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Modelling riverine habitat for robust redhorse: assessment for reintroduction of an imperilled species

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Abstract A critical component of a species reintroduction is assessment of contemporary habitat suitability. The robust redhorse, *Moxostoma robustum* (Cope), is an imperilled catostomid that occupies a restricted range in the south-eastern USA. A remnant population persists downstream of Blewett Falls Dam, the terminal dam in the Pee Dee River, North Carolina. Reintroduction upstream of Blewett Falls Dam may promote long-term survival of this population. Tillery Dam is the next hydroelectric facility upstream, which includes a 30 rkm lotic reach. Habitat suitability indices developed in the Pee Dee River were applied to model suitable habitat for proposed minimum flows downstream of Tillery Dam. Modelling results indicate that the Tillery reach provides suitable robust redhorse habitat, with spawning habitat more abundant than non-spawning habitat. Sensitivity analyses suggested that suitable water depth and substrate were limiting physical habitat variables. These results can inform decisions on flow regulation and guide planning for reintroduction of the robust redhorse and other species.

KEYWORDS: dams, flow manipulation, habitat modification, habitat suitability, minimum flow, *Moxostoma robustum*, regulated rivers, spawning habitat.

Introduction

Habitat loss is a major threat to fishes throughout North America, which often results in range reductions and imperilment of species, many of which reside in the south-eastern USA (Ricciardi & Rasmussen 1999; Jelks *et al.* 2008). One tool to augment a species with restricted ranges is reintroduction into habitats that were formerly occupied or relocation into similar habitats (George *et al.* 2009). Guidelines have been developed to assess fundamental factors that influence success through all phases of a reintroduction (IUCN 1998; Bearlin *et al.* 2002; Seddon *et al.* 2007). An initial step in a species' reintroduction is to evaluate whether the contemporary habitat contains sufficient resources (both in quality and quantity) to support all life stages and is large enough to promote genetic diversity of a self-sustaining population (Minckley 1995; Dunham *et al.* 2011). Reintroductions and relocations can be costly, and many are unsuccessful (Griffith *et al.* 1989). Furthermore, the success of a reintroduction hinges on understanding basic life-history requirements of a species, which are often understudied and poorly understood for imperilled species (Shute *et al.* 2005).

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Catostomids are one such poorly studied group of fishes (Jenkins & Burkhead 1994; Cooke *et al.* 2005). The redhorse genus *Moxostoma* is the most diverse of the family Catostomidae with 17 described species, including several species that are imperilled and in need of conservation measures (Cooke *et al.* 2005). The robust redhorse, *Moxostoma robustum* (Cope), is such a species that occupies a restricted range in the southeastern USA. It has been negatively affected by habitat alteration and fragmentation from dams, as well as water quality degradation, sedimentation and the introduction of non-native species (Ricciardi & Rasmussen 1999; Warren *et al.* 2000; Cooke *et al.* 2005; Jennings *et al.* 2010). Currently, the only wild stocks are found in the Pee Dee River (North Carolina and South Carolina), the Savannah River (Georgia and South Carolina) and the Altamaha drainage (Georgia). The adult spawning population in the Pee Dee River contains few individuals (RRCC (Robust Redhorse Conservation Committee, Yadkin-Pee Dee Technical Working Group) 2009) and is vulnerable to catastrophic events and extirpation.

The robust redhorse is among the largest of the redhorses (R.E. Jenkins, Roanoke College, unpublished data), reaching lengths over 700 mm and 8 kg. It is a mainstem river species that exhibits potamodromous behaviour and spawns in high velocity, shallow water over gravel substrates (Breder & Rosen 1966; Grabowski & Isely 2006; Fisk 2010). After being described by Edward Cope in 1870 from a collection in the Pee Dee River basin, the species was misidentified and overlooked by the scientific community for 120 years before again being detected in Georgia, North Carolina, and South Carolina rivers in the 1980s and 1990s (Bryant *et al.* 1996). The species is currently protected by state endangered status in Georgia and North Carolina but has no official listing in South Carolina (NCWRC 2005; SCDNR 2005).

Stocking programmes were initiated in Georgia in the 1990s and in South Carolina in the first decade of the 21st century to supplement existing robust redhorse populations and to establish new populations in suspected historical reaches. Robust redhorse have been stocked in the Broad and Wateree rivers (Santee basin) in South Carolina and in the Broad (Savannah basin), Oconee, Ocmulgee and Ogeechee rivers in Georgia. Spawning sites have been identified within these systems, and spawning of stocked fish has been observed in the Ocmulgee River, but recruitment by natural reproduction of stocked fish has not been observed. Selection of stocked rivers was based on historical and recent distributions, but no quantitative habitat suitability assessment was conducted prior to stocking.

Habitat alteration and fragmentation by dams are presumed causes for robust redhorse declines in the Yadkin–Pee Dee river system (Fisk 2010). Of the eight mainstem dams, six are operated to generate electricity. These hydroelectric dams have altered flow regimes and habitat, and inhibit migration to potential spawning sites. Lotic reaches occur downstream of dams and extend to the impounded waters of the downstream reservoir, but habitat suitability for any robust redhorse life stage in these reaches has not been assessed. Currently, a small remnant population of robust redhorse exists downstream of Blewett Falls Dam where spawning and adult non-spawning habitat have been described and quantified (Fisk 2010). The Pee Dee River adult population is small, and estimates from mark–recapture studies range from 38 (95% CI 23–80) individuals in 2006 to 55 (95% CI 34–118) individuals in 2008 (RRCC (Robust Redhorse Conservation Committee, Yadkin-Pee Dee Technical Working Group) 2009). The quality and quantity of spawning habitat is also a likely factor limiting robust redhorse recruitment because hydropeaking flows can create temporarily suitable habitat that degrades when flows subside. Dewatered robust redhorse redds have been observed in the Savannah River (Grabowski & Isely 2007) and in the Pee Dee River (personal observation), resulting in mortality of robust redhorse larvae in dewatered redds (Fisk *et al.* 2013).

Management efforts for robust redhorse in the Pee Dee River have focused on instream habitat. Tillery and Blewett Falls dams are the two most downstream on the Pee Dee River located at rkm 351 and rkm 302, respectively (Fig. 1). These dams underwent operating licence renewal through the Federal Energy Regulatory Commission (FERC), which included augmented flow regimes. Augmented minimum flows for both dams were proposed in part to keep gravel bars downstream of the dams inundated throughout the year. Blewett Falls Dam is the terminal downstream dam on the river, and its augmented flows were developed to benefit spawning anadromous fish species as well as the robust redhorse. An intensive habitat assessment projected that the augmented flows would create more suitable robust redhorse habitat during spawning and non-spawning periods than previous minimum flows (Fisk 2010).

Repeated boat electric fishing surveys in the lotic portion of the reach downstream of Tillery Dam (i.e. the Tillery reach) captured no robust redhorse, and they are presumed extirpated. This reach is being considered as a reintroduction site, but it has not been assessed for suitable habitat. The current FERC licence requires a minimum flow of 1.1 $m^3 s^{-1}$ from Tillery Dam, but flow is voluntarily maintained at 2.0–2.5 $m^3 s^{-1}$ during periods of no power generation. The proposed minimum flows

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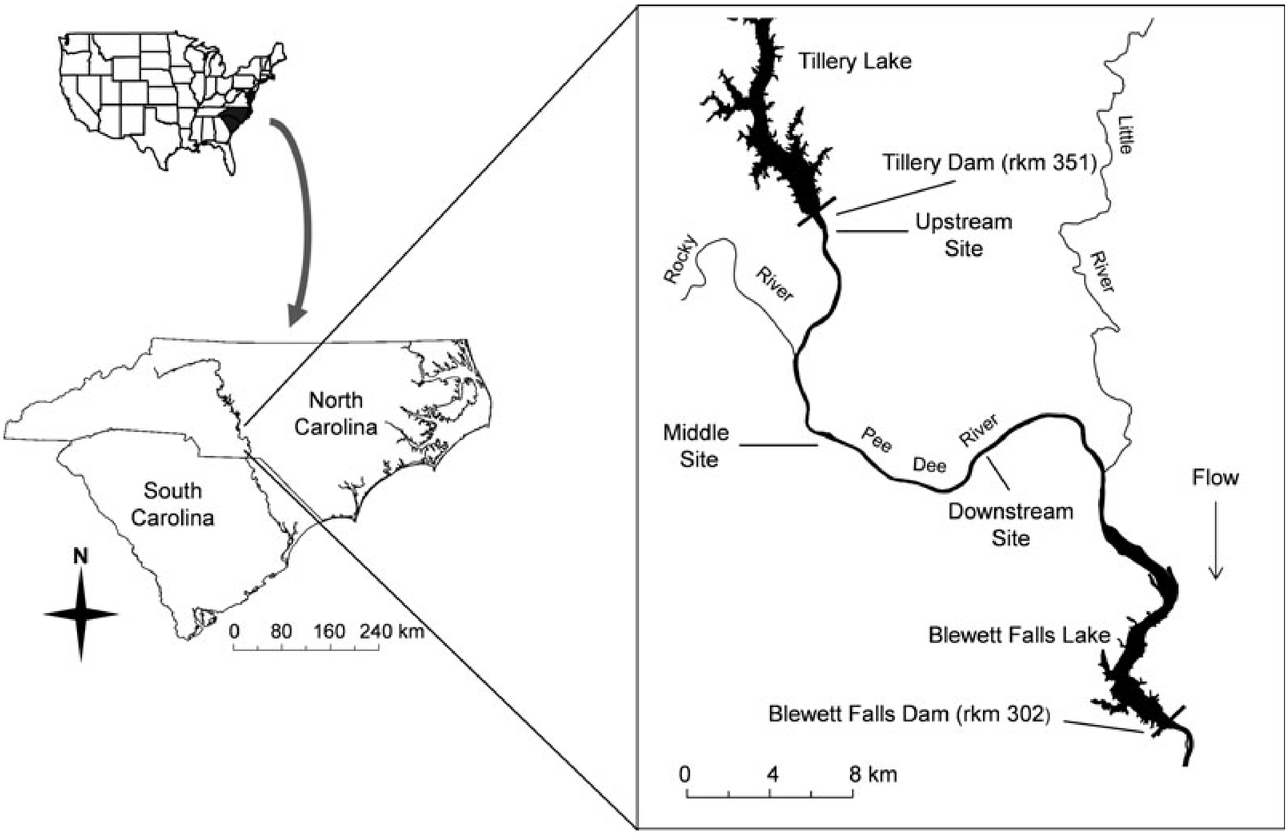

Figure 1. Study area on the Pee Dee River, North Carolina and South Carolina.

for Tillery Dam associated with relicensing are 9.3 $m^3 s^{-1}$ throughout the year, with a spawning flow of 20.5 $m^3 s^{-1}$ during April and May. These augmented flows were based on American shad, *Alosa sapidissima* (Wilson), spawning suitability indices and habitat requirements of other native fishes and are likely to enhance habitat for robust redhorse (Travnichek *et al.* 1995). Augmented flows may enhance habitat in the Tillery reach to sustain favourable robust redhorse spawning conditions and habitat during other seasons, but quantitative habitat assessment is required to ensure suitable habitat before reintroduction. Thus, suitability of habitat for robust redhorse was assessed in the Tillery reach of the Pee Dee River. The specific objectives for this study were: (1) to quantify suitable robust redhorse habitat for spawning and non-spawning adults; (2) to compare habitat under current and proposed minimum flow regimes between reaches downstream of Blewett Falls and Tillery dams; and (3) to identify specific micro-habitat variables limiting the amount of suitable habitat. This exercise on an imperilled species demonstrates the application of a modelling tool and the interpretation of the output for making an informed decision about reintroduction.

Methods

Study area

The reach from Tillery Dam downstream to Blewett Falls Dam (the terminal dam) is 49 rkm, with 30 rkm flowing (Fig. 1). The Tillery hydroelectric facility has four generating units with a total of 87 MW of power capacity (Progress Energy 2006). The dam is a peaking and load-following facility, and the discharge varies widely. During power generation, discharge varies from a mean of 221 $m^3 s^{-1}$ to a maximum of 510 $m^3 s^{-1}$. Under high flow conditions, maximum generating flows are exceeded 10% of the time at Tillery Dam and 50% of the time at Blewett Falls Dam through overflow spillways (Progress Energy 2006).

Habitat was assessed at an upstream site at the dam tailwater, a middle site and a downstream site within the 30 rkm lotic portion of the Tillery reach (Fig. 1). Sites and transect locations were selected based on hydrology and representation of available habitats throughout the Tillery reach (Progress Energy 2006). The upstream site began 1 rkm downstream of the Tillery Dam, was 3.9-rkm long, was sampled at nine transects and consisted of

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a long, shallow bedrock and gravel shoal (Fig. 1). The middle site began 10.1 rkm downstream of the dam, was 6.8-rkm long, and was sampled at 12 transects. This site consisted of side channels formed around islands that contain runs and gravel bars around Leak Island with pools upstream and downstream of the island complex. The downstream site began 20 rkm downstream of the dam and 16.5 rkm upstream of Grassy Islands, the upstream margin of Blewett Falls Lake. The downstream site was sampled at three transects and is 2-rkm long and consists of moderate-to-deep pools with some shallow glides with sand and gravel substrata. The Rocky River flows into the Pee Dee River and augments flow in the middle and downstream sites. Rocky River drains approximately 3774 km² or about 21% of the total drainage area at Blewett Falls Dam (Progress Energy 2006).

Habitat modelling

Microhabitat availability data were collected from the three study sites (Progress Energy 2006) generally following methods described by Bain and Stevenson (1999). At each site, depth, mean column velocity, substrate and cover were measured along each cross-sectional transect perpendicular to flow. Transects were selected to represent all available habitat types, and the variables were measured at 33.7 and 223.0 $m^3 s^{-1}$ to allow modelling habitat availability throughout the flow range of Tillery Dam (Progress Energy 2006). These data can be used to model suitable available habitat (as weighted usable area) for any species at each site if habitat suitability criteria are available. Weighted usable area (WUA; Bovee & Cochnauer 1977) does not quantify actual suitable habitat by area but indicates the relative suitability of available habitat.

Habitat suitability criteria derived from fish microhabitat use and availability in the field can be used to describe suitable conditions for different life stages, functions (e.g. spawning, feeding) of a single species or habitats for multiple similar species (Bovee 1986). Robust redhorse habitat suitability criteria were developed from fish captured at spawning sites, radio telemetry and cross-sectional transect surveys downstream of Blewett Falls Dam in the Pee Dee River as described by Fisk (2010). Habitat suitability was calculated for robust redhorse adult spawning sites and non-spawning periods. Spawning site suitability variable ranges were 1.0–1.5 m deep, 0.5–0.8 $m^3 s^{-1}$ mean column velocity, medium and large gravel substrates and no physical cover. Adult robust redhorse non-spawning suitability was 2.5–3.0 m deep, 0.1–0.3 $m^3 s^{-1}$ mean column velocity, sand substrate and woody debris and boulders as cover (Fisk 2010).

The quantity of suitable robust redhorse habitat for each site throughout the flow range of Tillery Dam was estimated using Riverine Habitat Simulation software (RHABSIM; Payne T.R. & Associates 1998). RHABSIM models physical stream channel hydraulics with habitat suitability criteria of aquatic organisms to quantify suitable habitat for a specific life-history period. Suitable habitat was modelled at flows of 2 $m^3 s^{-1}$, 2.5 $m^3 s^{-1}$, then from 5 $m^3 s^{-1}$ up to 500 $m^3 s^{-1}$ at 5 $m^3 s^{-1}$ increments. Suitable habitat was then quantified as WUA. Suitable habitat at the current minimum flow (2.0–2.5 $m^3 s^{-1}$) was then compared with that of the proposed spawning (20.5 $m^3 s^{-1}$) and non-spawning (9.3 $m^3 s^{-1}$) flow. The suitable habitat of the three sites in the Tillery reach was combined to facilitate comparison of WUA output to that from six sites in the Blewett Falls reach (Fisk 2010).

Sensitivity analysis

Sensitivity analyses were performed to assess which microhabitat variable (e.g. depth, velocity) or combination of variables was most limited in each study site. The spawning and non-spawning habitat suitability criteria were set to allow all values of a particular microhabitat variable range to be suitable, rather than the restricted range based on the species' suitability criteria. For example, all values of available spawning depth were set as suitable, rather than restricting depth suitability to the criterion of 1.0–1.5 m. Next, suitable habitat was modelled with this one variable unrestricted while the other variables were restricted to the suitable habitat for the species, and then this procedure was repeated for the other variables. The output in WUA from these unrestricted simulations was compared with the output restricted by the suitability criterion; if the unrestricted criterion output exhibited a substantial increase in WUA from the restricted results, then a relative limitation in suitable habitat attributed to the variable was inferred.

Results

Modelled suitable habitat

Modelled suitable habitat for robust redhorse varied widely between sites and flows and between spawning and non-spawning habitats (Table 1, Fig. 2). Weighted usable area was greater than zero for the spawning habitat for the middle site at the proposed minimum flow of 20.5 $m^3 s^{-1}$, but no suitable habitat was projected (WUA = 0) at the current minimum flow (2.0–2.5 $m^3 s^{-1}$) for spawning and non-spawning habitats for all three sites. Throughout the flow range for each site,

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Table 1. Weighted usable area (WUA) for spawning and non-spawning adult robust redhorse at flows up to 100 $m^3 s^{-1}$ for three sites downstream of the Tillery Dam in the Pee Dee River, North Carolina

	Upstream site		Middle site		Downstream site	
Flow, $m^3 s^{-1}$	Spawning	Non-spawning	Spawning	Non-spawning	Spawning	Non-spawning
2.0	0	0	0	0	0	0
2.5	0	0	0	0	0	0
5	0	0	0	0	0	0
10	**0**	**0**	**0**	**0**	**0**	**0**
15	0	0	0	0	0	0
20	**0**	**0**	**20**	**1**	**0**	**0**
30	0	0	13	12	0	0
40	0	0	33	33	0	35
50	29	0	150	43	0	51
60	73	0	210	47	41	68
70	139	0	293	42	88	44
80	366	0	273	37	124	44
90	544	0	294	48	83	21
100	942	0	257	25	118	21

Flows that approximate proposed minimum flows (9.3 $m^3 s^{-1}$ non-spawning flow and 20.5 $m^3 s^{-1}$ spawning flow) are shown in bold. Effects of flows greater than 100 $m^3 s^{-1}$ on WUA are provided in Figure 2.

WUA was considerably greater for spawning suitability than non-spawning. The upstream site contained the greatest amount of spawning WUA throughout the flow range, which was eight times greater than the middle and downstream sites (Fig. 2). Spawning WUA increased only slightly at the middle site from the proposed 9.3 $m^3 s^{-1}$ annual minimum flow to the 20.5 $m^3 s^{-1}$ spawning minimum flow. The middle and downstream sites peaked around similar values of WUA for spawning suitability (Fig. 2). All three sites exhibited similar trends of a restricted flow range where available spawning habitat peaked (i.e. narrow, steep modes). Spawning habitat was available at 50–250 $m^3 s^{-1}$ and peaked at 145 $m^3 s^{-1}$ at the upstream site. Spawning habitat peaked at 70–90 $m^3 s^{-1}$ at the middle site, and spawning WUA was greater at 50–200 $m^3 s^{-1}$. Spawning habitat peaked at the downstream site at 135 $m^3 s^{-1}$ with all WUA restricted to 50–200 $m^3 s^{-1}$.

Modelled non-spawning habitat was less than spawning habitat at each site, but the pattern varied between sites and flow rates (Fig. 2). No suitable non-spawning habitat was modelled for the upstream site throughout Tillery Dam's flow range, and minimal suitable non-spawning habitat was projected at any site at the two augmented minimum flows (Table 1). Non-spawning WUA was low but relatively stable throughout the flow range for the middle site, while the downstream site exhibited low but variable WUA with changes in flow.

Comparisons of projected robust redhorse suitable habitat between the Tillery reach (potential reintroduction site) and the Blewett Falls reach (extant population site) showed similar patterns among flow rates, with similar or greater amounts of suitable habitat in the Tillery reach (Fig. 3). Weighted usable area for the non-spawning period was similar in magnitude and variation throughout the flow ranges of the Tillery and Blewett Falls reaches, but spawning WUA was approximately three times greater in the Tillery reach.

Limiting habitat attributes

Sensitivity analysis identified water depth and substrate as the microhabitat variables limiting suitable habitat for the robust redhorse in the Tillery reach. The upstream site, which had the greatest WUA for spawning, was influenced most by the amount of gravel substrate (Fig. 4). Velocity and depth, followed by substrate, were most limited for suitable spawning habitat in the middle site, while substrate was the most limiting variable in the downstream site, followed by depth. Depth was the most limiting microhabitat variable for non-spawning suitable habitat at each site (Fig. 5). No WUA was estimated at the upstream site for any flow rate during the non-spawning period, and the sensitivity analyses indicated that this was due to lack of suitable water depth (i.e. depth was the only limiting variable in the upstream site for non-spawning habitat). Non-spawning habitat at the middle site was most limited by depth, but velocity was limiting to varying degrees throughout the flow range. Depth had the greatest non-spawning habitat effect on the downstream site at flows below 270 $m^3 s^{-1}$, while velocity was limiting at higher flows.

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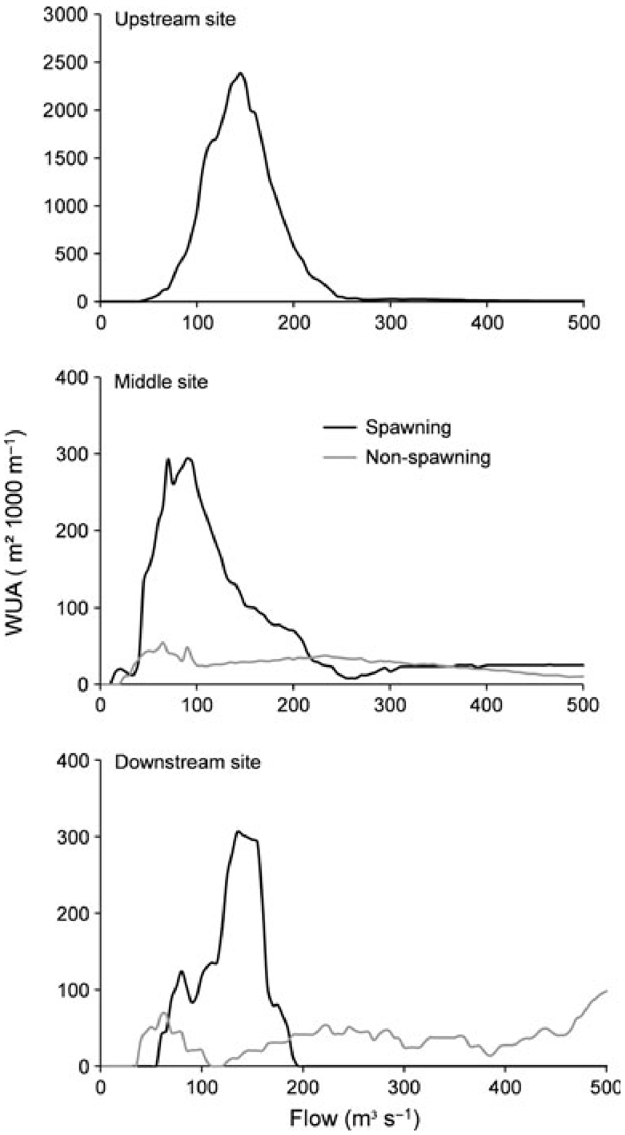

Figure 2. Weighted usable area (WUA) for robust redhorse spawning and non-spawning suitable habitat at three sites in the Tillery reach on the Pee Dee River, North Carolina. Proposed augmented minimum flows are 9.3 $m^3 s^{-1}$ (non-spawning period) and 20.5 $m^3 s^{-1}$ (spawning period). Note that *y*-axis scales differ among plots.

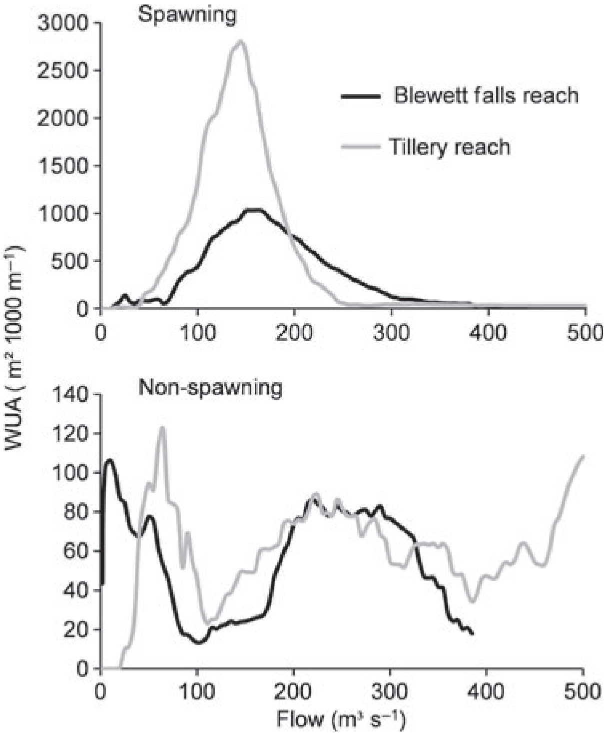

Figure 3. Weighted usable area (WUA) in Tillery and Blewett Falls reaches on the Pee Dee River, North Carolina and South Carolina, for spawning and non-spawning suitable habitat. Note that *y*-axis scales between plots.

Discussion

Habitat assessment of any potential translocation, reintroduction or augmentation site is a critical step in imperilled species conservation but is often overlooked (IUCN 1998; George *et al.* 2009). This modelling exercise is the first quantitative assessment to evaluate the feasibility of reintroducing robust redhorse into a river reach within its historical distribution. Suitable robust redhorse spawning and adult habitats were present in varying quantities throughout the flow range of Tillery Dam, but suitable spawning habitat was more abundant than adult non-spawning habitat in this reach. Reach comparisons revealed that suitable spawning habitat in the Tillery reach reintroduction site was proportionally more abundant than the spawning habitat of an extant population downstream of Blewett Falls Dam, whereas adult non-spawning habitat was similar between reaches. Sensitivity analyses identified water depth and substrate composition as more limiting variables for adult spawning and non-spawning robust redhorse.

Access to suitable habitat to satisfy all ontogenic stages, and seasonal behaviours are necessary for a species to thrive. There was little increase in suitable habitat for adult robust redhorse in the Tillery reach from the current minimum flow of 2.0–2.5 $m^3 s^{-1}$ and the proposed augmented flows of 9.3 $m^3 s^{-1}$ for the non-spawning habitat and 20.5 $m^3 s^{-1}$ for the spawning habitat. These flow rates are common and occur on a daily basis in the Tillery reach, but the augmented flows will ensure higher minima. Robust redhorse have been observed spawning at greater flows downstream of Blewett Falls Dam (approximately 140–200 $m^3 s^{-1}$) but have not been observed occupying spawning habitat unless flows of this magnitude are present (Fisk 2010). Modelled spawning

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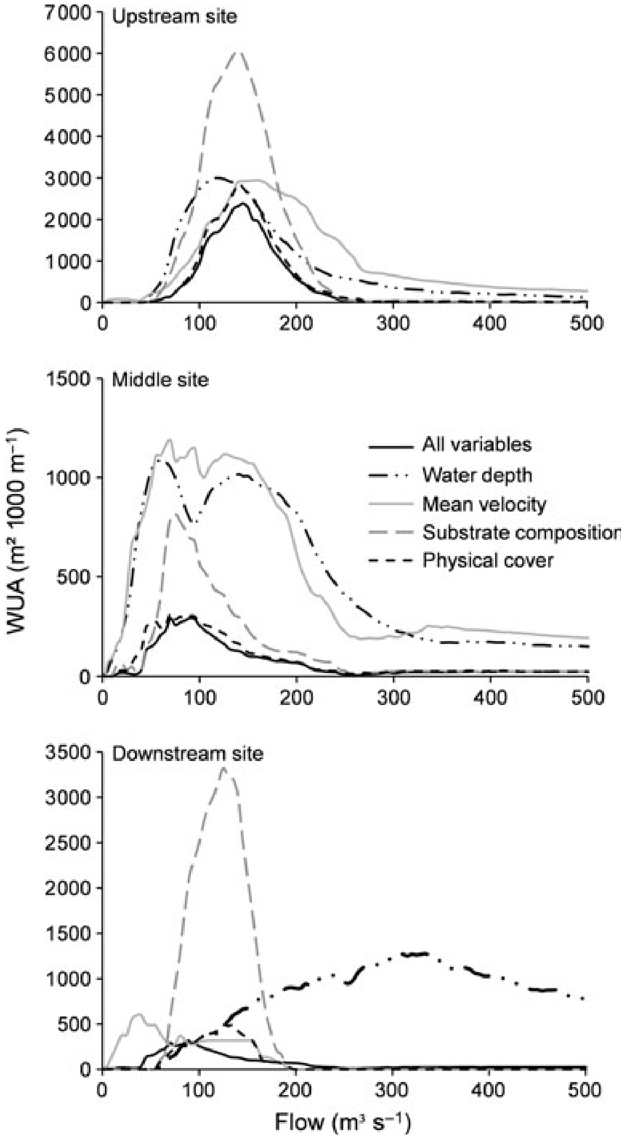

Figure 4. Sensitivity analysis for physical habitat variables affecting the amount of robust redhorse spawning habitat at three sites in the Tillery reach on the Pee Dee River, North Carolina. The line for all variables depicts a simulation with all variables restricted to their suitable ranges for robust redhorse. Other lines depict simulations with the specific variables unrestricted (i.e. all values encountered in the river were considered suitable). Simulations for variables with relatively high weighted usable area (WUA) compared with original modelling output indicate limiting variables. Note that *y*-axis scales differ among plots.

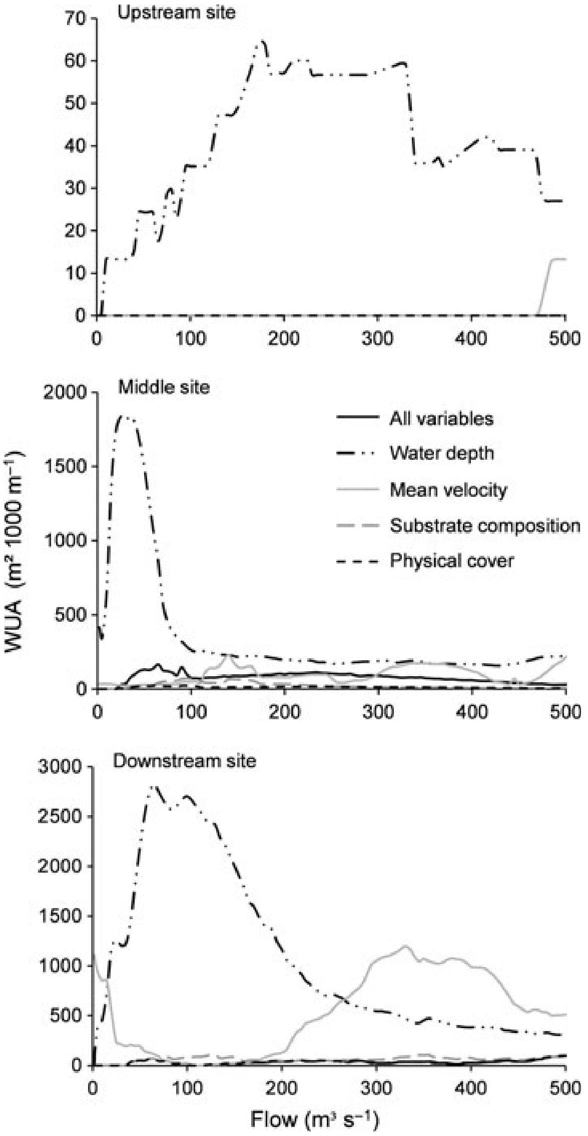

Figure 5. Sensitivity analysis for physical habitat variables affecting the amount of robust redhorse non-spawning habitat at three sites in the Tillery reach on the Pee Dee River, North Carolina. The line for all variables depicts a simulation with all variables restricted to their suitable ranges for robust redhorse. Other lines depict simulations with the specific variable unrestricted (i.e. all values encountered in the river were considered suitable). Simulations for variables with relatively high weighted usable area (WUA) compared with original modelling output indicate limiting variables. Note that *y*-axis scales vary among plots. [Correction added on 23 September 2013, after first online publication: Figure 5 was identical to Figure 4 in error previously. The correct figure is now in place.]

suitability in the Tillery reach is greatest at flows similar (between 100 and 200 $m^3 s^{-1}$) to those observed in the field (Fisk 2010). Robust redhorse is not likely to spawn at the proposed minimum flows for the Tillery reach, but these flows may still perform a critical function because such flow rates inundate gravel bars that were observed to be partially dewatered at the current minimum flow of 2.0–2.5 $m^3 s^{-1}$ (personal observation).

Redd dewatering has been observed in the Blewett Falls reach and in the Savannah River at known spawning areas for robust redhorse and has been found to be lethal to larvae in laboratory settings (Grabowski & Isely 2007; Fisk *et al.* 2013). Furthermore, the proposed minimum

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flows may keep fish closer to spawning shoals for longer durations, which may give robust redhorse more opportunities to spawn when optimal flows are present (Fisk 2010).

A single river reach rarely contains all habitats necessary for fish survival, growth and reproduction; but occurrence of and access to habitats for all ecological functions are critical (Northcote 1984; McDowall 1987). Spawning habitat was plentiful immediately downstream of the Tillery Dam. Non-spawning habitat was not available below Tillery Dam but occurred farther downstream. Each site in the Tillery reach had shortcomings as adult spawning or non-spawning habitats; but, in its entirety, the reach provided suitable habitat for reintroduction.

Robust redhorse have large home ranges, sometimes spanning over 100 rkm, that include a spawning migration within a river system (Grabowski & Isely 2006; Fisk 2010). Their potamodromous behaviour may be beneficial because they can seek specific habitats over long distances, which is evident from the high site fidelity observed in telemetered populations (Grabowski & Isely 2006; Grabowski & Jennings 2009; Fisk 2010). Enhancement of spawning habitat through flow augmentation will provide access to all critical habitats for the species within the confines of the Tillery reach, but that will remain untested until fish are reintroduced.

The greater WUA of spawning habitat in the Tillery reach than the Blewett Falls reach suggests that this life-history requirement may be met for a reintroduced population. Known robust redhorse spawning sites in the Pee Dee River and in other rivers are limited to small, isolated gravel bars (Grabowski & Isely 2006; Fisk 2010). Robust redhorse spawn over a few specific small gravel bars downstream of Blewett Falls Dam (Fisk 2010). The greater area of suitable spawning habitat in the Tillery reach grants a higher likelihood that this specific habitat requirement may be met. Spawning habitat enhancement (i.e. via flow augmentation) has been shown to increase fry survival in other fish species (Merz *et al.* 2004), and increases in minimum flows can result in positive effects on fish assemblages (Travnichek *et al.* 1995). Newly hatched larval robust redhorse stay in gravel up to 10 days before emerging, which emphasises the importance of higher minimum flows to reduce redd dewatering (Weyers *et al.* 2003; Fisk *et al.* 2013).

Sensitivity analyses provided insight into limiting attributes of habitats throughout the flow range of the Tillery reach. Water depth was the primary limiting microhabitat variable during the non-spawning period. Suitable non-spawning depth (2.5–3.0 m) is limited in the three study sites, but deeper habitats may be available in the Tillery reach and downstream in Blewett Falls Lake. Stocked robust redhorse occupied impounded water in Clarks Hill Reservoir in the Savannah River, Georgia (Freeman *et al.* 2002; Dennerline *et al.* 2010), and other redhorse species occupy lentic waters during non-spawning periods (Etnier & Starnes 1993; Jenkins & Burkhead 1994). Non-spawning habitat is described as more widely available and general and occurs downstream of the study reach in the Pee Dee River, while spawning habitat is more specified and has been identified as the major limiting factor for the species (Grabowski & Isely 2006, 2007; Fisk 2010).

Life-history bottlenecks usually occur in spawning, egg incubation and larval stages (Orth 1987; Stalnaker *et al.* 1995). Since the rediscovery of the robust redhorse, availability of habitat for spawning and early life stages have been assumed to limit the occurrence and abundance of the species (Cope 1870; Cooke *et al.* 2005). This study has shown that spawning habitat may not be limiting if dam discharge is sufficient to provide needed depth in the Pee Dee River below Tillery Dam. As newly hatched larvae remain in redds for approximately 10 days (Weyers *et al.* 2003; Fisk *et al.* 2013), the relationships between spawning and depth also apply to this early life stage. However, bottlenecks can occur at any life stage. Gathering data on other life stages between larval and adult has been difficult throughout its range because of the species' cryptic nature and inability of investigators to capture juveniles. Hence, large gaps in knowledge of the early and subadult life stages of robust redhorse remain unfilled. For example, it is unclear what nursery habitats are occupied by post-larval juveniles. Innovative sampling methods are needed to identify habitat criteria for subadult life stages. However, once critical habitat conditions have been established, methods used in this study can be implemented to assess the amount of suitable habitat.

This habitat modelling assessment addresses instream physical habitat requirements for robust redhorse at a potential reintroduction site, but other habitat components may be critical to reintroduction success. Directly applicable to robust redhorse is the finding by Hinck *et al.* (2009) that largemouth bass, *Micropterus salmoides* (Lacepède) in the Pee Dee River downstream of Blewett Falls Dam had the highest percentage of intersex condition (67–91%) among 111 riverine sites in the USA. The intersex condition is attributed to exposure to endocrine-disrupting compounds in the river and is linked to fish reproductive impairment and increased susceptibility to infection that may result in fish population declines (Nash *et al.* 2004; Blazer *et al.* 2010). The impact of traditional and emerging contaminants on the robust redhorse in the Pee Dee River is unclear but certainly is an important consideration in population restoration and reintroduction.

Sympatric, non-native species may also affect robust redhorse survival. Eleven non-native species have been collected in the Tillery and Blewett Falls reaches, and they dominate the fish biomass within this reach (Progress Energy 2006). The smallmouth buffalo, *Ictiobus bubalus* (Rafinesque), common carp, *Cyprinus carpio* Linnaeus, blue catfish, *Ictalurus furcatus* (Lesueur), and flathead catfish, *Pylodictis olivaris* (Rafinesque), are among the most abundant in these reaches and have the greatest potential to negatively affect robust redhorse. While the effects of non-native fishes on robust redhorse are presumed, they have not been studied and are only conceptually understood but remain an important factor related to species reintroduction. Other reintroduction efforts have been hindered by such non-native species interactions (Al-Chokhachy *et al.* 2009). Stocked fingerling razorback suckers, *Xyrauchen texanus* (Abbott) have been negatively affected by introduced flathead catfish and channel catfish, *Ictalurus punctatus* (Rafinesque) (Marsh & Brooks 1989), and introduced ictalurid catfish are known to alter riverine fish assemblages and food webs (Pine *et al.* 2007; Kwak *et al.* 2011). Although robust redhorse persist in the presence of these non-native species in the Pee Dee River, this population is considered imperilled (RRCC 2009) and their impact on the robust redhorse remains unknown.

Implications for reintroduction

Survival of an imperilled species often hinges on identifying suitable habitat and understanding how to conserve this habitat (Rosenberger & Angermeier 2003; Hewitt *et al.* 2009). Habitat assessment is a tool applied in this study to identify suitable habitat for species reintroduction. Habitat comparisons to sites with an extant population are especially informative. In particular, determining specific limiting habitat variables can be relevant to guide potential habitat modification before reintroduction. Applying techniques similar to the sensitivity analysis in this assessment facilitates identification of habitats that are marginally suitable or feasible for modification to benefit a target species (e.g. regulated river flow or gravel augmentation).

Under ideal circumstances, habitat suitability is best described under natural conditions. The Yadkin–Pee Dee River system has not experienced these conditions since the early 1900s, when the first dams were constructed, blocking access to and dramatically altering lotic habitats (NCWRC 2005). Robust redhorse spawning habitats have been identified downstream of Blewett Falls Dam, where suitability indices were developed (Fisk 2010), but these sites may represent the best habitat available in that area rather than the most suitable spawning habitat for the species. Stocking results in other rivers and telemetry findings in the Pee Dee River suggest this species may be more adapted to piedmont riverine habitat with higher gradient and coarse substrate material (B. J. Freeman, University of Georgia, personal communication; Fisk 2010) relative to coastal plain habitat. Robust redhorse historically used the Tillery reach and other upstream habitat at least for migratory purposes, as the holotype for the species (Cope 1870) was collected over 100 rkm upstream of this reach, but the remnant population is restricted downstream of Blewett Falls Dam. Eight mainstem impoundments exist in the Yadkin–Pee Dee River with varying lengths of lotic habitat in between dams. If an initial reintroduction is successful in the Tillery reach, then similar efforts could re-establish this species into other appropriate upstream reaches.

Establishing upstream populations of robust redhorse in the Yadkin–Pee Dee river system would benefit this imperilled species by expanding its range, protecting genetic diversity and acting as a buffer to catastrophic events. Habitat effects of flows on stream fish are considered ecologically important, but flow modification comprises a small percentage of instream habitat restoration studies; and, of these, salmonids are typically the species of concern (Roni *et al.* 2008). This initial assessment to quantify habitat suitability and understand how flow affects habitat availability provides valuable insight for managers in the restoration of this imperilled fish and can be applied to introduction or reintroduction of other imperilled species. Greater insights, however, will result from validation of the predictions after reintroduction.

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