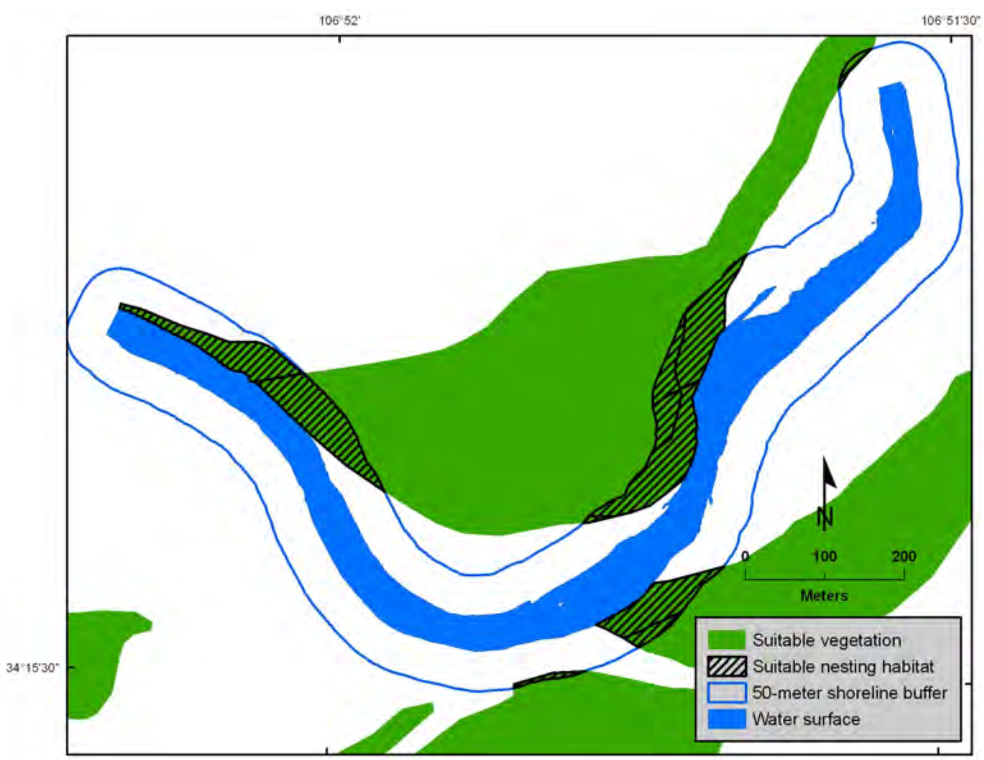

Figure 6-16. Nesting habitat for *E. t. extimus*, Rio Salado site, at 1,000 cubic feet per second.

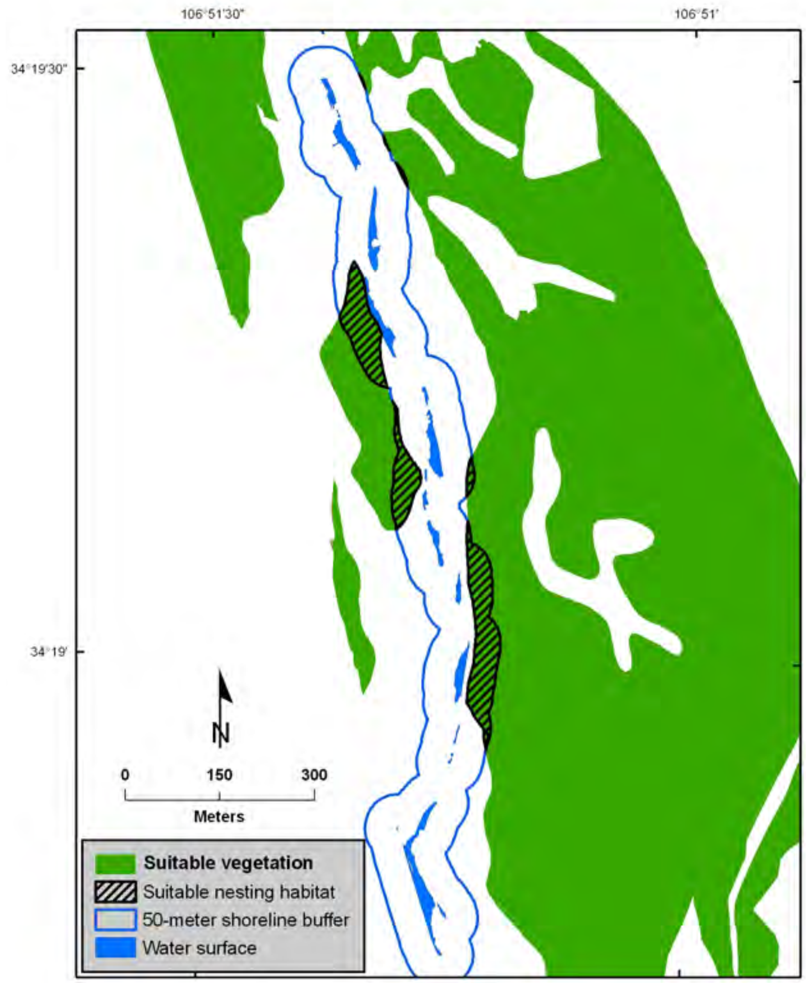

Figure 6-17. Nesting habitat for *E. t. extimus*, Sevilleta site, at 0 cubic feet per second.

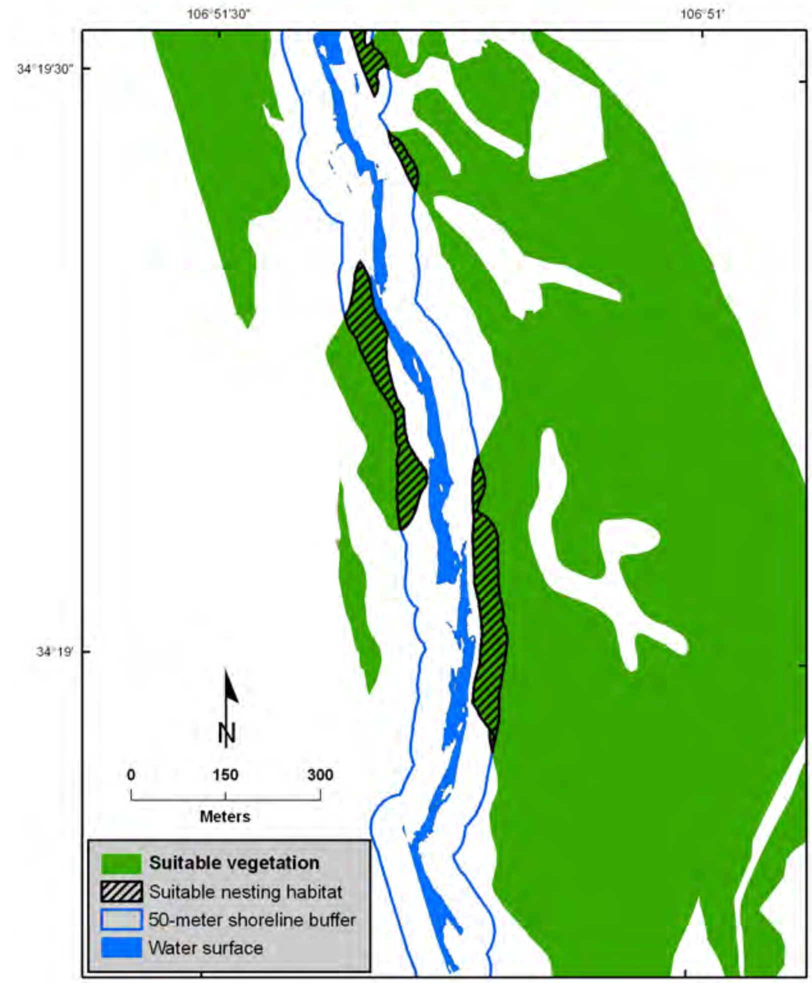

Figure 6-18. Nesting habitat for *E. t. extimus*, Sevilleta site, at 5 cubic feet per second.

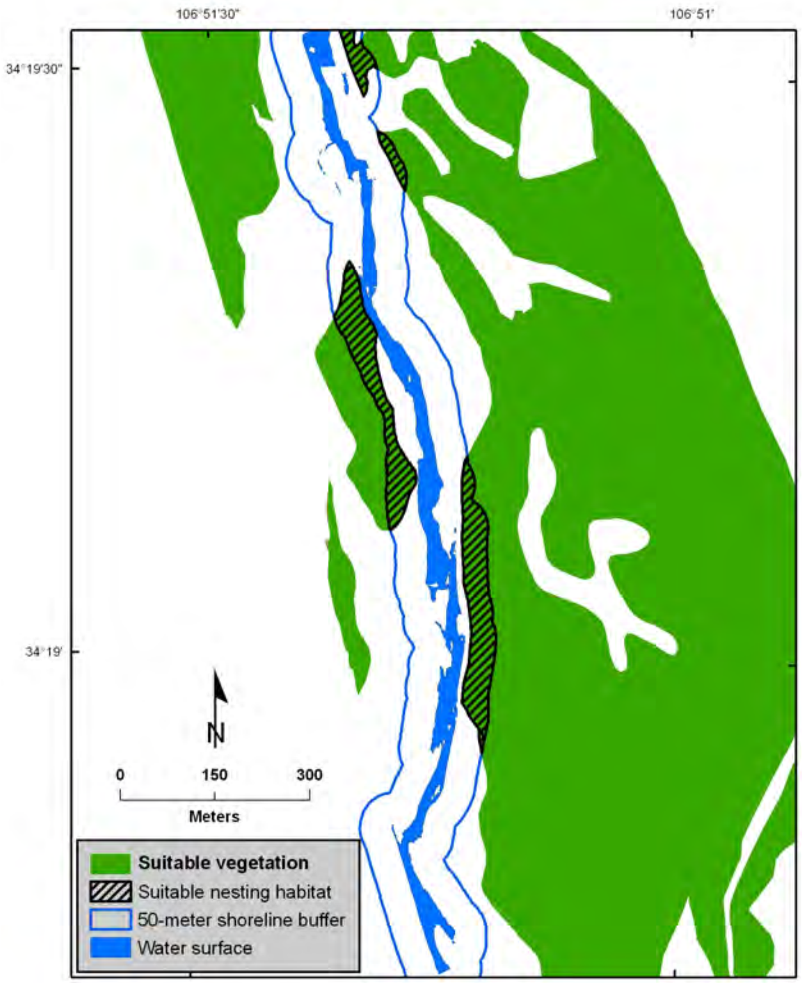

Figure 6-19. Nesting habitat for *E. t. extimus*, Sevilleta site, at 10 cubic feet per second.

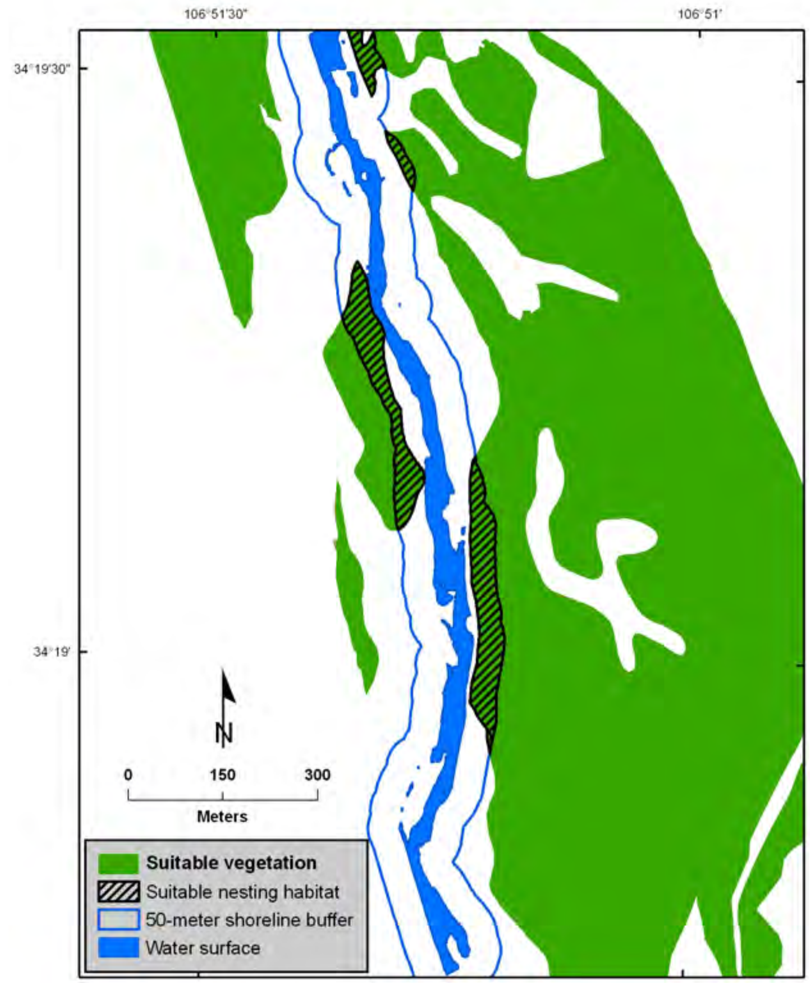

Figure 6-20. Nesting habitat for *E. t. extimus*, Sevilleta site, at 20 cubic feet per second.

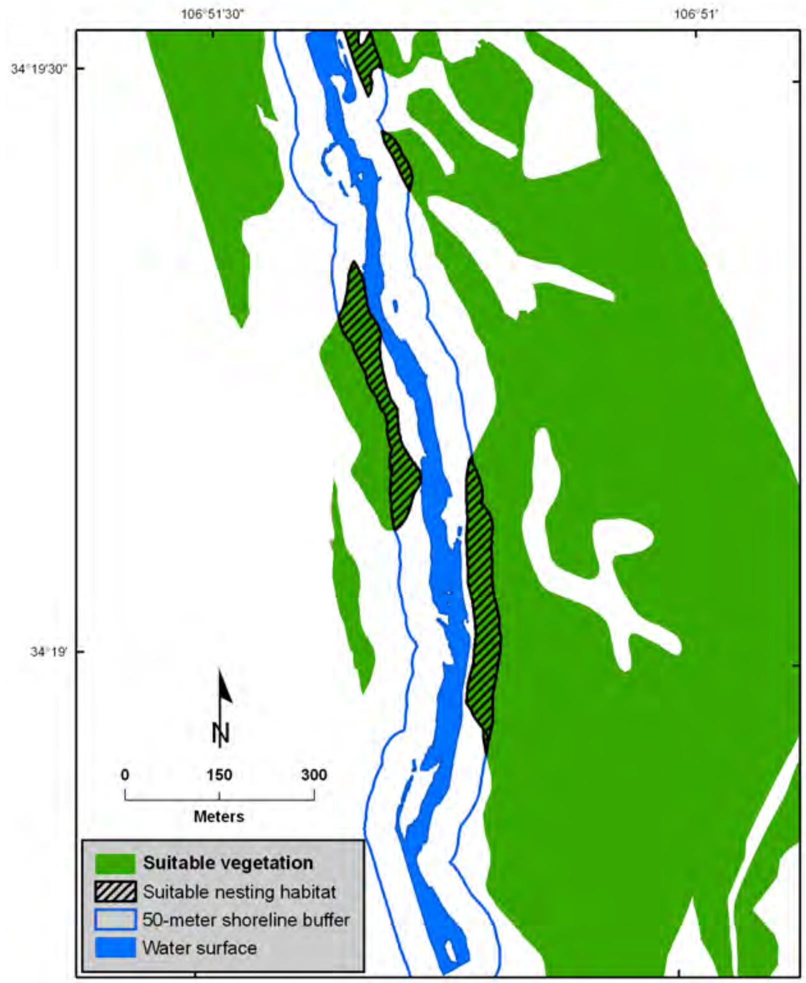

Figure 6-21. Nesting habitat for *E. t. extimus*, Sevilleta site, at 40 cubic feet per second.

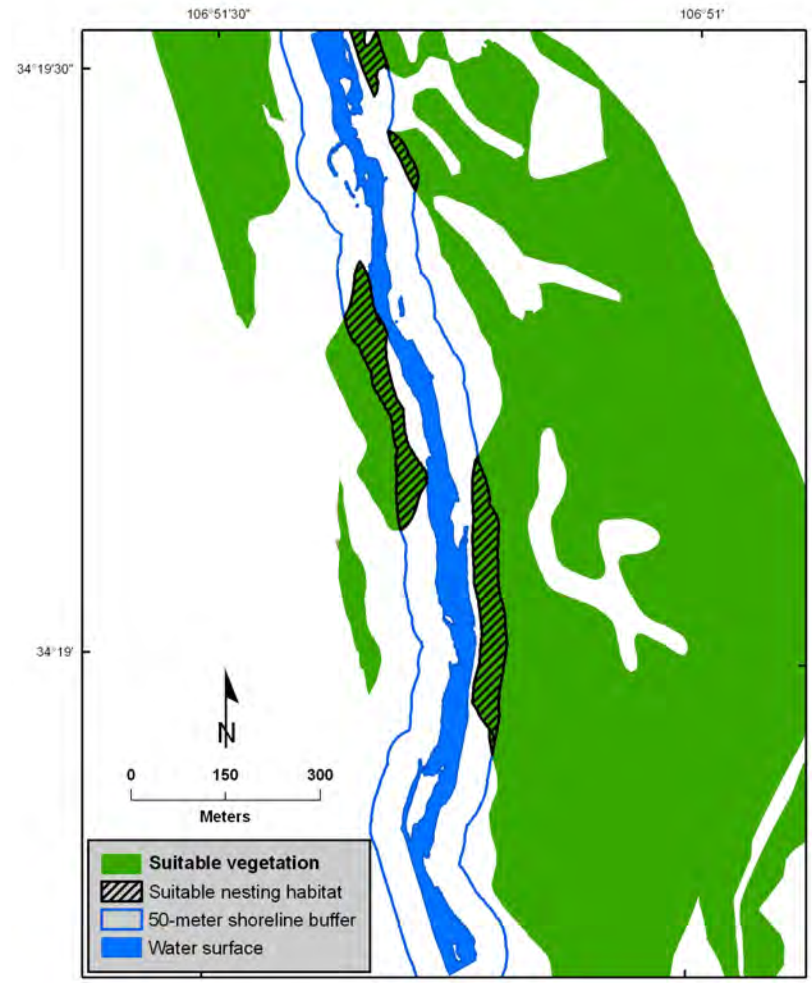

Figure 6-22. Nesting habitat for *E. t. extimus*, Sevilleta site, at 60 cubic feet per second.

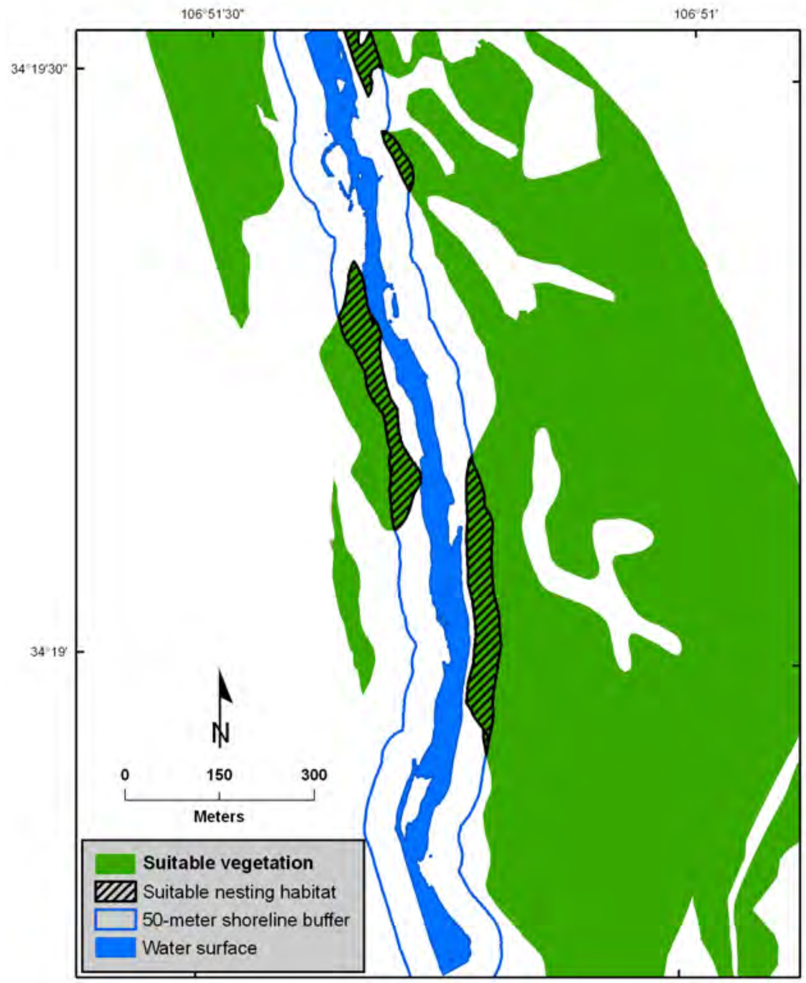

Figure 6-23. Nesting habitat for *E. t. extimus*, Sevilleta site, at 80 cubic feet per second.

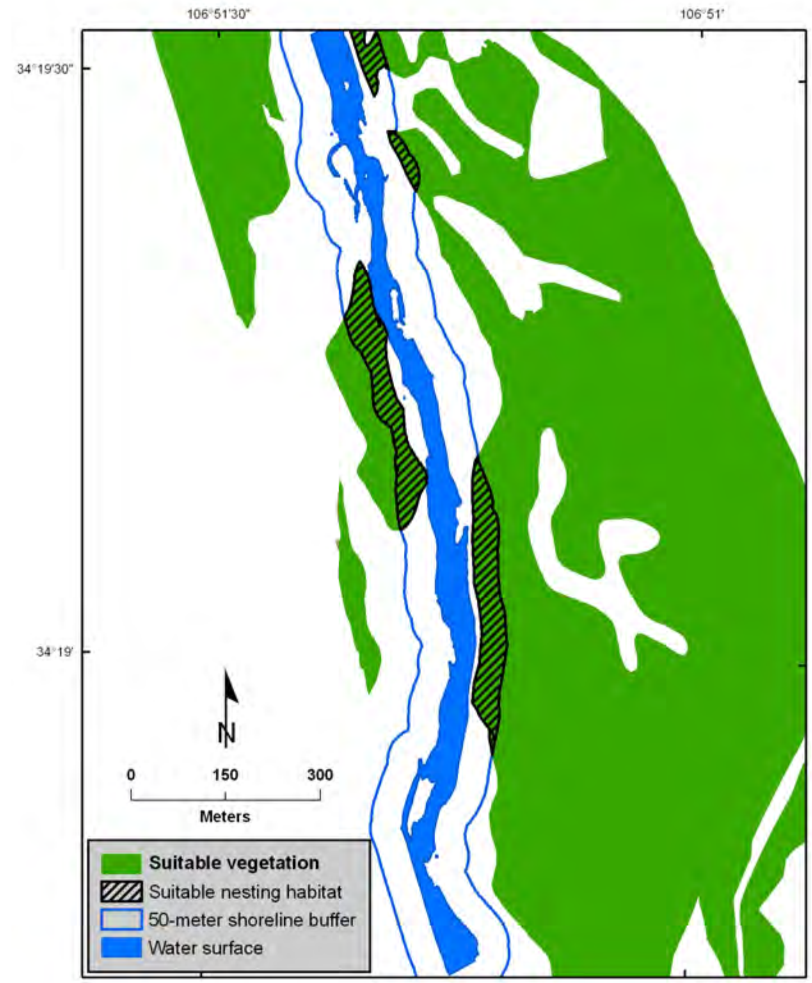

Figure 6-24. Nesting habitat for *E. t. extimus*, Sevilleta site, at 100 cubic feet per second.

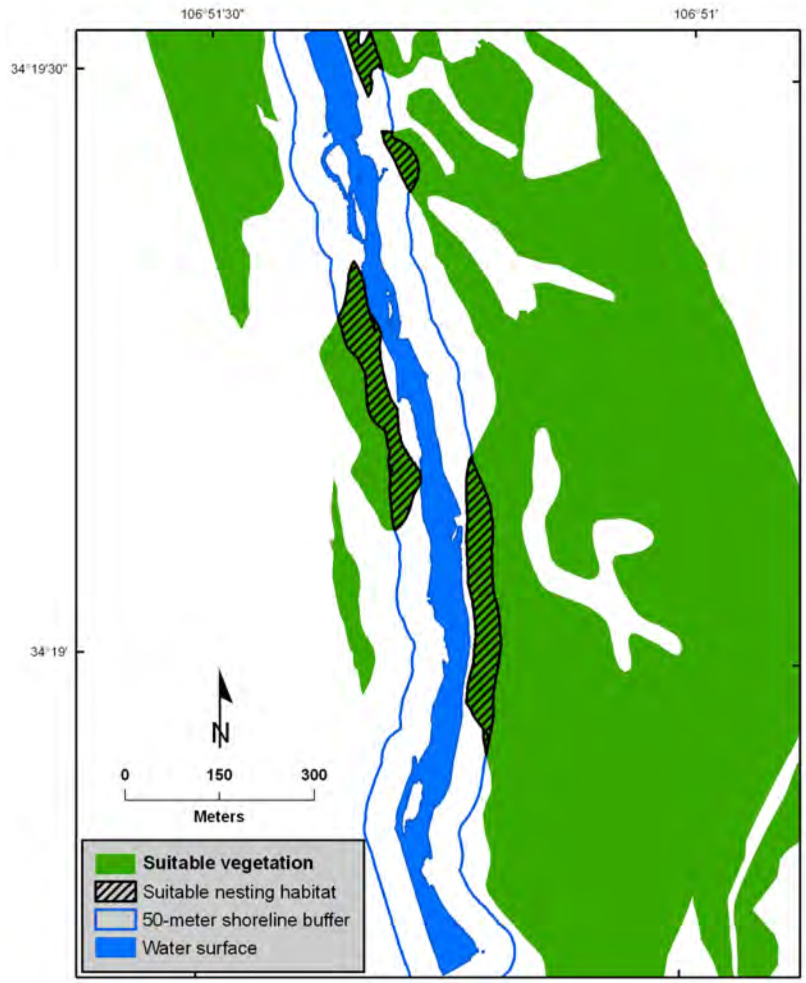

Figure 6-25. Nesting habitat for *E. t. extimus*, Sevilleta site, at 150 cubic feet per second.

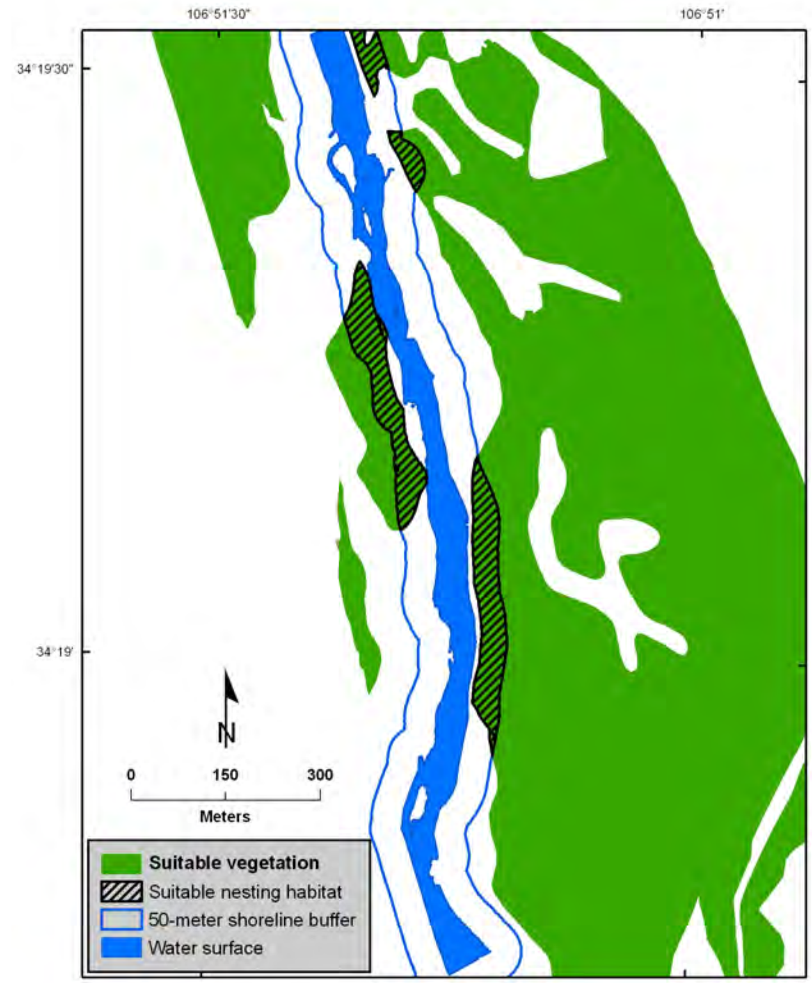

Figure 6-26. Nesting habitat for *E. t. extimus*, Sevilleta site, at 200 cubic feet per second.

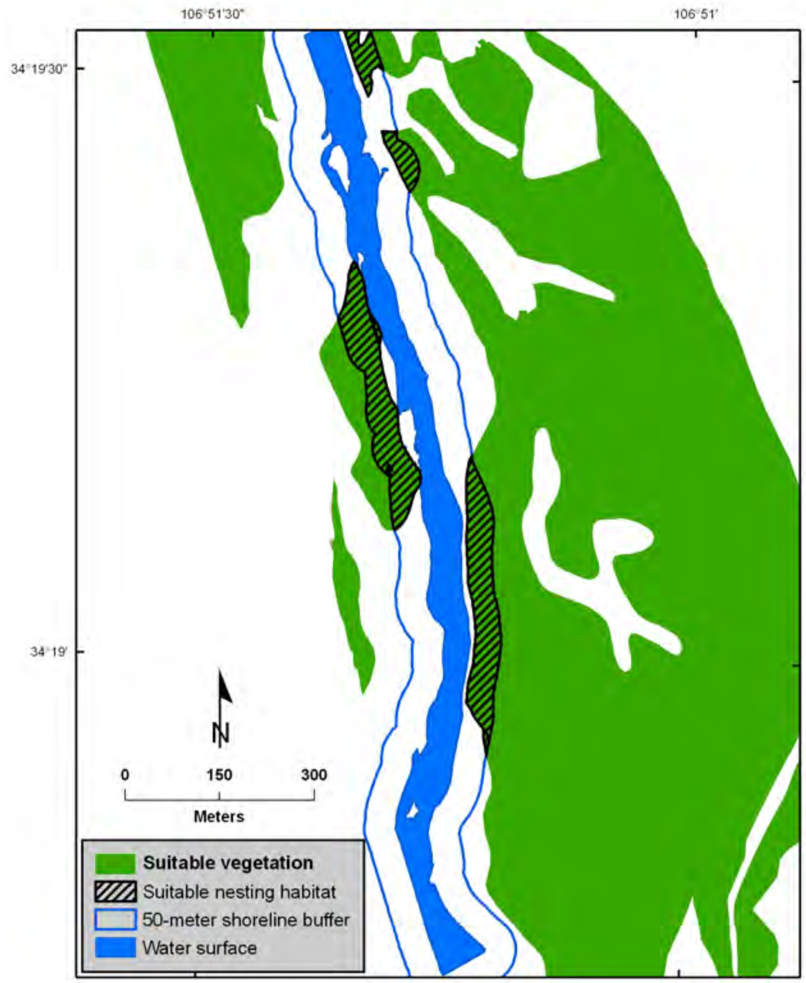

Figure 6-27. Nesting habitat for *E. t. extimus*, Sevilleta site, at 300 cubic feet per second.

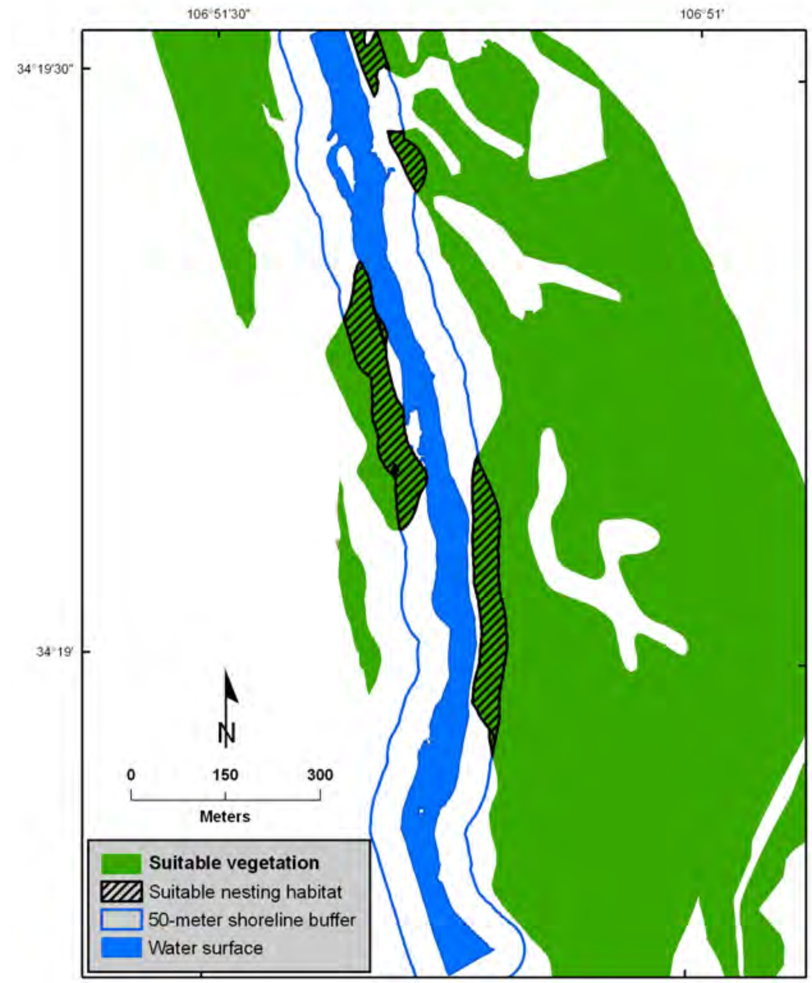

Figure 6-28. Nesting habitat for *E. t. extimus*, Sevilleta site, at 400 cubic feet per second.

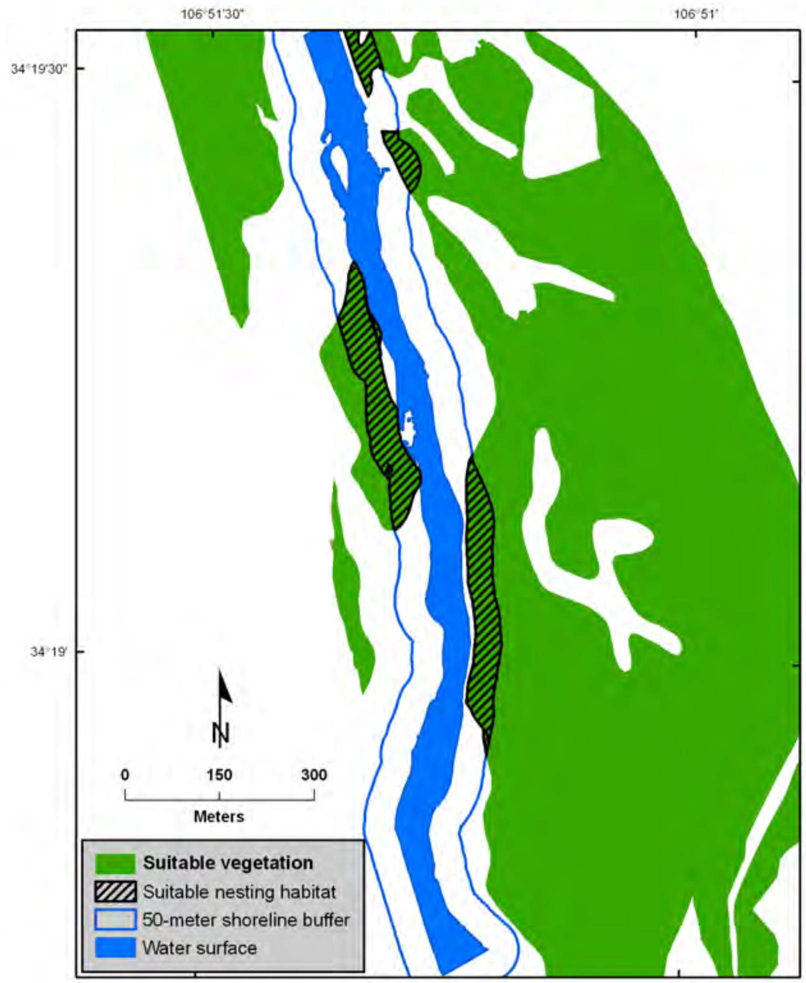

Figure 6-29. Nesting habitat for *E. t. extimus*, Sevilleta site, at 500 cubic feet per second.

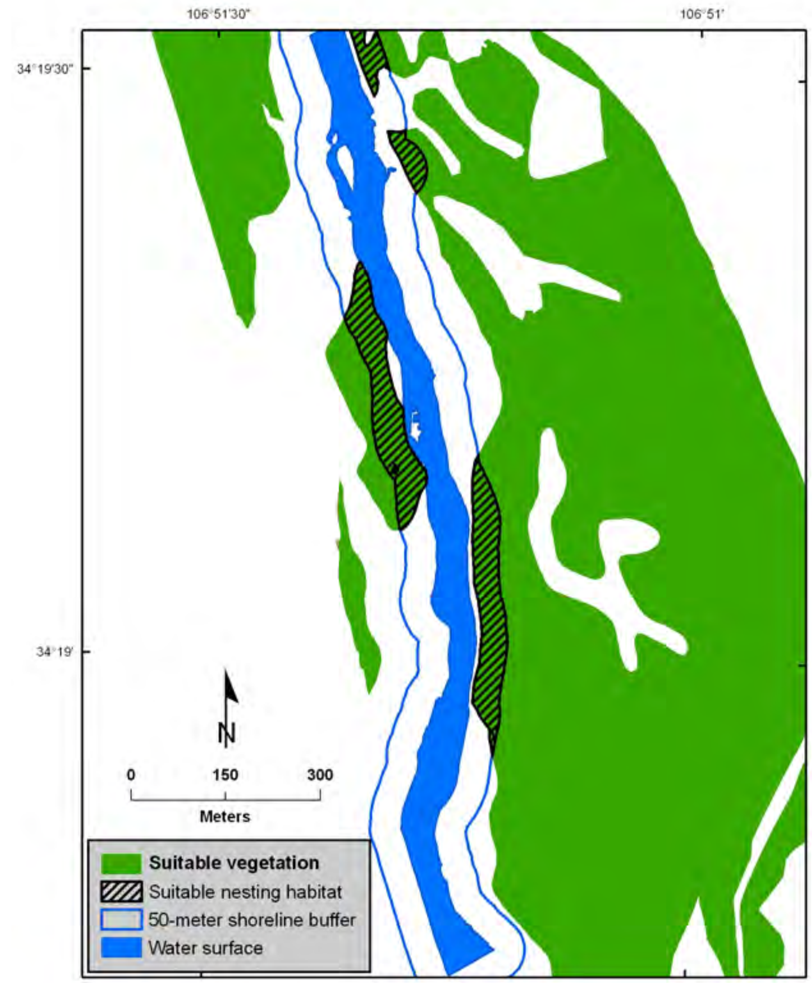

Figure 6-30. Nesting habitat for *E. t. extimus*, Sevilleta site, at 600 cubic feet per second.

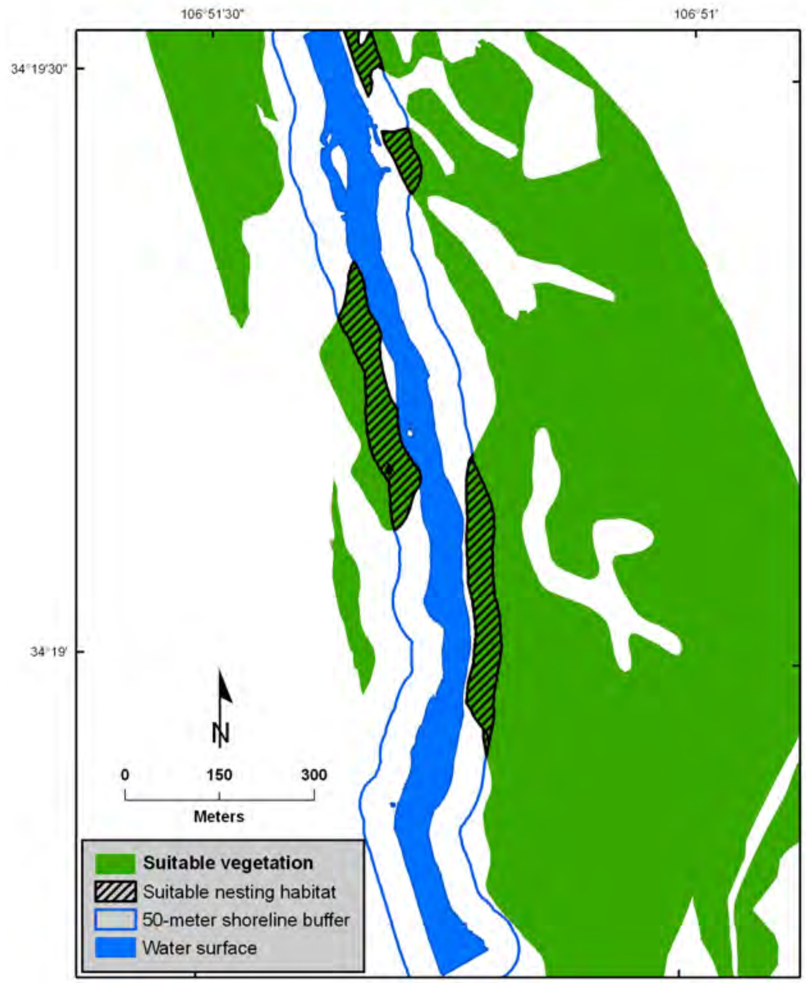

Figure 6-31. Nesting habitat for *E. t. extimus*, Sevilleta site, at 800 cubic feet per second.

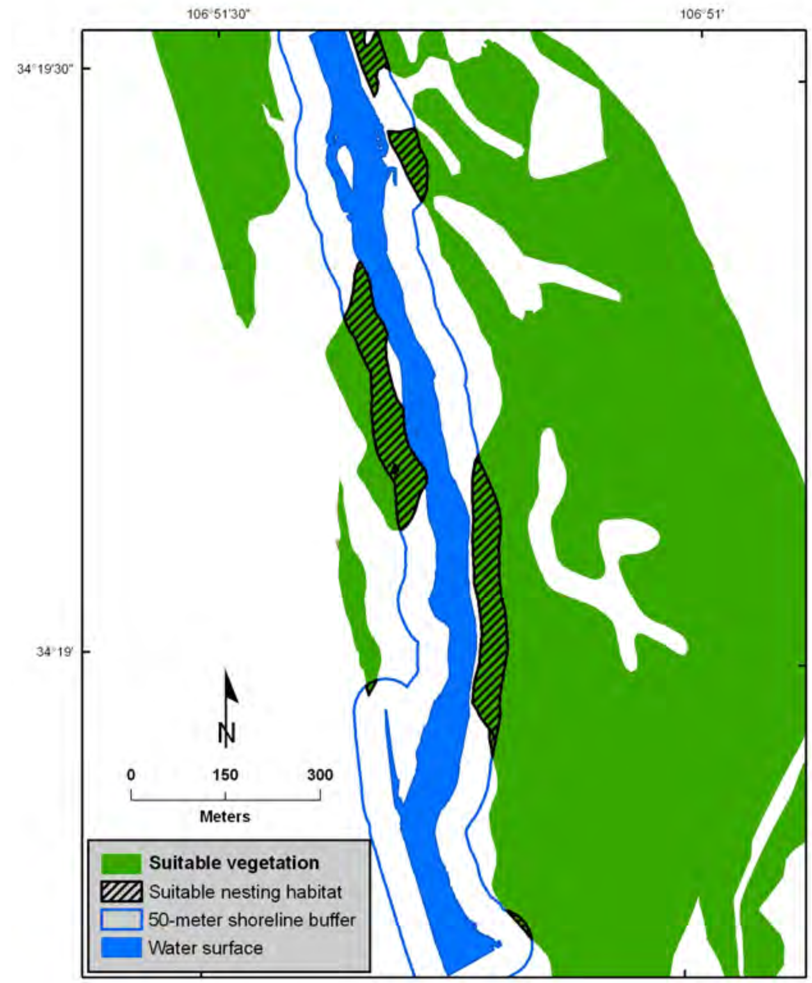

Figure 6-32. Nesting habitat for *E. t. extimus*, Sevilleta site, at 1,000 cubic feet per second.

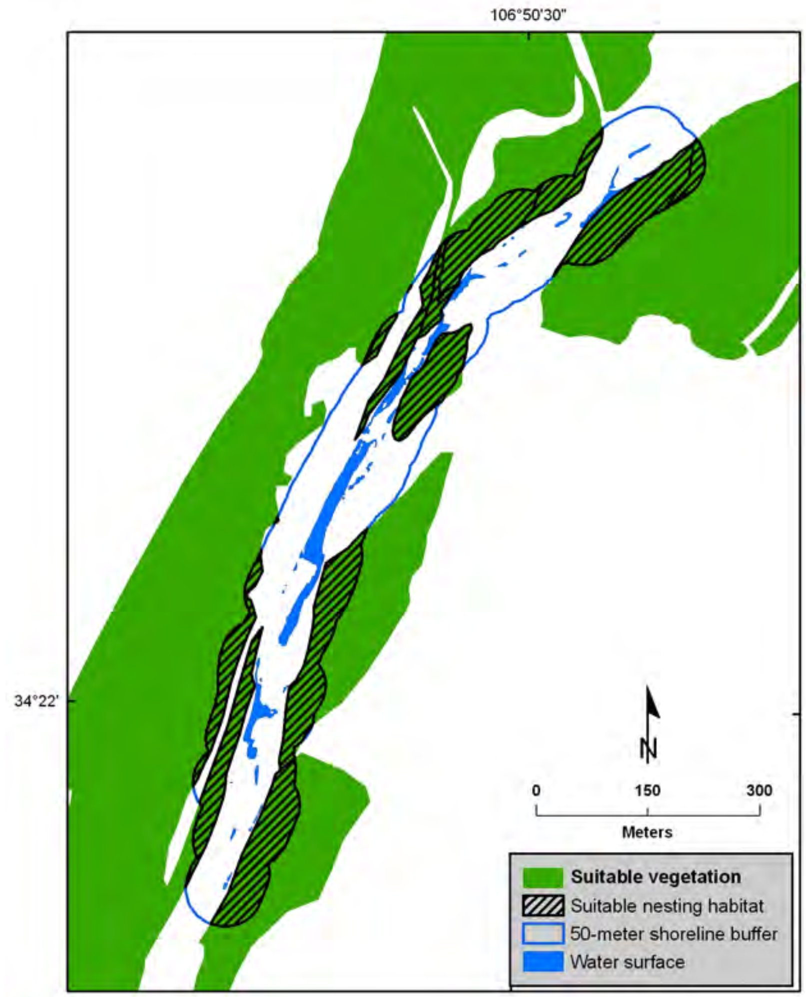

Figure 6-33. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 0 cubic feet per second.

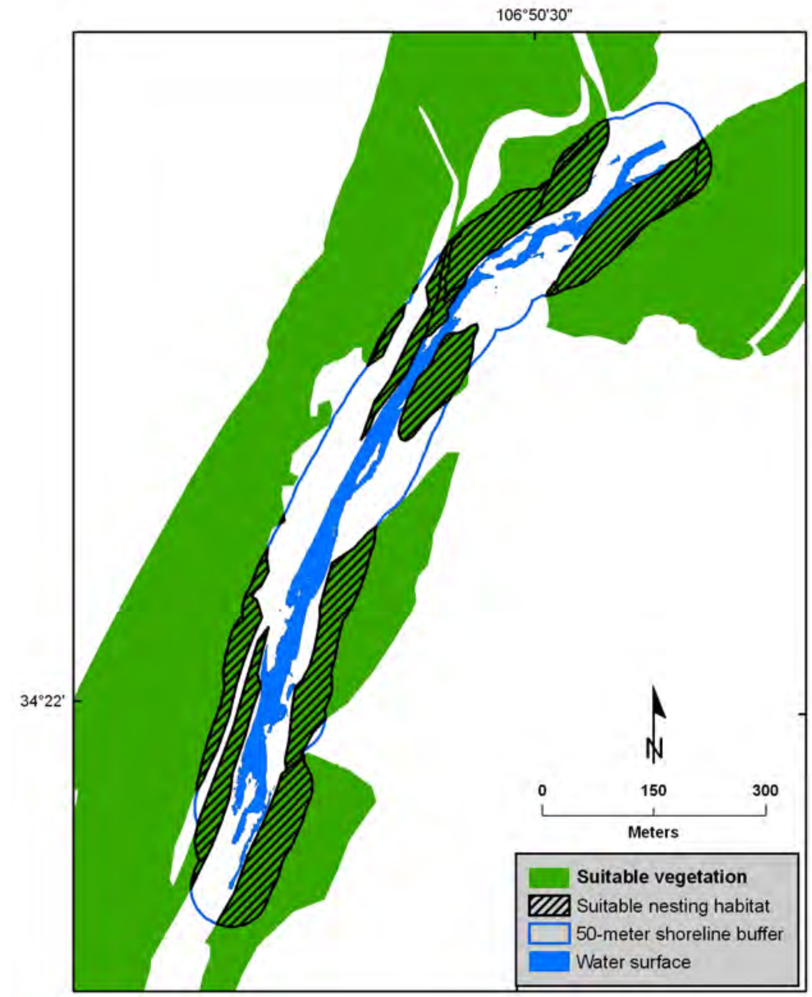

Figure 6-34. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 5 cubic feet per second.

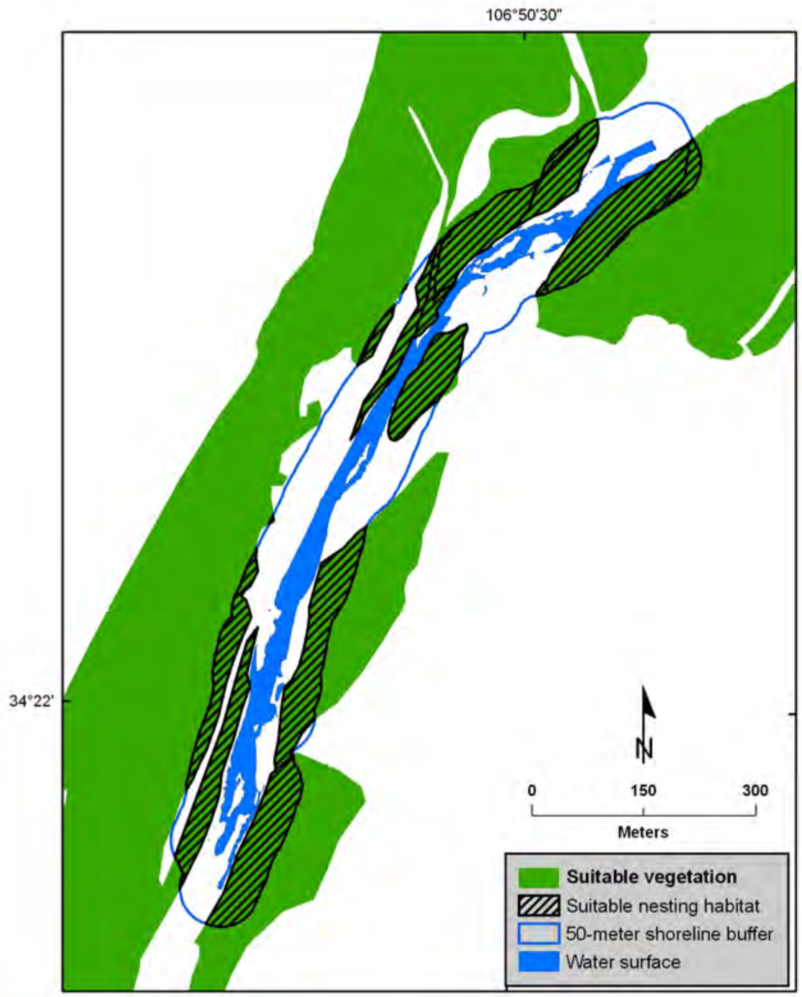

Figure 6-35. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 10 cubic feet per second.

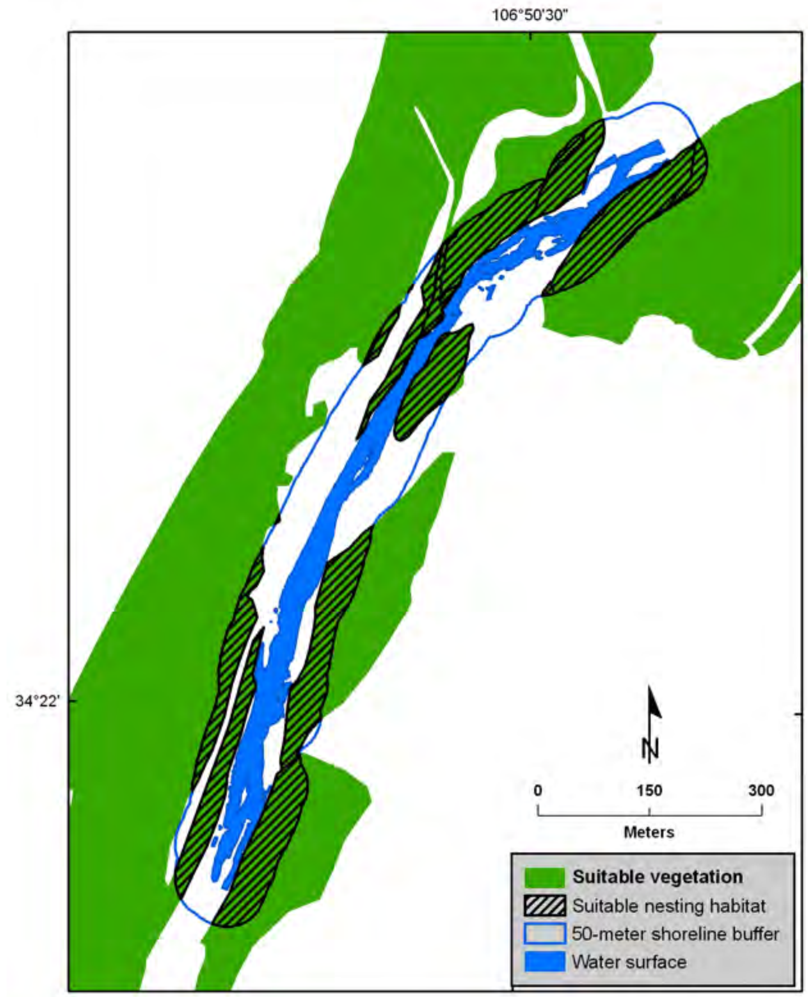

Figure 6-36. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 20 cubic feet per second.

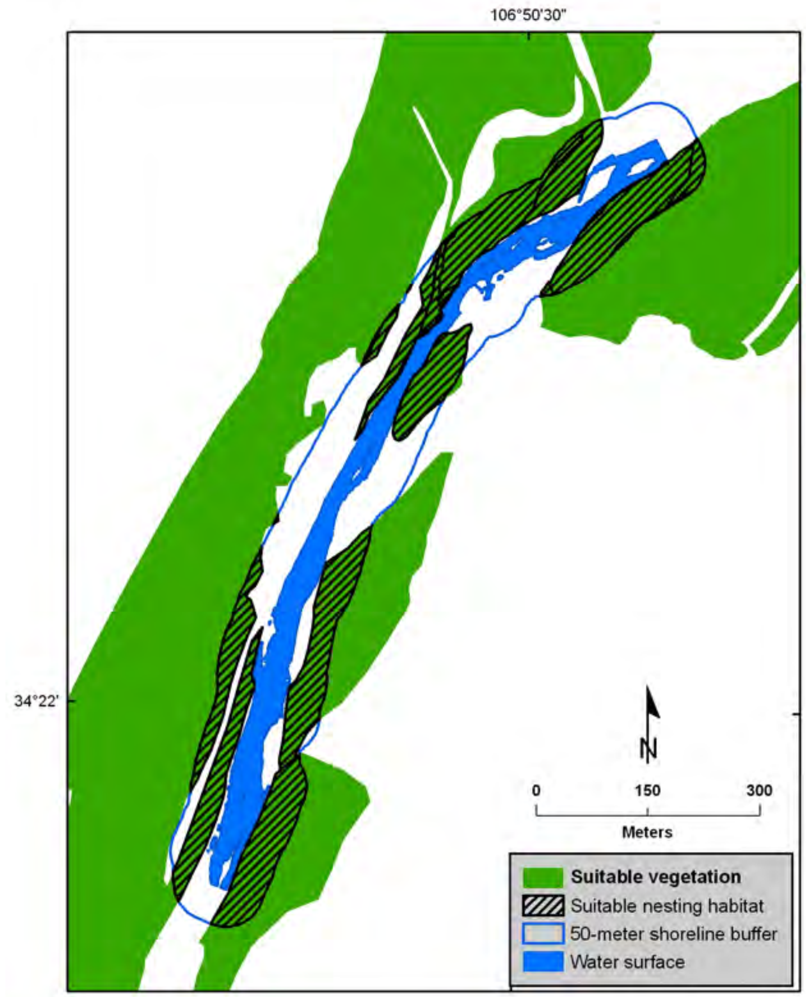

Figure 6-37. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 40 cubic feet per second.

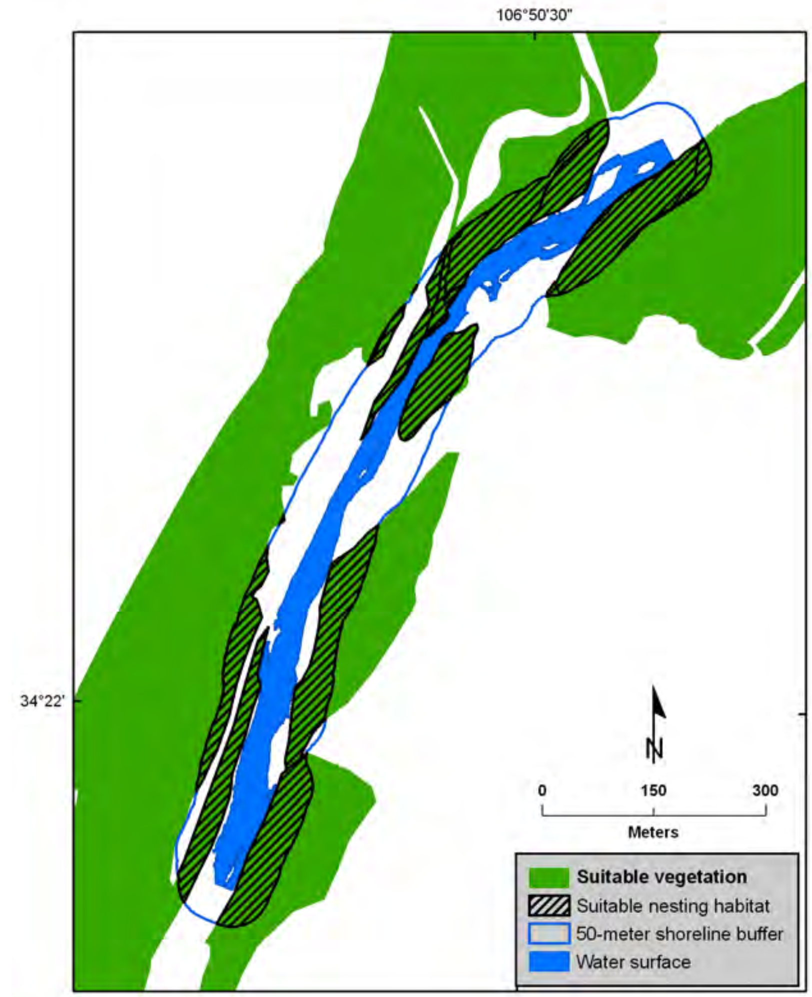

Figure 6-38. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 60 cubic feet per second.

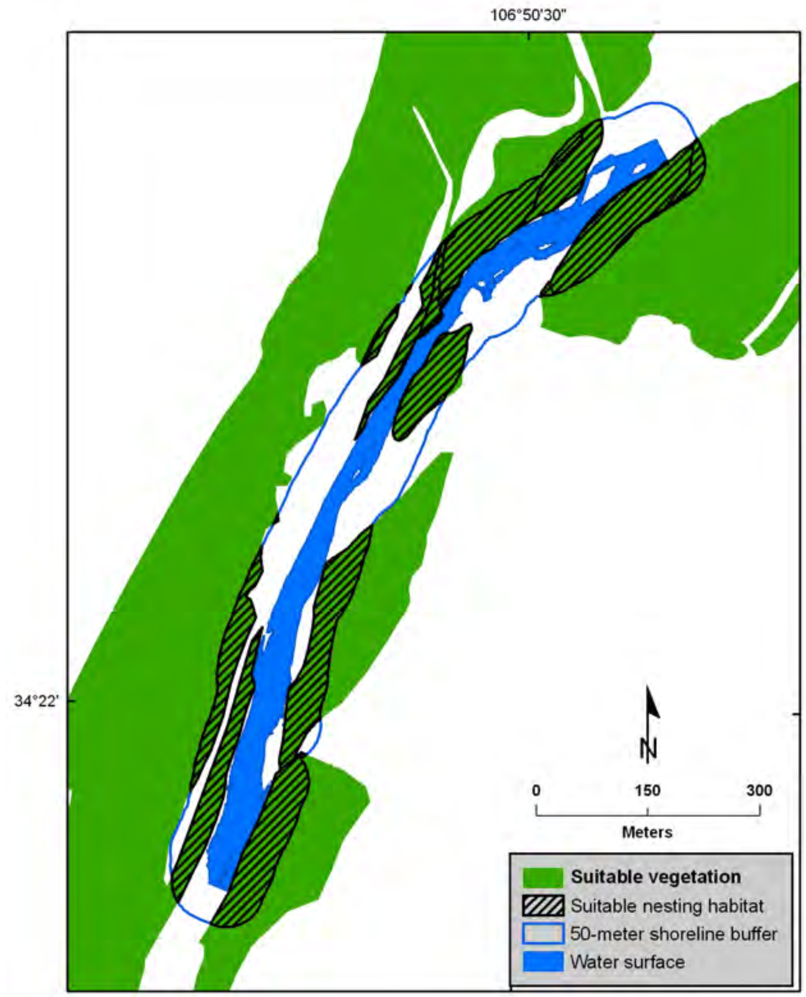

Figure 6-39. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 80 cubic feet per second.

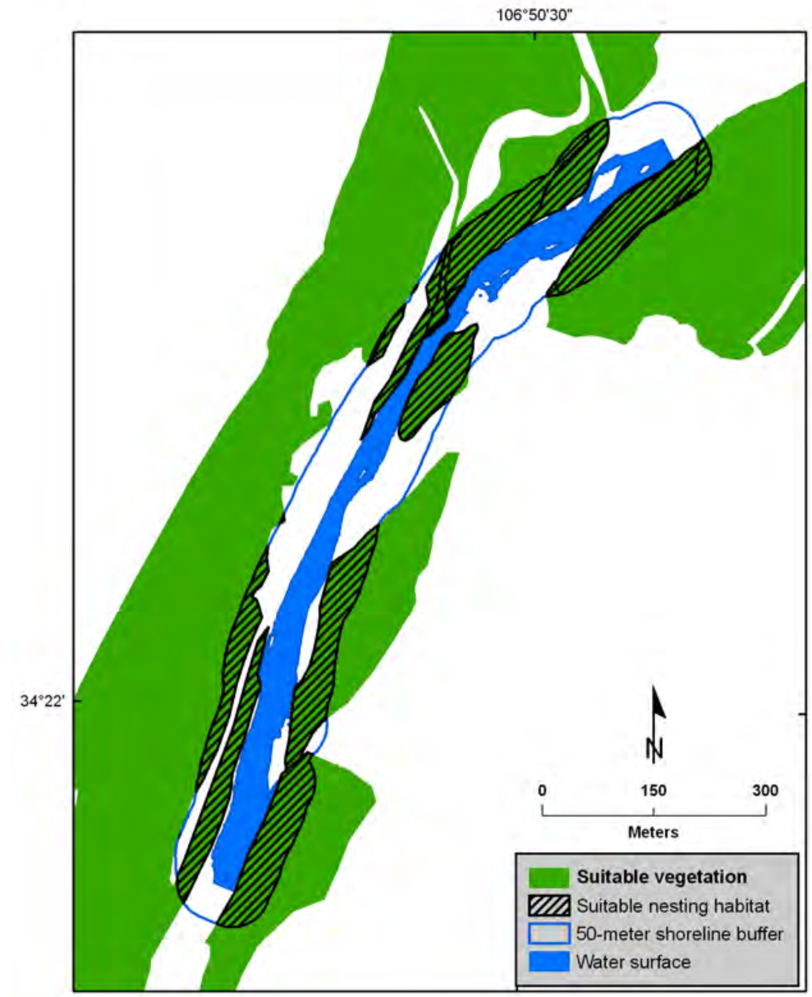

Figure 6-40. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 100 cubic feet per second.

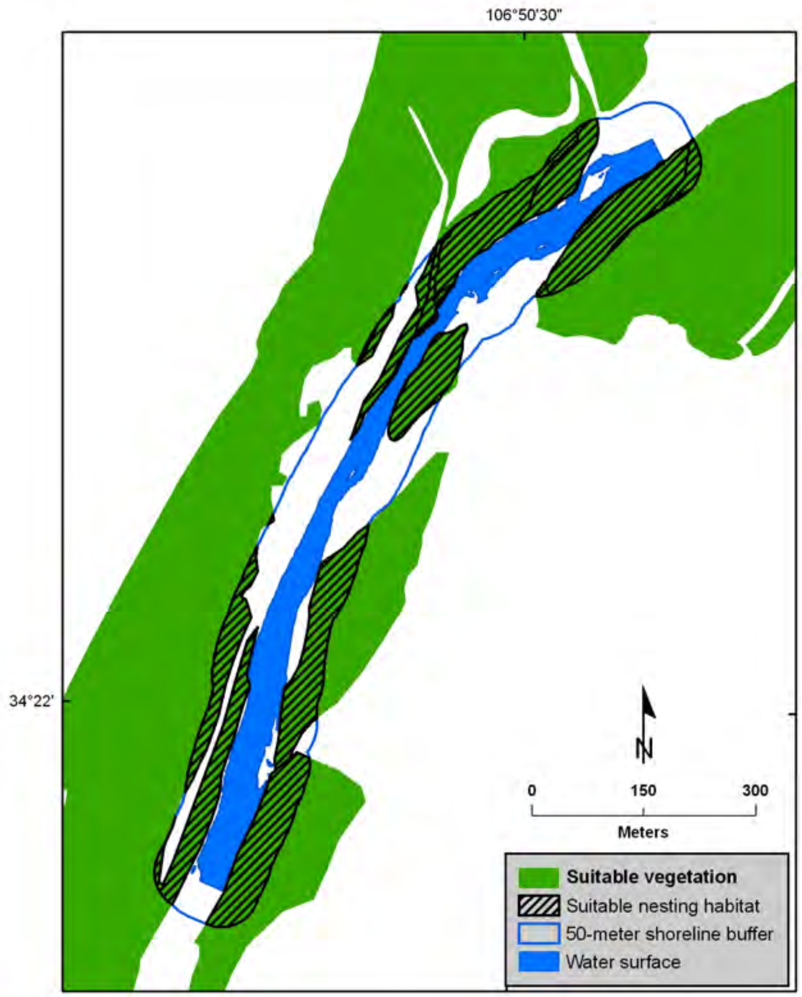

Figure 6-41. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 150 cubic feet per second.

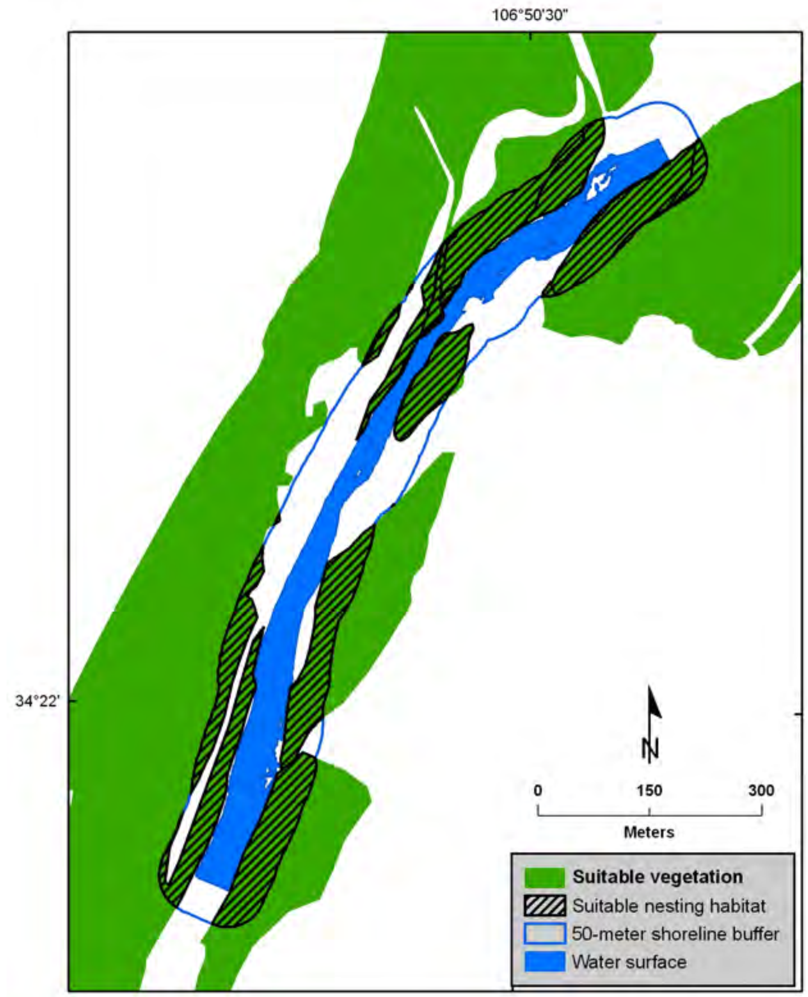

Figure 6-42. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 200 cubic feet per second.

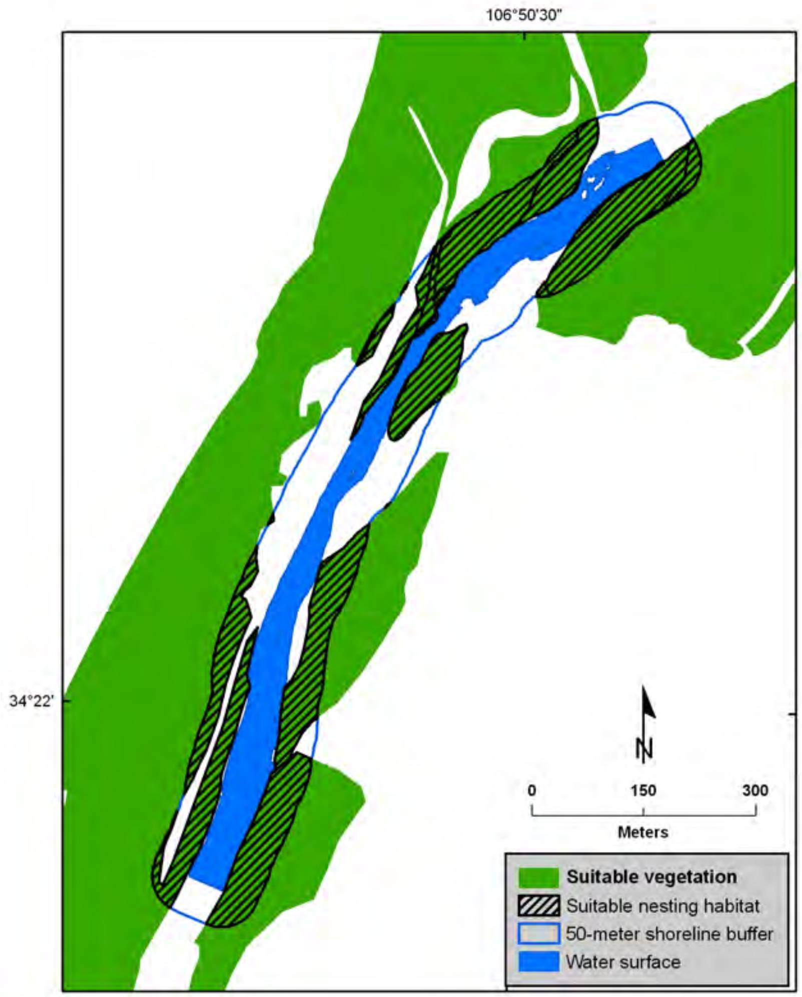

Figure 6-43. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 300 cubic feet per second.

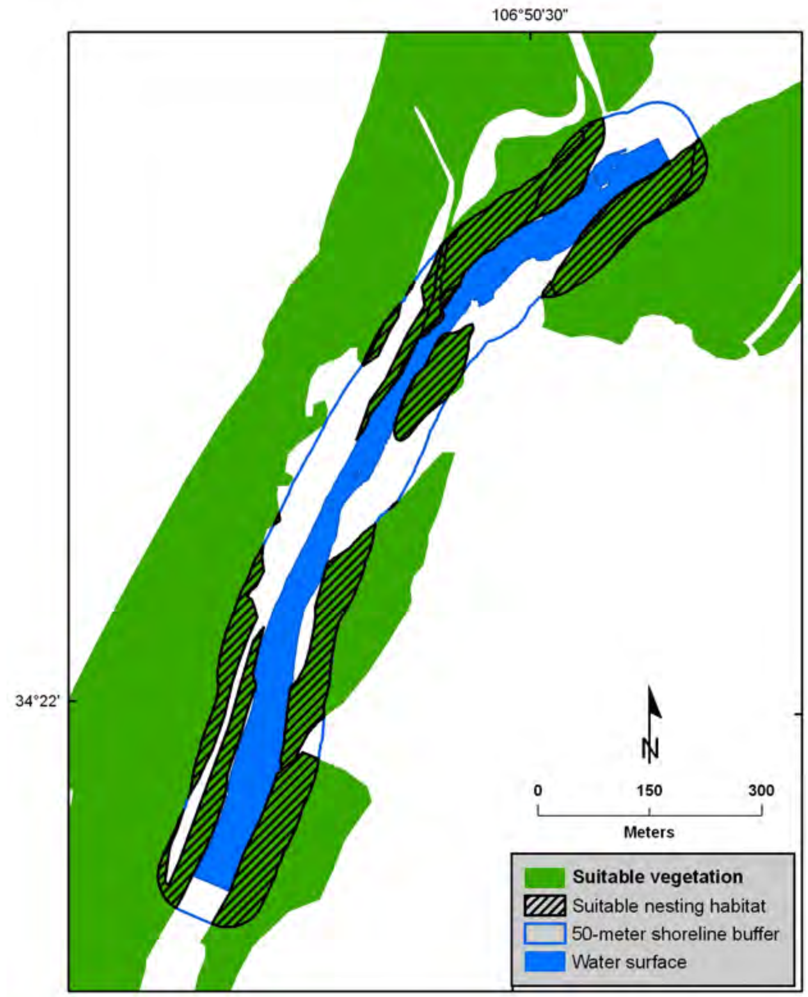

Figure 6-44. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 400 cubic feet per second.

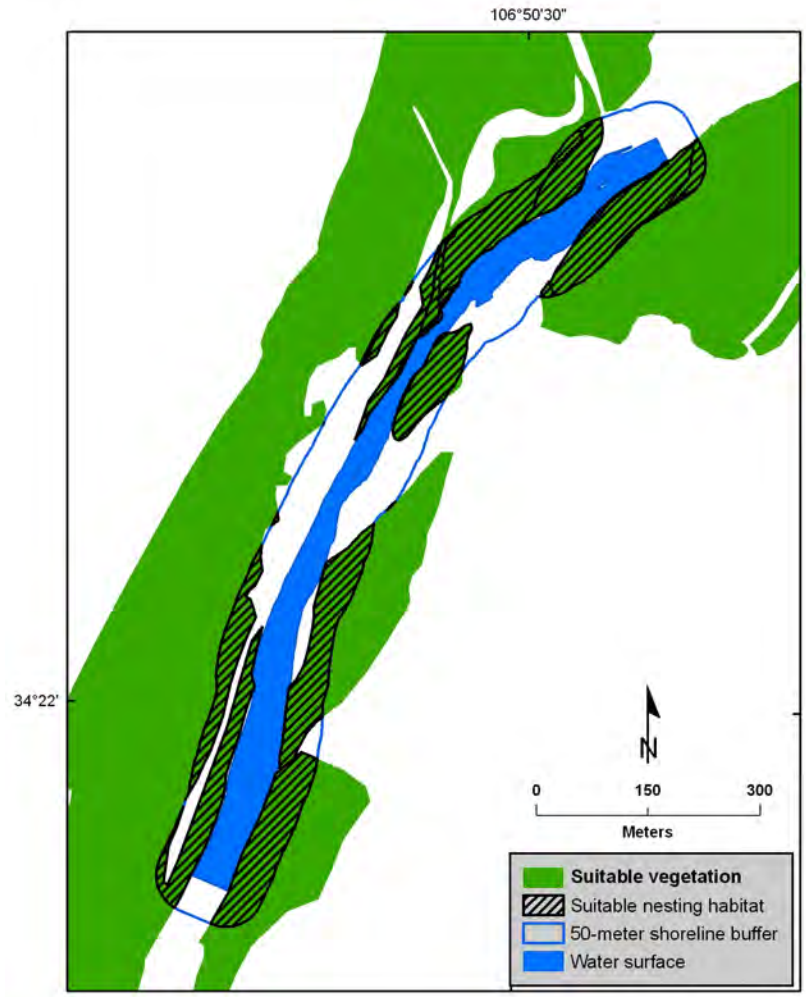

Figure 6-45. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 500 cubic feet per second.

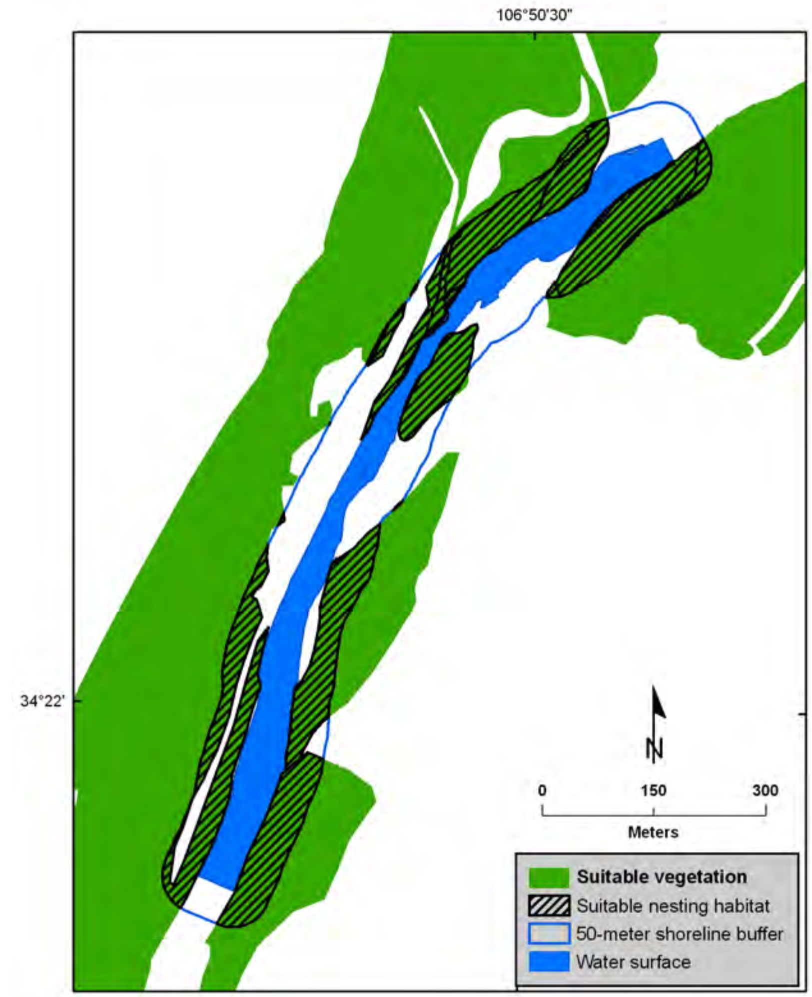

Figure 6-46. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 600 cubic feet per second.

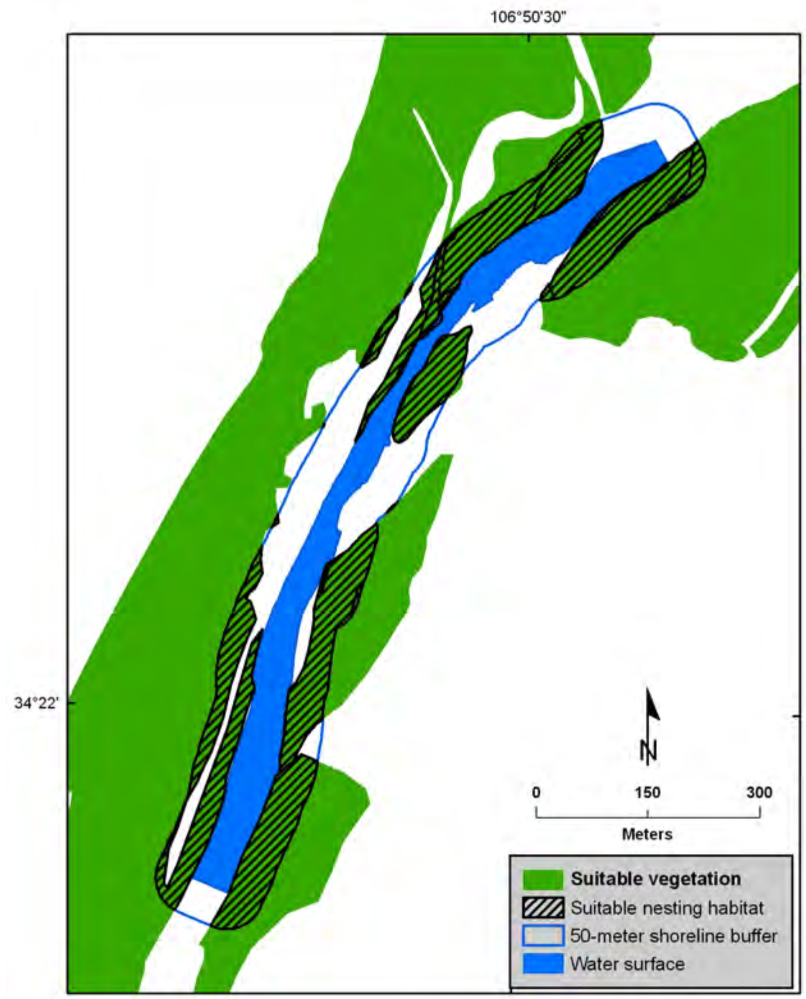

Figure 6-47. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 800 cubic feet per second.

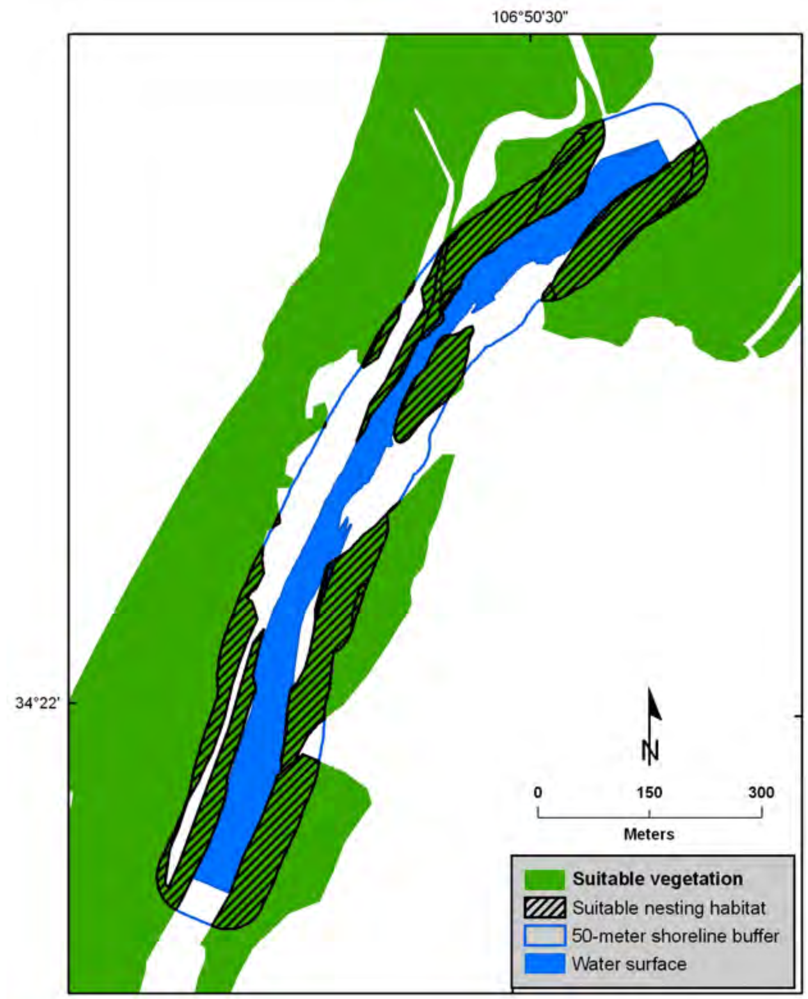

Figure 6-48. Nesting habitat for *E. t. extimus*, Rio Puerco site, at 1,000 cubic feet per second.

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