Environmental Management (2014) 54:465–478
DOI 10.1007/s00267-014-0318-7

Effects of Flooding and Tamarisk Removal on Habitat for Sensitive Fish Species in the San Rafael River, Utah: Implications for Fish Habitat Enhancement and Future Restoration Efforts

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Received: 20 November 2013 / Accepted: 16 June 2014 / Published online: 4 July 2014
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Abstract Tamarisk removal is a widespread restoration practice on rivers in the southwestern USA, but impacts of removal on fish habitat have rarely been investigated. We examined whether tamarisk removal, in combination with a large spring flood, had the potential to improve fish habitat on the San Rafael River in southeastern Utah. We quantified habitat complexity and the distribution of wood accumulation in a tamarisk removal site (treated) and a non-removal site (untreated) in 2010, 1 year prior to a large magnitude and long-duration spring flood. We used aerial imagery to analyze river changes in the treated and untreated sites. Areas of channel movement were significantly larger in the treated site compared to the untreated site, primarily because of geomorphic characteristics of the channel, including higher sinuosity and the presence of an ephemeral tributary. However, results suggest that tamarisk removal on the outside of meander bends, where it grows directly on the channel margins, can promote increased channel movement. Prior to the flood, wood accumulations were concentrated in sections of channel where tamarisk had been removed. Pools, riffles, and backwaters occurred more frequently within 30 m upstream and downstream of wood accumulations compared to areas within 30 m of random points. Pools associated with wood accumulations were also significantly larger and deeper than those associated with random points. These results suggest that the combination of tamarisk removal and wood input can increase the potential for channel movement during spring floods thereby diversifying river habitat and improving conditions for native fish.

Keywords Beaver · Channel change · Habitat complexity · Native fish · Tamarisk removal · Wood accumulation

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Introduction

The native and endemic fish fauna of desert rivers in the USA is highly imperiled due to a suite of factors including flow alteration by dams, habitat degradation and loss, and introduced fish species (Minckley and Deacon 1968; Williams 1981; Olden and Poff 2005). Well over 100 species of desert fish in North America are considered endangered, threatened, or of special concern (Deacon et al. 1979; Williams et al. 1985). Of the 14 fish native to the upper Colorado River Basin, four are endangered and many others are listed on state sensitive species lists (UDWR 2006; Dauwalter et al. 2011). Many fishes of rivers in the southwestern USA exist in highly fragmented populations and have life-history strategies that are poorly adapted to the modified habitat and flow regimes of many rivers in the region (Fagan et al. 2002; Olden et al. 2006).

One of the major modifications to southwestern rivers and drivers of native fish decline has been habitat loss and degradation through the construction of dams and diversions, which have altered natural hydrologic and sediment regimes (Stanford 1994; Bunn and Arthington 2002). The

reduction in the magnitude and duration of peak flow events, and consequent channel narrowing and loss of habitat complexity, is a pattern that has occurred on many rivers in the region, including the Green (Graf 1978; Allred and Schmidt 1999; Birken and Cooper 2006), upper Colorado (Van Steeter and Pitlick 1998), Rio Grande (Everitt 1998; Dean and Schmidt 2011), Escalante (Birkeland 2002), and Rio Puerco (Friedman et al. 2005b).

The colonization and stabilization of channel bars in river channels by tamarisk (*Tamarix* spp.) have contributed to channel narrowing along many southwestern rivers (Birkeland 2002; Birken and Cooper 2006; Dean and Schmidt 2011). Tamarisk is a non-native riparian shrub that has colonized extensively along river corridors in the southwest (Friedman et al. 2005a). Tamarisk develops extensive root systems and has been shown to substantially increase the resistance of sediment to erosion (Di Tomaso 1998; Pollen-Bankhead et al. 2009). In addition, dense tamarisk stands increase channel roughness, which in turn slows water velocity during a flood and promotes increased deposition and floodplain accumulation (Graf 1978; Griffin and Smith 2004; Birken and Cooper 2006). Thus, tamarisk can increase channel narrowing and loss of habitat complexity by stabilizing active channel bars, promoting sediment deposition, and preventing bank erosion and widening of channels during flood events.

In response to river channel alteration and decline of native fish communities, substantial investment has been made in the southwestern USA to restore degraded rivers and associated riparian zones (Follstad Shah et al. 2007). Tamarisk control and removal is one of the most common restoration activities in the region, with millions of dollars spent on such efforts each year (Hart 2003). Although there has been a large effort aimed at understanding how tamarisk removal efforts are likely to impact evapotranspiration rates, water yield, and riparian habitat conditions [see reviews by Glenn and Nagler (2005) and Shafroth et al. (2005)], few published studies have examined whether tamarisk removal is a viable strategy for restoring instream habitat conditions important for native fish (but, see Kennedy et al. 2005). Tamarisk removal is a costly endeavor; therefore, the ability to better understand whether or not it can improve conditions for native fish is critical to future management decisions on rivers throughout the southwestern USA.

In this paper, we aim to address this knowledge gap by examining whether and how a tamarisk removal project on the San Rafael River in southeastern Utah has affected fish habitat conditions. Similar to the pattern seen on other rivers in the southwestern US, the San Rafael River has experienced significant channel changes over the last century. Historically, the San Rafael River was multi-threaded, laterally unstable, and had a high width-to-depth ratio (Fortney 2014). A combination of altered hydrology, primarily reduction in magnitude and duration of snowmelt floods, and tamarisk colonization has led to narrowing and confinement of the river into a single-thread channel with steep banks; a low width-to-depth ratio; and a loss of complex habitat including pools, riffles, and backwaters (Fortney et al. 2011).

Previous work has shown that removal of tamarisk can lower river bank stability and allow greater erosion and channel widening during flood events (Vincent et al. 2009). Thus, tamarisk removal in combination with large flood events could potentially slow or reverse the channel narrowing and loss of habitat complexity associated with tamarisk colonization. In addition, tamarisk control and removal efforts often involve either killing plants through herbicide burn treatments, cutting plants and applying herbicide, or removing whole plants and piling and burning them in the riparian zone (e.g., Duncan 2003; McDaniel and Taylor 2003; Harms and Hiebert 2006). Biological control of tamarisk through release of the tamarisk leaf beetle (*Diorhabda* spp.) has also been widely applied (Hultine et al. 2010). If dead and cut plants were not burned or removed, it is possible that during high flow events, this woody material could be washed into the channel, collect in large accumulations, and create important habitat features for native fish (Lisle 1981; Abbe and Montgomery 1996; Buffington et al. 2002).

We took advantage of a unique opportunity to study channel response to the combination of tamarisk removal and a large magnitude spring flow that occurred just 3 years after initiation of a tamarisk removal project on the San Rafael River. The occurrence of this flow event within a few years of completion of tamarisk removal is a relatively rare occurrence (e.g., Vincent et al. 2009). Furthermore, areas of untreated tamarisk stands were intermixed along the river corridor with tamarisk removal areas, such that the flood event provided an ideal natural experiment for investigating the impacts of tamarisk removal on channel changes and fish habitat. We explored the potential for tamarisk removal to improve fish habitat through promotion of channel change during flood events and provision of wood accumulations by asking three research questions:

1. Was there greater channel change associated with a large flood event within a tamarisk removal area (treated) compared to a site outside the tamarisk removal area (untreated)?
2. Is habitat complexity greater in areas associated with wood accumulations compared to randomly selected locations along the San Rafael River?

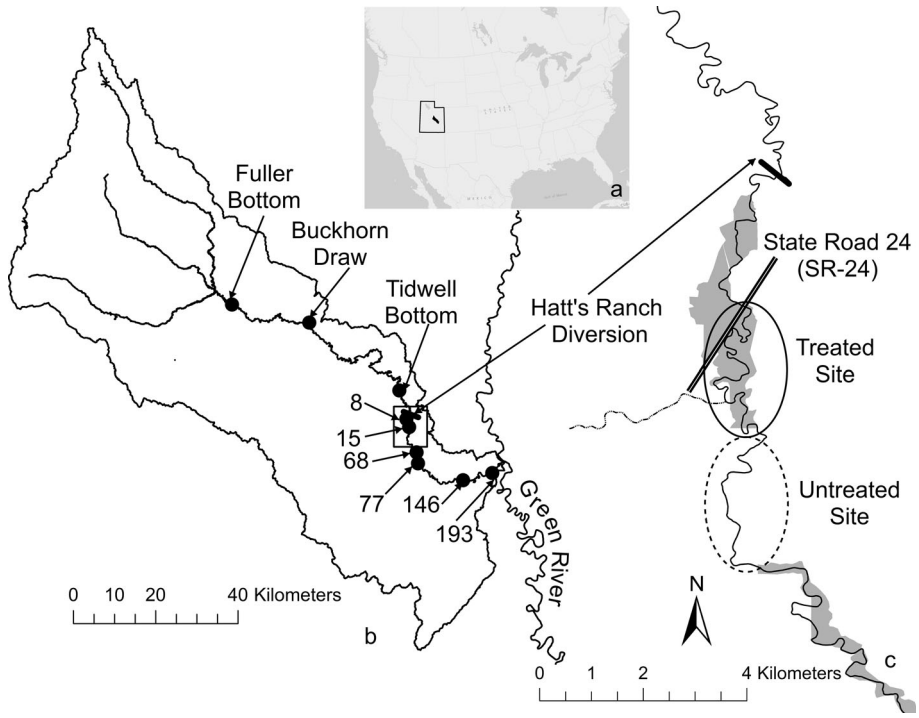

Fig. 1 Map of the San Rafael River drainage and study area. Map illustrates the locations of the San Rafael River drainage in Utah (*a*), fish and habitat sampling reaches (*black dots*) on the San Rafael River (*b*), and the reach of river (*box* in *b*) where treated and untreated study sites were located (*c*). The lower river was divided into 300 m sections; therefore, reach 8 refers to the reach 2,400 m (eight reaches) below the Hatt Ranch diversion. *Shaded areas* in *c* indicate areas where tamarisk was removed. Note the ephemeral tributary confluence in the treated site

3. Are there more wood accumulations in the river channel within the tamarisk removal area than in adjacent untreated areas?

We discuss these questions in terms of the potential for tamarisk removal efforts to contribute to restoration of fish habitat in southwestern rivers.

Study Location

The San Rafael River is formed by the confluence of Huntington, Cottonwood, and Ferron creeks whose headwaters are in the Wasatch Plateau at approximately 3,350 m above mean sea level (amsl) (Fig. 1). From the confluence of the three streams (1,676 m amsl), the river cuts through an uplifted dome of sedimentary rocks known as the San Rafael Swell and then flows through an alluvial valley to its confluence with the Green River (1,212 m amsl). The river extends approximately 174 km in length and the drainage encompasses almost 6,299 km^2.

The focus of this study is the lower 90 km of the river between the eastern edge of the San Rafael Swell and the confluence with the Green River. The lower 64 km of the river (lower river) is separated from the rest of the San Rafael River (upper river) by a water diversion dam on the Hatt Ranch that prevents upstream fish movement (hereafter referred to as Hatt's Ranch diversion; Fig. 1). Habitat degradation through channel change has been much more pronounced in the lower river than the upper river primarily due to geomorphic differences. The lower river is primarily a low-gradient meandering river through desert terrain with a well-developed floodplain and is primarily a depositional section, receiving large quantities of sediment from the upper San Rafael River and ephemeral tributaries. In contrast, the upper San Rafael River is higher gradient and has several reaches constrained by deep canyons, such that sediment deposition and channel narrowing have been less extensive. Non-native tamarisk has colonized both the upper and lower San Rafael River floodplains; however, the extent of dense stands is much greater on the lower river than the upper river. A variety of native vegetation, including alkali sacaton (*Sporobolus airoides*), saltgrass (*Distichlis* spp.), common reed (*Phragmites australis*), willow (*Salix* spp.), and Fremont cottonwood (*Populus fremontii*), is intermixed with tamarisk stands and is dominant in some areas throughout the river.

Native Fish Fauna

Despite the significant impacts to hydrological patterns and channel morphology, four species of native fish—the speckled dace (*Rhinichthys osculus*), the flannelmouth sucker (*Catostomus latipinnis*), the bluehead sucker (*Catostomus discobolus*), and the roundtail chub (*Gila robusta*)—all maintain populations in the San Rafael River. The flannelmouth sucker, bluehead sucker, and roundtail chub (hereafter the three species) are all considered sensitive in the state of Utah, meaning that there is substantial scientific evidence of threats to population viability, and collectively, these three species are generally managed as a unit (UDWR 2006). All three species currently occupy

about 50 % of their historic range, largely due to habitat perturbations, fragmentation, and interactions with non-native fish (Bezzerides and Bestgen 2002). The roundtail chub has been petitioned for listing under the Endangered Species Act in the Lower Colorado Basin (USFWS 2012). In addition to the three species, endangered fishes of the upper Colorado River Basin, including Colorado pikeminnow (*Ptychocheilus lucius*), razorback sucker (*Xyrauchen texanus*), and bonytail chub (*Gila elegans*), have been observed in the San Rafael River and likely made greater use of the river historically (McAda et al. 1980; Bottcher et al. 2013).

The three species are present in much higher abundances in the upper San Rafael River (above Hatt's Ranch diversion) compared to the lower San Rafael River for several reasons. First, Hatt's Ranch diversion has prevented movement of non-native fish into the upper San Rafael River, whereas competition and predation from non-native fish constitute a severe threat to persistence of native fish populations on the lower river (Walsworth et al. 2013). The presence of dams and diversions for water use in the watershed has also contributed to dewatering in the lower river during dry periods. Second, due to geomorphic differences between the upper and lower river discussed above, areas of preferred habitat are much more abundant in the upper San Rafael River compared to the lower San Rafael River. Previous work has found that the distribution of the three species in the lower river is highly correlated with the availability of complex habitat (e.g., pools, riffles, and backwaters; Bottcher 2009). The presence of all three species in the San Rafael River, combined with their low abundance in the lower river, makes the San Rafael River an area of high restoration priority.

Tamarisk Removal Project

In 2008, the Utah Division of Wildlife Resources (UDWR) and Natural Resource Conservation Service (NRCS) began tamarisk removal efforts on state-owned land along the lower San Rafael River. The goal of removal efforts was to improve the physical habitat of the lower San Rafael River by removing impediments to erosion and channel movement processes that work to maintain habitat complexity. Hatt's Ranch (the area between Hatt's Ranch diversion and SR-24—see Fig. 1) was the initial site selected for tamarisk removal in 2008 with removal being completed in 2009. Currently, 424.5 hectares of tamarisk have been removed along 24 river km, and efforts to re-establish native vegetation within the treated areas are ongoing. No tamarisk removal or other river restoration efforts have been undertaken on non-state land along the lower river [primarily US Bureau of Land Management (BLM)], although restoration planning for these remaining areas is in progress.

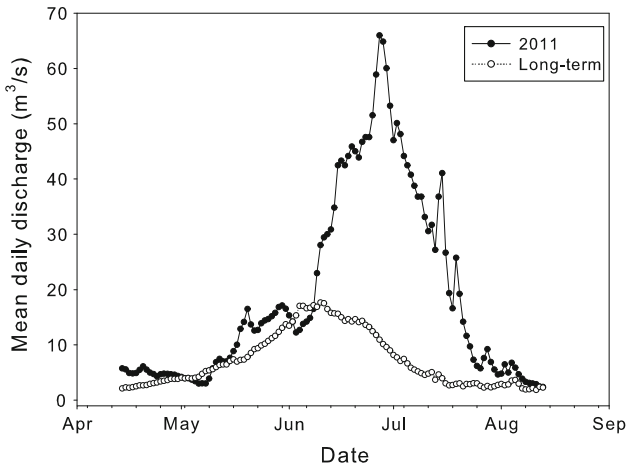

Fig. 2 Measured discharge of the San Rafael River, Utah in 2011 (*closed circles*) compared to mean daily discharge over the period of record (1910–1918 and 1946–2012; *open circles*)

All tamarisk removal was completed using a large tracked excavator to pluck individual trees from the ground. This mechanical process completely removed target trees and their root balls from the soil, along with a significant amount of their lateral roots, while minimizing disturbance to native woody vegetation to the extent possible. Removed tamarisk plants were piled in the removal areas in preparation for burning. Burning of piles was undertaken on the Hatt Ranch removal area; however, several overbank floods occurred between removal and burning and prior to the 2011 flood. Piles in removal areas downstream of SR-24 had not been burned prior to the 2011 flood event (described below). Removal was not preceded by herbicide treatment; however, tamarisk stands had been extensively defoliated by the tamarisk leaf beetle prior to removal. After initial mechanical removal, follow-up herbicide treatments (Garlon® 4 Ultra Triclopyr) were completed to reduce resprout density. The average cost for removal efforts and revegetation has been approximately US$839 per hectare.

Flood

Above-average snowpack within the San Rafael River drainage resulted in a large spring flood event in 2011. Discharge peaked on June 27 at about 68 m^3/s (US Geological Survey gage 09328500), corresponding to a 2.3-year recurrence event. Although the recurrence interval is relatively low, most of the largest flows historically have been monsoonal events, and the peak discharge in 2011 was a relatively large spring flood event. For example, this

flood represents one of the two highest magnitude spring flood events that have occurred since 1986 (a spring flood of similar magnitude occurred in 2005). In addition, the San Rafael River was at or above flood stage (>8.5 m^3/s) for approximately 65 days between May 21 and July 24 (Fig. 2), and thus completely inundated the floodplain for a long duration. Between initiation of tamarisk removal efforts and the 2011 flood, several smaller floods occurred that were also overbank, including a peak discharge of 28.3 m^3/s on September 16, 2009, 12.7 m^3/s on March 16, 2010, and 9.2 m^3/s on June 15, 2010.

Methods

Fish Abundance and Habitat Assessment

Although it has been demonstrated that both native fish abundance and habitat complexity are generally low throughout much of the San Rafael River, the surveys that led to these conclusions were all performed prior to the 2011 flood (Bottcher 2009; Walsworth 2011). Thus, we wanted to determine whether the 2011 flood may have altered this general pattern by sampling fish and surveying habitat across a number of representative reaches on the upper and lower San Rafael River that had been previously surveyed. The purpose of the fish surveys was not to directly assess changes in fish density in the tamarisk removal areas prior to and after the flood event, but to explore and validate the general relationship between fish density and the presence of particular habitat types (pools, riffles, and backwaters, see below).

Single-pass electrofishing surveys were conducted at ten 300-m-long reaches between August 9 and September 30, 2011. Native and non-native fish density were calculated by summing the species-specific catch for each reach and dividing by the total time spent electrofishing [catch-per-unit-effort (CPUE)] at each reach. A total of four reaches were surveyed in the upper river (Fuller Bottom, Buckhorn Draw, Tidwell Bottom, and just above Hatt's Ranch diversion) and six in the lower river below Hatt's Ranch diversion, including two within the tamarisk removal areas (reaches 8, 15, 68, 77, 146, and 193, see Fig. 1). Sampling reaches corresponded to long-term sampling locations established by UDWR, but were initially chosen systematically to provide spacing between sampling reaches and to capture the range of habitat conditions found on the San Rafael River and for ease of access (see Bottcher 2009). During initial reach selection, the entire lower river below Hatt's Ranch diversion was divided into continuous 300-m reaches; therefore, reach numbers refer to the number of 300-m reaches below Hatt's Ranch diversion (e.g., reach 8 refers to the reach 2,400 m downstream of Hatt's Ranch diversion; Fig. 1).

Percent pool, riffle, and backwater habitat was surveyed at nine of the fish sampling reaches (habitat data for one reach was lost). Pools were identified as concave depressions (laterally and longitudinally), which spanned the thalweg (i.e., the line defining the lowest points along the length of a river bed) and had a maximum depth of at least 1.5 times the pool tail depth. Riffles were identified as fast water areas with surface turbulence and gravel or coarser substrate sizes (Hawkins et al. 1993). Backwaters were identified as near-shore areas with currents flowing counter to the prevailing main-channel current (Hawkins et al. 1993). All remaining habitat was classified as glide or run habitat, having a moderate current with low surface turbulence and mostly sand substrate. Thus, pools, riffles, and backwaters added habitat complexity to the otherwise homogenous channel. Areas of pools, riffles, and backwaters were determined by flagging both the upstream and downstream ends of each habitat feature and measuring length and width (measured at the widest point) of each feature. The percent of complex habitat by reach was calculated by summing the area of pools, riffles, and backwaters and dividing by the total area of each reach. The use of maximum width to calculate complex habitat area overestimates the actual percent complex habitat such that comparison with other rivers would be problematic; however, our goal was to compare the relative complexity in different reaches in the San Rafael River, and due to the limited area of the available complex habitat in the river, using average widths would likely have little effect on the relative differences between reaches.

Assessment of Channel Change

In order to determine whether the 2011 flood resulted in more channel change within tamarisk removal areas compared to untreated areas, we identified an untreated site (untreated) and a removal site (treated) that satisfied the following criteria:

1. Tamarisk removal within the treated site must have been completed before March 1, 2011 (prior to spring flood event).
2. The untreated site must be neighboring the treated site and be comparable in size.
3. The aerial imagery of the selected untreated and treated sites must be similar in quality to ensure our ability to accurately delineate changes in the river.

Based on the criteria listed above, we selected an area immediately downstream of the SR-24 bridge as the treated site (tamarisk removed prior to 2011 flood) and an equally sized area on BLM and private property located

immediately downstream from the treated area as the untreated site (Fig. 1). The treated area encompassed 18 of the 300-m reaches (reaches 14–31) in the lower river (established during initial reach sampling selection as described above), and the untreated area encompassed 11 of the 300-m reaches (reaches 34–44). Although tamarisk was removed widely in the treated site, there were areas within the treated site where the tamarisk was removed on one side of the channel, but not the other due to equipment access issues and property boundaries. Having the treated and untreated sites in close proximity was necessary to minimize geomorphic differences between the sites, such as valley confinement and slope, which may confound the evaluation of the impacts of tamarisk removal.

Despite their close proximity, there were important differences in channel properties between the sites. The sinuosity of the channel was higher in the treated site (2.46 m/m) than the untreated site (1.42 m/m), and the average channel width was lower in the treated site (7.2 m) than the untreated site (8.1 m); however, the sinuosity and channel width of individual 300-m reach were variable in both areas. The channel length was higher in the treated site (6,943 m) than the untreated site (4,242 m) due to the higher sinuosity in the treated site. There was also an ephemeral tributary that entered the main channel approximately 2,250 m above the downstream end of the treated site (at the beginning of reach 27), whereas there were no tributaries of similar size entering the channel in the untreated site. The ephemeral tributary in the treated site is a sediment source, and thus alters the local sediment transport dynamics, potentially influencing bank erosion and channel migration processes (Dean and Schmidt 2013).

In August 2010, the Bureau of Reclamation (BOR) in collaboration with BLM and Utah State University (USU) photographed the entire length of the San Rafael River from a helicopter at approximately 450 m above ground level. In 2011, we contracted a second flight of the San Rafael River using an unmanned aerial system (Aggie Air™, Logan, Utah, USA). Both sets of aerial photographs were georeferenced and imported into ArcGIS (Environmental Systems Research Institute, Redlands, California, USA). The 2010 (pre-flood) imagery was compared to the 2011 (post-flood) imagery to assess channel changes attributable to the flood. ArcGIS was used to delineate the active channel in both sets of images. The 2010 active channel polygon was then overlain on the 2011 active channel polygon to calculate the amount of channel widening between years and identify areas of lateral channel movement.

The amount of channel widening was determined by dividing the increase in area of the active channel between 2010 and 2011 by the channel length. The amount of widening was calculated for each 300-m reach of channel and for the entire channel length in the treated and untreated sites. Locations of lateral channel migration were identified visually within both the untreated and treated site, and were digitized using ArcGIS (Fig. 3). Total area (m^2) was then calculated for each location of lateral movement.

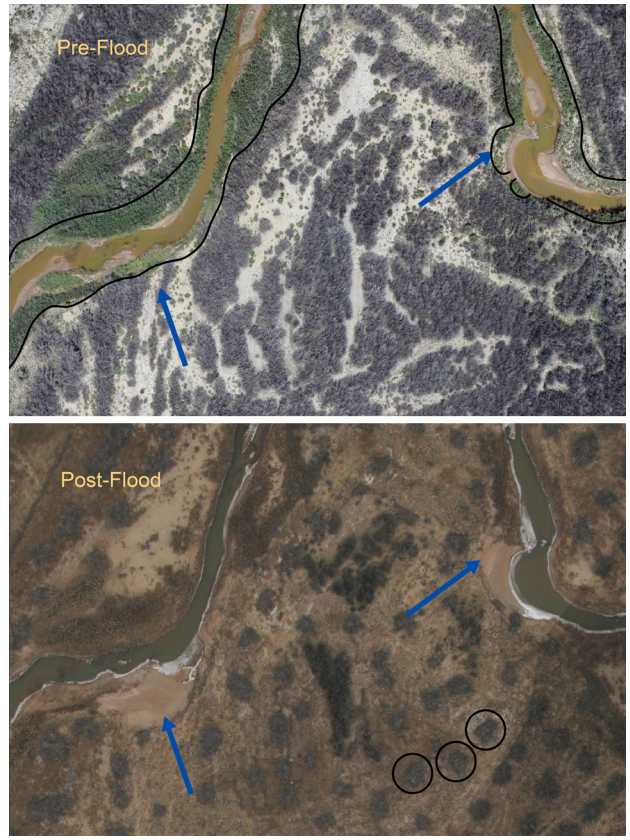

Fig. 3 Before (*above*) and after imagery of a location within the tamarisk removal treated area. River flow is from *top right* to *lower left* in the pictures. *Arrows* indicate areas of post-flooding lateral movement. *Lines* on pre-flood imagery demarcate the band of mixed willow/*Phragmites* vegetation that flanked the channel. Note that the willow/*Phragmites* band was classified as growing completely between the channel and existing tamarisk stands for the downstream area of lateral movement, but not for the upstream area because some tamarisk was growing directly on the bank edge. Post-flood imagery shows the extensive tamarisk removal in this area (*dark spots* in *bottom* image, three of which are *circled*, are slash piles that were later burned)

We tested whether the mean size of channel movement areas was significantly different between the treated and untreated site using a Student's *t* test. Recognizing that the results of this test would be difficult to interpret based on differences in channel properties between the treated and untreated sites, we performed two additional tests to further investigate the impacts of tamarisk removal on the magnitude of channel changes. First, we took a subset of the areas of lateral movement that had tamarisk growing on the immediate edge of the active channel and tested (using a

Student's *t* test) whether the mean size of movement areas was significantly different in places where the tamarisk had been removed and where it had not been removed. We did not use areas of channel movement that had a band of mixed willow/*Phragmites* vegetation (average width 4 m) growing between the active channel and tamarisk stands in this test (see Fig. 3, for an example). Second, within the treatment site, tamarisk was not removed everywhere, and there were sections of the channel where tamarisk was still growing on the channel banks during the 2011 flood. Thus, to control for geomorphic differences between the treatment and control sites, we tested (using a Student's *t* test), within the treatment area only, whether the mean size of areas of lateral movement was different along banks where tamarisk had been removed and had not been removed.

Wood Accumulations and Habitat Complexity

The spatial correlation between complex habitat and wood accumulations was evaluated by identifying wood accumulations on high-resolution imagery and coupling the accumulations with the spatial location of each complex habitat feature recorded on the ground. A census of wood accumulations was completed in 2010 by identifying each accumulation in the 2010 aerial imagery (pre-flood imagery). A census of pools, riffles, and backwaters for 2010 was obtained from Walsworth (2011) who delineated each habitat feature and measured the area of each feature by walking the entire length of the lower San Rafael River below Hatt's Ranch diversion in 2010. As part of the census of habitat features, beaver (*Castor canadensis*) activity was noted if the section contained beaver dams, which were identified based on beaver-cut material.

Buffers of 60 m (30 m upstream and downstream) were created around selected wood accumulations ($n = 40$, see below for selection criteria) and at an equal number of random points located throughout the lower San Rafael River generated using a random point GIS function. Evaluation of aerial imagery indicated that lengths of typical pool, riffle, and glide features were <30 m; therefore, a 30 m buffer upstream and downstream of wood accumulations captured the influence of accumulations on the formation of these habitats. Backwaters often occurred adjacent to accumulations as flow was deflected around the wood; therefore, a 30 m buffer was sufficient to capture the influence of accumulations on this habitat feature as well. In order to maintain consistency on how accumulations for analysis were selected, the following criteria were followed:

1. The wood accumulation must have spanned approximately 50 % or more of the active river channel.
2. When multiple accumulations were located within 60 m of each other (30 m upstream or downstream), only one point was selected in a centralized location between the accumulations.
3. Wood accumulations formed near braided channels or islands were excluded from the analysis to avoid biasing the results in favor of a positive relationship between wood accumulations and complex habitat. In this situation, it was unclear if the island or the resulting wood accumulation at the top end of the island was having more influence on the hydraulic processes and the localized formation of complex habitat.

Using GIS, we clipped each complex habitat feature from within the buffers to determine the number, type, and area of habitat features associated with each wood accumulation and random point. We tested whether the mean number of complex habitat features and the mean area of each habitat type (pool, riffle, and backwater) differed significantly between wood accumulation buffers and random buffers using a Student's *t* test. Previous work in desert systems has often shown that deep pool habitats serve as potential refugia during dewatering periods (Labbe and Fausch 2000; Davey and Kelly 2007); therefore, we also tested whether the mean depth of pools associated with wood accumulations was greater than the mean depth of pools in random buffers using a Student's *t* test. Finally, to address the question of whether tamarisk removal promoted accumulation of wood in the channel, we simply counted the number of accumulations within the treated site and the neighboring untreated site in both 2010 and from the aerial photographs taken in 2011 post-flood.

Results

Fish Abundance and Habitat Assessment

We captured native fish at greater rates in the upper San Rafael River in 2011 compared to the lower river. Native fish catch rates at the Fuller Bottom and Buckhorn Draw reaches were much greater than any other reaches sampled, 21 and 37 fish/h, respectively (Table 1). We captured few native fish in the lower San Rafael River below Hatt's Ranch diversion; however, we had low catches of bluehead sucker (2 fish/h) at reach 8, approximately 2.4 km below Hatt's Ranch diversion, and low catches of flannelmouth sucker (3 fish/h) at reach 15, approximately 4.5 km below Hatt's Ranch diversion. Both reaches were within tamarisk removal areas. We did not find roundtail chub in the lower San Rafael River. We found the highest catch rates of roundtail chub at the Buckhorn Draw reach in the upper

Table 1 Catch-per-unit-effort (CPUE) of fish and habitat types as percentage or reach measured during electrofishing and habitat surveys on the upper and lower San Rafael River in 2011

Reach	CPUE (fish/h)		Habitat type (% of reach)		
	Native	Non-native	Pool	Riffle	Backwater
Upper river					
Fuller bottom	21	0	16	17	0
Buckhorn draw	37	0	16	30	0
Tidwell bottom	2	0	10	0	0
Above Hatt's Ranch diversion	7	4	2	0	0
Lower river					
8	2	68	2	0	2
15	3	34	10	45	1
68	0	48	–	–	–
77	0	50	7	0	0
146	0	45	3	0	0
193	0	26	2	2	0

Fuller Bottom is the furthest upstream reach, and 193 is the furthest downstream reach, near the Green River confluence. Habitat data for reach 68 were lost and were indicated with a "–" symbol

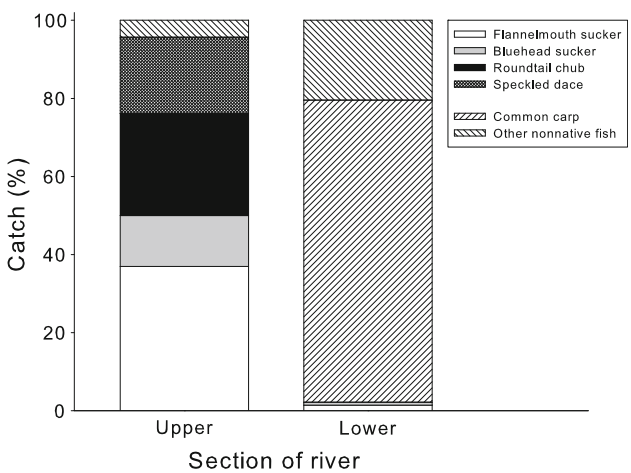

Fig. 4 Percent catch of fish captured in the upper San Rafael River Utah (*left*) compared to the lower San Rafael River (*right*) during 2011 electrofishing surveys. The four native species: flannelmouth sucker, bluehead sucker, roundtail chub, and speckled dace are shown individually. Non-native common carp is shown individually, and all other non-native fish are shown together

San Rafael River (8 fish/h). Native fish were absent from all four reaches below reach 15 (Table 1). At the lower river reaches, common carp (*Cyprinus carpio*) and channel catfish (*Ictalurus punctatus*) dominated the fish assemblage, while native fish comprised the majority of the catch in the upper river (Fig. 4).

Sample reaches in the upper San Rafael River had a greater proportion of pool and riffle habitats. The Fuller Bottom reach was comprised 16 % pool and 17 % riffle habitat, and the Buckhorn Draw reach was comprised 16 % pool and 30 % riffle habitat (Table 1). Complex habitat was less available in the lower San Rafael River; however, there were exceptions such as reach 15 within the tamarisk removal area, which was dominated by riffle habitat (45 %) and also contained pools and backwaters (Table 1).

Channel Change Due to the 2011 Flood

Channel widening occurred during the 2011 flood in both the treated (18, 300-m reaches) and untreated sites (11, 300-m reaches); however, the magnitude was higher in the treated site (32 %) than the untreated site (3 %). Local peaks in channel widening occurred in reaches with high sinuosity, downstream of the tributary in the treated site, and in reaches with low channel width prior to the 2011 flood event (Fig. 5).

The area of channel change per unit channel length (lateral movement and channel widening) in the treated site was 2.8 m^2/m compared to 1.3 m^2/m in the untreated site. A total of 15 areas of lateral channel movement were identified in the untreated site and 18 in the treated site. All movement areas were located on the outside of meander bends. While the number of areas of channel change was similar, the magnitude of change was significantly greater in the treated site (mean = 408 m^2, SE = 66.7) compared to the untreated site (mean = 153 m^2, SE = 42.9, Student's *t* test $P = 0.003$; Fig. 6). The largest movement area within the treated site was 1,256 m^2, while the majority (12 of 15) of the areas within the untreated site were less than 200 m^2, and none exceeded 700 m^2 (Fig. 6). Within the treated site, the average area of channel change along banks where tamarisk was removed (mean = 348 m^2, SE = 53.7) was not significantly different from the average area of channel change along banks where tamarisk was not removed (mean = 620 m^2, SE = 224.7, Student's *t* test $P = 0.31$). Many of the large movement areas (>500 m^2) occurred on the outside of sharp meander bends (90° turns over <200 m channel length), regardless of whether tamarisk had been removed from the bank or not. However, the area of channel change along banks where tamarisk was growing on the immediate edge of the active channel, but was not removed, was lower (mean = 93 m^2, SE = 31.2) compared to similar banks where tamarisk was removed (mean = 258 m^2, SE = 55.4, Student's *t* test $P = 0.04$; Fig. 6).

Wood Accumulations and Habitat Complexity

Based on the analysis from 2010 aerial imagery and habitat surveys, the mean number of complex habitat features within wood accumulation buffers (mean = 2.45, SE = 0.195)

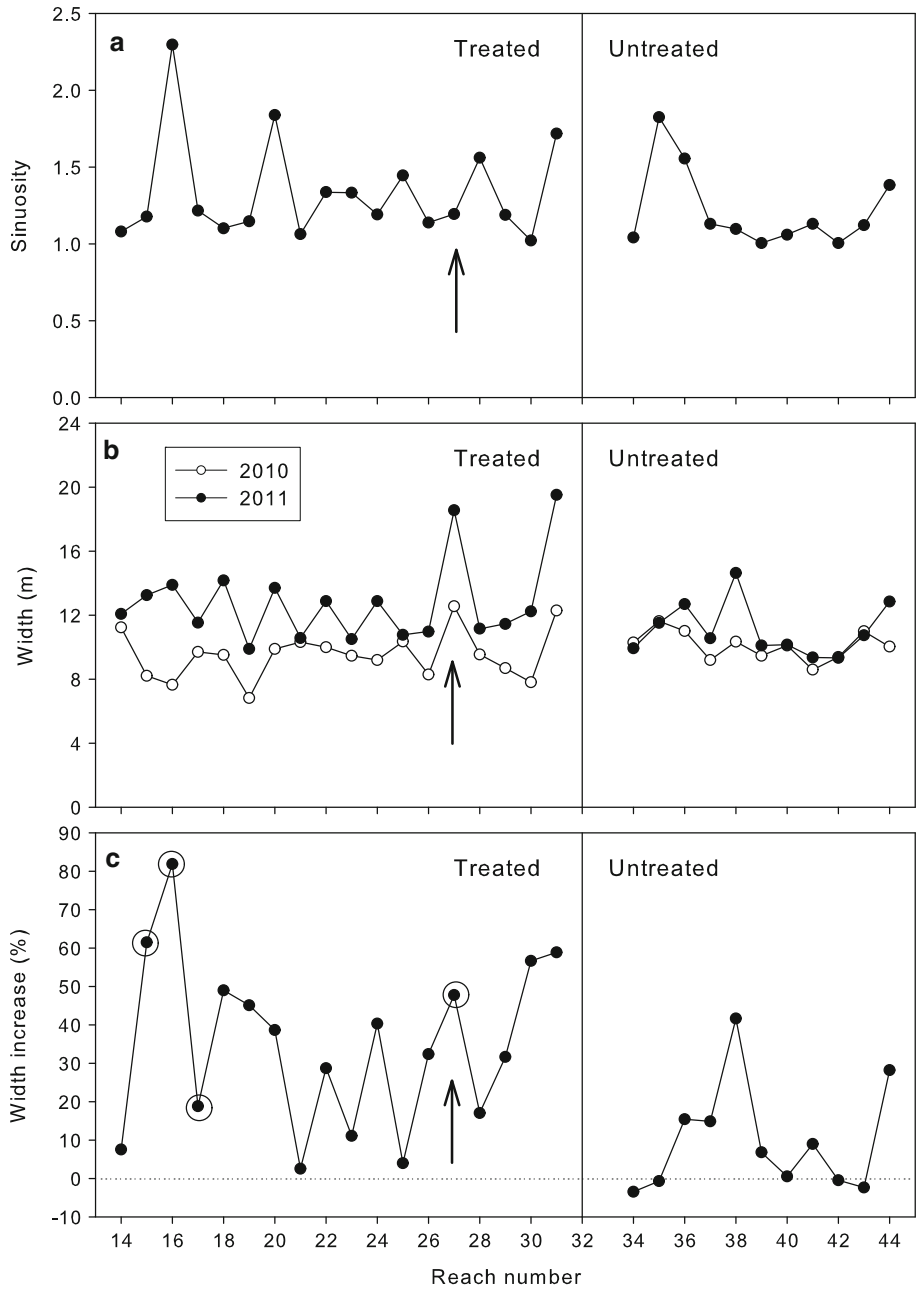

Fig. 5 Sinuosity (**a**), channel widths in 2010 and 2011 (**b**), and percent width increase between 2010 and 2011 (**c**) for individual 300-m reaches in the treated and untreated sections. *Arrow* indicates location where an ephemeral tributary enters the main channel within the treated section. *Circles on bottom panel* indicate reaches in which tamarisk was removed directly along the channel banks

was significantly different from the mean within random buffers (mean = 1.05, SE = 0.171, Student's t test $P < 0.0001$; Table 2). There were slightly more backwaters associated with wood accumulations than random buffers, and there were many more pools and riffle habitats formed near wood accumulations (Table 2). Pools within accumulation buffers were significantly larger (Student's t test $P = 0.002$) and significantly deeper (Student's t test $P = 0.004$) than those within random buffers, though since area was calculated using maximum width, it is possible that the larger pool area simply represents wider pools around wood accumulations. The mean size of riffle and backwater habitat was not significantly different between wood accumulation buffers and random buffers (Student's t test $P = 0.14$, $P = 0.94$, respectively; Table 2).

Thirty-seven of the total 40 accumulations used in the analysis from 2010 were found grouped together within a 19 km stretch below Hatt's Ranch diversion (Fig. 7). The 45 km below this aggregation was relatively devoid of wood accumulations. Much of this 19 km stretch overlaps very closely with areas where tamarisk was removed. Only five wood accumulations were present in the untreated site, where tamarisk was not removed. Only four wood accumulations were counted in the 2011 imagery, indicating

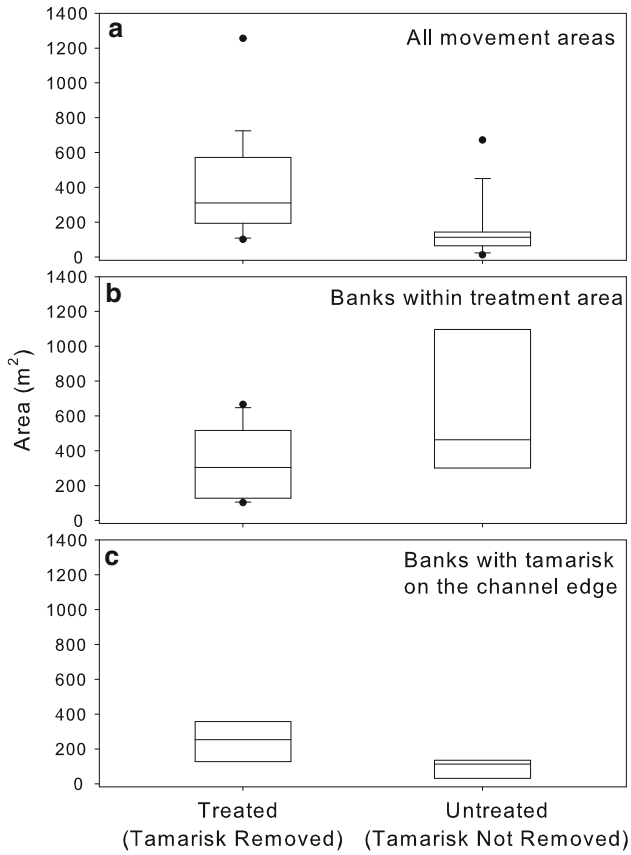

Fig. 6 Box and whisker plots of areas showing lateral movement in response to the 2011 flood on the San Rafael River Utah. The *top panel* (**a**) shows all areas of channel movement in the treated ($n = 18$) and untreated sections ($n = 15$). The *middle panel* (**b**) shows areas of channel movement along banks, within the treated site only, where tamarisk was ($n = 14$) and was not ($n = 4$) removed. The *bottom panel* (**c**) shows areas of channel movement along banks where tamarisk was growing directly on the edge of the active channel (i.e., no band of willow/*Phragmites* on the channel bank) and was removed ($n = 6$) and was not removed ($n = 3$)

that much of the wood was flushed from the river by the 2011 flood. However, visual inspection of post-flood imagery suggests that many of the complex habitat features associated with wood accumulations persisted after the flood, and that many were enhanced or newly created during the 2011 flood.

Discussion

The rationale for removing tamarisk on the San Rafael River was provided by dendrogeomorphic evidence suggesting that tamarisk contributed to the pattern of channel narrowing and loss of complex channel features (Fortney 2014). The 2011 spring flood event that occurred just 3 years after tamarisk removal efforts began provided a unique opportunity to test whether tamarisk removal could

Table 2 Mean (±SE) number and area of complex habitat features (backwaters, riffles, and pools) within individual wood accumulation buffers and random buffers and associated *P* values from paired Student's *t* tests

	Accumulation buffers	Random buffers	*P* value
Mean number per buffer	2.5 (0.20)	1.1 (0.17)	<0.001*
Pool	1.2	0.5	
Riffle	1.0	0.5	
Backwater	0.23	0.15	
Mean area (m^2)	46 (6)	47 (10)	
Pool	38 (8)	12 (2)	0.002*
Riffle	61 (12)	95 (19)	0.14
Backwater	12 (2)	13 (4)	0.94

* Significant differences (Student's *t* test, $\alpha = 0.05$) between accumulation buffers and random buffers

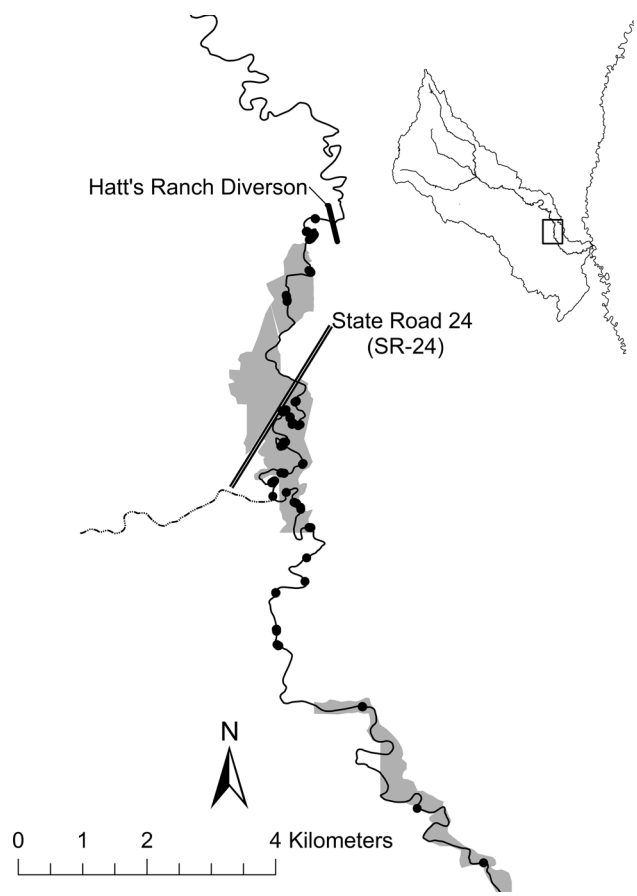

Fig. 7 Distribution of wood accumulations (*black circles*) on the lower San Rafael River Utah in 2010; *inset* shows location on the San Rafael River. All but 3 out of 40 accumulations on the lower river occurred in this 19 km stretch (which includes the treated and untreated study sites) below the Hatt Ranch diversion (*black bar*). The 2011 flood washed all, but four of the accumulations observed in 2010 out of the river. Tamarisk removal areas are shown in *gray shading*

allow increased channel movement in combination with a large flood event. The tamarisk removal project appears to have increased the potential for high flow events to diversify river habitat, primarily by promoting greater wood accumulation within the channel, and to a limited degree, by allowing greater channel movement during floods. By promoting these changes, tamarisk removal may contribute to restoration of native fish populations within the San Rafael River and potentially on other southwestern rivers as well.

The 2011 spring snowmelt flood caused significant channel change, and the amounts of channel widening and average size of areas of channel movement were significantly higher in the tamarisk removal (treated) site. However, differences in channel properties between the treated site and untreated site may also provide an explanation for observed differences in channel movement. All areas of lateral channel movement were located on the outside of meander bends, and thus, the higher sinuosity in the treated site may have provided greater potential to erode sediment on the outside banks of channel meanders because flow hits the bank at high angles (Begin 1981, 1986). Previous research has shown that channels widen to a greater degree downstream of tributary junctions due to inputs of energy and materials (Dean and Schmidt 2013), and a local increase in widening was observed in the reach just below the tributary input in the treated site (reach 27, see Fig. 5). In addition, the narrower channel in the treated site may have had a greater potential to respond to the flood compared to the wider channel in the untreated site.

The similarity in magnitude of channel change between banks within the treated site where tamarisk had and had not been removed also suggests that properties of the flood and channel configuration were the primary drivers of the patterns of channel movement as opposed to tamarisk removal. In particular, erosion along sharp meander bends (>90°) occurred in several locations where vegetation (but not always tamarisk) was growing on the channel banks. However, in analyzing only those movement areas that occurred on banks where tamarisk was the dominant vegetation on the immediate channel edge, we did observe a tendency toward greater channel movement areas along banks where tamarisk was removed compared to similar banks where tamarisk was not removed. The higher channel movement along banks where tamarisk was removed does suggest that in specific cases where floods are likely to cause channel movement (e.g., the outside of meander bends), and if tamarisk is the primary vegetation type on the channel banks, tamarisk removal can potentially reduce the resistance of bank material to erosion and provide greater opportunities for channel change. In many locations on the San Rafael River, a band of willow/*Phragmites* vegetation occurred on the immediate edge of the channel, and this may have limited the impact of tamarisk removal on channel change in these locations. In a study of channel response to a flood event on the Rio Puerco River in the US state of New Mexico, Vincent et al. (2009) observed greater sediment erosion in a channel reach where aerial herbicide treatment had eliminated both tamarisk and a fringe of willow compared to a channel reach where no herbicide was applied. In addition, the flood event studied here was a large magnitude flood event of especially long duration. As such, the flood may have masked impacts of tamarisk removal, which may be more apparent during smaller magnitude floods with less time and energy available to erode and transport sediment. Future studies of channel response to smaller magnitude flood events in tamarisk removal and untreated areas will help clarify whether this is the case.

The promotion of channel movement and bank erosion during flooding through targeted tamarisk removal should be directly beneficial for the creation of fish habitat on the San Rafael River. These processes are critical for creation and maintenance of deep scour pools and backwater habitats that serve as critical habitat components for native fish (Pitlick and Van Steeter 1998). The 2011 flood event and associated channel movement were observed to increase the amount of complex habitat in several surveyed reaches, including reaches within the tamarisk treatment section. In addition, floodplain scour created lower elevation surfaces that will likely be in closer proximity to groundwater at low flows, increasing the likelihood that native vegetation species (e.g., willow and cottonwood) will colonize these areas. Reconnection of the channel and floodplain will likely also provide opportunities for native fish to access food resources and refugia during floods (Robinson et al. 2002; Balcombe et al. 2005).

Tamarisk removal in combination with several smaller flood events that occurred prior to the 2011 flood also appeared to enhance fish habitat by allowing greater amounts of wood to enter the channel. By affecting the patterns of flow, in-channel wood can lead to scour, which results in deeper pool habitat and provides cover and backwater habitat for fish (Angermeier and Karr 1984; Fausch and Northcote 1992; Abbe and Montgomery 1996). Accumulations of wood were concentrated within the tamarisk removal areas (especially in the Hatt Ranch area). These accumulations were likely derived from tamarisk piles that washed into the river after removal efforts but prior to the 2011 flood. Several flows that exceeded flood stage (8.5 m^3/s) occurred prior to burning of tamarisk piled on the floodplain, and wood from tamarisk trees was observed directly in several of these accumulations. Pool, riffle, and backwater habitats were significantly more abundant around wood accumulations than random locations on the river. In addition, pools associated with wood

accumulations were both deeper and wider compared to other scour pools. Future studies are needed to directly assess whether native fish are using the habitat associated with wood accumulations; however, given the limited habitat availability on the lower San Rafael River, increased habitat provision through wood accumulation is predicted to be beneficial for native fish. Deep scour pools may be especially important on the San Rafael River as a thermal refuge during low water years and periods of dewatering, when surface temperatures can exceed 35 °C (Bottcher 2009). The beneficial impact of wood accumulations on fish habitat through tamarisk removal was dependent on moderate flood events, given that the large magnitude and long-duration spring flood of 2011 flushed most of the wood accumulations present during 2010 out of the channel. Despite the flushing of wood during the 2011 event, many habitat features around removed accumulations persisted through the flood and many were enhanced, likely by the interaction between high flows and the accumulations.

An alternative explanation for the high concentration of wood accumulations around Hatt's Ranch (upstream of the studied treated site but within the UDWR tamarisk removal area) is beaver activity. Of the eight locations within the lower 64 km of river where beaver activity was recorded during the 2010 habitat surveys, six were between reaches 5 and 79, which overlaps the area with a high concentration of wood accumulations (Fig. 7). The flood irrigation that has been in practice at Hatt's Ranch since 1953 might provide more abundant food resources (willow and cottonwood) in that area or there could be an attraction due to the hydrologic influences of Hatt's Ranch diversion. Whether beavers were directly responsible for moving large amounts of wood into the channel or were using wood that had already been washed into the channel is unknown, but it is clear that beavers were helping to concentrate wood into large accumulations by constructing dams. The relative role of beavers versus physical forces in creating wood accumulations in the San Rafael River should be examined further; however, either way, our results clearly show that wood accumulations are an important component of fish habitat in the San Rafael River.

Management Implications

The data on habitat complexity reported here and in previous work on the San Rafael River (Bottcher 2009; Walsworth 2011) showed very limited availability of complex habitat in the lower river. The limited habitat availability is likely contributing to the observed low abundance of the three sensitive native species in the lower river (Budy et al. 2009). Thus, by increasing the amount of complex habitat in the lower San Rafael River through increased wood inputs and promoting greater channel movement in local areas, tamarisk removal coupled with high flow events has a strong potential to contribute toward efforts to increase abundances of native fish species. Continued efforts to improve habitat on the lower river are warranted, because despite beneficial changes for fish habitat associated with the tamarisk removal project and flooding events, the lower river habitat was still found to be degraded relative to upper river habitat (Table 1). For example, reach 15, within the tamarisk removal area, had increased channel complexity as a result of the flood, but still had much lower habitat complexity than most of the reaches in the upper San Rafael River.

Tamarisk removal in the absence of flood flows would have had little effect on channel movement and fish habitat. High flows are needed to drive erosion and channel movement processes and also to scour pools and backwaters around wood accumulations. In addition, many of the beneficial changes observed here are likely to be lost over time without additional large flooding events due to continual deposition during monsoon floods. Therefore, provision of enhanced flood flows during some years (e.g., through water agreements or improved irrigation efficiency) will be critical. Even minor increases in the peak spring flows are likely to enhance native fish habitat and survival on the San Rafael River.

Habitat restoration may also benefit endangered fishes of the Colorado River system, in particular Colorado pikeminnow, razorback sucker, and bonytail chub, individuals of which have been observed in the San Rafael River (McAda et al. 1980; Bottcher et al. 2013). However, restoration of habitat complexity in the San Rafael River may also benefit non-native fish species, such that restoration of complex habitat will likely have to be coupled with non-native removal programs in this system to realize increased abundances of the three species (Walsworth et al. 2013).

Due to the fact that many wood accumulations were flushed from the river during the 2011 flood event, addition of wood to the channel could also facilitate the formation of complex habitat. Often, removed tamarisk stems are piled and burned at the restoration site (e.g., Taylor and McDaniel 1998; McDaniel and Taylor 2003). Considering the importance of wood in creation of complex habitat discussed here, allowing removed, dead tamarisk (live tamarisk stems can resprout if buried in moist sediments) to wash into the river or adding the dead tamarisk directly to the channel would reduce the need of costly prescribed burns, and potentially create complex river habitat. Promoting dam-building activity by beavers in the lower San Rafael River also has the potential to increase wood accumulations and associated complex habitat. Beaver may also encourage the development of native floodplain

vegetation through dam-building activities, which could over time provide a natural source of wood inputs (Naiman et al. 2000). Coupling use of beaver with tamarisk removal may be a particularly effective option, as the wood removed during tamarisk removal may be used by beaver in building dams or could be used as material for constructing beaver assist structures (DeVries et al. 2012).

Mechanical extraction of tamarisk using heavy machinery can result in a significant level of soil disturbance (e.g., Laub et al. 2013) and may require substantial revegetation efforts. Thus, it is important to minimize disturbance caused during the removal process. Our results show that channel movement was most enhanced by tamarisk removal where tamarisk was the dominant bank vegetation on the outside of meander bends. Therefore, removal could be limited to the outside of meander bends to minimize disturbance on the floodplain.

On the San Rafael River, previous research provided strong evidence that a lack of complex habitat contributed to low abundances of native fish. There was also detailed evidence showing that tamarisk had facilitated channel degradation. Results presented here suggest that where similar conditions occur, tamarisk removal, coupled with high flow events, has the potential to contribute to fish habitat restoration efforts. However, our study was opportunistic in nature (i.e., it was not planned a priori), and this limited our ability to replicate untreated and treated areas. Given likely differences in geomorphic and ecological histories between different rivers, we urge additional monitoring of the impacts of tamarisk removal projects on fish habitat to determine the general applicability of using tamarisk removal as a habitat restoration tool.

Acknowledgments Funding for the restoration work was provided by the Wildlife Habitat Incentive Program (WHIP). Additional funding for projects and support was received through the Bureau of Reclamation Actions to Avoid Jeopardy program, the Bureau of Land Management, the Utah Watershed Restoration Initiative, the National Fish and Wildlife Foundation, the US Geological Survey, Utah Cooperative Fish and Wildlife Research Unit (in-kind), and the Natural Resource Conservation Service (NRCS) Technical Center, Portland, Oregon. Barry Hamilton, Wayne Greenhalgh, and Ammon Boswell from the NRCS were instrumental in providing funding and support for this work. We would like to thank Nathan Owens and Mike Ault of the Utah Division of Wildlife Resources for their efforts in the field, Justin Hart for his oversight and management of this project, and Gary Thiede and Phaedra Budy for help with figure preparation and for providing editorial comments. Thanks to Ian Gowing and Austin Jensen from Aggie Air™ for their collaboration and quick processing of the 2011 imagery that made this work possible.

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