Restoration and Monitoring Plan for Native Fish and Riparian Vegetation on the San Rafael River, Utah

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Overlook of San Rafael River at Moonshine Wash confluence looking upstream and showing cottonwood trees and thick stand of defoliated tamarisk upstream. Photo taken by B. Laub on May 22, 2013

Primary Author

Brian G. Laub, *Utah State University, Logan, Utah*

Contributing Authors

David Dean, *Utah State University, Logan, Utah*
Jeremy Jarnecke, *BLM Utah State Office, Salt Lake City, Utah*

Scientific Advisory Committee

Justin Jimenez, *BLM Utah State Office, Salt Lake City, Utah*
Phaedra Budy, *Utah State University, Logan, Utah*
Dan Keller, *Utah Division of Wildlife Resources, Price, Utah*
Wally Macfarlane, *Utah State University, Logan Utah*
Chris McGinty, *Utah State University, Logan Utah*
Paul Birdsey, *Utah Division of Wildlife Resources, Salt Lake City, Utah*
Dan Eddington, *Utah Division of Wildlife Resources, Price, Utah*
Ian Gowing, *Water Research Laboratory, Utah State University, Logan, Utah*
Cassie Mellon, *Utah Division of Wildlife Resources, Salt Lake City, Utah*
Jack Schmidt, *Grand Canyon Monitoring and Research Center, Flagstaff, Arizona*
Michael Scott, *U.S. Geological Survey, Fort Collins, Colorado*
Dave Speas, *U.S. Bureau of Reclamation, Salt Lake City, Utah*
Krissy Wilson, *Utah Division of Wildlife Resources, Salt Lake City, Utah*

Reviewers

Paul Badame, *Utah Division of Wildlife Resources, Salt Lake City, Utah*
Melissa Dickard, *BLM National Operations Center, Denver, Colorado*
Julie Knudson, *Tamarisk Coalition, Grand Junction, Colorado*
Thomas Mendenhall, *BLM, Washington, DC*
Christine Rasmussen, *U.S. Geological Survey, Grand Junction, Colorado*
Michael Roberts, *Professional Hydrologist*
Janice Staats, *US Forest Service, Washington, DC*

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Acknowledgements

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Executive Summary

In this report, a restoration and monitoring plan for the San Rafael River, a tributary to the Green River in the upper Colorado River Basin, is presented. The plan is intended to guide restoration and management of the San Rafael River over the next 40-50 years and is developed as an adaptive management plan. The recommended restoration actions are intended to recover and enhance natural river processes, and are based on the best available information regarding the history of hydrologic, geomorphic, and ecological changes that have occurred on the river over the last century. Sites for implementation are prioritized systematically using data on stream and riparian habitat and potential response of native fish populations to restoration. An experimental design is recommended for implementing restoration actions. Combined with sufficient monitoring, the experimental design will help in identifying the most successful restoration actions. The most successful restoration actions can then be applied to other sites on the San Rafael River and restoration of other river systems.

The plan focuses on recovery of three native fish species and riparian vegetation, but impacts to other native fish species and native wildlife species will be monitored as well. The three focal native fish species are the flannelmouth sucker (*Catostomus latipinnis*), the bluehead sucker (*Catostomus discobolus*), and the roundtail chub (*Gila robusta*). All three species are listed as sensitive species throughout their range. The restoration plan focuses on these three species, because maintenance and enhancement of populations in the San Rafael River will help ensure their persistence throughout their range and avoid future Endangered Species Act listing and associated regulations for stakeholders within the San Rafael River watershed. Native riparian vegetation, particularly cottonwood and willow species, are important sources of wood and associated fish habitat within the San Rafael River, and persistence and enhancement of native vegetation communities is indicative of a dynamic, functioning river system. Native vegetation communities should also provide important habitat for terrestrial wildlife species.

The main cause of degradation on the San Rafael River has been altered hydrology. The magnitude and duration of spring snowmelt floods has been reduced compared to the early 1900s by decreased precipitation and water storage. Monsoon floods have also been reduced in magnitude but still transport large quantities of sediment to the river, and this sediment is deposited on the floodplain and as levees or berms along the channel. Reduced frequency of the large spring snowmelt floods that transported large quantities of sediment through the river system has led to narrowing and confinement of the channel and loss of complex habitat used by native fish. Tamarisk colonization in the 1950s accelerated channel narrowing by stabilizing channel bars and floodplain sediments. Loss of the processes that created and maintained stream and floodplain habitat has contributed to reduced populations of native fish and vegetation. Native fish are also impacted by a diversion dam that prevents upstream movement, predation and competition from non-native fish, and dewatering of the river during dry periods. Due to

these multiple threats, populations of native fish in the lower portion of the San Rafael River are persisting primarily due to immigration from the Green River and from upstream sources.

The goals of the restoration plan are to improve native fish populations, improve instream and riparian habitat, and learn from the restoration project so that the plan can be adapted over time and so the likelihood of success of restoration efforts on other river systems can be improved. Recovery of the river system to conditions that existed prior to settlement in the late 1800s is infeasible, but actions can be taken to enhance fish populations and channel and riparian habitat on both local and broad scales. On the local scale, recommended actions include strategic removal of tamarisk and other non-native woody vegetation, addition of wood and boulders to the channel, addition of gravel to the channel, and installation of temporary structures to enhance dam-building activity by beavers. Sections of the river on which to apply these local-scale efforts are prioritized based on the potential benefit to the native fish community. Sections of the river that are currently providing quality habitat are also identified as reference areas. On the broad scale, recommended actions are: 1) working with stakeholders in the watershed to implement an ecological flows plan for habitat creation and maintenance and to prevent dewatering, 2) increasing connectivity throughout the river system by provision of fish passage at an irrigation dam, and 3) control or removal of non-native fish.

To accomplish the goal of learning from the restoration project, a comprehensive monitoring plan is developed that includes measurement of a suite of variables in restoration sections, reference sections, and control sections of the river that do not receive restoration treatments. Variables monitored will include native fish populations, habitat, and movement patterns; riparian vegetation communities; geomorphic features; and flow patterns among others. Variables will be measured over time to determine the impacts of restoration on the river system. Similar to restoration actions, both local-scale monitoring using on-the-ground techniques and broad scale monitoring using aerial photography and remote sensing will be completed.

The report is divided into six sections. Section I covers the basic geology and watershed characteristics of the San Rafael River as well as the historic river conditions including the causes and consequences of river degradation over time (summarized in Fig. 18). Section II presents the guiding vision and restoration goals for the plan, and section III presents the specific restoration objectives (summarized in Table 1). In section IV, restoration actions are proposed (Table 3) and priority sites for restoration identified (Figs. 20 and 21). The monitoring plan is detailed in section V (summarized in Table 4). Section VI is a short conclusion section that discusses the importance of adaptive management and the relationship of the San Rafael River restoration project to broader management goals for the upper Colorado River Basin.

The plan represents a culmination of a number of detailed scientific investigations that have been conducted since 2007. These investigations are included as appendices and are referenced throughout as the scientific justification for the goals, objectives, site prioritization, recommended actions, and monitoring needs of the restoration plan.

I. Historic and current ecological and geomorphic conditions on the San Rafael River: Establishing the impetus for restoration

Introduction

Recent scientific investigations have indicated that the lower San Rafael River is in a severely degraded state, with low abundance of native fish species, poor fish habitat quality, limited native riparian vegetation recruitment, and abundant stands of non-native tamarisk. Restoration will be necessary to reverse the causes of degradation and assist recovery of the river ecosystem, and therefore a restoration plan is developed herein. The San Rafael River offers an ideal opportunity to undertake restoration for a number of reasons. First, land along the San Rafael River is mostly publicly owned and thus restoration can be easily coordinated over large spatial extents. Large scale restoration will be necessary to ensure that the causes of ecosystem degradation are addressed. Second, the river harbors populations of sensitive native fish, and several endangered native fish species use the river to spawn and rear young fish. Thus, efforts to improve the ecological conditions of the San Rafael River will help ensure the persistence of native fish populations into the future (Dauwalter et al. 2011). By targeting recovery of these native species now through collaboration with river stakeholders, it will hopefully be possible to avoid imposition of a strict regulatory environment in the future, e.g., if the river were to be designated as critical habitat for an endangered species. Third, recent research on the river has provided a thorough understanding of the river and historical hydrological and channel changes, vegetation changes, and native fish population dynamics, such that there is a sound scientific basis for designing restoration.

The primary focus of this restoration plan is native fish populations and their habitat, therefore, prioritization of restoration sites and recommended methods primarily focus on potential native fish response. However, in natural, dynamic river systems, the river and riparian zones are intimately linked through processes of flooding and material exchange between the channel and floodplain (Ward and Stanford 1995). In this restoration plan, hard-engineering structural approaches are avoided in favor of techniques that promote recovery of natural river processes. Thus, restoration that targets improvement of fish populations and fish habitat will necessarily impact the riparian zone, and for this reason, the restoration plan also considers native riparian vegetation dynamics in formulating goals, objectives, and methods. No species of terrestrial wildlife are specifically targeted in this plan; however, by working to improve conditions for native riparian vegetation, wildlife habitat will hopefully be improved through restoration. Monitoring of bird communities will be conducted over the course of the restoration plan to understand the impacts of restoration on terrestrial wildlife (see Section V of this report).

An important first step in the restoration planning process is to document the degraded state of the river and identify the causes of degradation (see Fig. 1). In this section of the restoration plan, the history of channel and floodplain geomorphic changes are summarized and explained in terms of altered hydrological patterns, sediment supply and transport, and vegetation establishment (i.e., Outcome 1 of the restoration plan identified in the NFWF proposal – see Appendix I). The current understanding of present fish distribution and abundance patterns and water quality and riparian vegetation conditions in the San Rafael River is also summarized and linked to historical geomorphic alterations. Research on the San Rafael River is integrated with relevant literature to produce this synthesis. In the following sections of the plan, information on the extent and causes of degradation will be coupled with the habitat requirements of native fish and vegetation to establish the need for conservation and river restoration, formulate the goals of a restoration program, and suggest restoration approaches that are likely to reverse degradation of the river system (i.e., Outcomes 3 and 4 of the restoration plan identified in the NFWF proposal – see Appendix I).

Synthesis of the geomorphic changes and causes of change will also help identify constraints on restoration. Complete restoration of the San Rafael River to conditions that existed in the early 20th century is infeasible, as this would require returning all water to the river and completely removing non-native fish and vegetation species. However, restoration can be viewed as part of a larger land management plan that aims to address the processes that have led to ecosystem degradation (Hobbs and Humphries 1995, Hobbs and Norton 1996). Restoration of processes is needed, because fish and riparian habitat on river systems is continually being formed and altered over time as rivers progress through natural cycles of widening and narrowing (Schumm and Lichty 1963, Osterkamp and Costa 1987, Ward et al. 2001). Restoration that aims to recover a specific channel form with static habitat features is unlikely to succeed – the processes that lead to habitat formation and maintenance should be targeted instead (Kondolf et al. 2001, Smith and Prestegaard 2005, Wohl et al. 2005). Thus, in developing a conservation and restoration plan for the San Rafael River, broader land management actions, such as securing water to enhance flood flows, are identified that will enhance specific restoration activities within the river channel and floodplain. Approaching restoration at this broad scale is necessary, because the causes of river degradation have acted over a similarly broad scale (Kondolf et al. 2008). A broad time scale for recovery of the river system is also needed, because restoration trajectories often do not follow degradation trajectories due to hysteresis and feedback effects (Hobbs and Norton 1996, Sarr 2002). At the same time, there is opportunity for smaller scale restoration activities, e.g., activities that improve physical habitat, to benefit native fish, native riparian vegetation, and potentially water quality. Given the imperiled status of the native fish species, such small scale restoration can be an important step toward ensuring persistence of native species in the San Rafael River and thus contribute toward rangewide efforts to maintain and enhance the long-term viability of native species.

In synthesizing the causes and consequences of river degradation, the geologic setting of the river, land use within the watershed, and the unaltered hydrologic and sediment transport characteristics of the river are described first (i.e., Outcome 2 of the restoration plan identified in the NFWF proposal – see Appendix I). After establishing the unaltered river hydrologic and geomorphic patterns, a summary of the anthropogenic modifications of the river is provided. Next, changes in water quality, hydrologic patterns, channel characteristics, and riparian vegetation communities in response to river modifications are described, with an emphasis on how processes have changed. Response of native and non-native fish to these changes is then summarized. The section concludes with a summary of the current degraded state of the river and the prospects for restoration.

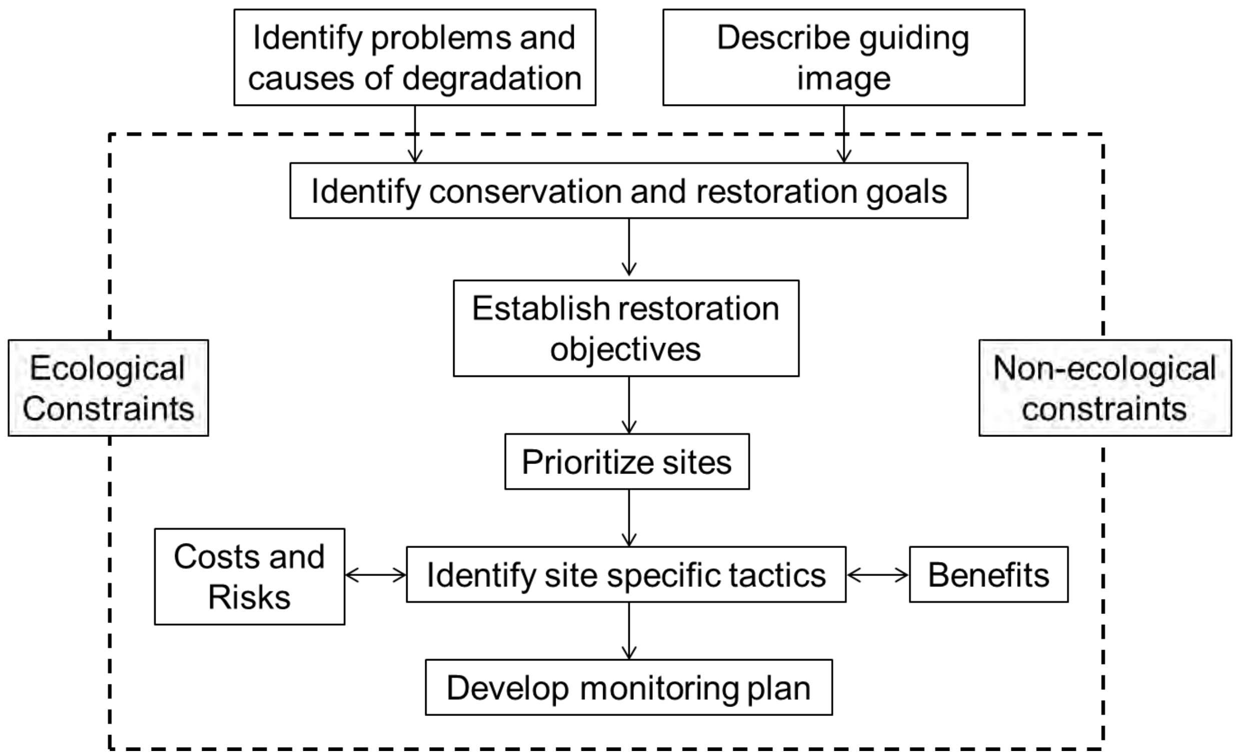

Figure 1. Diagram of the planning process that was followed in developing the San Rafael River restoration plan. Figure adapted from Figure 1 of Shafroth et al. (2008).

The San Rafael River and Watershed

Geology

The San Rafael River watershed is located in the Upper Colorado River Basin, primarily in Emery County in southeastern Utah (Fig. 2). The San Rafael River begins at the confluence of Huntington, Cottonwood, and Ferron Creeks and flows 190 km southeastward toward its confluence with the Green River (Fig. 2). The river, including the three tributaries, drains an area of 6,200 km^2 and covers an elevation range from ≈3,000 m in the tributary headwaters to 1,220 m at the Green River confluence. The three tributaries originate on the western edge of the Wasatch Plateau in the Manti-La Sal National Forest and descend ≈1,200 m before exiting the mountains into the broad alluvial Castle Valley. The three tributaries join at the eastern end of Castle Valley to form the San Rafael River, which then flows through the San Rafael Swell, a southwest-northeast oriented dome of sedimentary rocks approximately 112 km long and 50 km wide (Gilluly 1929). Four distinct river segments within the Swell have been identified, based primarily on channel slope (Fortney 2013a – included as Appendix II; Fig. 2). The upstream segment is characterized as an alluvial valley with a relatively gentle slope, though valley width is narrower within the Little Grand Canyon than upstream at Fuller's Bottom and downstream at Buckhorn Wash. Downstream of Buckhorn Wash the river enters the second segment within the Swell, a narrow bedrock valley known as the Black Box, which has a much higher channel slope than the upstream segment. After exiting the Black Box, the channel slope decreases as the river flows through a broad meander around Mexican Mountain, and this marks the third segment within the Swell. In the fourth segment within the Swell, the river cuts through a sandstone escarpment known as the San Rafael Reef (hereafter the Reef), marking the eastern edge of the San Rafael Swell (Trimble and Doelling 1978). After exiting the Reef, the river flows approximately 90 kilometers through the San Rafael Desert to its confluence with the Green River. The Reef marks the divide between the upper and lower sections of the San Rafael River.

The lower San Rafael River is a low-gradient meandering river that alternates between broad and more confined valleys (Fortney 2013a; Fig. 3). The lower river has been divided into five sections based on abrupt changes in valley width (Fortney 2013a). The upstream-most section has a fairly broad valley (average width 446 m) and extends from the Reef to about 1 km downstream of the Interstate-70 (I-70) bridge, where the river cuts into the Morrison Formation. In section two the river is constrained by the Morrison formation in a narrower valley (average width 267 m). After exiting the Morrison Formation at the upstream end of Hatt's Ranch, the river valley widens in section three, which extends to just upstream of the confluence of Dugout Wash downstream of Frenchman's Ranch. The valley is widest in segment three (average width 692 m), but also most variable in this section. Section four extends from Dugout Wash to 4 km downstream of Moonshine Wash and has the narrowest valley, as the river cuts through the Carmel and then Navajo Formations (average width 164 m). Section five is a short section of river that extends from 4 km downstream of Moonshine Wash to the Green River confluence and has a similar valley width as section one.

The orientation of bedrock strata and regional faults has forced the lower river to flow along the northern edge of the watershed, and thus the primary tributaries originate south of the river (Trimble and Doelling 1978). Although these tributaries can deposit alluvial fans that control the course of the river over local scales, the primary control on movement of the river over geologic time scales is thought to be valley confinement (Fortney 2013a). Bed sediments within the lower San Rafael River are primarily sand and mud, except where the river flows over bedrock or impinges on bedrock at the valley margins and where tributary inputs deposit coarse sediment. The lower river is the main focus of the restoration plan and further description of the river focuses mainly on this section.

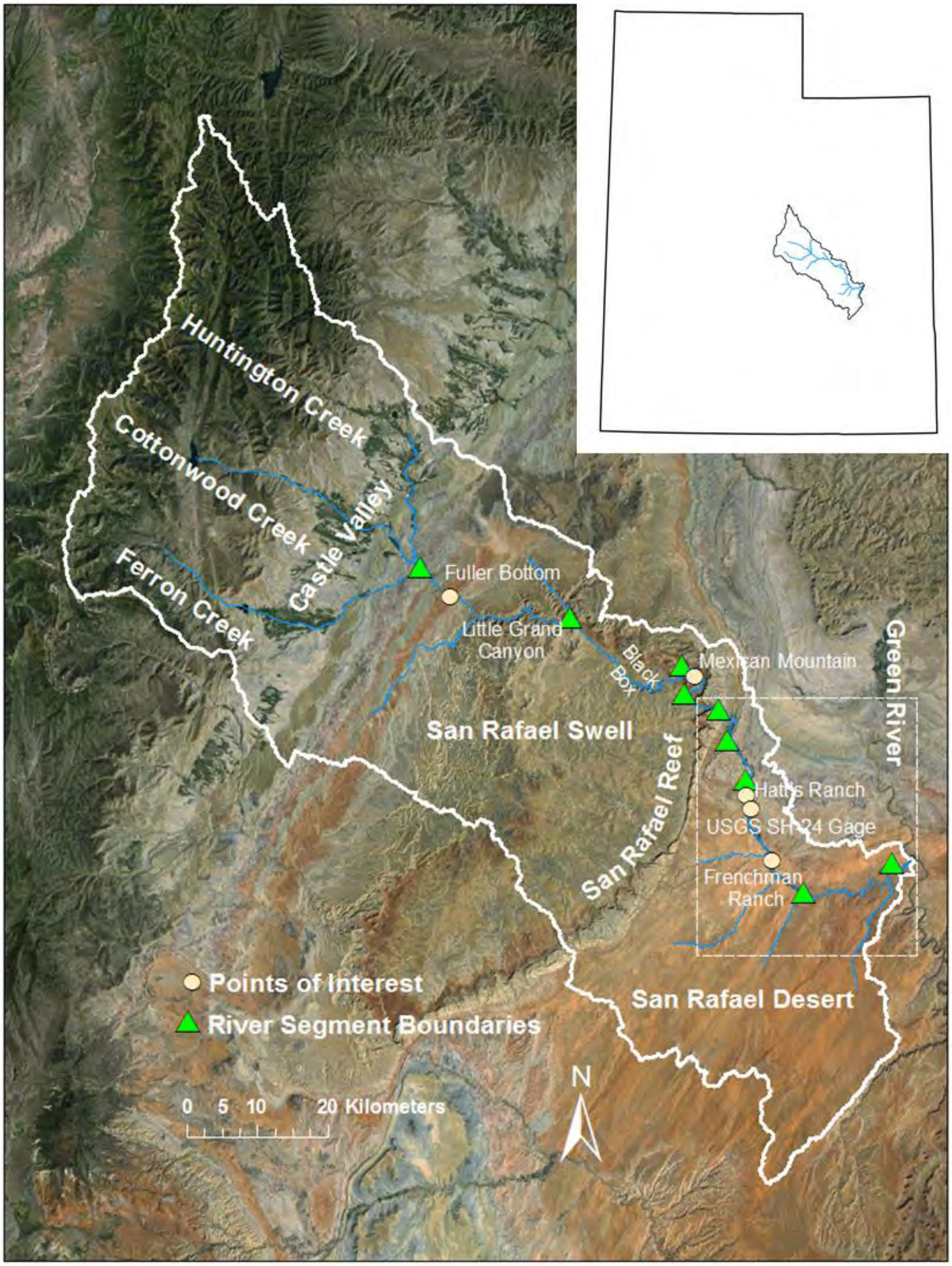

Figure 2. Map of the San Rafael River and watershed. Triangles mark the borders between different river sections. The lower San Rafael River, which is the focus of restoration, begins downstream of the San Rafael Reef and is outlined in the dashed box (see Fig. 3). Inset shows the location of the San Rafael River watershed in Utah.

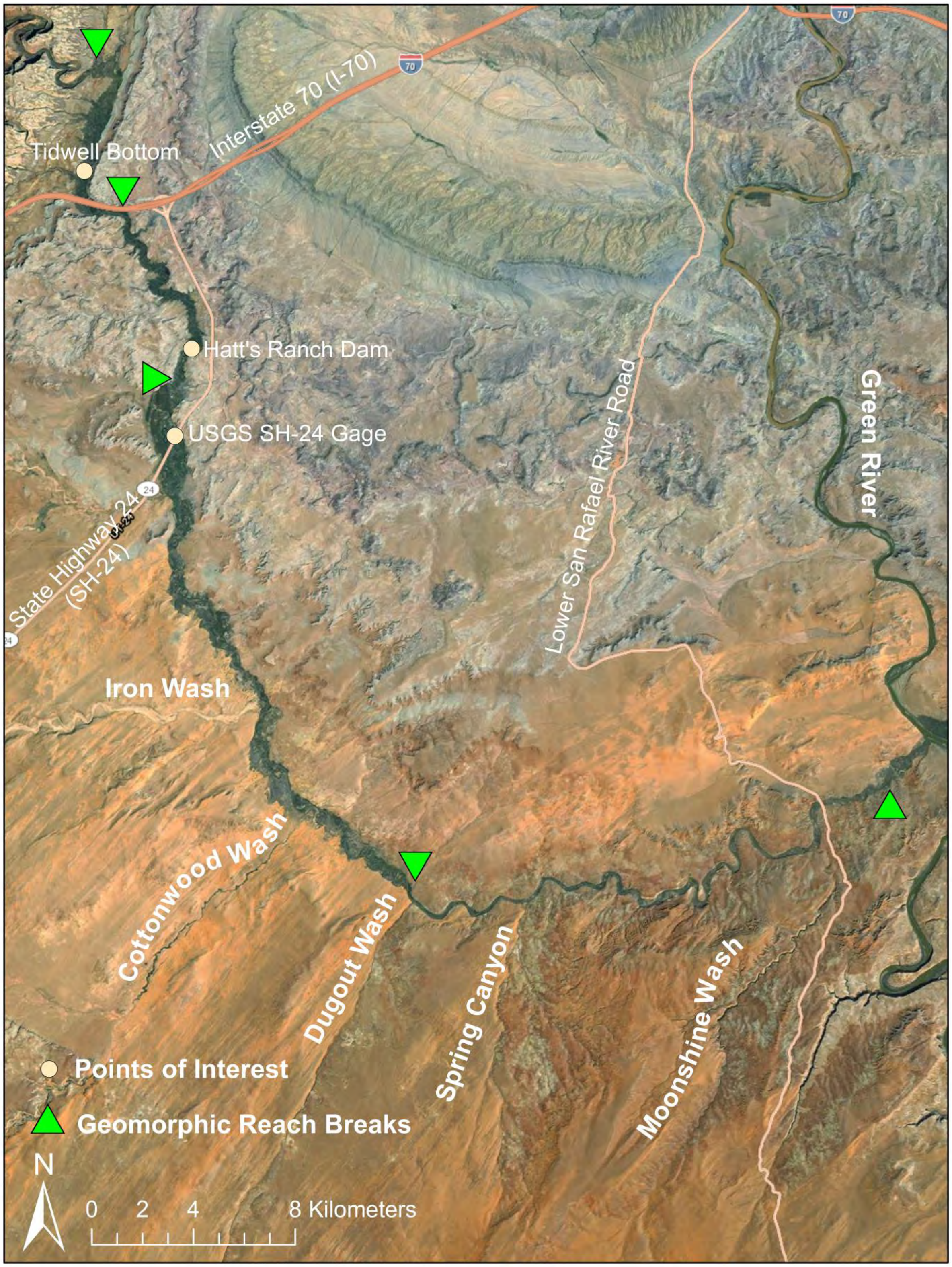

Figure 3. Map of the lower San Rafael River. Triangles mark the borders between different geomorphic river sections identified by Fortney (2013a).

Land ownership and land use

A majority of the lower San Rafael River watershed is public land (Fig. 4), primarily BLM (60% of land in the watershed) with some State land (9% of land in the watershed). State land along the river and floodplain contains about half of the length of the lower river (UDNR 2007). The state land along the river is formerly private land that was purchased by PacificCorp and subsequently transferred to the Utah Department of Natural Resources, Division of Wildlife Resources to manage as a Wildlife Management Area. The 334 hectare Hatt's Ranch is state-owned but leased by the Hatt family, who currently run a pheasant farm on the property (UDNR 2007). The Hatt's constructed a diversion dam in its current location on the upstream end of the ranch sometime in the early 1950s (PSI 2009), and the diversion currently supplies water to flood-irrigate pheasant pastureland (Fig. 5). There are only a few sections of private land along the lower San Rafael River and together these plots contain several kilometers of river (UDNR 2007). The most extensive section of private land is located between the Reef and I-70.

Hydrology

The U.S. Geological Survey (USGS) has operated a gaging station on the lower San Rafael River near Hatt's Ranch at its current location (State Highway 24) since 1976 (gage 09328500, hereafter the SH-24 gage). The river was gaged at various other locations from 1909-1918 and from 1945-1976. Analysis of this discharge record has shown that the lower San Rafael River was historically characterized by large, long duration snowmelt floods in the spring and early summer (generally May-July) and occasional large, short-duration floods in the late summer and fall caused by monsoon thunderstorms and cut-off low pressure systems (Webb and Betancourt 1990, Dean et al. 2009, Fortney et al. 2011; Fig. 6). Warm season floods have produced some of the highest peak discharges, but have a much shorter duration compared to spring snowmelt floods (see Fig. 12 in Fortney 2013b – included as Appendix III). Baseflow is maintained by groundwater, though in dry periods the lower river can become dewatered in large sections due to irrigation withdrawls (McAda et al. 1980, UDNR 2007, Bottcher 2009).

Sediment regime

Considerable differences in suspended-sediment transport exist between snowmelt floods and monsoon floods. Convective thunderstorms during the monsoon season and dissipating tropical storms are relatively high energy, and precipitation during these events over the San Rafael Swell and San Rafael Desert, which are composed of easily erodible soils, delivers large quantities of fine sediment to the San Rafael River. Suspended-sediment concentrations during the monsoon season have been measured as high as 115,000 mg/L at the USGS SH-24 gage. Conversely, snowmelt runoff occurs when ephemeral tributaries in the San Rafael Swell and Desert are dry, and the only sediment available for transport is the fine-grained alluvium that composes the bed, banks, and floodplain of the river. The maximum suspended-sediment concentration measured during snowmelt runoff was 32,100 mg/L, over an order of magnitude less than the maximum concentration measured during the monsoon season. Due to the lower concentrations during snowmelt runoff, sediment loads during monsoon floods are almost always half an order of magnitude, or more, greater than winter and spring flood loads (Fig. 7).

Analyses of mean daily loads show that floods during the winter and spring transported a greater total amount of sediment during the period when suspended sediment concentrations were measured (1949-1957). Winter and spring floods transported a total of 1.0×10^{10} tons of suspended sediment, and summer and fall floods transported a total of 6.7×10^{9} tons of sediment over the same period. The total suspended load may have been greater for spring snowmelt floods in this period due to an especially long-duration flood event that occurred in 1952. Thus, whether the total transported load is greater during spring snowmelt or monsoon flood is likely to vary from year to year. Nevertheless, the large transport loads in winter and spring floods are due to their longer duration despite having lower daily concentrations. These differences in load between the two types of storm suggest that historically, monsoon floods were generally depositional events and spring snowmelt floods were erosive events that transported the monsoon-derived sediment through the lower San Rafael River.

Anthropogenic Modification

Water use is one of the main anthropogenic impacts within the San Rafael River watershed. The San Rafael River is one of the most over-allocated rivers in Utah, with 360 dams and 800 points of diversion located primarily upstream of the San Rafael River on the three tributaries (Walker and Hudson 2004). Water is diverted primarily to supply agricultural uses in Castle Valley, but is also used to provide water for municipal and industrial use, in particular, coal-fired power generation plants on Huntington Creek and Cottonwood Creek (UDWR 2012). About 35,000 acre-feet/year of water is transferred out of the San Rafael River watershed into the Price River watershed north of the San Rafael and the San Pitch watershed on the western side of the Wasatch Plateau. However, about 6,500 acre-feet/year of water is diverted into the San Rafael River watershed from the Muddy Creek watershed south of the San Rafael River, such that the total transfer of water out of the San Rafael River is about 30,000 acre-feet/year, or about 14% of the total precipitation inputs in the watershed not lost to evapotranspiration (UDWR 2012). Although isolated farms and ranches were operated throughout the San Rafael River watershed in previous decades, the Hatt's Ranch property on the lower river is currently the only major water user throughout the watershed below the confluence of the three tributaries (Gowing and Thomas 2012). A diversion dam is used to supply flood irrigation water for the Hatt's Ranch property and is currently a barrier to upstream fish passage (Bottcher 2009). Construction of dikes and levees associated with Hatt's Ranch and the SH-24 crossing has caused channel straightening in the area of Hatt's Ranch (Fortney et al. 2011). Cattle grazing occurs on public land throughout the San Rafael River watershed, including within the riparian zone of the lower river. In addition, some off-highway vehicle and other recreational uses occur within the lower San Rafael River watershed. However, the impacts of grazing and recreation are thought to be minor relative to water use impacts.

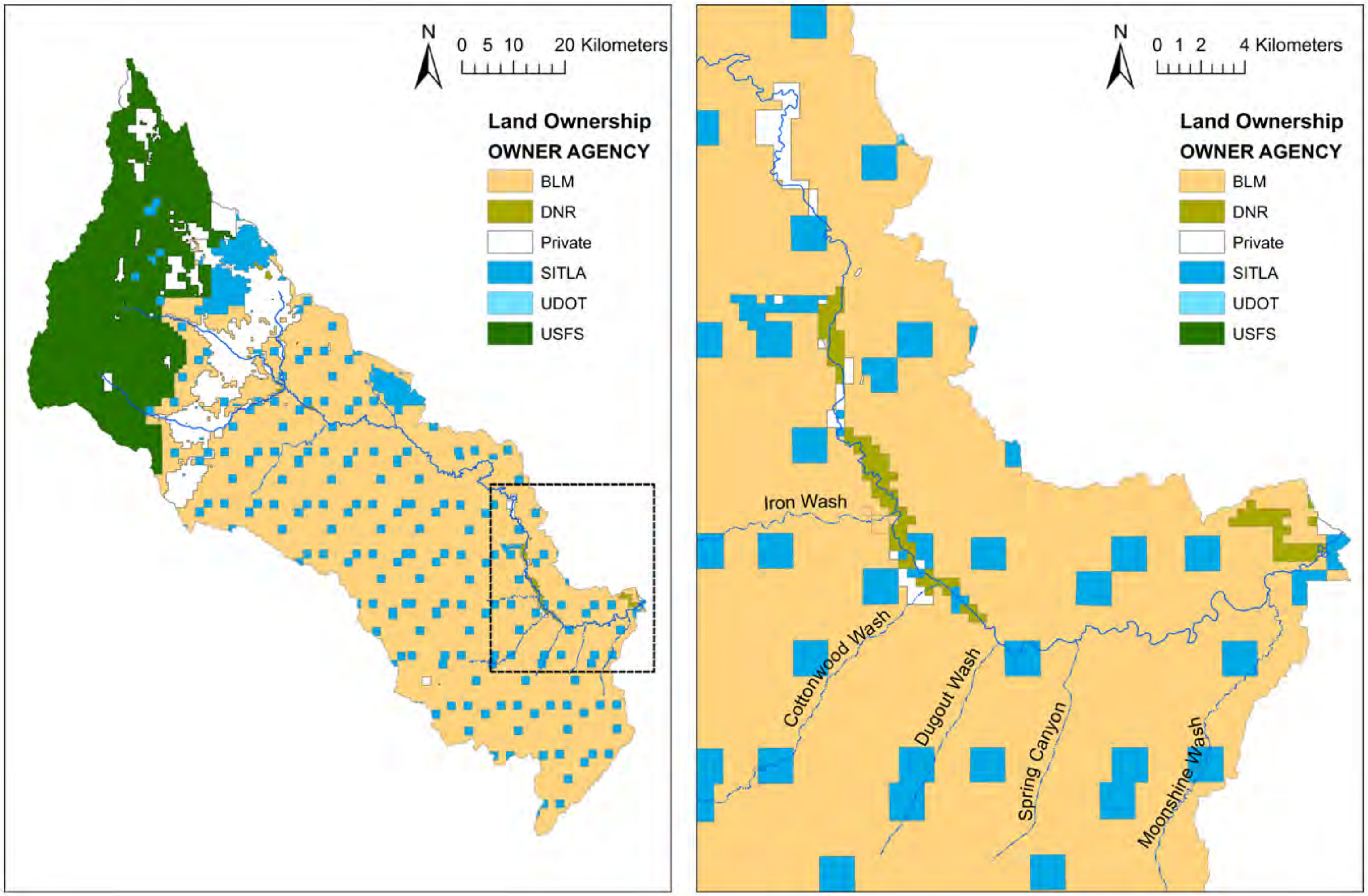

Figure 4. Land ownership map of the San Rafael River watershed (Dataset provided by Bureau of Land Management and State of Utah School and Institutional Trust Lands Administration). The left map shows the entire San Rafael River watershed and the right map shows the lower river only (dashed box in left map). The lower river watershed is mostly BLM and state (DNR and SITLA) land. Abbreviations as follows: BLM – Bureau of Land Management; DNR – Utah Department of Natural Resources; SITLA – State School and Institutional Trust Lands; UDOT – Utah Department of Transportation; USFS – United States Forest Service.

Figure 5. Picture of Hatt's Ranch diversion dam, which is a barrier to upstream fish movement. The dam is located on bedrock and was constructed in its current location in the early 1950s. Photo by B. Laub on October 12, 2012 at a flow of 18 cfs.

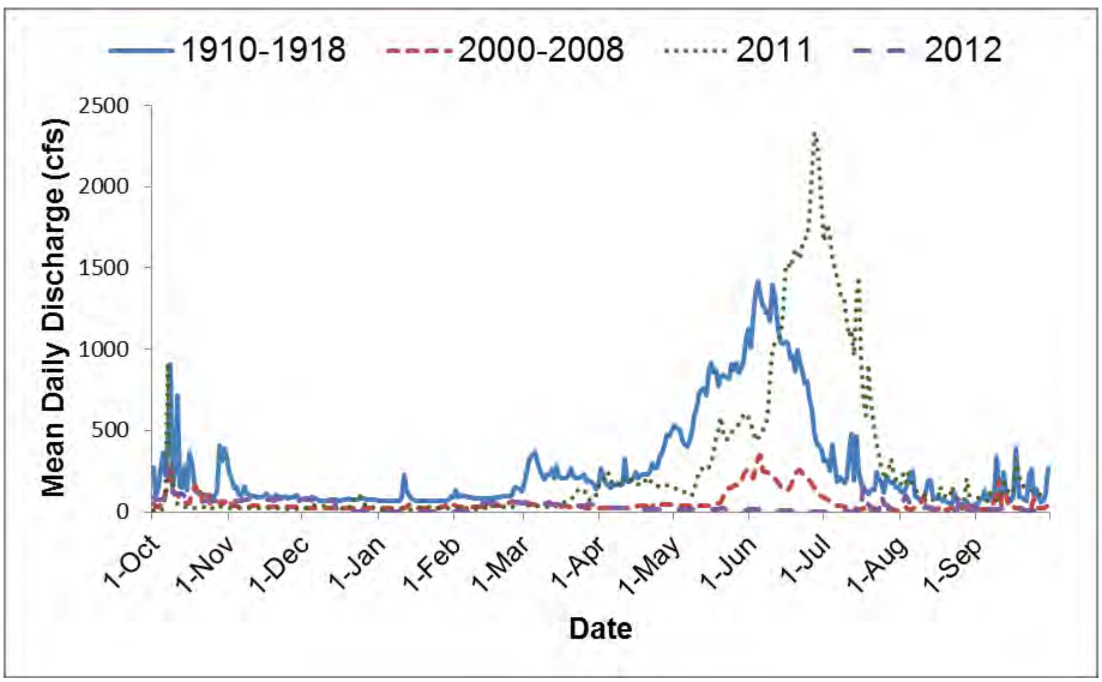

Figure 6. Average mean daily discharge for water years 1910-1918 and 2000-2008 from the USGS SH-24 gage (09328500). Mean daily flow of the 2011 and 2012 water years are also shown. The water year runs from October 1 to September 30. The period 1910-1918 represents the earliest period of record for the gage and 2000-2008 is the most recent decadal period. Mean annual flow in 1910-1918 (272 cfs) was above average for the period of record (132 cfs) and represents a particularly wet period, whereas mean annual flow in 2000-2008 was below average (55 cfs) and represents a drought period. Note the long duration spring snowmelt flood peak and shorter duration summer and fall floods. Also note the reduced spring snowmelt flood peak and duration for 2000-2008 compared to 1910-1918. Adapted from Fig. 8 of Fortney et al. 2011.

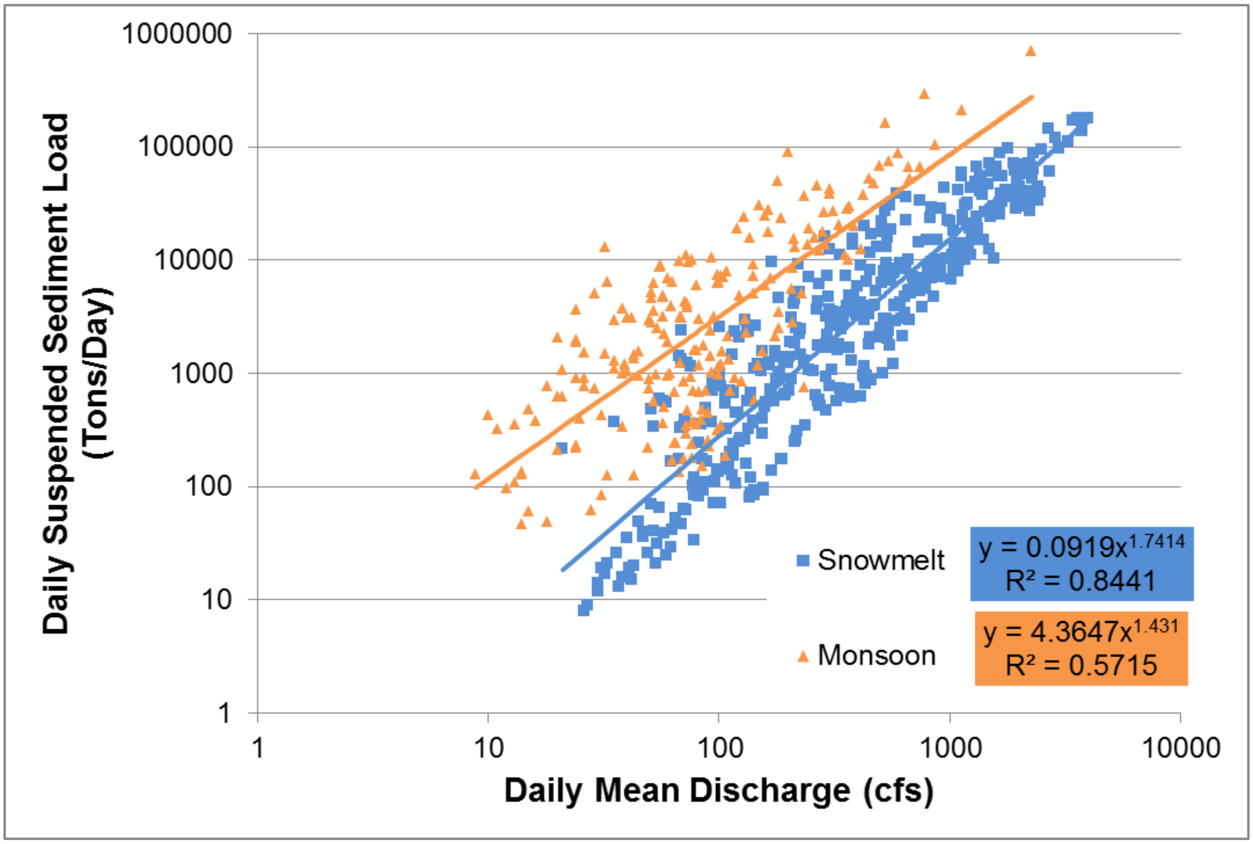

Figure 7. Suspended sediment rating curves measured in 1949 and 1951-1958. Flood types were distinguished on the combination of season and flood duration. In general, snowmelt floods occurred in spring and monsoon floods occurred in summer.

Water Quality Conditions

The Utah Department of Environmental Quality, Division of Water Quality (UDEQ-DWQ) is required to identify beneficial uses and associated water quality standards for Waters of the State. Beneficial uses and water quality standards are listed in the Utah Administrative Code R317-2, available on the web (http://www.rules.utah.gov/publicat/code/r317/r317-002.htm). The San Rafael River, as a tributary to the Green River, is located within the Colorado River West Watershed Management Unit. The San Rafael River is divided into two assessment units: the San Rafael Lower Assessment Unit (San Rafael River from Green River confluence to Buckhorn Wash) and the San Rafael Upper Assessment Unit (San Rafael River from Buckhorn Wash to the confluence of Huntington and Cottonwood Creeks). Perennial waters within the San Rafael Assessment Units are identified to support the following beneficial uses:

2B – protected for secondary contact recreation such as boating, wading, or similar uses.

3C – protected for nongame fish and other aquatic life, including the necessary aquatic organisms in their food chain.

4 – protected for agricultural uses including irrigation of crops and stock watering.

The Clean Water Act requires UDEQ-DWQ to report the condition of all surface waters to the Environmental Protection Agency (EPA) and Congress every two years. This is done through submission of the "Integrated Report". This report summarizes the overall condition of waters within Utah and identifies waterbodies that are not supporting designated beneficial uses (i.e., 'impaired').

Both the Upper and Lower San Rafael River Assessment Units were included on the 2000 UDEQ-DWQ 303(d) List of Impaired Waters (UDWR 2012) for not supporting the Beneficial Use Class 4 – Agriculture for total dissolved solids (TDS) of 1,200 mg/L. This listing requires development of a Total Daily Maximum Load (TMDL) report. As a result, a TMDL for the Price River, San Rafael River, and Muddy Creek was developed and approved by the EPA in 2004 (MFG, Inc. 2004). This report described the nature and occurrence of the TDS water quality impairment and developed target reductions. Total dissolved solids are composed mostly of ionic dissolved minerals with small amounts of organic matter, and is thus often referred to as an indicator of salinity (e.g., Gerner 2008). In the 2010 Integrated Report (UDEQ 2010), the Upper San Rafael River Assessment Unit was included on the 303(d) List for Benthic Macroinvertebrate Bioassessment for not supporting Beneficial Use Classification 3C – Non-game fish and other aquatic life. This is the first assessment cycle for this listing, so further investigation is needed to understand and address this impairment.

The cause of the elevated salinity/TDS in the San Rafael River is thought to be a combination of natural sources and anthropogenic modifications to the landscape. TDS levels can increase naturally when water is exposed to or travels through soluble sedimentary geologic strata or soils with soluble salts or minerals, or when summer thunderstorms generate and transport large amounts of sediments and solutes to the streams (Gerner 2008). These natural sources of loading are particularly prevalent in the Mancos Shale, a marine-derived deposit of silts and clays that is high in sodium-sulfate minerals and underlies much of the mid-elevations in the San Rafael River watershed. (Waddell et al. 1981, Mundorff and Thomspon 1982, Whittig et al. 1982, Warner et al. 1985). In addition, evaporation or loss of soil moisture in the semiarid to arid climate enhances the physical precipitation of dissolved solids. Land anagement activities that affect upland or riparian vegetation or soils, increase runoff, or increase stream sedimentation rates can also influence TDS.

Despite natural sources of TDS loading, the 2004 TMDL identifies the main source of TDS in the San Rafael River as return flows from irrigated agriculture in Castle Valley (MFG, Inc. 2004, see Fig. 2). Much of the agriculture in the San Rafael River watershed was historically flood-irrigated, which led to overwatering and either direct runoff or seepage of water through Mancos Shale soils to the groundwater, both of which cause elevated salinity/TDS levels in irrigation return-flows (Warner et al. 1985). These irrigation return-flows are thought to be the primary cause of elevated TDS concentrations in the San Rafael River, but land use practices such as intensive grazing and recreation are also thought to contribute by increasing erosion and delivery of soil particles to the river (UDWR 2012). Other sources of TDS loading, including leaky stock ponds and municipal water lines, urban runoff, use of water in coal bed methane wells, and for cooling in coal generation plants are also thought to be minor sources of loading relative to agricultural sources (MFG Inc., 2004).

Current salinity levels observed in the San Rafael River are below values where acute impacts are observed on fish (Sorensen et al. 1977). However, previous work has found shifts in macroinvertebrate communities at levels of salinity comparable to those in the San Rafael River (Metzeling 1993, Marshall and Bailey 2004), and this could impact native fish. Furthermore, non-native tamarisk are known to out-compete native cottonwood at elevated salinity levels (Shafroth et al. 1995), suggesting that the elevated salinity levels in the San Rafael River could have negative impacts on native riparian vegetation communities. As a tributary within the Colorado River Basin, efforts to reduce salinity levels will fall under the goals of the Colorado River Basin Salinity Control Program (NRCS 2012). Efforts to reduce TDS loading to the San Rafael River are underway, primarily through conversion of flood irrigation systems to pressurized-pipe sprinkler irrigation systems (UDWR 2012). These efforts are likely to continue and will likely be accelerated in 2015 when rotating funding from DWQ becomes available for the San Rafael River watershed and surrounding areas.

Hydrologic Changes

Water storage and diversion in the headwaters of the San Rafael River have severely altered the river flow regime. Mean annual flow has declined approximately 200 cubic feet per second (cfs) from the early 1900s (Fortney et al. 2011). The decline in mean annual flow is due in large part to reduction in magnitude and duration of spring snowmelt floods, from a median peak discharge of 1,320 cfs and duration of 70 days in the early 1900s to 345 cfs and duration of 23 days in the previous decade (Fortney et al. 2011; Fig. 6). Large magnitude warm season flows have also been rare in recent decades, with the five largest warm season floods all occurring prior to 1960. The early 1900s was the period of highest average streamflow over the last 500 years in the Green River basin (Piechota et al. 2004), and although the trend in reduced peak discharges has been temporarily interrupted on multiple occasions, most notably by large spring snowmelt floods in 1983 and 1984 and most recently by a large spring snowmelt flood in 2011, there has been a general change in the flow regime from consistent large magnitude, long duration spring snowmelt floods coupled with large magnitude, short duration warm season floods to small magnitude, short duration spring snowmelt and warm season floods.

Changes in low flows over time have been less well studied. Based on the USGS SH-24 gage record, dewatering of the lower river has occurred in dry years since the early 1900s. However, irrigation development in Castle Valley was already extensive by this time (Geary 2003), so whether drying occurred naturally is unknown. In some systems impacted by dams and diversions, low flows remain higher than natural during dry periods due to releases from dams for water delivery downstream (Petts 1984). Elevated low flows are not an issue on the lower San Rafael River, because all major dams in the San Rafael River watershed are located on the tributary streams, and nearly all water withdrawls occur upstream of the San Rafael River mainstem. Thus, the primary impact to low flows on the lower San Rafael River has most likely been an increase in frequency and duration of dewatering (see also Fig. 49).

Geomorphic Changes

Historic photographs and cross-section measurement data from the USGS SH-24 gage has indicated that the channel in the vicinity of Hatt's Ranch was historically wide, braided, and shallow with several active channels, bars, and riffles, but that over time, the channel has narrowed and incised (Dean et al. 2009, Fortney et al. 2011; Figs. 8, 9 and 41, also see Fig. 6 in Fortney 2013b – attached as Appendix III). Width to depth ratio has decreased from a mean of 66 in the early 1900s to 22.4 in the period 1958-2010. Historical aerial photographs and floodplain stratigraphic analysis have indicated that the general pattern of channel change from a wide, shallow, braided system to a narrow, single-thread, confined pattern have generally been consistent throughout the lower San Rafael River (Fig. 10, also see Figs. 27 and 31 in Fortney 2013b), though the degree of incision has been greatest in the vicinity of Hatt's Ranch. The width to depth ratio of the early 1900s may be unusually high because average discharge during this period was unusually high compared to historical records (Piechota et al. 2004). If heavy grazing occurred in the watershed during this time, sediment loads may have also been unusually high, but this is unknown. In any case, it is clear that channel narrowing and confinement have resulted in reduced channel complexity, measured by the amount of pools, riffles, and backwaters within the lower river (Fortney et al. 2011). These channel adjustments have been paralleled by adjustments in floodplain surfaces along the lower river. The narrowing of the river channel has created a lower floodplain that roughly follows the former active channel, and this floodplain is inset within the former river floodplain (Fortney 2013a). The lower floodplain is now the primary active floodplain, whereas the older floodplain surface is only rarely inundated (Fig. 9).

The pattern of channel narrowing documented on the San Rafael River has been observed on other rivers throughout the southwest, including the Green (Graf 1978, Andrews 1986, Allred and Schmidt 1999, Birken and Cooper 2006), the Escalante (Birkeland 2002), the Paria (Hereford 1986, Graf et al. 1991), and the Rio Grande (Everitt 1998, Dean and Schmidt 2011), and has generally been attributed primarily to dam and climate-induced alterations of historic flow regimes, although local slope changes may drive changes in channel geometry as well (Topping 1997). Work on rivers with a snowmelt-dominated discharge pattern has found that reduction in magnitude and duration of spring snowmelt floods has reduced the potential for these rivers to scour and rework in-channel features such as gravel bars (Graf 1978, Andrews 1986, Everitt 1998, Allred and Schmidt 1999, Dean and Schmidt 2011). The bars thus become stabilized and further sediment deposition fills in backwaters and side channels and causes the channel to narrow. Sediment deposition on floodplains causes vertical accretion of the floodplains, so that the river is further confined in a narrow channel. Importantly, the confinement of the channel is not due to incision within the historic floodplain, but primarily to vertical accretion of floodplains and formation of riparian berms or levees during overbank flooding and associated sediment deposition (Figs. 8 and 9). The persistence of summer monsoon floods exacerbates channel change, because the river channel now holds less water, such that these small floods overwhelm the channel capacity, flow onto the floodplain and deposit additional sediment, leading to further channel narrowing and confinement (Birkeland 2002, Dean et al. 2009, Dean and Schmidt 2011, Fortney et al. 2011). Essentially, flood flows have decreased in many rivers of the southwest, whereas sediment inputs have not changed, and rivers have adjusted their channel dimensions to the altered water and sediment regimes.

The changes in channel geometry on the San Rafael River have been attributed to similar processes as those for other snowmelt-driven desert rivers (Fortney et al. 2011). The frequency of large, long-duration spring snowmelt floods capable of reworking channel bars, eroding channel banks, and transporting large quantities of sediment through the river has been reduced. At the same time, sediment supply has been maintained because warm season flows that carry high sediment loads still occur with regularity. Warm season floods contribute to floodplain accretion and produce further channel narrowing and confinement. The general pattern of channel narrowing has been consistent throughout the San Rafael River, but the magnitude and proportion of channel narrowing has been variable in the different sections of the lower San Rafael River (Fig. 10). Sections of the river in wider valley segments have seen greater channel narrowing relative to sections in narrow valleys, likely due to the more frequent impingement of the channel on the bedrock valley perimeters in narrow valleys (Fortney 2013a). The effect of this greater proportional narrowing in wider valley segments, where the river was historically wider, has reduced overall variability in channel width throughout the lower San Rafael River (Fig. 10). In addition, the greatest magnitude of channel confinement has been observed in the vicinity of Hatt's Ranch due to channel incision. Incision in the vicinity of Hatt's Ranch was caused by channel straightening in this reach and loss of a gradient control point downstream from Hatt's Ranch in 1983 when the river cut-off a meander bend and abandoned an existing diversion dam (Fortney 2013b). As a result of these changes, the channel has transitioned from a wide, shallow, complex system to a homogenous deep narrow sandy run with few pools and backwaters and other complex channel elements.

Figure 8. Pictures showing channel changes just upstream of Cottonwood Wash on the San Rafael River (photos are looking downstream toward Cottonwood Wash). The top photo shows the channel in 1917 (photo by W. B. Emery) and the bottom photo shows the channel in 1994 (photo by E. Hindley). Note the unvegetated bar on the left side of the 1917 picture and the wide active channel. In the bottom photo, vegetation has colonized the bar and the channel is confined within high vertical banks. The confinement into a narrow, deep channel is a result of sediment deposition and stabilization by vegetation within the former active channel and deposition on the floodplain which has caused vertical floodplain aggradation and the formation of riparian berms (see Fig. 10). The channel in this location was abandoned in 2011 as a result of a meander cutoff event (see Figs. 14 and 37).

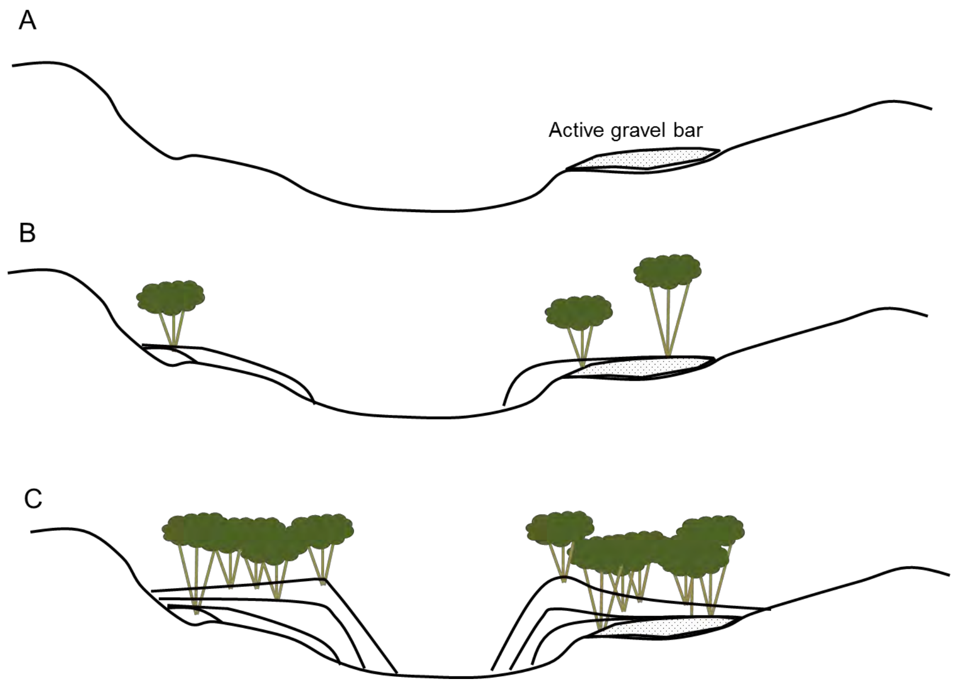

Figure 9. Generalized schematic of channel changes on the San Rafael River. In the top figure (A), the active channel is wide and maintains gravel bars free of vegetation. As spring flood flows decrease in magnitude, duration, and frequency, vegetation, including non-native tamarisk, is able to colonize gravel bars and floodplain deposits and the channel begins to narrow (B). Continued deposition due to monsoon floods further promotes floodplain accretion, formation of riparian berms, and channel confinement (C). Note that the channel elevation has remained the same and there is now an inset floodplain occupying the former active channel.

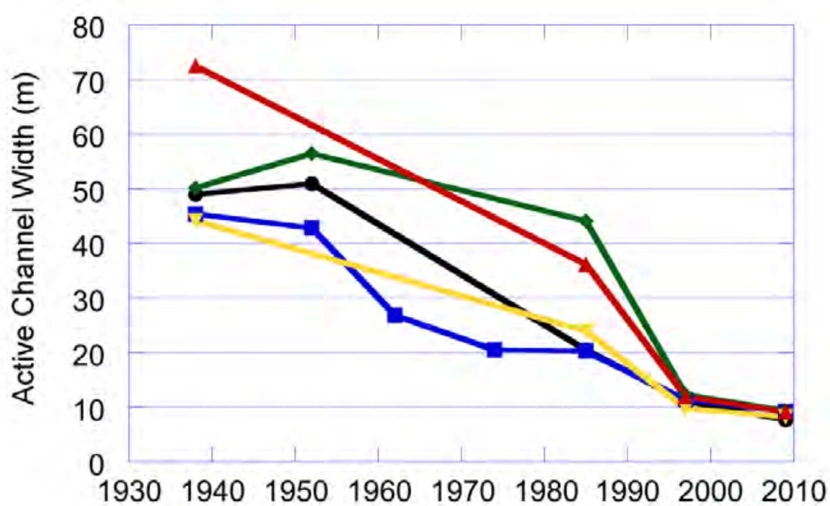

Figure 10. Reach-averaged active-channel width measurements from aerial photographs for the five geomorphic reach segments of the lower San Rafael River (adapted from Fortney 2013b). Triangles are geomorphic reach 5 (most downstream reach), diamonds are reach 3 (reach between Hatt's Ranch dam and Dugout Wash), circles are reach 1 (most upstream reach), squares are reach 2 (between I-70 and Hatt's Ranch dam) and upside-down triangles are reach 4 (between Dugout Wash and Chaffin's Ranch).

Vegetation Changes

The combination of active channel migration and spring snowmelt floods likely supported establishment of cottonwood and other native vegetation, though likely only episodically and in patches. In particular, cottonwood establishment requires specific hydrologic patterns, including a sufficient flood magnitude that creates bare mineral surfaces as seed beds at the appropriate channel elevation during seed release, followed by a prolonged recession limb to support seedling root system growth (Braatne et al. 1996, Scott et al. 1997, Mahoney and Rood 1998). This model of cottonwood recruitment is generally applicable to alluvial systems characterized by spring snowmelt floods and their associated sediment movement, but such conditions were likely not met every year. Such conditions are provided only episodically by floods and associated sediment movement processes that temporarily widen the channel and cause channel meander cutoffs (Friedman and Lee 2002). Subsequent high spring flows deposit seeds on areas where the channel widened and in abandoned meander bends, which provide fresh sediment and moist soil conditions suitable for germination. However, subsequent high flows and additional channel movement can induce significant mortality of newly established seedlings (Braatne et al. 1996, Mahoney and Rood 1998). Thus, recruitment tends to be on the local scale on active river channels such as the historic San Rafael River, and recruitment is critically dependent on channel change driven by espisodic high flow events (Friedman and Lee 2002).

The reduction in spring snowmelt floods has likely reduced opportunities for cottonwood and other native vegetation recruitment. Partly due to reduced channel movement, tamarisk (*Tamarix* spp.) was able to colonize the lower San Rafael River starting in the 1950s (Fortney et al. 2011). Tamarisk subsequently increased in abundance and likely exacerbated channel narrowing and confinement. Tamarisk is a woody shrub that has colonized river floodplains throughout the southwestern US (Sanchez and Shaver 2003, Friedman et al. 2005a). Tamarisk develops extensive root systems and has been shown to substantially increase resistance of sediment to erosion (Di Tomaso 1998, Pollen-Bankhead et al. 2009, Vincent et al. 2009). Tamarisk often establishes dense thickets that can enhance floodplain accretion by reducing water velocity and allowing sediment to settle out (Cooper et al. 2003, Griffin and Smith 2004, Friedman et al. 2005b). This sediment deposition often results in the formation of riparian berms or levees that sever channel and floodplain connectivity and such berms have been observed throughout much of the lower San Rafael River (Figs. 13 and 30). Previous work on rivers in the southwestern U.S. has indicated that tamarisk colonization and stabilization of active gravel bars in river channels has contributed to channel narrowing (Graf 1978, Allred and Schmidt 1999, Birkeland 2002, Birken and Cooper 2006, Dean and Schmidt 2011). Thus, tamarisk colonization has likely been a contributing factor in driving channel narrowing in the lower San Rafael River, but narrowing is likely to have occurred in the absence of tamarisk due to reduction in spring snowmelt floods.

Tamarisk colonization can reduce the abundance of native woody riparian vegetation species, primarily willow (*Salix* spp.) and cottonwoods (*Populus* spp.) by shading out native riparian seedlings (Engel-Wilson and Ohmart 1978, Di Tomaso 1998, Smeins 2003). Although no studies have formally determined whether the abundance of willow or cottonwood has declined along the San Rafael River from the early 1900s, replacement of native vegetation by tamarisk appears to have occurred in at least some places on the San Rafael River. In particular, the section between the San Rafael Reef and Hatt's Ranch dam contains very few cottonwood trees but thick tamarisk stands (Fig. 11). However, cottonwood stands with multiple age classes are found on other reaches of the river on the lower floodplain surface (Fortney 2013a; Fig. 12), indicating that tamarisk has not completely eliminated cottonwood recruitment. In addition, stands of willow and native phragmites are abundant along the riparian berms in many places throughout the lower San Rafael River, and tamarisk stands are generally set back from the channel edge and occupy much of the floodplain (Fig. 13).

Previous work has shown that cottonwood and willow seedlings can out compete tamarisk in areas where flood flows deposit fresh sediment and water tables and soil moisture are elevated (Sher et al. 2000, Lite and Stromberg 2003, Bhattacharjee et al. 2006); tamarisk only gains a competitive advantage when under dry or salty soil conditions (Glenn and Nagler 2005, Stromberg et al. 2007). Tamarisk has been viewed as an opportunistic invader, colonizing primarily along rivers that have altered flow regimes or on surfaces unsuitable for colonization by native vegetation (Di Tomaso 1998, Everitt 1998, Lesica and Miles 2001, Cooper et al. 2003, Glenn and Nagler 2005, Stromberg et al. 2007). In addition, tamarisk produces seeds throughout the growing season, whereas cottonwood and willow only release seeds in the spring (Di Tomaso 1998, Sanchez and Shaver 2003). Thus, reduction of native vegetation along the San Rafael River has likely been driven primarily by a combination of altered flows and tamarisk colonization. Reduction in the magnitude and duration of spring snowmelt floods reduces the area available for native seedling establishment, and the continuation of warm season floods that deposit floodplain sediments when tamarisk seeds are available allows tamarisk seedlings to establish (Cooper et al. 2003). The presence of thick tamarisk stands has likely contributed to reduced establishment of native vegetation across large areas even when spring floods have occurred, due to shading effects and competition for soil moisture.

In recent years, nearly all tamarisk along the lower San Rafael River has been annually defoliated by the tamarisk leaf beetle (*Diorhabda* spp.). The beetle was initially released by the Emery County Weed Department on the upper San Rafael River at Fuller Bottom in 2005 and was later released on the lower San Rafael River at Hatt's Ranch (Keller 2012). Vegetation mapping on the lower San Rafael River has revealed that only a few locations on the lower San Rafael River were not defoliated in the summer of 2012, including in the immediate vicinity of the Green River confluence and the mouth of Dugout Wash (vegetation map available at url: http://bit.ly/1awJyOr). Currently there is no direct evidence that the beetle has caused wide-spread tamarisk mortality; however, previous research has shown that consistent, severe beetle defoliation can cause mortality of tamarisk after 4 years (Dudley et al. 2006), suggesting that there may be significant tamarisk mortality in the near future. Russian olive (*Elaeagnus* *angustifolia*), another non-native woody species that has colonized riparian areas over much of the southwestern U.S. (Friedman et al. 2005a), is also present on the San Rafael River, though at much lower abundance than tamarisk. Reduction of tamarisk extent through beetle mortality may provide an opportunity for Russian olive and non-native herbaceous vegetation to increase their distribution on the San Rafael River in the future.

Secondary impacts of vegetation changes

In addition to the channel changes exacerbated by tamarisk and other floodplain vegetation encroachment, alteration of native vegetation communities has likely impacted in-stream ecological processes and wildlife communities as well. Replacement of native vegetation, particularly large cottonwoods, by tamarisk may have negatively impacted habitat for native fish on the San Rafael River by reducing the amount of large wood and wood accumulations in the river. Analyses of aerial imagery and on-the ground observations have found that wood accumulations and large pieces of wood, primarily large cottonwood trees, increase channel complexity and provide important fish habitat including scour pools, backwaters, and overhead cover (Keller 2012 – attached as Appendix IV, see also Fig. 28).

Beaver (*Castor canadensis*) may also have been impacted by colonization of tamarisk. Beaver currently occupy the San Rafael River and likely were present throughout the river system historically, based on observations of old beaver cuttings (personal observation). However, beaver may be restricted in their current distribution, because they are known to strongly prefer species of *Populus* and *Salix* as a food source (e.g., Doucet and Fryxell 1993), and tamarisk is considered undesirable forage due to its low nutrient content and branched condensed tannins (Sharma and Parmar 1998). Although beaver are not listed as a species of conservation concern in Utah, reductions in their populations on the San Rafael River could have negative consequences for maintenance of high quality fish habitat and native vegetation establishment. Beaver directly provide woody debris accumulations through dam building activities, which, as discussed above, have been shown to be important areas for creation of fish habitat. In addition, beaver dams can trap large volumes of sediment and maintain local groundwater levels during dry periods (Naiman et al. 1986, Butler and Malanson 2005, Westbrook et al. 2006, Pollock et al. 2007), which can promote establishment and growth of native vegetation (Westbrook et al. 2011). Indeed, the positive effects of beaver dams for vegetation establishment have been directly observed on the San Rafael River (Fig. 14). Thus, replacement of native vegetation by tamarisk may have negative consequences for beaver populations, and through the reduction of dam-building activities, may have contributed to habitat degradation for native fish and vegetation.

Lowland riparian habitats consisting of native cottonwood and willow communities have been identified as a key habitat type in the state of Utah, supporting a high diversity of bird species (UDWR 2005). Colonization by non-native species including tamarisk has been identified as a major threat to these habitats (UDWR 2005), and this is supported by previous research showing that many bird species selected native vegetation communities over tamarisk stands and that overall diversity and abundance of birds is often lower in tamarisk stands (Di Tomaso 1998). Thus, the quality of habitat for many wildlife and fish species has likely declined in many areas of the San Rafael River as native vegetation has been replaced by tamarisk.

Fish Community Response

Little information on fish assemblages in the San Rafael River is available for the period prior to initiation of hydrologic and geomorphic changes (McAda et al. 1980). However, recent work has provided detailed information on the current distribution patterns of native and non-native fish within the river (Bottcher 2009, Walsworth 2011 – attached as Appendices V and VI). In combination with research from other rivers on the same species found in the San Rafael River, this work provides useful information about how fish assemblages have likely responded to hydrologic and geomorphic changes within the San Rafael River.

Four native fish species have been observed regularly within the San Rafael River during sampling: speckled dace (*Rhinichthys osculus*), flannelmouth sucker (*Catostomus latipinnis*), bluehead sucker (*Catostomus discobolus*), and roundtail chub (*Gila robusta*) (McAda et al. 1980, Bottcher 2009, Walsworth 2011). Endangered fishes of the Colorado River Basin, including Colorado pikeminnow (*Ptychocheilus lucius*) and razorback sucker (*Xyrauchen texanus*), have also been observed in the San Rafael River (McAda et al. 1980, Bottcher 2009), and although abundances of these endangered species are low, they likely made greater use of the San Rafael River historically. A rangewide conservation agreement was signed to manage the flannelmouth sucker, bluehead sucker, and roundtail chub in 2004 (UDNR 2006). The focus of restoration on the San Rafael River will be these three species (hereafter the three species), but restoration efforts are likely to benefit endangered fishes of the upper Colorado River Basin as well.

Densities of the three species have been consistently higher in sampling locations in the upper San Rafael River than in the lower San Rafael River (McAda et al. 1980, Bottcher 2009, Walsworth 2011). The reduced density of the three species in large sections of the lower San Rafael River has been attributed to a suite of factors, including competition and predation from non-native fish, dewatering during dry periods, low productivity, increased water temperatures, and a lack of complex habitat, including riffles, pools, and backwaters (Bottcher 2009, Budy et al. 2009, Walsworth 2011, Keller 2012). However, native fish have been observed in the lower San Rafael River where complex habitat is available (Bottcher 2009).

In terms of habitat requirements, roundtail chub adults have been found to prefer deep pools with abundant cover with forays into riffles and runs for feeding (McAda et al. 1980, Bestgen and Propst 1989, Barrett and Maughan 1995, Bezzerides and Bestgen 2002, Bottcher 2009). Bluehead sucker adults have been found to prefer deep riffles with coarse sediment (McAda et al. 1980, Bezzrerides and Bestgen 2002, Anderson and Stewart 2003, Bottcher 2009). Flannelmouth sucker adults are more generalist in their habitat preferences but also prefer deep, swift riffles, runs, and pools (Bezzerides and Bestgen 2002, Anderson and Stewart 2003, Bottcher 2009). Younger age classes of each species prefer slower, shallower areas with cover, such as pool margins and backwaters (Bestgen and Propst 1989, Barrett and Maughan 1995). Deep pools may also be important as thermal refugia and as refugia during low-water periods in the summer (Magoulick and Kobza 2003). Spawning generally occurs in spring and early summer over gravel bars or in deeper riffles with gravel substrate (Bezzerides and Bestgen 2002).

Much of the lower San Rafael River appears to contain poor habitat quality for the three species (Budy et al. 2009; Fig. 15). The narrowing and entrenchment of the channel has led to elimination of riffle and pool sequences and loss of backwaters that are critical habitat areas for the three species. Riffle-pool sequences with coarse bed material also provide important habitat for a diverse assemblage of macroinvertebrates, and the low abundance of riffle habitat in the lower San Rafael River likely limits available food resources for the three species (Walsworth et al. 2011). Thus, although there are no records of historic abundance of the three species in the San Rafael River, changes in channel geometry have likely reduced the amount of available habitat for the three species and their preferred prey items since the early 1900s. There are some isolated sections of the lower river that contain more complex habitat (Walsworth 2011). In particular, at tributary confluences there tends to be an upstream pool and a downstream sequence of riffles with coarse sediment and alternating bars (Fortney 2013a; Fig. 16). Bedrock controls and beaver dams have similar local influence on channel geomorphic complexity (Fortney 2013a). Higher densities of the three species have been found or are predicted to occur in these areas of more complex habitat (Budy et al. 2009, Walsworth 2011; Fig. 15). However, these patches of relatively complex habitat are exceptions to the general pattern of low quality habitat that exists in large stretches of the lower river (INSE 2012).

Non-native fish are also found in the lower San Rafael River and include red shiner (*Cyprinella lutrensis*), sand shiner (*Notropis stramineus*), mosquitofish (*Gambusia spp.*), fathead minnow (*Pimephales promelas*), common carp (*Cyprinus carpio*), black bullhead (*Ameiurus melas*), and channel catfish (*Ictalurus punctatus*) (McAda et al. 1980, Walker and Hudson 2004, Bottcher 2009, Walsworth 2011). Non-native fish are preying on and competing with the three species in the lower San Rafael River and are a severe threat to persistence of native fish in the lower river (Walsworth 2011, Walsworth et al. 2013). Competition may be especially intense in the lower river due to the limited availability of habitat for production of food resources such as macroinvertebrates (Walsworrth 2011). Non-native fish can also restrict habitat use by native fish to non-preferred or non-optimal habitats (e.g., Scoppettone et al. 2005). Many non-native fish, particularly the larger predatory species, are not present in the upper San Rafael River due to Hatt's Ranch dam, which prevents upstream movement of both native and non-native fish (McAda et al. 1980, Bottcher 2009).

Native fish populations and movement within the San Rafael River are also likely limited by occasional drying of the lower river during periods of low water and complete freezing of the water column during cold periods in winter (Bottcher 2009, Ian Gowing, Utah State University Water Research Lab, personal communication). Previous work on other intermittent rivers has found that river drying can extirpate individual fish species and alter fish communities relative to perennial reaches (Davey and Kelly 2007, Falke et al. 2011). Temperature may also limit distribution of native fish in the lower river. Although the impact of temperature on the three species has not been assessed, temperature monitoring by the USGS at the SH-24 gage between 1950 and 1977 indicated that summer temperatures at this location consistently approached and sometimes exceeded 30°C (Fig. 17), which is at the upper end of temperature preferences for the three species (Bezzerides and Bestgen 2002). Temperatures exceeding 35°C have also been observed in isolated pools when the river has become dewatered (Bottcher 2009). Even if temperatures do not exceed 30°C in the summer, as temperature increases metabolic demands increase, and the low productivity combined with competition from non-native species in the lower San Rafael River may prevent native fish from obtaining sufficient resources to meet metabolic demands when temperatures are elevated. Thus, temperature may be a limiting factor for native fish in some years. The spatial variability of temperatures and the availability of temperature refugia through the lower San Rafael River have not been assessed; however, the Utah State University (USU) Water Lab is currently conducting a study of temporal patterns in water temperatures at multiple locations and habitat features throughout the lower San Rafael River that should help inform this issue (UWRL 2013). The presence of non-native species, occasional drying and freezing, and possible inhospitable temperature regimes in the lower river have combined with the low-quality habitat to create a situation in which populations of native fish in the lower river exist as sink populations, even in isolated areas where habitat quality is higher, and are sustained only by immigration from populations in the upper San Rafael River and Green River (Bottcher 2009, Budy et al. 2009, Walsworth 2011).

Figure 11. Picture looking upstream of Hatt's Ranch diversion dam. Note the general lack of cottonwood and willow overstory cover and the abundant tamarisk, which has been defoliated by the tamarisk leaf beetle. Picture taken by B. Laub on October 12, 2012.

Figure 12. Picture taken at Frenchman's Ranch showing a stand of cottonwood trees of multiple age classes. The low abundance of tamarisk in this picture is due to a tamarisk removal effort carried out by Utah Division of Wildlife Resources (UDWR). Photo taken by B. Laub on October 12, 2012.

Figure 13. Picture looking upstream toward Dugout Wash. Note the band of willows and other vegetation along the riparian berm and the thick tamarisk stand that occupies much of the floodplain. Photo taken by B. Laub on October 12, 2012.

Figure 14. Impacts of a beaver dam on cottonwood recruitment. The top panel shows a beaver dam upstream of the confluence with Cottonwood Wash (note riparian ecologists for scale). Photo taken by B. Laub on November 7, 2012. The bottom panel is a picture of the channel upstream of the beaver dam, looking upstream, taken by B. Laub on October 12, 2012. As seen in the bottom panel, the dam backed up water in the channel and likely aided cottonwood recruitment in this area (shown in inset, taken by B. Laub on October 12, 2012).

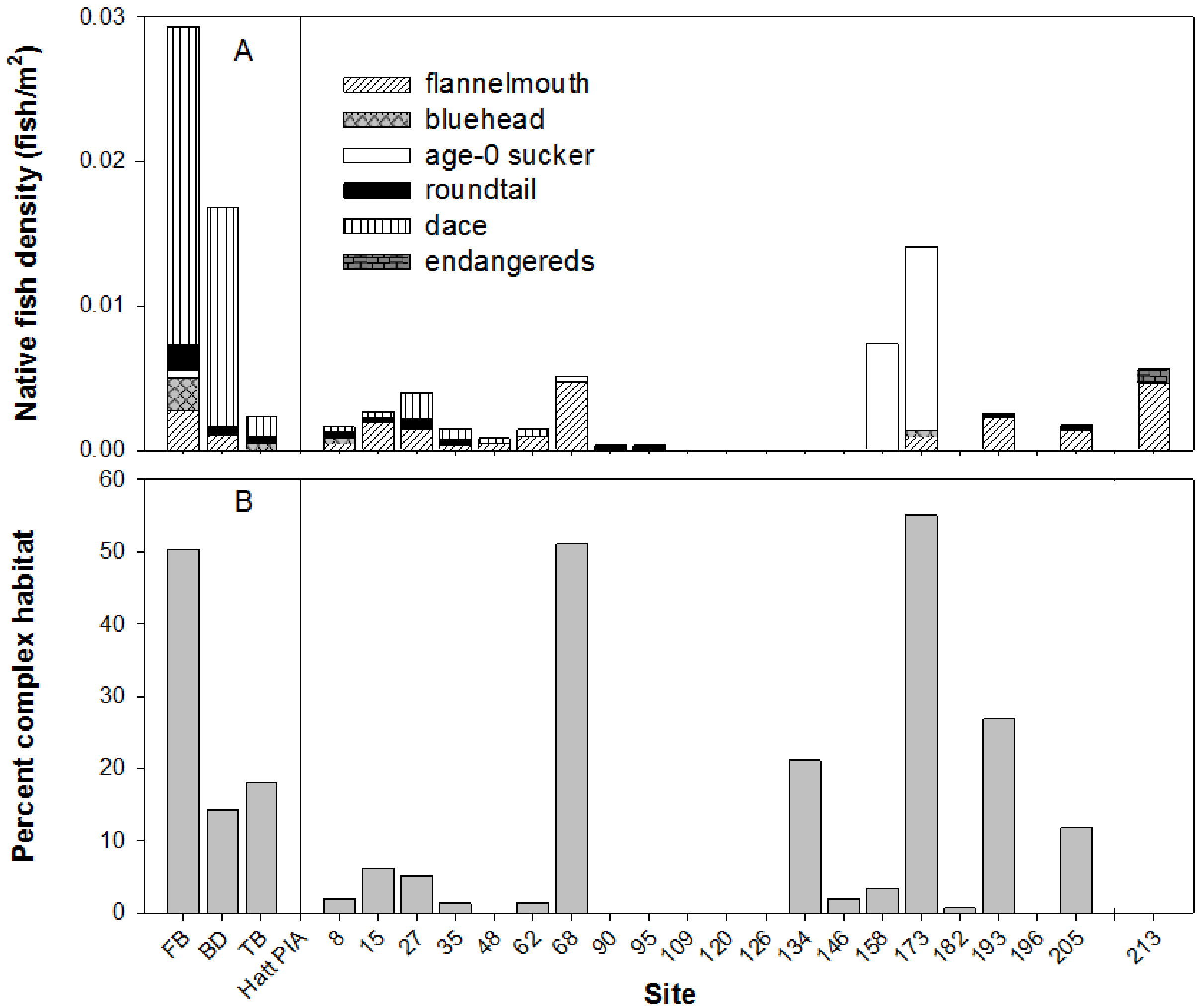

Figure 15. Fish density (top) and percent complex habitat (bottom) at sampling locations along the lower San Rafael River. Percent complex habitat was assessed as percent of sampling reach comprised of riffles, pools, and backwaters. Sampling locations are arranged from upstream to downstream. The Hatt pit-tag antenna (Hatt PIA) was installed at the USGS SH-24 gage. Abbreviations as follows: FB – Fuller Bottom; BD – Buckhorn Draw; TB – Tidwell Bottom. Adapted from Budy et al. 2009.

Existing Restoration Efforts

There are two efforts aimed at improving ecological conditions on the San Rafael River that have been undertaken in recent years. First, the Utah Division of Wildlife Resources (UDWR) in conjunction with the Natural Resources Conservation Service (NRCS) removed tamarisk along the river on a large proportion of the land they own (see Fig. 4). These efforts were initiated in 2008 and by the end of 2012, 1,049 acres of tamarisk had been removed over 24 river kilometers (Keller 2012). Removal was conducted by plucking whole trees, including large roots, from the ground using an excavator. Tamarisk was piled on the floodplain, and in some areas the piles were burned. Removal efforts concentrated on tamarisk growing along the river margins but were also extended across the entire valley in some locations. Cottonwood and willow were left standing where they occurred in mixed stands with tamarisk. Reseeding and cottonwood planting has been conducted on about half of the removal areas and follow-up treatment of secondary weeds with herbicides has also been ongoing.

A second effort that has been undertaken by the NRCS and the Bureau of Reclamation is conversion of flood-irrigated crop and pastureland in Castle Valley to pressurized-pipe sprinkler irrigation. To date, these projects have been applied to about 25,600 acres in the San Rafael River watershed, and are planned for another 28,000 acres (UDWR 2012). Salt load reductions from these completed and planned projects have been estimated at about 190,000 tons/year (UDWR 2012).

Figure 16. Picture looking upstream toward the confluence of Spring Canyon, showing the riffles and bars formed by the tributary junction. Photo taken by B. Laub on May 2, 2013.

Summary and Prospects for Restoration

Research on the lower San Rafael River indicates that the river channel exists as a narrow, single-thread, confined, primarily sandy run and has much reduced complex habitat features such as riffles, pools, and backwaters relative to the channel condition in the early part of the 20th century. These changes have been driven primarily by a reduction in magnitude and duration of high sediment transport capacity spring snowmelt floods coupled with occurrence of short duration warm season floods that carry high sediment loads. Tamarisk colonization of the floodplain has likely enhanced channel changes and has likely replaced native vegetation along some stretches of the lower river. These channel changes have reduced habitat complexity in large sections of the lower river, native species of fish found in the upper San Rafael River are found in low abundance throughout much of the lower river, where non-native species are now numerically dominant (Fig. 18). In addition, salinity levels in the river have been increased primarily through irrigation run-off.

As described in the introduction to this section, the intention of the restoration plan is not to recover pristine conditions that existed prior to settlement of the area in the late 1800s. However, understanding the changes that have occurred will help in setting realistic goals for restoration (see *Guiding Vision and Project Goals* section). Understanding the causes of degradation will also help formulate restoration activities that work with or enhance natural river processes. Some activities will necessarily be targeted at a broad scale; in particular, recovery of spring flood flows will be a basin-wide project. However, small-scale projects can also contribute toward improving conditions for native fish and vegetation. For example, because native fish are using complex habitat wherever it is available in the lower river, any increase in habitat complexity, even on a small scale, will likely increase densities of native fish, especially if non-native fish density is reduced. Efforts to rehabilitate the San Rafael River may benefit endangered fishes of the upper Colorado River Basin and thus contribute to wider basin-scale restoration goals as well (e.g., Dauwalter et al. 2011).

In the remainder of the document, design and scientific rationale of a conservation and restoration plan for the San Rafael River are presented, following recommended procedures for restoration planning (Shafroth et al. 2008; Fig. 1). The plan begins with a statement of the potential condition of the river under idealized conditions. Using this guiding image in combination with the current state of the river as described above, conservation and restoration goals for the river are established. Constraints to achieving these goals are identified and used to design specific objectives that can be used within existing constraints to help achieve project goals. After objectives are set, discussion of potential restoration actions is presented along with prioritization of sites. Finally, a monitoring plan is developed that will be used to assess changes in the river and associated vegetation, fish, and wildlife populations as a result of restoration actions. Monitoring will be used to determine whether the project objectives are being met and may inform alterations to the restoration plan if objectives are not being met. Careful monitoring will also yield information on the relative success of different restoration efforts, reasons for their success or failure, and the cumulative impacts of different restoration actions over the watershed scale. Monitoring will thus ensure that lessons learned from the San Rafael River Restoration project will be transferrable toward restoration of other rivers in the region.

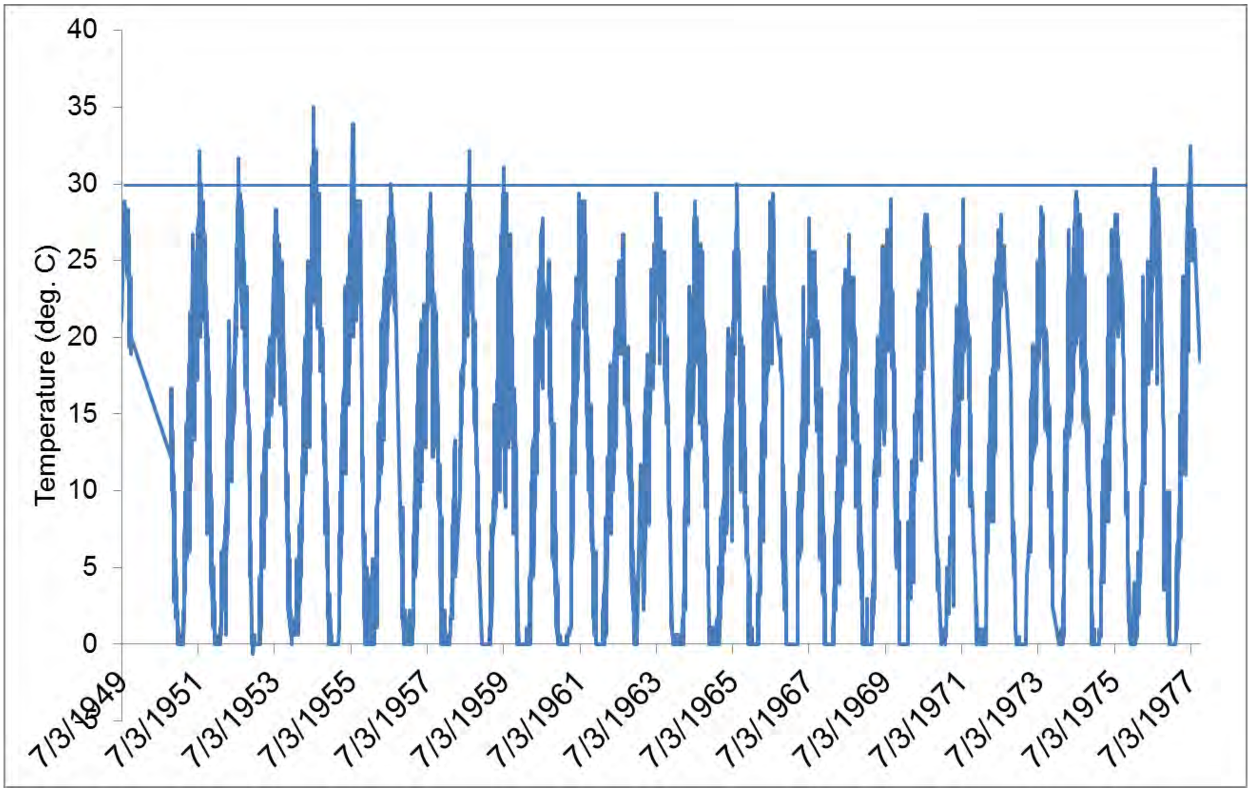

Figure 17. Temperature record of sporadic spot measurements at the USGS gage at SH-24 for the period 3 July 1949 to 28 September 1977. The horizontal line at 30°C represents the upper end of temperature preferences for native fish.

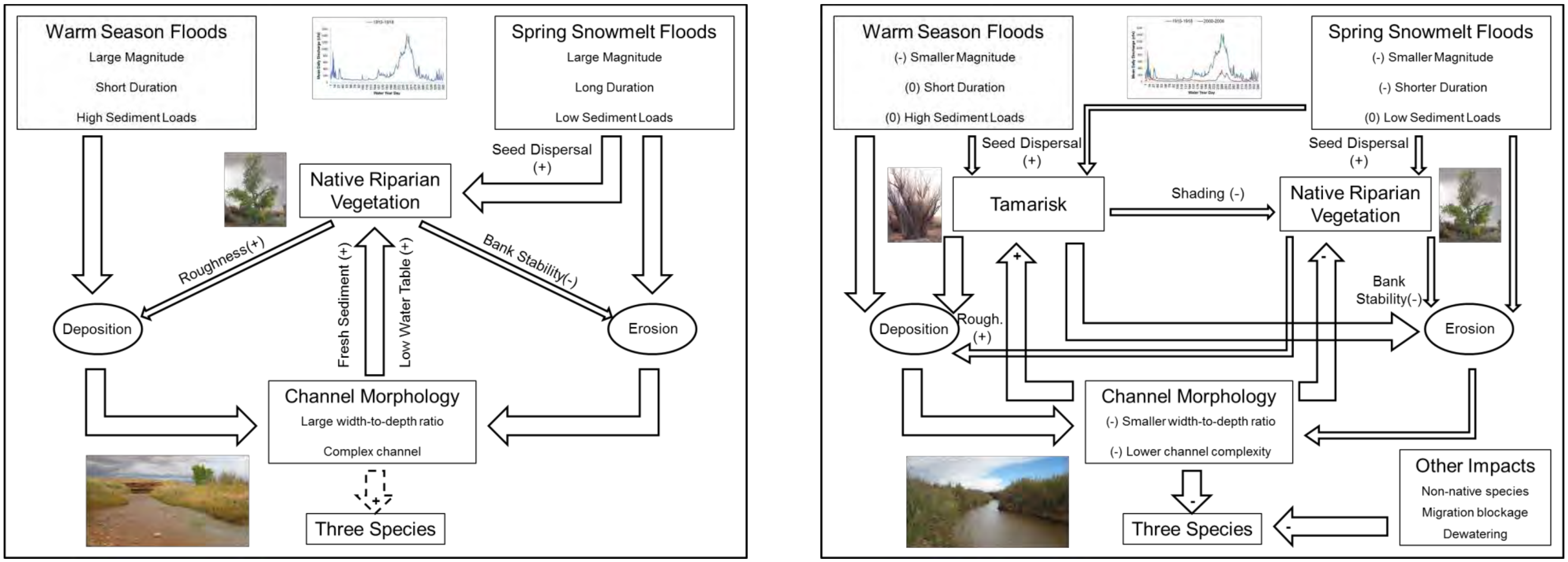

Figure 18. Conceptual model summarizing hydrological, channel, vegetation, and fish assemblage changes on the lower San Rafael over the last century. The left panel shows the state of the river in the early 20th century, prior to hydrological development within the watershed. The right panel shows the state of the river today. The right panel also gives the direction of change of hydrological and channel morphology properties as a result of water development: (+) indicates an increase, (-) a decrease, and (0) no significant change. State variables are shown in boxes and processes in circles. Arrows indicate direction of influence and arrow thickness gives relative strength of influence. Descriptions associated with arrows indicate the method of influence and whether the influence leads to an increase (+) or a decrease (-) in the state or process variable. The dashed arrow between channel morphology and three species in the left panel indicates that channel morphology (represented by the picture in the lower left corner of each panel) in the early 20th century is assumed to provide high quality habitat for the three species, but this has not been tested explicitly due to lack of data on fish populations from this time period.

II. Guiding Vision and Project Goals

Introduction

Effective ecological restoration requires that overall goals for the restoration project be clearly identified, so as to guide planning of restoration activities in a coordinated manner (Shafroth et al. 2008). By clearly defining project goals, the scope, intent, and expected outcomes of the restoration project are made clear to all those involved and further design of the restoration plan can move forward under an established framework. Development of the project goals should be based on an understanding of the causes and consequences of degradation together with an established vision of the full recovery potential of the ecosystem. The previous section described the current degraded state of the San Rafael River and the causes of geomorphic and ecological changes. In this section, the overall goals of the restoration project are articulated by combining the causes of degradation with the guiding vision for restoration potential of the river system.

Guiding Vision

The purpose of a guiding vision (or guiding image) in restoration planning is to provide a conceptual picture of the river ecosystem and its level of functionality as the desired outcome of the restoration plan. In other words, the vision provides the overall target for the restoration plan. The vision should be achievable over the long-term scope of the restoration project, and thus irreversible constraints (e.g., land development, some level of water use) should be acknowledged in articulating the vision (Palmer et al. 2005).

The state of the San Rafael River in the early 20th century provides a starting point for defining a vision for restoration (described in previous section), but several constraints suggest that the unaltered river system from the early 1900s is an unrealistic vision for restoration. First among these is that the floods of the early 20th century were some of the largest floods that have occurred throughout the last 500 years throughout the region (Piechota et al. 2004). Climate-driven reductions in precipitation throughout the 20th century make it likely that floods of the magnitude that occurred in the early 20th century will not occur anytime in the foreseeable future with regularity. Thus, adopting the state of the channel as it existed in the early 20th century as a vision for restoration would be unrealistic even if there were no water development and water use within the San Rafael River watershed, which is extensive. Removing all dams and diversions and eliminating all water use within the watershed with the aim of recovering a completely natural flow regime would be infeasible and is beyond the scope of this restoration project. However, the large spring flood event in 2011 (see Fig. 6) shows that flooding can still occur within the river, and a study of channel change before and after this event has shown that when floods do occur, they can erode and transport sediment and cause channel migration (Keller 2012 – attached as Appendix IV). In addition, stakeholders in the San Rafael River watershed have recognized the importance of providing ecological flows to maintain fish populations and fish habitat (UDWR 2012), suggesting that the basic processes of sediment movement and channel migration can be maintained by managed flows, even if they are at a lower level than existed historically.

The necessity of recovering channel processes that maintain fish habitat and native riparian vegetation recruitment combined with the irreversible constraints of water use and development within the watershed have been acknowledged in defining the following guiding vision for the San Rafael River restoration project:

> *The San Rafael River is a dynamic riverine ecosystem and is functioning to provide necessary and sufficient habitat to ensure persistence of native aquatic and riparian species*.

Restoration Goals

There are three overall goals for the San Rafael River Restoration project that need to be accomplished in order to shift the river ecosystem from its current degraded state towards the state of the river identified in the restoration vision, and one additional goal that identifies monitoring as a critical part of the restoration project.

1. Recover self-sustaining populations of the three species and other native fish in the San Rafael River (Two tiers)
    a. Maintain and enhance connectivity between the upper and lower San Rafael River and the Green River
    b. Increase populations of the three species and other native fishes throughout the San Rafael River
2. Ensure persistence of native riparian vegetation, including willow stands and cottonwood stands with several age classes
3. Provide necessary and sufficient habitat to ensure persistence of native fish and vegetation
4. Conduct sufficient monitoring of restoration impacts to quantitatively assess whether the restoration actions are accomplishing the restoration objectives and to determine the causes of success or failure

The first goal is broken into two tiers because the source-sink structure of native fish populations (described in the preceding section) makes it necessary that connectivity between the upper and lower San Rafael River and the Green River be maintained and enhanced in order to ensure persistence of native fish species. However, the populations of native fish species are presumed to be low and populations of non-native fish high relative to their historic populations, such that increasing populations of native species and decreasing populations of non-native fish is also required to ensure long-term sustainability of native fish.

In addition to the three goals that are aimed at moving the current state of the San Rafael River ecosystem toward the restoration vision, an additional goal focuses on monitoring.

Monitoring is critical for two reasons. First, evaluation of restoration actions is needed to determine whether they are accomplishing the first three goals of the restoration plan. By monitoring the impact of restoration actions on the San Rafael River, the restoration project can be set up in an adaptive management framework that allows restoration actions to be altered as information on their effectiveness becomes available. A second reason that monitoring is a critical part of the San Rafael River restoration project is to determine successful and unsuccessful restoration approaches that can be used to guide other restoration projects on rivers in the region.

Together, these four goals set the scope and broad framework for the remainder of the restoration plan and are used to guide development of more specific restoration objectives and actions in the next section.

III. Objectives

Introduction

In this section, specific objectives for the restoration plan are proposed (see Table 1 for a summary of goals and objectives). Each objective is stated and followed with an explanation of how it will help achieve the goals of the restoration project. Whereas the goals are meant to provide general guiding targets for restoration, the objectives are designed to be measurable, such that progress in meeting the objectives can be quantitatively assessed. The objectives are designed to help achieve restoration goals while being realistically achievable given the natural and anthropogenic constraints identified in Section I of this report (e.g., the naturally lower precipitation compared to the early 20th century constrains restoration of the morphologic properties of the channel, as does the need to provide irrigation and municipal water). However, achieving the objectives is expected to take decades in many cases, because changes to the river system will be dependent not only on restoration actions but on appropriate flows and associated processes of sediment movement that occur episodically. The process of river degradation has been ongoing for a century now, and restoration should not be expected to transform the river instantaneously. Specific recommended actions to accomplish the objectives will be proposed in the next section.

Objective 1: Facilitate a change in the morphologic form of the lower San Rafael River channel from its current confined, single-thread, low-complexity state towards a state with greater channel-floodplain connectivity and increased channel complexity (i.e., greater amounts of woody material and pool, riffle, and backwater habitats) by promoting natural river processes of erosion, deposition, and lateral channel migration.

> *Rationale*: Research on populations of the three species in the San Rafael River has identified low habitat complexity in the lower river as one of the major threats to their persistence (Bottcher 2009, Budy et al. 2009, Walsworth 2011). Other threats, including periods of dewatering due to irrigation withdrawls, predation and competition from non-native fish species, and a lack of fish passage between the upper and lower San Rafael River are addressed in subsequent objectives. In-stream habitat complexity has been degraded by accumulation of sediment and formation of riparian berms within the lower San Rafael River (described in Section I), and recovery of natural processes that can erode and transport this sediment are needed to enhance complexity in the lower San Rafael River (Fortney et al. 2011). Enhancing these natural river processes and decreasing channel confinement will also likely benefit native vegetation, because cottonwood and willow establish on fresh sediment deposits and require contact with the groundwater table to persist through dry summers (Braatne et al. 1996, Scott et al. 1997, Mahoney and Rood 1998).

Goals addressed: By focusing on recreating complex habitat in the lower San Rafael River, this objective addresses the goal of providing sufficient habitat for native fish species (Goal 3). In addition, because populations of the three species are limited by a lack of complex habitat and native riparian vegetation is limited by a lack of establishment sites, this objective also addresses the goals of increasing populations of native fish (Goal 1: Tier 2) and ensuring the persistence of native riparian vegetation (Goal 2).

Objective 1a: 10-20% of the 300-m sampling reaches on the lower San Rafael River will have >30% complex habitat by area, 20-30% will have >20% complex habitat and 40-70% will have >10% complex habitat, with complex habitat defined as pools, riffles, and backwaters.

Rationale: The ranges for habitat complexity targets were based on two methods: 1) the distribution of percent complex habitat in sampling reaches where the three species were observed – including three reaches above Hatt's Ranch dam, and 2) the distribution of percent complex habitat in the vicinity of the Spring Canyon confluence (300 m upstream to 900 m downstream), an area with one of the highest proportions of complex habitat on the lower San Rafael River (see Fig. 16). Thus, together these methods indicate a distribution of complex habitat that should be capable of supporting populations of the three species and can reasonably be achieved through restoration. The first method showed that 18% of the 300-m reaches where the three species were captured had percent complex habitat >30%, 23% had percent complex habitat >20%, and 41% had percent complex habitat >10% (data from Bottcher 2009). The second method showed that 14% of the reaches near Spring Canyon had percent complex habitat >30%, 29% had percent complex habitat >20% and 71% had percent complex habitat >10% (data from Walsworth 2011). The final targets for the objective were derived by rounding all numbers to the nearest 10% and using the high and low values from the two methods as the ranges. Based on data for the entire lower San Rafael River collected in 2010, currently 3% of the lower river has percent complex habitat >30%, 12% has percent complex habitat >20%, and 30% has percent complex habitat >10%, thus the targets represent a substantial increase in percent complex habitat from the state of the river in 2010.

Timeframe: Facilitating a change in the morphologic form of the channel by promoting natural river channel processes will take time, because sediment movement, channel migration, and creation of habitat are critically dependent on large, spring snowmelt floods (see discussion of ecological flows in Section IV of this report). Large spring floods may only occur once every 3-5 years or longer, and multiple floods will likely be needed to achieve the objective. Thus, the objective will take a minimum of 5-10 years to achieve and will more likely take on the order of decades (see also Fig. 47).

Objective 2: Increase establishment of native riparian vegetation on the floodplain of the lower San Rafael River.

Rationale: Although native riparian vegetation persists in many areas of the lower San Rafael River, the spatial and temporal scales of persistence are likely very different than historic conditions would have supported. For example, many cottonwood stands are now "relict" stands that consist of mature trees of a single age, and there has been limited recruitment of cottonwoods over the last decade (based on vegetation mapping). Specifically, the most recent known widespread cottonwood recruitment event occurred in 1996 (based on limited tree coring), and even the high-water year of 2011 resulted in little recruitment except in the area immediately upstream of Cottonwood Wash (see Fig. 14). In addition, non-native tamarisk has established in dense stands in many areas and likely prevents establishment of native plant communities in these areas due to shading and competition for soil moisture. Thus, there has likely been a reduction in the extent of native vegetation and an increase in the extent of non-native tamarisk relative to historic conditions on the lower San Rafael River. New recruitment of native vegetation, including replacement of tamarisk stands with native communities, is thus necessary to recover native vegetation communities toward their historic spatial distribution and ensure their long-term persistence. Ensuring persistence of native vegetation should benefit native fish habitat, because wood accumulations are associated with complex instream habitat (Keller 2012). Cottonwood trees are especially important as a source of large wood, but willows are also important as a source of food and dam-building materials for beaver. Recovery of native riparian vegetation communities will likely benefit wildlife species as well, because lowland riparian habitats have been identified as a key habitat type for many species of birds and other wildlife in Utah (UDWR 2005).

Goals addressed: By enhancing establishment of native vegetation, this objective addresses the goal of ensuring persistence of native vegetation communities (Goal 2).

Objective 2a: 8-11% of the riparian area along the lower San Rafael River will be composed of native woody vegetation (willow and cottonwood), with 4-6% composed of cottonwood as measured by canopy coverage on aerial photos.

Rationale: The ranges for native woody riparian vegetation targets were based on the coverage of native woody vegetation at two sites along the river identified as reference areas: just below Iron Wash and just below Spring Canyon (see section on site prioritization). Vegetation mapping indicated that the coverage of native woody vegetation was 8% downstream of Iron Wash, with 6% cottonwood coverage and 5% a mixture of willow and native phragmites (Macfarlane and McGinty 2013, attached as Appendix VII). Mapping indicated that coverage of native woody vegetation was 11% below Spring Canyon, with 4% cottonwood coverage and 7% willow/phragmites. The two areas were used as upper and lower bounds to provide the range for target native woody riparian vegetation coverage. Cottonwood coverage is 3% and willow/phragmintes is 2% across the entire lower San Rafael River corridor (see Fig. 21 in Macfarlane and McGinty 2013), suggesting that achieving the target coverage will require a substantial increase in native woody riparian vegetation over time. Providing a target for native herbaceous vegetation is not possible at this time, because native and non-native herbaceous vegetation cannot be separated in the vegetation mapping, such that the current coverage of native herbaceous vegetation is unknown.

Timeframe: Native vegetation establishment is dependent on a specific series of flow events over a few years, and these flow events generally occur only once every 5-10 years on western river systems (Mahoney and Rood 1998). Even if appropriate flows occur, recruitment is often patchy due to other local-scale mortality factors such as water table elevation and subsequent scouring (Friedman and Lee 2002). Thus, multiple decades will likely be needed to accomplish the objective, in order to give enough time for sufficient native vegetation to establish and grow to a detectable size on aerial photos.

Objective 3: Reduce abundances of non-native fish species in the lower San Rafael River, so that native fish species are numerically dominant.

Rationale: Research on populations of the three species in the lower San Rafael River has identified predation and competition from non-native fishes as one of the major threats to their persistence (Walsworth 2011). Other threats, including lack of habitat complexity, periods of dewatering due to irrigation withdrawls, and a lack of connectivity between the upper and lower San Rafael River are addressed in other objectives. Non-native species contribute to the source-sink dynamic of the three species populations in the San Rafael River by preying on and competing with, particularly young-of-year and juveniles that migrate into the lower river from spawning areas in the upper river (Walsworth 2011). Due to the abundance of non-native species in the lower San Rafael River, restoration of habitat complexity, which also limits native fish species, may end up benefitting non-native species to the detriment of native species, if the abundance of non-native species is not reduced (Walsworth 2011). Although eradication of all non-native fish from the lower San Rafael River would be the ideal management objective, successful eradication will be difficult due to the connection of the San Rafael River to upstream and downstream sources of non-native colonists. Nonetheless, research has shown that if the abundance of non-natives can be reduced sufficiently so that natives are numerically dominant, this may allow natives to outcompete non-natives (Saunders et al. 2011).

Goals addressed: Competition and predation by non-native fish species is threatening the persistence of native fish species in the lower San Rafael River. By reducing the abundance of non-native fish species, these threats can be reduced and will likely help increase populations of native fish species in the lower river (Goal 1: Tier 2).

Objective 4: Implement an ecological flows plan that identifies flows necessary to maintain and enhance stream and floodplain habitat, support native fish populations, and ensure maintenance and increased establishment of native vegetation communities. Based on these ecological flow requirements, a flow plan should be developed that includes recommendations for:

- Minimum base flows
- Optimal flows for providing in-stream habitat
- Magnitude, duration, frequency, timing, and pattern of habitat-forming flood flows

These flow recommendations should form the basis for discussions with the San Rafael River stakeholders group (including the Emery County Water Conservation District, PacificCorp, and others), so that an agreement on a water management plan for the river can be developed. The intention is not to recover the hydrograph of the early 20th century but rather to establish a flows plan that can enhance the ecological condition of the river over its current state within the constraints of non-ecological water use.

> *Rationale*: A recent gain/loss study on the lower San Rafael River showed that there are no significant natural losses of surface base-flows throughout the lower river during the late fall and winter periods (Gowing and Thomas 2012). However, the San Rafael River often becomes dewatered during summer low-water periods due to irrigation withdrawls (McAda et al. 1980, Bottcher 2009). In addition, the magnitude and duration of spring snowmelt floods has been reduced due to capture of snowmelt runoff in the headwaters of the San Rafael River. Dewatering in the lower San Rafael River prevents fish movement throughout the lower river and between the upper San Rafael River and the Green River. Dewatering also concentrates fish into isolated pools where they are more susceptible to predation from non-native fish and negative effects from high water temperatures and low oxygen (Labbe and Fausch 2000, Scheurer et al. 2003, Larned et al. 2010). Even reduced baseflows may result in limited fish movement and high water temperatures that are outside the optimal range for native species. Loss of spring flood flows has reduced erosion and channel migration processes, which work to reduce channel confinement and create complex channel habitat. In addition, native vegetation, particularly willows and cottonwoods, require a specific sequence of flows over multiple years for seeds to germinate and seedlings to establish (Braatne et al. 1996, Scott et al. 1997, Mahoney and Rood 1998). In general, the requirements are: 1) a high spring flow that recedes slowly – this is needed to create fresh alluvial deposits, facilitate germination at a relatively specific elevation of geomorphic surface within the stream channel, and allow seedlings to maintain root contact with the water table as they grow; 2) lower-magnitude spring and monsoon flows following establishment – this ensures that established seedlings are not lost to scour mortality; and 3) a sustained baseflow following establishment to provide an elevated water table and ensure persistence through the second summer. Provision of minimum flows to the lower river would help ensure connectivity throughout the San

Rafael River during dry periods and would help alleviate the effects of river drying on native fish and vegetation. Provision of spring flood flows would help maintain and create favorable habitat for native fish and vegetation communities. Overall, there are multiple ecological requirements for particular flows on the San Rafael River, and a plan detailing the recommendations for ecological flows on the river should be developed and used as a basis for discussions with the San Rafael River stakeholders group.

Goals addressed: Recommending specific flows would help in developing a plan in conjunction with the San Rafael River stakeholders group to provide ecological flows for the San Rafael River. Provision of these flows would help provide necessary habitat for native fish and riparian vegetation and thus help recover populations of native fish species and ensure persistence of native riparian vegetation communities (Goals 1-3).

Objective 5: Improve connectivity between the upper and lower San Rafael River and Green River by providing fish passage at flow diversions or completely removing flow diversions.

Rationale: The Hatt's Ranch diversion dam is a complete barrier to upstream fish movement. Thus, if populations of the three species in the upper San Rafael River, particularly flannelmouth sucker and roundtail chub, were to be extirpated, the natural reestablishment of these populations by colonization from downstream sources would be prevented. Extirpation of the upstream populations is a threat, as demonstrated by fires that occurred in the headwaters of Huntington Creek in 2012 and resulted in debris and ash flows that severely reduced populations of the three species in the upper San Rafael River (Dan Keller, Utah Division of Wildlife Resources, personal communication). The dam also likely prevents upstream spawning movements by the three species and possibly endangered species of the Colorado Basin, particularly the Colorado pikeminnow and razorback sucker. However, providing passage at the dam will not be straightforward due to considerations of increasing non-native fish distribution, water supply for Hatt's Ranch, and channel alterations after dam removal (discussed in more detail in the Recommended Restoration Actions section). While providing passage at Hatt's Ranch dam will help improve connectivity between the upper and lower San Rafael River and Green River, other factors limiting fish movement such as dewatering must also be addressed to maximize connectivity throughout the river system (see Objective 4).

Goals addressed: Providing native fish passage at Hatt's Ranch dam will help increase connectivity between the upper and lower San Rafael River, because it currently prevents upstream fish movement (Goal 1: Tier 1).

Objective 6: Enhance ongoing efforts within the San Rafael River watershed to meet total maximum daily load targets for total dissolved solids in the lower San Rafael River.

Rationale: The Colorado River Basin Salinity Control Program is an effort to reduce salt loads delivered to the Colorado River in Arizona, California, and Mexico and these efforts extend to the San Rafael River as a tributary within the Colorado River Basin (NRCS 2012). The primary source of salinity loading above natural loading in the San Rafael River is irrigation return-flow from flood-irrigated agricultural fields, and this source is being remediated through conversion to pressurized-pipe sprinkler systems (UDWR 2012). However, river restoration has the potential to contribute to reducing salinity levels by focusing on recovering a more natural flow regime and by restoring river-floodplain connections that can reduce the volume of water moving directly through the currently confined channel and increase the amount of water retained in off-channel wetlands and floodplain soils. Contributing toward efforts to reduce salinity in the San Rafael River will help ensure that salinity does not increase to a point that stresses fish through osmotic imbalances or becomes unsuitable for native vegetation growth. The objective may not be achievable in the short term (i.e., over the next 10-20 years), because many restoration actions are likely to promote bank erosion and sediment movement to recreate habitat (see discussions under *Recommended Restoration Actions* below). However, over the long term (20-50 years), by working to recover a natural flow regime and increased channel-floodplain connectivity, the objective should be achievable (see further discussion in the *Monitoring Recommendations* section of this report).

Goals addressed: Helping to maintain or reduce salinity to levels that do not adversely impact native fish or vegetation will help ensure that in-stream and floodplain habitat are suitable for native species (Goal 3).

Objective 7: Develop a monitoring plan that will provide an evaluation of the effectiveness of restoration actions and thus provide guidance for adapting and improving the restoration plan over time. The monitoring plan should identify and addresses data needs for assessing the impact of restoration actions on fish populations and movement, riparian vegetation abundance and establishment, and channel morphologic and habitat properties on the San Rafael River. This will include:

- Establishing a pre-restoration baseline data set
- Collection of existing data sets, including data on fish populations and movement, vegetation distribution, and channel morphologic and habitat properties
- Developing a plan to continue existing monitoring efforts and implement additional monitoring that can inform adaptive management efforts

Rationale: Although research on the San Rafael River has provided a sound conceptual understanding of how the river ecosystem has responded to anthropogenic modification over the last century (see section I of this report and Fig. 18), there is still uncertainty as to the likely response of in-channel habitat, riparian vegetation, and fish populations to further manipulations of the river system as part of restoration efforts. In addition, future changes to climate or land use may alter the river system in ways that are not predictable at this time. These uncertainties should not prevent restoration from moving forward, because more intensive scientific investigations and modeling will not necessarily lead to improved predictions of system response to restoration, especially without direct observations of system response to manipulation, i.e., restoration (Walters 1997). However, the restoration plan must acknowledge this uncertainty and be adaptable if recommended restoration actions are found to have detrimental or no effects on the river system. To determine whether restoration actions are effective, it is necessary to have a monitoring plan established prior to restoration implementation, so that knowledge of the system response to restoration can be updated efficiently and help reduce uncertainty over time. To assess the effectiveness of restoration efforts, it will be necessary to monitor response of fish populations, vegetation distribution, and channel properties to restoration efforts and compare the response to conditions that existed prior to restoration. Making this comparison will require a baseline data set of the existing state of the San Rafael River in addition to monitoring the response of the river to restoration. Metrics that will be included in the baseline and post-restoration data sets, some of which were identified in the original NFWF proposal (attached as Appendix I), include:

- Patterns of flow
- Amount of fish passage between the upper and lower San Rafael River
- Percent of pool, riffle, and backwater habitat
- Creation or loss of habitat over time
- Catch per unit effort of native and non-native fish
- Population size, age structure, and spatial distribution of native fish
- Amount of woody debris in the channel
- Density of cottonwood of different height classes
- Spatial and age distribution of cottonwood seedlings, saplings, and mature stands
- Width:depth ratio of the channel
- Rate of lateral channel movement
- Narrowing, widening, and incision of the channel over time

Previous and current research efforts on the San Rafael River can help establish the baseline data set, and are identified in the *Monitoring* section of this report (Section V). Additional data sets that are needed to completely establish the baseline conditions of the San Rafael River are also identified in the *Monitoring* section. Establishing a plan to continue current monitoring efforts and identify monitoring priorities post-restoration will ensure that future data collection will be comparable to the baseline information being collected.

Goals addressed: Developing this monitoring plan will help quantitatively assess whether and how restoration actions are accomplishing the plan goals and objectives (Goal 4), and this monitoring plan is presented in detail in section V of this report.

Table 1. Summary of project goals, objectives that need to be accomplished to ensure that each goal is met, and rationale behind the objectives for each goal.

Goal 1: Recover self-sustaining populations of the three species and other native fish in the San Rafael River **Tier 1:** Maintain and enhance connectivity between the upper and lower San Rafael River and the Green River • Objective 4: Implement an ecological flows plan that identifies flows necessary to maintain and enhance stream and floodplain habitat, support native fish populations, and ensure maintenance and establishment of native vegetation communities *Rationale*: Low water levels can prevent fish movement throughout the river • Objective 5: Improve connectivity between the upper and lower San Rafael River and Green River by providing fish passage at flow diversions or completely removing flow diversions *Rationale*: Hatt's Ranch dam is impassable by native fish attempting to move upstream
Goal 1: Recover self-sustaining populations of the three species and other native fish in the San Rafael River **Tier 2:** Increase populations of the three species and other native fishes throughout the San Rafael River • Objective 1: Facilitate a change in the morphologic form of the lower San Rafael River channel from its current confined, single-thread, low-complexity state towards a state with greater channel-floodplain connectivity and increased channel complexity by promoting natural river processes of erosion, deposition, and lateral channel migration *Rationale*: Lack of habitat complexity is one limiting factor for native fish on the lower San Rafael River and habitat complexity is formed and maintained by natural river processes • Objective 3: Reduce abundances of non-native fish species in the lower San Rafael River so that native fish species are numerically dominant *Rationale*: Predation and competition from non-native fish severely threaten persistence of native fish in the lower San Rafael River • Objective 4: Implement an ecological flows plan that identifies flows necessary to maintain and enhance stream and floodplain habitat, support native fish populations, and ensure maintenance and establishment of native vegetation communities *Rationale*: High flows create habitat and sufficient low flows provide habitat, minimize impacts from increased water temperatures, and provide connectivity between habitat patches

Table 1 cont.

Goal 2: Ensure persistence of native riparian vegetation, including willow stands and cottonwood stands with several age classes

- Objective 1: Facilitate a change in the morphologic form of the lower San Rafael River channel from its current confined, single-thread, low-complexity state towards a state with greater channel-floodplain connectivity and increased channel complexity by promoting natural river processes of erosion, deposition, and lateral channel migration
  Rationale: Greater channel-floodplain connectivity will help create establishment sites for native vegetation and provide elevated groundwater tables to help native vegetation persist during dry periods
- Objective 2: Increase establishment of native riparian vegetation on the floodplain of the lower San Rafael River
  Rationale: Native vegetation is present on the San Rafael River currently, but particularly with cottonwoods, many trees are old (some > 200 years) and without new recruitment cottonwood stands will eventually be lost from the system
- Objective 4: Implement an ecological flows plan that identifies flows necessary to maintain and enhance stream and floodplain habitat, support native fish populations, and ensure maintenance and establishment of native vegetation communities
  Rationale: Native vegetation, particularly cottonwoods and willows, require a specific pattern of flows over multiple years to recruit successfully

Goal 3: Provide necessary and sufficient habitat to ensure persistence of native fish and vegetation

- Objective 1: Facilitate a change in the morphologic form of the lower San Rafael River channel from its current confined, single-thread, low-complexity state towards a state with greater channel-floodplain connectivity and increased channel complexity by promoting natural river processes of erosion, deposition, and lateral channel migration
  Rationale: The current form of the channel provides limited complex habitat for native fish and both in-stream and riparian habitat is created by river processes
- Objective 4: Implement an ecological flows plan that identifies flows necessary to maintain and enhance stream and floodplain habitat, support native fish populations, and ensure maintenance and establishment of native vegetation communities
  Rationale: High flows are necessary to drive sediment erosion and transport that creates both in-stream and riparian habitat and low flows are necessary to maintain in-stream habitat during dry periods and to provide an elevated water table for native vegetation
- Objective 6: Enhance ongoing efforts within the San Rafael River watershed to meet total maximum daily load targets for total dissolved solids in the lower San Rafael River
  Rationale: High salinities may favor non-native vegetation and may alter stream invertebrate communities that provide food for native fish

Table 1 cont.

Goal 4: Conduct sufficient monitoring of restoration impacts to quantitatively assess whether the restoration actions are accomplishing the restoration objectives and to determine the causes of success or failure • Objective 7: Develop a monitoring plan that will provide an assessment of the effectiveness of restoration actions and thus provide guidance for adapting and improving the restoration plan over time. *Rationale*: Having a monitoring plan in place prior to the start of restoration will ensure that sufficient data is collected to assess the impacts of restoration

IV. Site Prioritization and Recommended Actions

Introduction

In this section, existing data on in-stream habitat, modeling of fish response to potential restoration activities, fish and cottonwood distributions, and geomorphic properties of the river are combined in a spatial analysis to identify priority areas for restoration actions. The spatial analysis is supplemented with a discussion of fish passage issues, non-native fish impacts, and ecological flow considerations in order to recommend restoration actions to address Objectives 1-6 identified in the objectives document (Objective 7 will be addressed in the monitoring plan which follows). After identifying priority restoration areas, recommended site-specific restoration actions and their rationale and intended impacts are discussed (see Table 3 for a summary of recommended actions and their associated risks and benefits). Next, a description of the ecological and geomorphic properties of priority restoration areas and the locations where restoration actions will be applied in each area is provided. Water quality considerations, options for providing native fish passage at Hatt's Ranch dam, and ecological flow recommendations are discussed separately as they are not applied to individual restoration areas.

The recommended actions are based on the available information on the San Rafael River and the best understanding of the causes of degradation and system stressors (see section I of this report). However, given the large spatial and temporal variability in many ecosystem attributes throughout the river system, the recommended actions should be viewed as the best available predictions of how the river will respond to manipulation. In other words, the recommended actions are based on a conceptual model of the river system (Fig. 18) that may need to be altered and updated as the impacts of restoration actions are evaluated. To test the validity of these predictions, it will be necessary to implement the recommended actions in an experimental design. This will require that some areas on the river be set aside as control areas, receiving no restoration treatment in the first phase of implementation, although such areas may be treated in the future as knowledge is gained on effective methods. Approaching the restoration plan as an experimental design will also require a relatively long time-frame for implementing all recommended actions, because it will require at least several years of monitoring to evaluate whether restoration activities are having the predicted effect on the river system. Although implementation of restoration in this stepped or staged approach will require a long time-frame commitment, by closely evaluating the effectiveness of recommended actions, the plan can and should be adapted over time. In this way the most effective combination of restoration strategies can be used over the greatest amount of time and area, saving money and effort invested in ineffective restoration strategies over the long-term. Employing an experimental design will also allow critical evaluation of when and how restoration strategies are effective or not, so that knowledge gained about restoration on the San Rafael River can be applied to restoration of other desert river systems in the region.

Site Prioritization

A key aspect of conducting a large-scale restoration project is to prioritize sites where restoration actions will have the greatest benefit (Wohl et al. 2005). In prioritizing sites for restoration, it is important to identify areas with intact habitat that do not need to be restored but can instead be set aside as areas to be protected from further degradation (Beechie et al. 2008). Identifying areas that can be easily connected to source populations of target species is also an important consideration in prioritization (Beechie et al. 2008). In this way, prioritization helps ensure that initial funding and resources available for restoration are used in the most efficient way possible. Lower-priority areas can be targeted in the future using the techniques found to be most effective. As restoration progresses, if conditions are improved in high-priority areas, the potential benefit for restoring the initially lower-priority areas should increase.

A two-stage approach was used to prioritize sites (Fig. 19). In the first stage, sites with intact habitat that are not in need of restoration were identified and set aside as sites to serve as reference areas for comparison with restored areas. In the second stage, areas not identified as reference areas were ranked for their potential benefit to native fish. Ranking was determined by comparing the potential response of native fish under restoration (restoration weight) to the existing habitat conditions (conservation weight). Areas with a high potential for native fish response (high restoration weight) but relatively low existing habitat value (low conservation weight) were ranked as top priority sites, because they had the potential for achieving the greatest benefit to native fish with the least risk to degradation of existing habitat.

Site prioritization was based mostly on potential native fish response. However, existing cottonwood stands were factored into the conservation weighting (see below and Fig. 19), and in deciding on the priority areas for restoration, restoration weights were compared to conservation weights. Therefore, cottonwood overstory cover did factor into site prioritization indirectly, because areas with low cottonwood cover had lower conservation weights and thus were more likely to be selected as high-priority sites for restoration.

To calculate conservation and restoration weights, a number of metrics indicative of existing habitat conditions and potential fish response were identified (see Fig. 19 for a flowchart of the prioritization process). Each metric was grouped into 2-5 categories and each category was assigned a weight from 0-1. Habitat complexity, channel bed material, and relative cottonwood density were used as metrics to indicate existing habitat conditions, with higher values of each metric indicating higher quality habitat. Habitat complexity was determined as the proportion of pool, riffle, and backwater habitat within a given section of the river, and this metric was used because it is significantly correlated with native fish density on the lower San Rafael River (Bottcher 2009). Channel bed material was used because coarser substrate supports greater production of benthic invertebrates, and thus provides greater food resources compared to fine-grained bed material (Walsworth 2011). The three species are also known to favor coarse substrates for spawning areas (Bezzerides and Bestgen 2002). Relative cottonwood density was used as a metric because cottonwoods are a source of large wood to the channel that forms important fish habitat. Relative cottonwood density was a measure of the relative coverage of cottonwood canopies on aerial photos between different sections of the river (see Fig. 19). The weights for habitat complexity, substrate size, and relative cottonwood density were multiplied together to assess the relative conservation benefit of different sites (the conservation weight). Sites with the highest relative conservation weight were identified as reference areas.

Modeled potential response of native fish to habitat restoration (analysis presented in Walsworth 2011 – attached as Appendix VI) and the minimum distance to a source population of native fish (the Green River or above Hatt's Ranch dam) were used to calculate the value of restoration at different sites (i.e., the restoration weight, see Fig. 19). Potential response of native fish included three metrics (potential response of roundtail chub to riffle habitat, potential response of roundtail chub to pool habitat, and potential response of flannelmouth and bluehead sucker to riffle habitat), each of which was estimated using generalized linear models and random forest models that incorporated the predictor variables of complex habitat, bed sediment size standard deviation, and distance to source population (Walsworth 2011). Minimum distance to source population was used, because it indicated whether a particular site could more readily be connected to source populations, an important consideration in prioritizing sites (Beechie et al. 2008). The weights for modeled fish response to habitat restoration and minimum distance to source population were multiplied together to determine the relative potential value of restoration at different sites (the restoration weight). The overall restoration weight was then compared to the conservation weight of each site to determine the highest priority restoration sites, i.e., those areas that had a high restoration potential relative to their conservation potential (Fig. 19 and 20).

A relative conservation and restoration weight was calculated for each 300-m reach between Hatt's Ranch dam and the Green River confluence based on data from Walsworth (2011) and vegetation mapping (Macfarlane and McGinty 2013). Habitat complexity, substrate size, and modeled fish response data were not available for the section between the Reef and Hatt's Ranch dam. This section was divided at I-70, which marks a geomorphic division between a wider valley segment upstream and narrower valley segment downstream (see Fortney 2013a and Fig. 3). Weights were not calculated for these sections; however, the potential benefit of restoration in these sections was assessed based on vegetation mapping and the knowledge that the abundance of non-native fish is much less in these sections than the remainder of the lower river, due to Hatt's Ranch dam blocking upstream fish movement (Budy et al. 2009). Conservation and restoration weights were plotted and general patterns in these weights were combined with known geomorphic reach breaks and other river features (e.g., major tributary junctions) to break the lower river into 13 sections in addition to the two above Hatt's Ranch diversion (Fig. 20, Fig. 21, Table 2). Each of these 13 sections was categorized as a reference area, where no restoration will be applied, or as a restoration area, with restoration areas split into four priority rankings (see Table 2). All sections of the lower San Rafael River were categorized into one of these five groups.

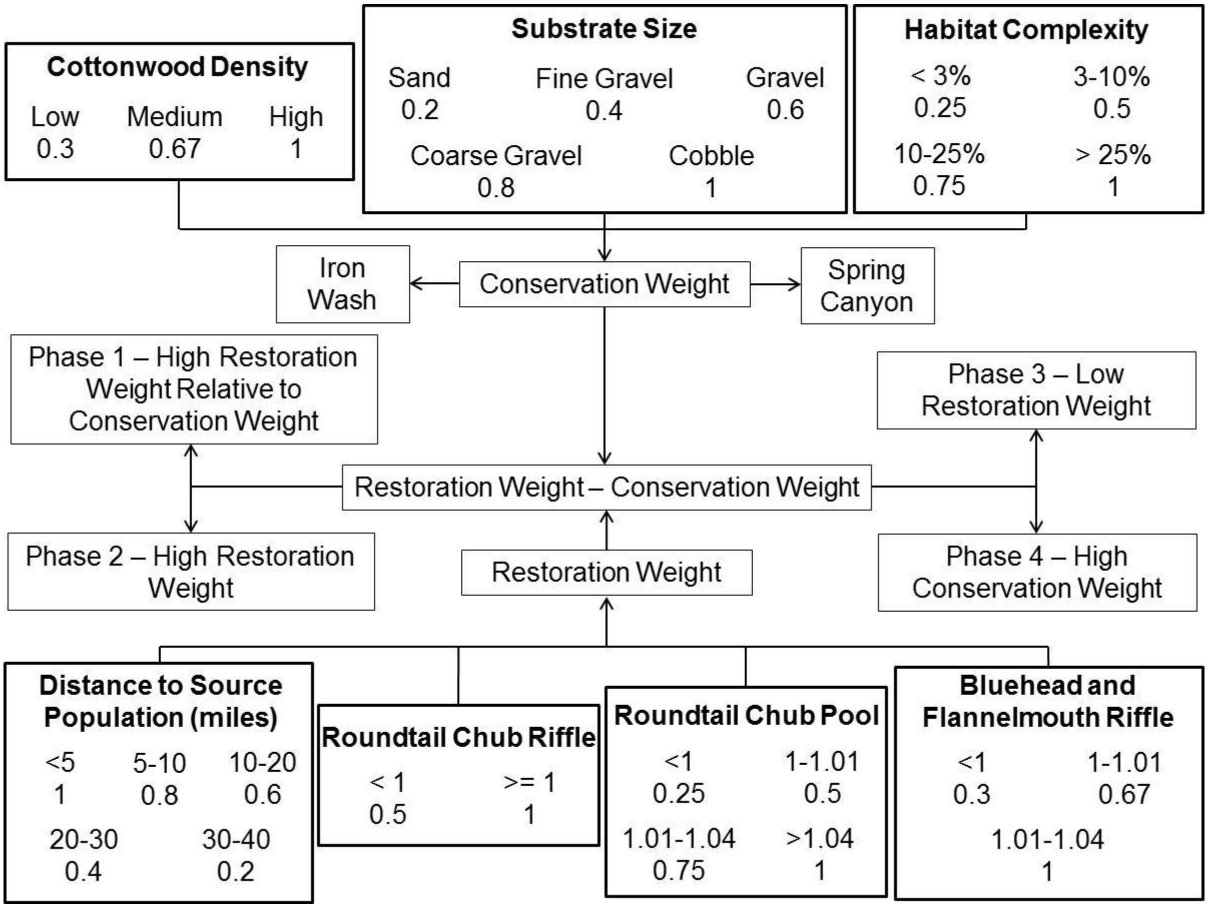

Figure 19. Flow chart of the prioritization method applied to the lower San Rafael River between Hatt's Ranch dam and the Green River (sites between the Reef and Hatt's Ranch dam were not prioritized using this method, because the necessary data was not available). Each box gives the different categories of each variable and their associated weights. Relative cottonwood density in the riparian zone, substrate size, and habitat complexity weights were multiplied for each 300-m reach and used to separate the Iron Wash and Spring Canyon sections as reference areas. Distance to native fish source population, predicted response of roundtail chub to riffle and pool restoration, and predicted response of bluehead and flannelmouth sucker to riffle habitat weights were multiplied to produce a restoration weight for each 300-m reach. Restoration and conservation weights were compared for all reaches except the conservation areas to prioritize restoration sections into four phases. Values for substrate size, habitat complexity and predicted fish responses were taken from Walsworth (2011). Relative cottonwood density was calculated by converting all 0.5 m raster cells identified as cottonwood canopy on a vegetation map (Macfarlane and McGinty 2013, maps available at http://bit.ly/1awJyOr) to points and calculating density of cottonwood points within 100 m of each cell (see Fig. 19 in Macfarlane and McGinty 2013). Predicted response of roundtail chub to riffle restoration is used as a do-no-harm weighting, because riffle habitat was predicted to negatively impact roundtail chub in some reaches (where Roundtail Chub Riffle values were <1). Predicted response to pools for roundtail chub and to riffles for the suckers are used because pools and riffles are the preferred habitat for chubs and suckers, respectively. Higher values for these variables indicate a stronger predicted positive response of the three species to restoration.

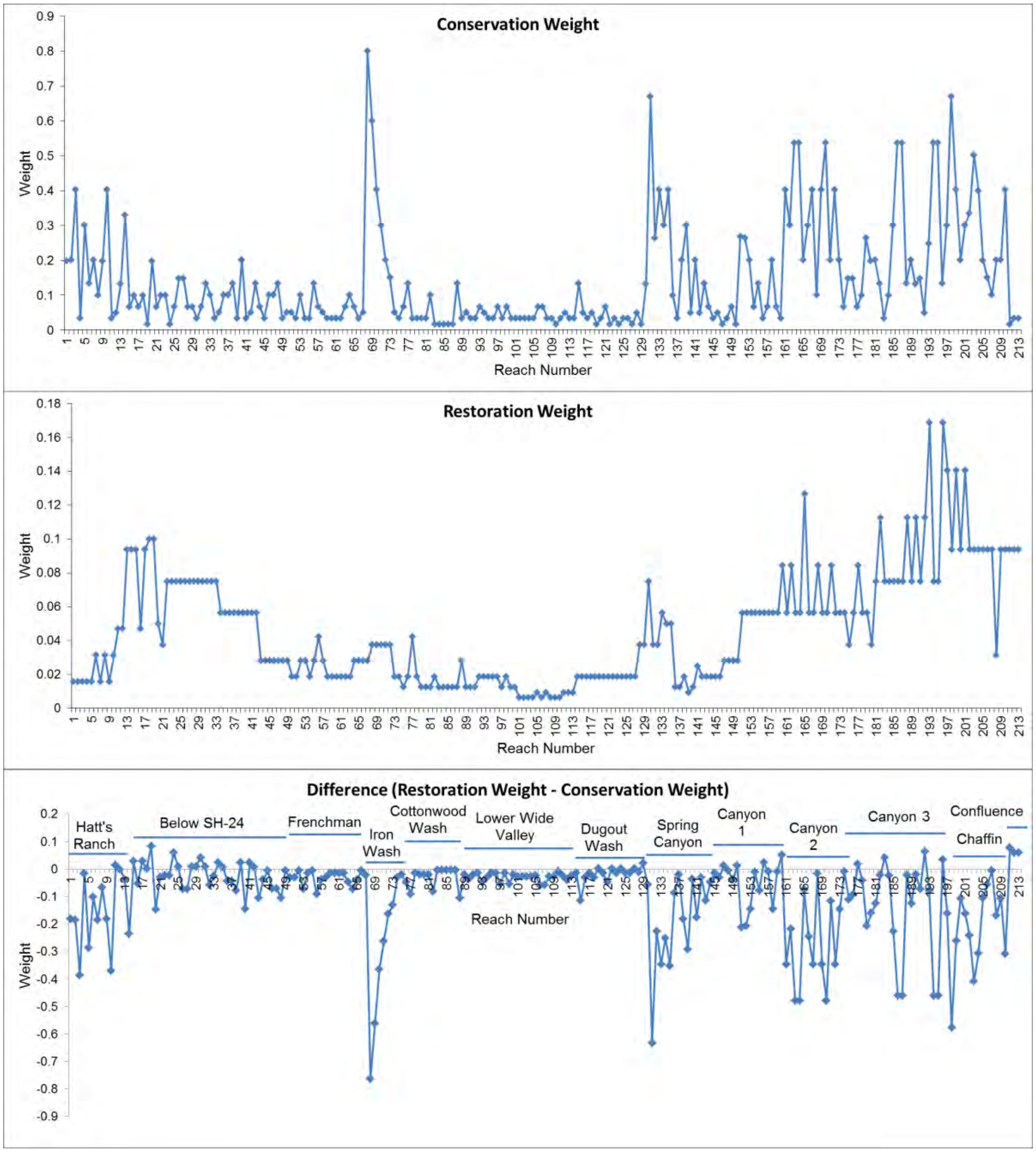

Figure 20. Conservation and restoration weight values and the difference between the two for each 300-m reach between Hatt's Ranch dam and the Green River confluence. The difference between conservation and restoration weights was used to highlight which reaches of the river have a high restoration potential relative to their conservation potential. In other words, the difference highlights the areas that currently have low habitat complexity but that could support relatively abundant native fish populations if habitat is restored. Weights are relative values ranging from 0 to 1, and therefore reaches in the difference plot with values below 0 still have restoration potential, but this potential is less, relative to reaches with values above 0. These conservation and restoration weight values were used, along with major geomorphic divisions on the river to divide the lower river into 15 sections, shown on the difference plot (the sections between the Reef and Hatt's Ranch dam are not shown).

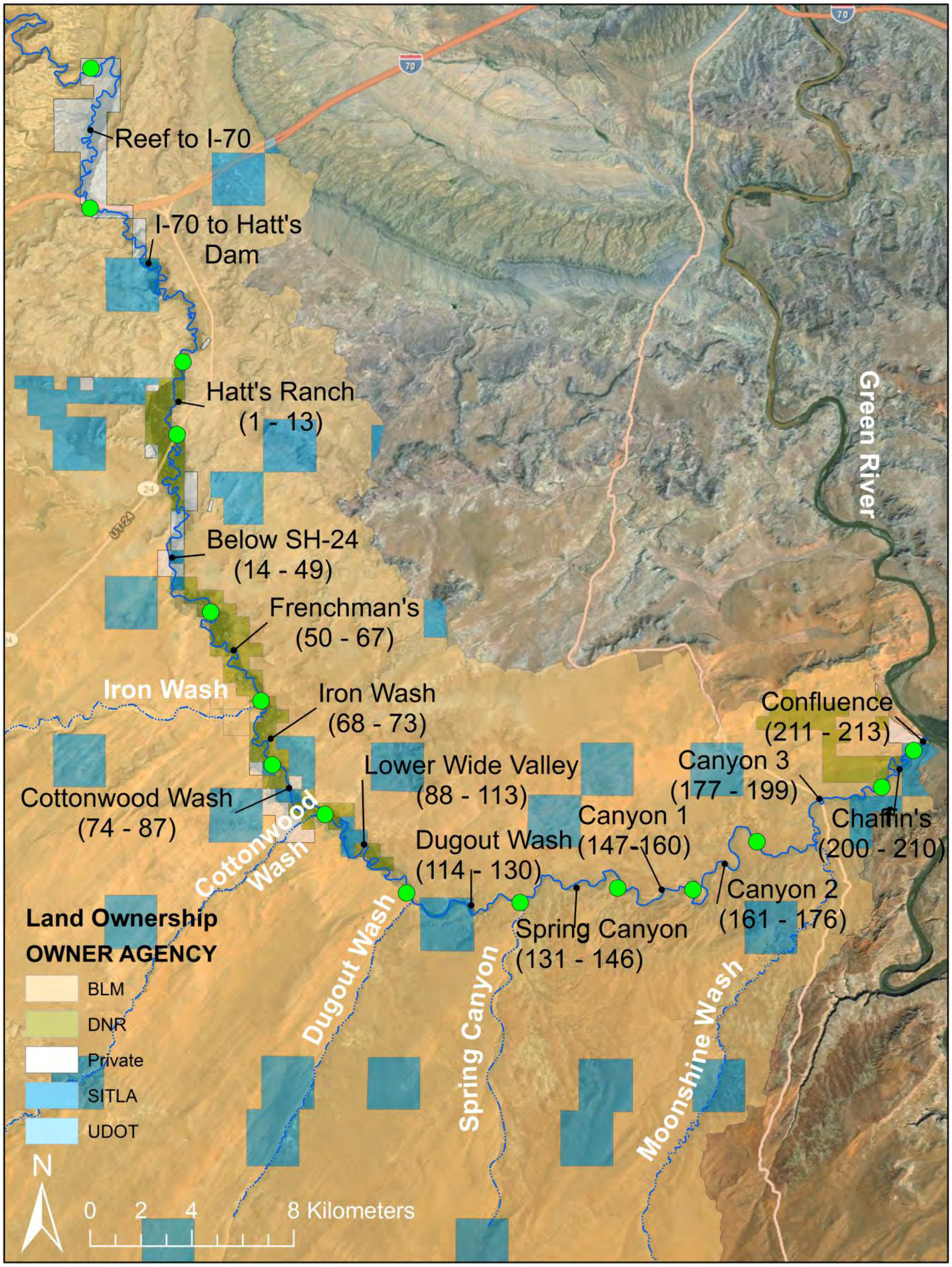

Figure 21. Map of the lower San Rafael River showing major section divisions, reach numbers in parentheses, and land ownership. Dots mark the divisions between sections.

Table 2. Sections of the San Rafael River identified using conservation and restoration weighting analysis (see Fig. 20), their restoration priority, associated reaches, and general geomorphic reach type. Phase refers to the order in which sections will be restored, moving from the highest priority sections in phase 1 to the lowest priority sections in phase 4.

Restoration Priority (Phase)	**Sections**	**Reaches**	**Geomorphic Reach Type**
Conservation Areas	Iron Wash Spring Canyon	68-73 131-146	Wide Valley Canyon-Bound
1	Reef to I-70 Confluence Below SH-24 Cottonwood Wash Canyon 3	NA 211-213 14-49 74-87 177-199	Wide Valley Wide Valley Wide Valley Wide Valley Canyon-Bound
2	Dugout Wash Canyon 1	114-130 147-160	Canyon-Bound Canyon-Bound
3	I-70 to Hatt's Dam Frenchman's Ranch Lower Wide Valley	NA 50-67 88-113	Canyon-Bound Wide Valley Wide Valley
4	Hatt's Ranch Chaffin Canyon 2	1-13 200-210 161-176	Wide Valley Wide Valley Canyon-Bound

Reference sections

Two sections below Hatt's Ranch dam stood out as valuable reference areas (Fig. 20): immediately downstream of Iron Wash (reaches 68-73; see Fig. 22) and immediately downstream of Spring Canyon (reaches 130-146; see Fig. 23). Both of these sections had high habitat complexity, large substrates, and abundant cottonwood stands. They both also had relatively low potential response of native fish to restoration. The lowermost canyon-bound section (Canyon 3) had reaches with a similar conservation weight as Spring Canyon (e.g., reach 198); however, these reaches had higher restoration weights than Spring Canyon (Fig. 20), and hence Spring Canyon was chosen as a reference area. The Iron Wash and Spring Canyon sections should not be targeted for restoration (although the UDWR has removed tamarisk in the Iron Wash section), but should instead serve as reference or desired condition sections for the wide valley segments (reaches 1-114 and 200-211) and narrow valley segments (reaches 114-200), respectively. The Hatt's Ranch (reaches 1-13), Chaffin's Ranch (reaches 200-212), and Canyon 2 (reaches 161-176) sections also had relatively high conservation weights, but they also had higher restoration weights than the Iron Wash and Spring Canyon sections. These three sections were given a low priority for restoration due to their relatively high conservation weights. Whether restoration should occur in these sections or whether they might be suitable as reference sites should be reassessed in the future.

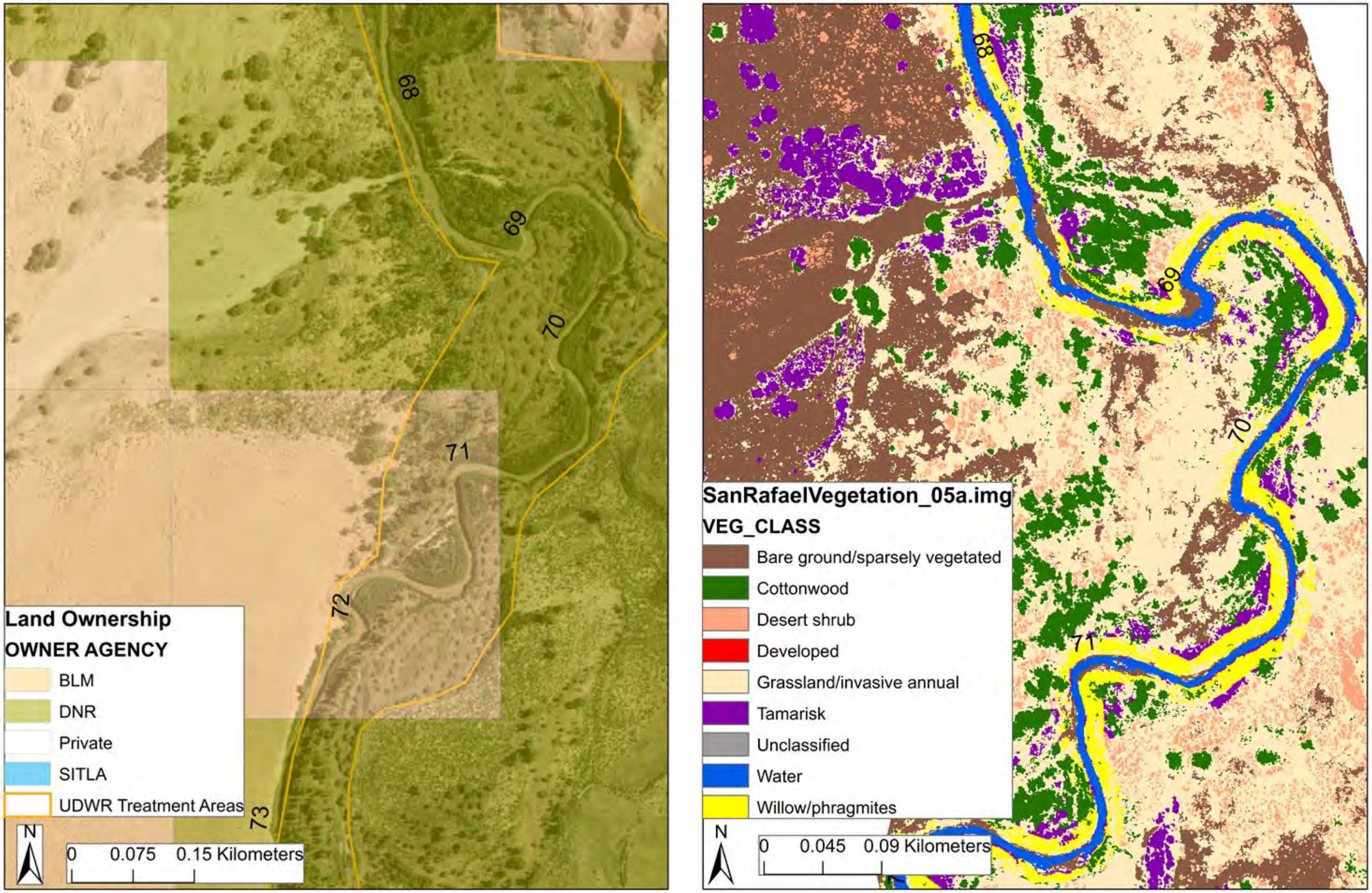

Figure 22. Map of the Iron Wash section showing land ownership (left) and a vegetation map (right). Numbers mark the upstream end of reaches. Additional vegetation maps available at: http://bit.ly/1awJyOr.

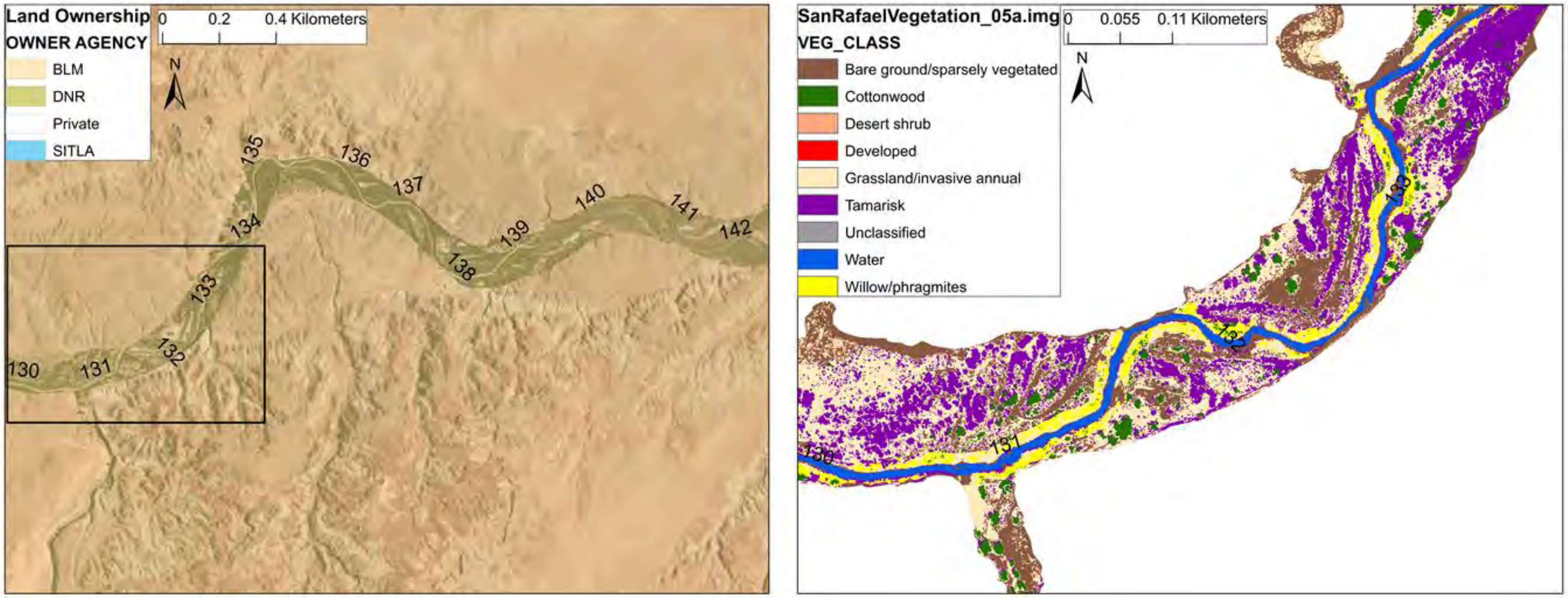

Figure 23. Map of the Spring Canyon section showing land ownership (left, area is entirely BLM) and a vegetation map (right). Numbers mark the upstream end of reaches. Box on the left figure shows area of vegetation map. Additional vegetation maps available at: http://bit.ly/1awJyOr.

Restoration sections

The remaining sections are placed into four groups, which can be viewed as a preliminary determination of restoration phases, moving from highest-priority areas to lowest-priority areas over time (Table 2). The grouping is based primarily on the restoration weight relative to the conservation weight (Fig. 20). An important trend in this ranking is that the restoration weight is generally lowest in the middle section of the river (about reaches 70-114) due primarily to this section being farthest away from source populations of native fish (Fig. 20). The strong effect of distance to source population on restoration weight (see also Walsworth 2011) suggests that the two reaches above Hatt's Ranch dam have relatively high restoration weight because they are closest to source populations in the upper San Rafael River and also have low abundances of non-native fish. Among these two sections, there are a few arguments for prioritizing the section between the Reef and I-70 above the section between I-70 and Hatt's Ranch dam. First, while both sections contain native fish, the section upstream of I-70 contains more cottonwood stands than the section downstream of I-70 (see Fig. 33 and Fig. 11), suggesting that efforts to create conditions for native vegetation establishment would likely be more effective in the section upstream of I-70. Second, the presence of Hatt's Ranch dam limits the gradient in the section downstream of I-70 and its potential to erode sediment, migrate laterally, and create complex habitat, at least in the area immediately above the dam. Third, if Hatt's Ranch dam is removed (see discussion in the *Improving Connectivity* section below), there is the potential for channel incision above the dam and this could counteract any restoration projects that were applied prior to dam removal. If a decision is made to leave Hatt's Ranch dam in place, the prioritization of this section should be reassessed.

The highest priority areas for restoration based on the weighting analysis and the above discussion are the section between the Reef and I-70 (Fig. 33), the Green River confluence section (Confluence; reaches 211-213; Fig. 34), the 11 km section downstream of SH-24 (Below SH-24; reaches 15-49; Fig. 35), and the lower-most canyon-bound section (Canyon 3; reaches 177-200; Fig. 36). The area immediately upstream of Cottonwood Wash (Cottonwood Wash; reaches 74-87; Fig. 37) is also ranked as a high-priority reach because this was an area of high cottonwood recruitment from the 2011 flood and this vegetation is not captured by the vegetation mapping (Figs. 37 and 38). Remaining sections were ranked as lower priority due either to having a relatively high conservation weight currently (Chaffin's Ranch, reaches 200-210; Canyon 2, reaches 161-176) or having a low restoration weight (Frenchman's Ranch, reaches 50-67; Lower Wide Valley Section, reaches 88-114). These sections should serve as control study sections that receive no restoration treatment during initial restoration phases as part of the monitoring protocol (section V of this report). Recommended restoration actions and the high-priority restoration areas where they should be applied are discussed below (also see Table 3).

Table 3. Recommended restoration actions and proposed priority restoration sections where they could be applied. Also included are the intended benefits and some potential risks associated with each action. The first three actions together constitute one option for providing fish passage at Hatt's Ranch dam, with the fourth action providing an alternative option.

Recommended Actions	**Implementation Sections**	**Intended Benefits**	**Potential Risks**
Dam removal	Hatt's Ranch dam	Allow native fish movement between lower and upper river	Increased presence of non-native fish upstream
Selective barrier at Green River confluence	Green River confluence	Prevent non-native fish recolonization (if non-natives removed in lower river)	Reduced native fish movement between Green River and San Rafael River Lack of long-term funding and personnel commitment
Non-native fish removal	Hatt's Ranch dam to Cottonwood Wash (pilot study)	Reduce competition and predation on native fish	Stress to native fish
Fish weir at Hatt's Ranch dam	Hatt's Ranch dam	Allow native fish movement, prevent non-native movement between lower and upper river	Lack of long-term funding and personnel commitment
Implement Ecological Flows	NA	Habitat creation and maintenance, provide connectivity, prevent river drying	
Tamarisk whole-tree removal	Reef to I-70 (with landowner participation) Confluence Canyon 3	Allow greater channel movement, habitat creation, and native vegetation establishment during floods	Secondary weeds Short-term reduction in wildlife habitat

Table 3 cont.

Recommended Actions	Implementation Sections	Intended Benefits	Potential Risks
Tamarisk fire treatment	I-70 to Hatt's Ranch	Large-scale tamarisk removal Allow greater channel movement, habitat creation, and vegetation establishment during floods	Secondary weeds Short-term reduction in wildlife habitat Loss of existing cottonwoods Vigorous tamarisk regrowth
Cottonwood plantings	Confluence	Establish native vegetation	Mortality due to desiccation or flooding
Gravel addition	Below SH-24 Canyon 3	Create riffle-pool sequences and other complex habitat	Gravel buried by sand and mud
Russian Olive removal	Throughout lower San Rafael River	Prevent further spread of Russian olive	Short-term reduction in wildlife habitat
Large substrate additions	Reef to I-70 Canyon 3	Improve habitat complexity	Disturbance to cliff faces and surrounding areas
Beaver-assist structures	Reef to I-70 Below SH-24 Canyon 3	Improve habitat complexity Capturing of sediment, water table elevation, and greater native vegetation establishment	Temporary fish barrier Temporary loss of cottonwood trees (though resprouting from the base of cut trees has commonly been observed) Structure failure during floods
Large wood addition	Canyon 3	Improve habitat complexity	Washed away during floods Buried by sand and mud
Livestock mgmt. including riparian fencing	Cottonwood Wash	Prevent loss of newly established cottonwoods and willows	

Recommended Restoration Actions

Tamarisk whole-tree removal and follow-up treatments to control secondary weeds and resprouts

As discussed in the problem statement, research on the history of geomorphic changes on the San Rafael River suggested that tamarisk facilitated channel narrowing and confinement as hydrologic patterns were changing by stabilizing active channel bars and bank sediments (Fortney et al. 2011). Tamarisk and other vegetation can stabilize bank sediments and reduce the ability of flood flows to erode sediments (Di Tomaso 1998, Pollen-Bankhead et al. 2009), thus reducing the ability of the channel to widen, migrate laterally, and form complex in-channel habitat during flood events. Research on the Rio Puerco in New Mexico has demonstrated that sediment erosion from a flood event can be higher in areas where tamarisk has been treated with herbicides (Vincent et al. 2009). Research on the channel response to the 2011 flood on the San Rafael River in one stretch of the UDWR removal area suggested that whole-tree removal of tamarisk promoted greater channel widening and lateral scour compared to non-removal areas (Keller 2012 - attached as Appendix IV). Habitat surveys also suggested that the 2011 flow event caused greater increases in habitat complexity in tamarisk removal areas compared to treatment areas (see Fig. 44). A unique feature of the UDWR tamarisk removal study area on the San Rafael River is high sinuosity, which likely also facilitated channel changes compared to the non-removal reach, which was straighter and thus had less potential for lateral scour and bank erosion. In addition, tamarisk was removed along the bank margins in many locations on the UDWR study reach. In areas with a riparian berm dominated by willow and native phagmites, there was less channel movement even if tamarisk had been removed on the floodplain. Thus, tamarisk whole-tree removal is suggested as a method to promote channel change and creation of habitat complexity during large flooding events in river sections with high sinuosity and tamarisk growing along the bank margins (see Fig. 24 for predicted response). To promote channel changes and creation of in-channel habitat complexity, tamarisk would only need to be removed along the bank margins. However, thick tamarisk stands also likely prevent establishment of native vegetation due to shading effects (Engel-Wilson and Ohmart 1978, Di Tomaso 1998, Smeins 2003). In many sections of the river, there are likely adequate isolated cottonwood stands that can provide a seed source for cottonwood regeneration. Thus, tamarisk removal across the valley bottom in these sections is also recommended as a method to increase the potential for cottonwood establishment. Many tamarisk on tributaries to the San Rafael River are not as impacted by the leaf beetle (e.g., Dugout Wash, based on vegetation mapping and personal observation), such that removal of tamarisk around existing cottonwood stands on tributaries could also benefit native vegetation by removing competition for existing cottonwood trees and by removing a seed source of tamarisk in close proximity to tributary junctions.

Whole-tree removal is generally recommended as opposed to other methods of tamarisk removal such as aerial herbicide application or burning for several reasons (though see I-70 to Hatt's Ranch dam section for one potential area for fire treatment). First, whole-tree removal has proven effective at promoting channel changes in response to a large flood event in the UDWR removal areas (Keller 2012). Second, whole-tree removal can be conducted without removing existing cottonwood trees, which may not be possible with fire treatment. Third, the tamarisk leaf-beetle is currently defoliating tamarisk stands effectively, suggesting limited additional effectiveness of herbicide applications. Finally, removed tamarisk trees could be moved into the channel as a source of large wood once the trees have died and fully dried out (see *Large wood addition* section below). Secondary weed treatment will likely be necessary for several years following tamarisk removal. Depending on whether understory vegetation is primarily native or non-native, native vegetation seeding and preliminary treatment of secondary weeds may also be useful to help deter colonization by secondary weeds. Resprouting may or may not be an issue depending on the effectiveness of whole-tree removal and the ability of the beetle to control resprouting.

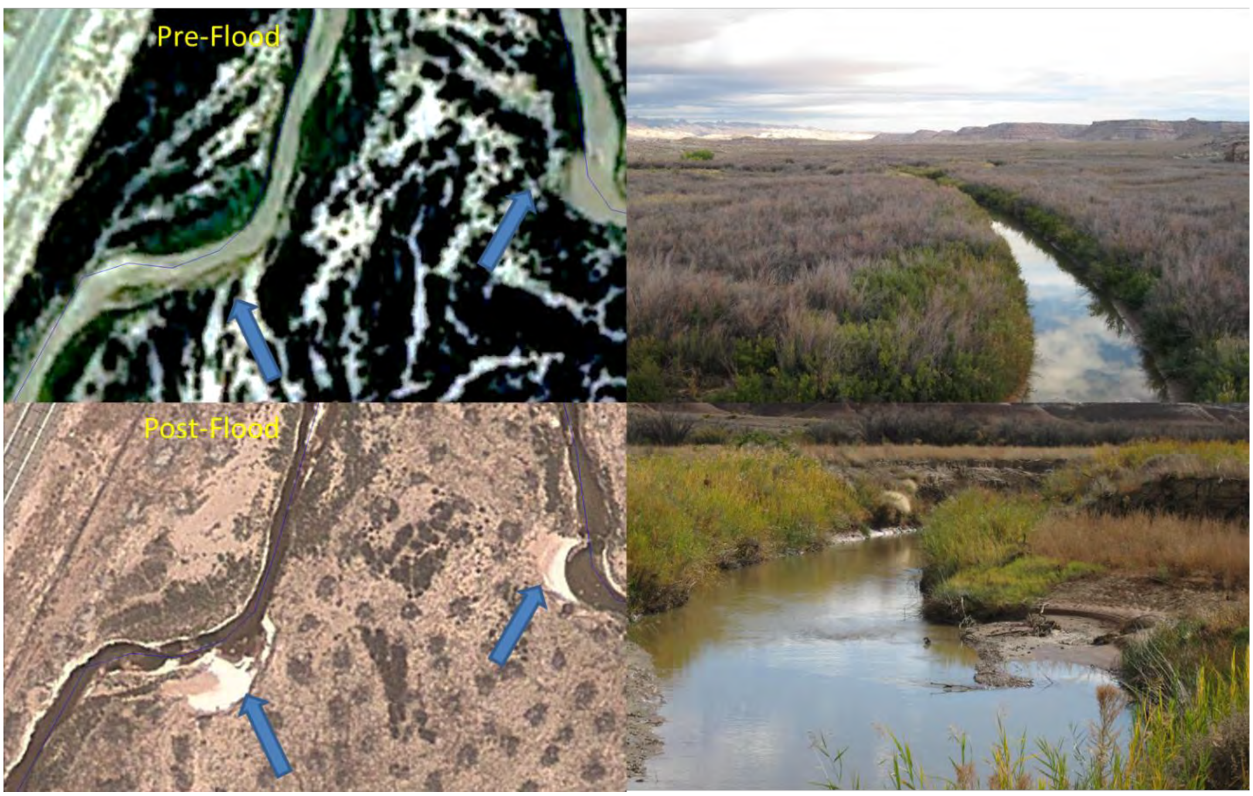

Figure 24. Left column shows before (above) and after (below) aerial imagery of the UDWR tamarisk removal treatment area just downstream of SH-24. Arrows indicate areas showing post-flooding lateral movement. Post-flood imagery shows the extensive tamarisk removal in this area (dark circles in bottom image are slash piles that were later burned). Photographs in the right column show the goal of recommended tamarisk removal on the San Rafael River. In the top picture, the channel is straight and confined within tall banks and tamarisk is abundant. The bottom figure shows an area of lateral scour and formation of a backwater and inset floodplain (on the right side of the picture) as a result of tamarisk removal and the 2011 flood (Photo taken at Hatt's Ranch by B. Laub on October 12, 2012). Figure adapted from Keller (2012).

Russian Olive removal

Although tamarisk is the dominant non-native woody vegetation on the lower San Rafael River, 19 individual overstory Russian olive trees have been identified on the lower San Rafael River (Fig. 25), and there are likely more seedling and sapling-size trees that have not been identified. As tamarisk removal proceeds and because tamarisk is being defoliated by the leaf beetle, there is a potential for Russian olive to expand on the lower San Rafael River and have a similar impact on habitat and riparian vegetation communities that tamarisk had in the past. While Russian olive does provide a food and structural habitat resource for native wildlife species, removing the limited number of Russian olives is unlikely to have a significant impact on fish or riparian habitat at the current time. In addition, management strategies for Russian olive often emphasize the importance of early detection and treatment, because removal becomes impractical for large infestations (USDAFS 2012). Moreover, limiting non-native species is often much more cost-effective than future removal (e.g., Leung et al. 2002, Simberloff 2003). Therefore, it is recommended that all Russian olives throughout the lower San Rafael River be removed during the first phase of restoration. Removal will likely involve cut-stump and herbicide treatment application by hand crews. Some of the trees are located on private land and thus landowner participation will be needed.

Partnering with beaver

Beaver are present in the San Rafael River and where they build dams, they help create complex fish habitat (Fig. 26). In the Reef to I-70 section of the river, roundtail chub have been observed using the pool downstream of a beaver dam at Tidwell Bottom, thus, the habitat created by beaver dams is likely beneficial for native fish. In addition, research on use of beaver in restoration at Bridge Creek, Oregon has demonstrated that beaver dams or dam-mimicking structures can promote sediment accumulation, which helps reduce channel incision, raise water tables, and promote overbank flow (Pollock et al. 2007). Thus, beaver dams may also facilitate cottonwood and other native vegetation recruitment (Pollock et al. 2007, Westbrook et al. 2011). However, beaver dams appear to be limited in their extent given the available resources. A preliminary analysis of potential dam capacity using the Beaver Restoration Assessment Tool (Macfarlane and Wheaton 2013) indicated that the vegetation resources could support >10 dams/km in many river reaches, but currently dam density is <1 dam/km throughout the lower river. One potential reason that beaver dams are limited in extent is that beaver cannot maintain dams through flooding events in the confined channel of the San Rafael River. In Bridge Creek, beaver dams often washed out due to the high stream power of flood events that were constrained within the incised channel (Pollock et al. 2011). Similar channel morphology exists on the San Rafael River and may be limiting the ability of beaver to maintain dams. Installation of beaver-assist structures is thus recommended as a restoration tool. Beaver assist structures consist of willow branches weaved in between wooden posts hammered into the streambed (Pollock et al. 2011). Beaver assist-structures could potentially help beaver maintain additional dams, but even if beaver do not use the structures, the structures alone can provide similar benefits as natural beaver dams (Pollock et al. 2011). Reintroduction of beaver into locations on the river where dams are desired may also be warranted if beaver are not colonizing restoration areas naturally. It may be possible to move beaver around within the San Rafael River, but translocating beaver from other watersheds or from upstream tributaries will require listing the San Rafael River on the state list of beaver reintroduction locations (UDWR 2010). This may be possible in the future as the San Rafael River has been petitioned for inclusion on the state list (Dan Keller, UDWR, personal communication). Finally, a moratorium on trapping in the lower San Rafael River should be pursued. Whether trapping is a significant source of mortality on the San Rafael River is unknown at this time, however a moratorium would reduce any trapping-associated mortality that is ongoing and help prevent any future trapping mortality.

Large boulder additions

Another process that has been observed to create complex fish habitat on the San Rafael River is the addition of boulders and other large substrates into the channel where it flows against the valley margins in the canyon-bound section (Fig. 27). However, large substrates have not fallen into the channel at every contact with the valley margin (Fig. 27). Therefore, it is recommended that at locations where the river contacts the valley margin and cliff faces are already fractured but have not dropped boulders into the channel, large substrate be dislodged from the canyon wall or pushed into the channel either by mechanical or blasting techniques. Of course, an assessment of potential negative impacts to archaeological and other resources will need to be conducted prior to implementing such actions.

Large wood additions

The rationale behind large wood additions is very similar to the rationale for large boulder additions. Where large wood occurs in the channel it helps create scour pools, backwaters, and other complex habitat structure for native fish. A study on the San Rafael River found that pools, riffles, and backwaters were more common around wood accumulations than around random points on the river (Keller 2012 – attached as Appendix IV). Similarly to beaver dams, accumulations of instream wood can also improve river-floodplain connections by directing flow toward the river banks to increase bank erosion and aggrading the channel through sediment capture (Wohl 2013). Thus, where large wood can be moved into the channel, it should help to create complex fish habitat (Fig. 28). Tamarisk that is removed through whole-tree removal constitutes one source of wood that will be available for movement into the channel eventually. Addition of tamarisk into the channel must be delayed until removed trees are fully dead to prevent resprouting of live trees within the channel. In addition, if sources of wood are available opportunistically beyond the channel for little cost, they could be transported to the river and added into the channel in the priority restoration sections. For example, a planned debris basin construction project will require removal of some cottonwood trees on Huntington Creek (BLM 2013). Such wood could be moved to the San Rafael River.

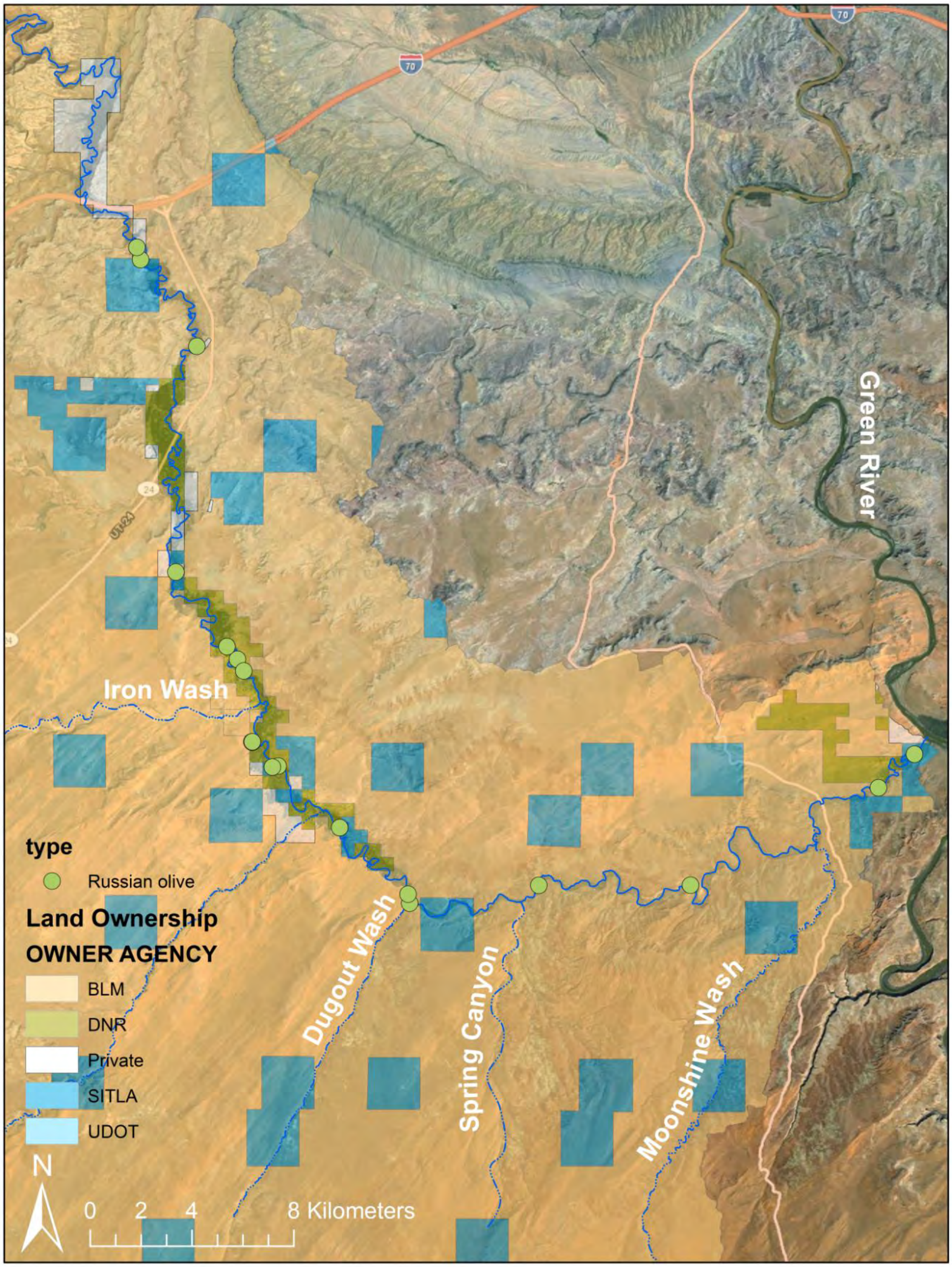

Figure 25. Map of the lower San Rafael River showing location of all 19 known Russian olive trees visible in aerial photographs. The first dot below Iron Wash represents 3 closely clustered trees.

Figure 26. Pictures of four different active beaver dams observed on the San Rafael River in 2012 and 2013. Clockwise from top left locations are: reach 32, Tidwell Bottom, reach 47 (see Fig. 35), and just upstream of the Dugout Wash confluence. All pictures by B. Laub.

Figure 27. Pictures showing the intended effect of large substrate addition. Picture on the left shows a reach where the channel flows along the valley margin but there is a lack of large substrate in the channel and little channel complexity (Photo looking downstream below confluence of Dugout Wash, taken by Dave Dean on May 21, 2013). In the picture on the right, substrate has fallen from the cliff wall into the channel and is creating complex fish habitat (Photo looking upstream near Moonshine Wash, taken by B. Laub on May 22, 2013).

Gravel addition

There are several lines of evidence to suggest that gravel addition could help promote channel changes and creation of fish and riparian habitat (Dean and Schmidt, *article in press*). Where tributaries that carry gravel enter the San Rafael River, habitat complexity increases substantially below these tributaries. This happens both at Iron Wash and Spring Canyon and is the primary reason these areas stand out as conservation areas. Cottonwood stands are also relatively abundant in the immediate vicinity of these two tributaries (see Figs. 22 and 23). Cottonwoods may be particularly successful in these locations due to more frequent disturbance of the channel and floodplain as a result of the tributary input. Floodplain substrate may be somewhat coarser in these areas due to tributary inputs of gravel, which can provide greater access to the water table and improve water uptake by cottonwood trees (Sher et al. 2002). In addition, the channel is wider and less confined within steep banks in the areas below the tributary inputs, suggesting greater connection between the channel and floodplain (Figs. 29 and 30). There is also a positive relationship between instream habitat complexity and substrate size on the San Rafael River, with the highest magnitude of increase occurring between sand reaches and gravel reaches (Fig. 31). Finally, the transport of gravel by river channels is a natural process that leads to formation of bars, riffles, and pools (Knighton 1998). Gravel addition has been used as a restoration technique to enhance habitat on a diverse array of rivers (e.g., Kondolf 1998, Barlaup et al. 2008, McManamay et al. 2010). The idea behind gravel addition on the San Rafael River is to mimic a tributary input by dumping loads of gravel into the channel at one location at one time and letting the river transport the gravel downstream during subsequent flood events. Gravel transport during high flows is predicted to form alternating bars, which will increase sinuosity. Through this process, it is predicted that riffles and other habitat features will form and channel confinement will be reduced (see Figs. 29 and 30 for predicted response). If this technique is applied, it will be necessary to calculate the total amount of gravel needed and the sediment size that can be transported by the river at addition locations.

Figure 28. Pictures showing the intended effects of large wood additions to the channel. In both pictures, large logs and other wood accumulations in the channel create variations in flow and depth in an otherwise straight, generally uniform channel.

Figure 29. Pictures showing intended impact of gravel addition on channel morphology and fish habitat. The top picture shows the channel just upstream of the Spring Canyon confluence and is straight and confined with little channel complexity (View is upstream, taken by B. Laub on May 2, 2013). The bottom picture is downstream of Spring Canyon, which delivers gravel to the San Rafael River. The channel below the confluence has riffle-pool sequences, gravel bars, and a much-less confined channel (View is downstream, taken by B. Laub on November 7, 2012). Gravel addition is intended to mimic the impacts of this tributary input.

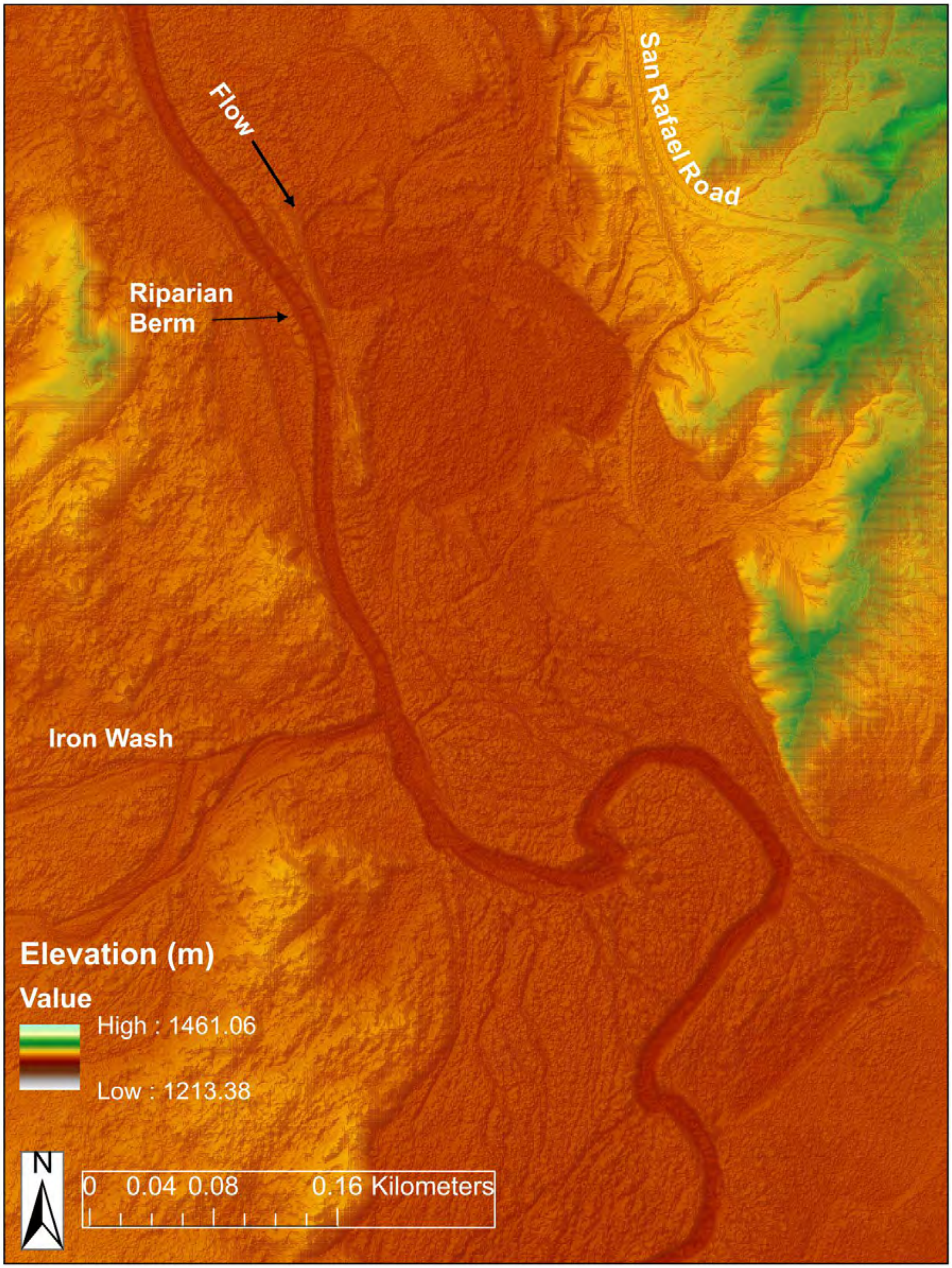

Figure 30. LiDAR-based digital elevation model of the Iron Wash confluence. Note the immediate widening of the channel downstream of the Iron Wash confluence and the less confined channel. The riparian berm that is present along much of the channel is visible in some places above the confluence, but is not present immediately downstream of the confluence.

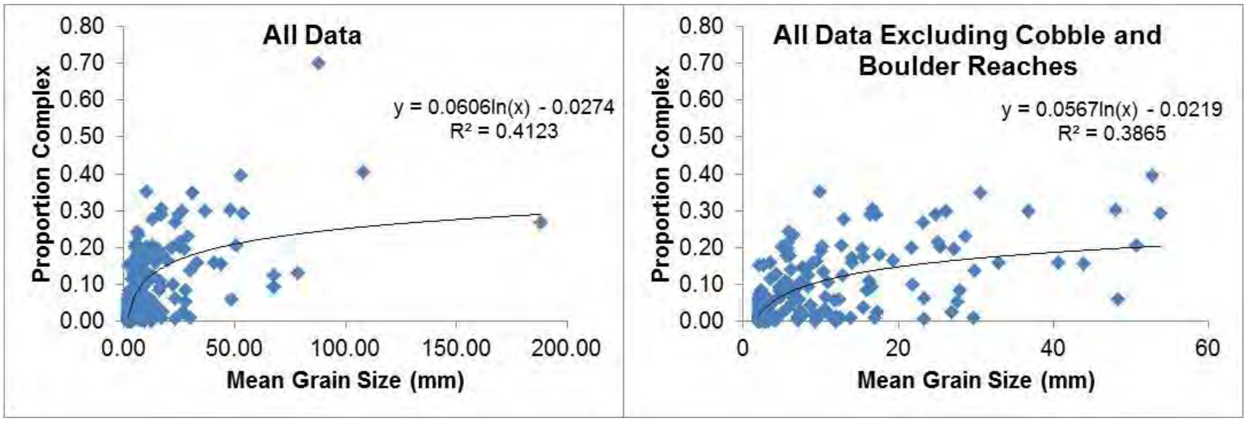

Figure 31. Relationship between mean grain size of a 300-m reach and proportion of the reach composed of complex fish habitat (pools, riffles, and backwaters). Left graph shows data for all reaches between Hatt's Ranch dam and the Green River. Right graph excludes reaches containing cobble and boulder substrates.

Livestock management including riparian fencing

One of the primary threats to newly established cottonwood and willow seedlings on the San Rafael River is likely to be browsing and trampling by cattle, with desiccation another major threat. Cattle should therefore be excluded from areas where regeneration has occurred until the trees reach an age at which cattle browsing and trampling is no longer a significant threat.

Cottonwood pole planting and supplemental watering

Although cottonwood stands exist in many areas of the San Rafael River and do provide a seed source for regeneration, appropriate flow conditions over a number of years are needed for successful establishment (Braatne et al. 1996, Scott et al. 1997, Mahoney and Rood 1998). Based on observations of stand sizes and limited tree dating, it appears that recruitment of cottonwoods has been very limited over the last 20 years. Therefore, pole plantings could help supplement natural establishment and also help provide an additional seed source in areas where cottonwood stands are limited. Seasonal groundwater dynamics and soil salinity should be assessed at any location where planting is desired to determine whether water will be available throughout the year for plantings and whether soil conditions are amenable to cottonwood growth. Supplemental watering of plantings or of naturally established seedlings may be necessary for several years to ensure survival of newly planted or established trees.

Non-Native fish control and removal

As discussed in Objective 3, restoration of habitat will be much more beneficial for native fish if non-native fish can be removed or reduced in numbers (Walsworth 2011). The feasibility of effective non-native control or removal is currently unknown, however, there are a number of factors that suggest it could be possible on the lower San Rafael River. First, the only significant colonization source of non-native fish is the Green River, because no perennial tributaries enter the lower San Rafael River and the abundances of non-native fish in the upper San Rafael River are very low. Second, much of the lower San Rafael River has a simplified ditch-like morphology which should improve the efficiency of removal efforts. Third, the river often becomes dewatered during dry periods which will concentrate fish and thus allow non-native removal over large stretches of river with reduced effort. Efforts aimed at complete non-native removal would need to be coupled with establishment of a selective fish barrier near the Green River confluence (see discussion in the *Improving Connectivity* section).

The possibility for efficient non-native removal on the lower San Rafael River suggests that a pilot-study should be conducted to determine the effectiveness of removal efforts and its potential benefit for native fish. A unique opportunity exists for such a study at the current time. During the flood of 2011 the river abandoned a meander bend upstream of the confluence of Cottonwood Wash due to a large input of sediment from the wash that plugged the channel. The shortened length of channel caused a local increase in the channel gradient and subsequent knick-point formation in the channel that now cuts across the meander bend (Fig. 32). These knick points are likely a barrier to upstream fish dispersal and therefore if non-native removal efforts were undertaken between Cottonwood Wash and Hatt's Ranch dam, the effectiveness of these efforts could be studied.

Given the potential benefit of non-native fish removal and the situation at Cottonwood Wash, it is recommended that a mechanical non-native removal effort be undertaken between Hatt's Ranch dam and Cottonwood Wash if the river becomes dewatered in the next 1-2 years. Mechanical removal is recommended because this will allow native fish to stay in the river so that their response to non-native removal can be studied. Dewatering is necessary so that this effort is feasible. In addition, the knick points at Cottonwood Wash are migrating upstream (personal observation) and thus need to be monitored to determine whether they remain a barrier to fish movement. If the knick points dissipate prior to a removal effort, the proposed action should be reconsidered to determine whether a different reach of the river should be targeted for a pilot study. However, even if the knick points dissipate after a removal effort has occurred, such an effort will still allow study of the effectiveness of non-native removal efforts, just without a barrier to non-native colonization. The latter case would still be worthwhile, because a pilot study to determine the effectiveness of non-native removal should be undertaken regardless of whether a natural barrier exists on the river or not.

If the pilot study shows that non-native control efforts can depress non-native fish abundance and if native fish respond favorably, non-native control efforts should be applied periodically in restoration areas. However, even without the results of a pilot study, non-native control efforts are predicted to be beneficial, because previous research on the San Rafael River has indicated that native fish are more likely to respond positively to habitat restoration if non-natives can be removed (Walsworth 2011, Walsworth et al. 2013).

Priority Restoration Sections and Their Recommended Treatments

Reef to I-70

The majority of land in this section is privately owned (Fig. 33). If the landowner is willing to partner in the restoration effort, a large-scale restoration effort can be conducted in this section. If the landowner is unwilling, restoration actions will be limited to only a few individual locations. Either way, the landowner should be contacted regarding the planned restoration efforts. Recommended restoration actions and their locations are:

- Tamarisk whole-tree removal and follow-up treatments to control secondary weeds and resprouts (dependent on landowner participation)

  Location: Throughout the section (pending landowner participation).

- Installation of beaver-assist structures

  Location: Structures should be installed on the BLM property in this section (Fig. 33). If landowner participation is secured, structures can be installed in approximately half the length of this section as an experimental design testing the impacts of tamarisk removal alone and in combination with beaver assist structures.

- Large boulder and wood addition

  Location: There is one location in this section where the channel impinges on a canyon wall on BLM property and this area should be checked for the presence of large substrates (Fig. 33). If large substrates are not present, they should be added at this location. If landowner consent is obtained, there are other locations in this section where this technique can be applied. If landowner consent is obtained, large wood should also be added where it is found in close proximity to the channel.

Figure 32. Photograph of a knick point on the San Rafael River in the vicinity of Cottonwood Wash. Photo taken by B. Laub on October 12, 2012.

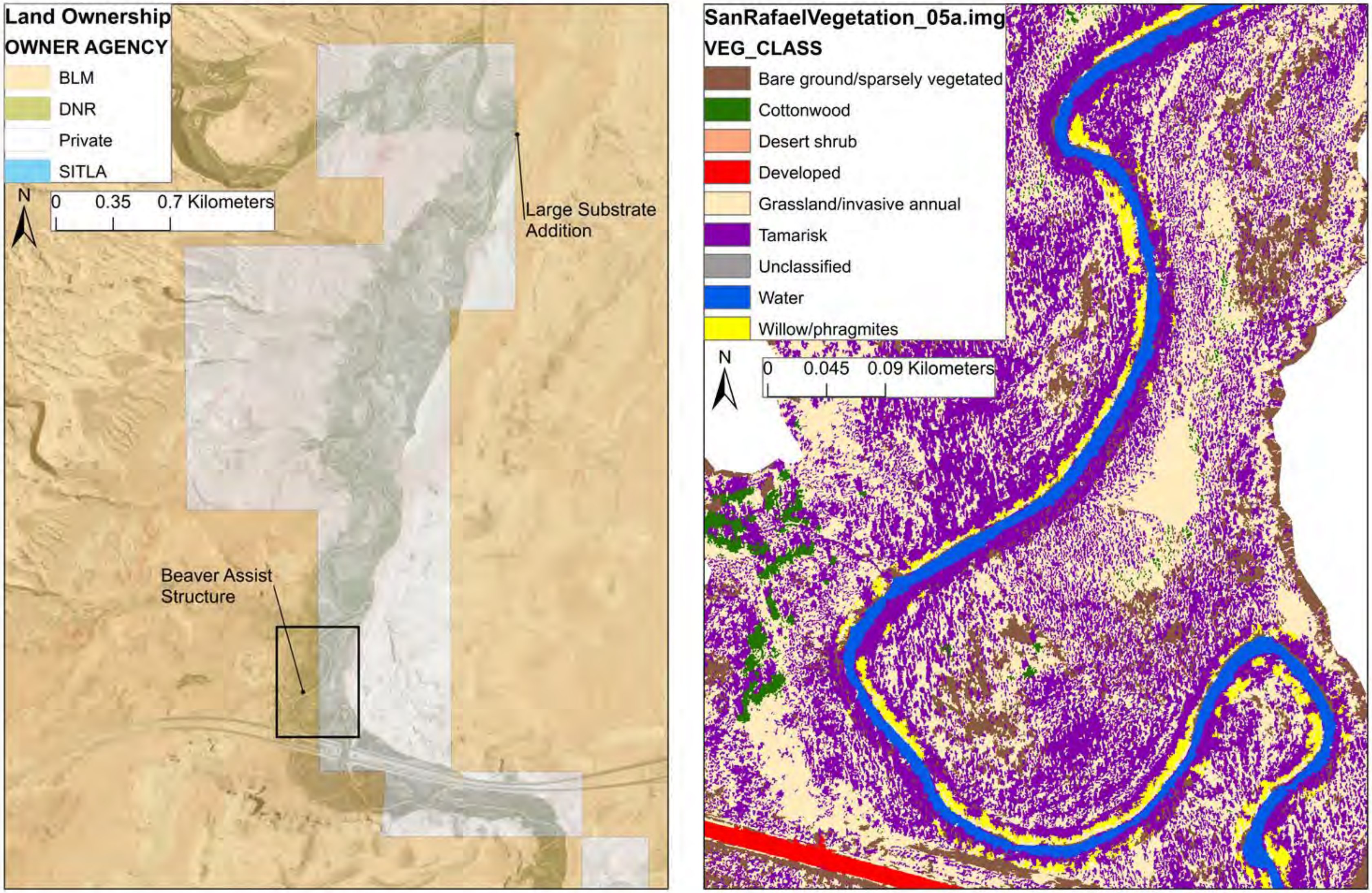

Figure 33. Map of the Reef to I-70 section showing land ownership and proposed locations for restoration treatments on BLM land (left) as well as a vegetation map (right). Box on the left figure shows location of vegetation map. Additional vegetation maps available at: http://bit.ly/1awJyOr.

Green River Confluence (Reaches 211-213)

The Green River Confluence section is an approximately 1 km reach at the downstream end of the San Rafael River (Fig. 34). This reach becomes a backwater area of the Green River during high flows on the Green River. Habitat complexity is low in this section, and being just upstream from the Green River, it has a high potential restoration benefit for native fish (Fig. 20). However, the benefit of habitat restoration for native fish in this section will be highly dependent on whether non-native fish can be controlled or excluded, because the Green River is also a source of colonists for non-native fish. Regardless of whether non-native fish can be excluded, native vegetation could benefit substantially from restoration in this section, because tamarisk is the dominant vegetation type in this reach, particularly along the channel (Fig. 34). Land ownership in this section is primarily state, however, there is one small section of private land (Fig. 34). Thus, restoration of this section is dependent on UDWR commitment and landowner participation. Recommended restoration actions for this section and their locations are:

- Tamarisk whole-tree removal with revegetation and follow-up treatments to control secondary weeds and resprouts (dependent on landowner participation).

  Location: Throughout the section (pending landowner participation).

- Russian olive removal

  Location: One Russian olive tree has been identified in this section (see Fig. 34), but any existing Russian olive trees in this section should be removed.

- Cottonwood pole planting and supplemental watering

  Location: Plantings could be undertaken in this section on UDWR land and may or may not need supplemental watering depending on whether elevated water tables are present due to the Green River. Water table levels and soil conditions should be assessed prior to planting, but even if water tables are not elevated, supplemental watering may be an option due to the close proximity of a permanent water source in the Green River.

- Non-native fish control

  Location: Throughout the section, but will be dependent on results of the non-native removal pilot study (described above) and whether a barrier to non-native movement from the Green River is installed in this section.

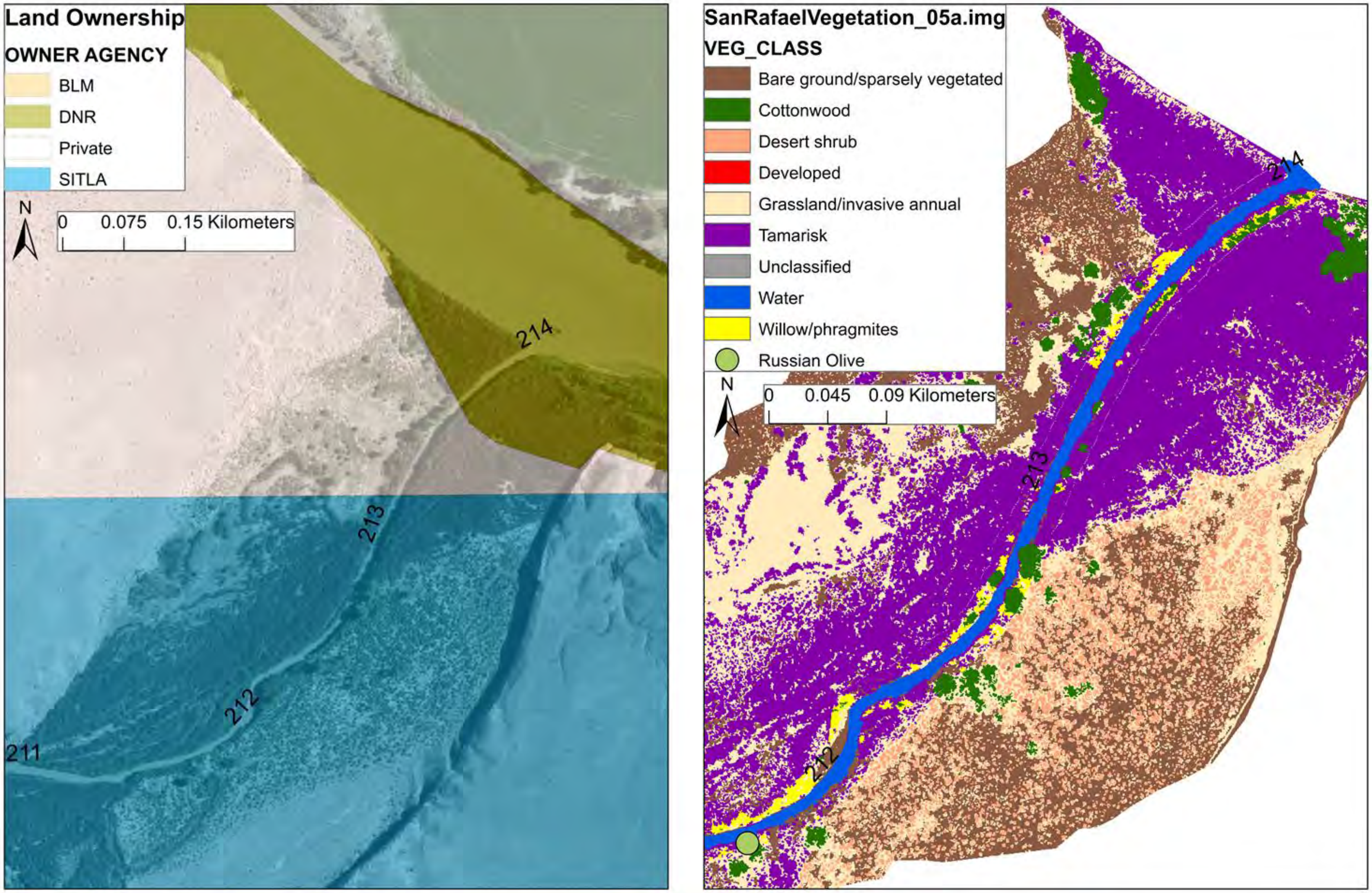

Figure 34. Map of the Confluence section showing land ownership and a vegetation map (right). Numbers mark the upstream end of reaches.

Below SH-24 (Reaches 14-49)

The section begins immediately downstream of SH-24 and extends about 10 km downstream (Fig. 35). Habitat complexity and existing cottonwood stands are variable between reaches in this section but potential restoration benefit for native fish is relatively high until reach 41 (Fig. 20). The downstream end of this section was extended because reaches 38-49 are similar in their sinuosity and extending the reach allows for additional experimentation with restoration methods (see below). UDWR has removed tamarisk along reaches 14-31 and 46-49. The remaining sections have not had tamarisk removed and are in a mix of landownership, including state, BLM, and private (Fig. 35). In addition, reaches 14-32 have much higher sinuosity than the remainder of the section. The mix of reaches with and without tamarisk removal in this section provides an opportunity to experiment with different combinations of treatment types in the process of restoring this section. Three additional treatments are recommended in addition to the existing state tamarisk removal treatment in this section:

- Gravel addition

  Location: In reach 48 there is a road that ends at a small cliff over the river that would allow trucks to unload the gravel directly into the channel (Fig. 35).

- Installation of beaver-assist structures

  Location: An experimental design consisting of three treatment types (beaver structures only, beaver structures + tamarisk removal, and tamarisk removal + gravel addition) can be established by installing beaver-assist structures at different locations (Fig. 35). Structures should be installed in the reaches immediately upstream of the gravel addition site where tamarisk has been removed (reaches 46 and 47) to create a tamarisk removal + beaver structures treatment. An existing beaver dam in this stretch could be reinforced rather than installing a new structure (Fig. 35). Beaver structures should be installed on the BLM and state lands in reaches 42-45, 38, and 33 to create a beaver structures only treatment. Beaver structures could also be installed in reaches 28-30 of the state removal areas, because this stretch is also relatively straight and this would increase the number of tamarisk removal + beaver structures treatments. The UDWR is currently making plans to install beaver structures in the sinuous reach of this section immediately below SH-24.

- Russian olive removal

  Location: One Russian olive tree has been identified in this section (see Fig. 27), but all existing Russian olive trees should be removed. The known tree is located on private land and thus removal will require land owner participation.

- Non-native fish removal

  Location: Throughout section as part of a pilot study (described above).

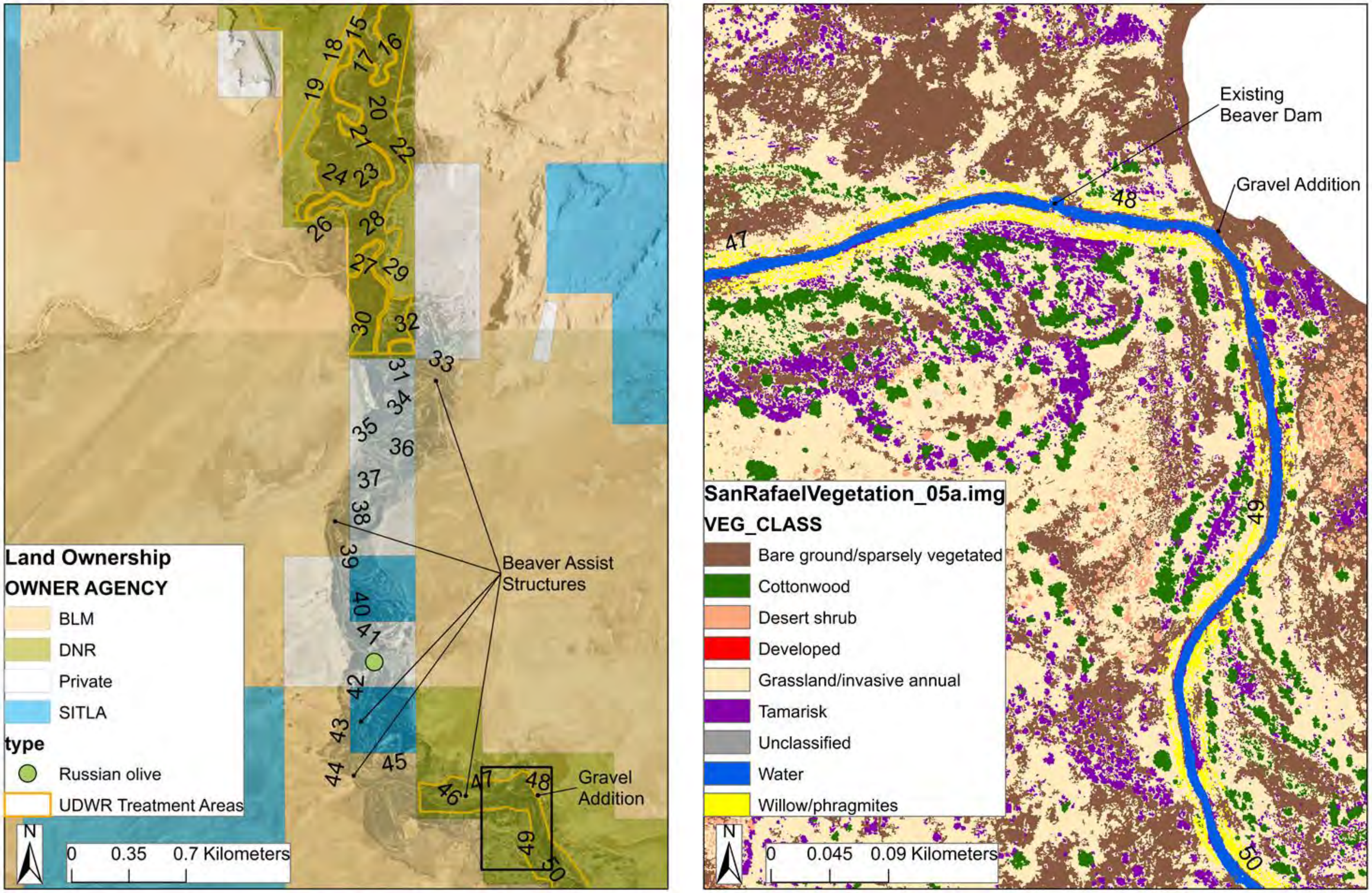

Figure 35. Map of Below SH-24 section showing land ownership and proposed locations for restoration treatments (left) as well as a vegetation map (right). Box on the left figure shows location of vegetation map. Numbers mark the upstream end of reaches. Additional vegetation maps available at: http://bit.ly/1awJyOr.

Canyon 3 (Reaches 177-199)

The section is in the narrow valley width, canyon-bound reach of the lower San Rafael River (Fig. 21). Land ownership is mostly BLM (Fig. 36). The conservation weight is variable between reaches in this section, however, the potential restoration benefit for native fish is consistently high (Fig. 20). Access to the section is facilitated by the lower San Rafael River Road, which crosses the river at reach 193, making it an ideal location to test different treatment types. Moonshine Wash enters the San Rafael River in this section at reach 185. Recommended treatments are similar in this section as the Below SH-24 section, with the addition of large wood and substrate additions, and can again be implemented in an experimental design framework.

- Gravel Addition

  Location: Many reaches of the river in this section have coarse substrate due to inputs from Moonshine Wash, other smaller tributaries, and where the channel impinges on the valley margins. However, reaches 195-197 have lower substrate sizes, and access to these reaches is provided by a road. Thus, gravel addition is recommended at reach 195. Gravel for addition to the river may be obtained locally from terraces above the valley bottom near the gravel addition location. No other treatments should occur downstream of this gravel addition site in order to establish a gravel only treatment (Fig. 36).

- Tamarisk whole-tree removal and follow-up treatments to control secondary weeds and resprouts

  Location: Tamarisk removal should occur upstream from the gravel addition site to Moonshine Wash (Fig. 36). Where tamarisk occurs directly on the channel banks it should be removed using whole-tree removal. Tamarisk should also be removed around existing cottonwood stands either using whole tree removal or by cut-stump techniques if whole-tree removal is not possible without damaging existing cottonwood trees.

- Installation of beaver assist structures

  Location: Beaver assist structures should be installed in half of the reaches between Moonshine Wash and the gravel addition site. Considering the Moonshine Wash confluence to be another gravel addition site, installing beaver structures in half the section length between Moonshine Wash and the gravel addition site will allow three treatment types to be established: gravel addition + tamarisk removal + beaver structures where beaver structures are installed, gravel addition + tamarisk removal where beaver structures are not installed, and gravel addition only below the gravel addition site.

- Large wood and boulder additions

  Location: Boulder addition should occur by the canyon-dislodgement method wherever the channel contacts the valley margin but does not currently contain coarse material.

Large wood lying on the floodplain can be added to the channel. These additions should only occur upstream of Moonshine Wash so as not to confound the experimental design of the tamarisk removal, beaver assist structure, and gravel addition treatments.

- Non-native fish control

  Location: Throughout section, but will be dependent on results of the non-native removal pilot study (described above).

Cottonwood Wash (reaches 74 to 87)

This reach comprises the 4 km stretch of river upstream of Cottonwood Wash (Fig. 37). Although this section does not break out as a priority reach based on the weighting analysis, this is one of the only locations on the lower San Rafael River where cottonwood regeneration following the 2011 flood event has been observed (see Fig. 14 and Fig. 38). Cottonwood germination likely occurred in 2012 but was the direct result of the 2011 flood and associated sediment input from Cottonwood Wash that caused a meander cut-off event, created fresh sediment deposits, and raised water tables upstream of the tributary junction (Fig. 14). Facilitating the survival and proliferation of these saplings is recommended. Desiccation, browsing and trampling by cattle, and subsequent high-flow events all represent potential sources of mortality for the saplings. There is little that can be done to prevent mortality from a high-flow event, therefore monitoring of the area should be conducted periodically to determine the survival of the current saplings. However, the other sources of mortality can be addressed with restoration actions listed below. In addition, most of the known overstory Russian olive trees on the lower San Rafael River are located in this section and should be removed.

- Livestock management including exclosure fencing to prevent browsing and trampling

  Location: Throughout reach

- Supplemental watering

  Location: Currently, an existing beaver dam and sediment wedge associated with a tributary-derived debris flow from 2011 are maintaining elevated water tables (Fig. 14). If the water table drops due to loss of the beaver dam or migration of knick points (Fig. 32), it may be useful to maintain some of the saplings through supplemental watering. UDWR is currently watering pole plantings in the area, so this may be a feasible option.

- Russian olive removal

  Location: Five Russian olive trees have been identified in this section (see Fig. 37), but all existing Russian olive trees should be removed. The known trees are located on UDWR and SITLA land and thus removal will require participation from UDWR.

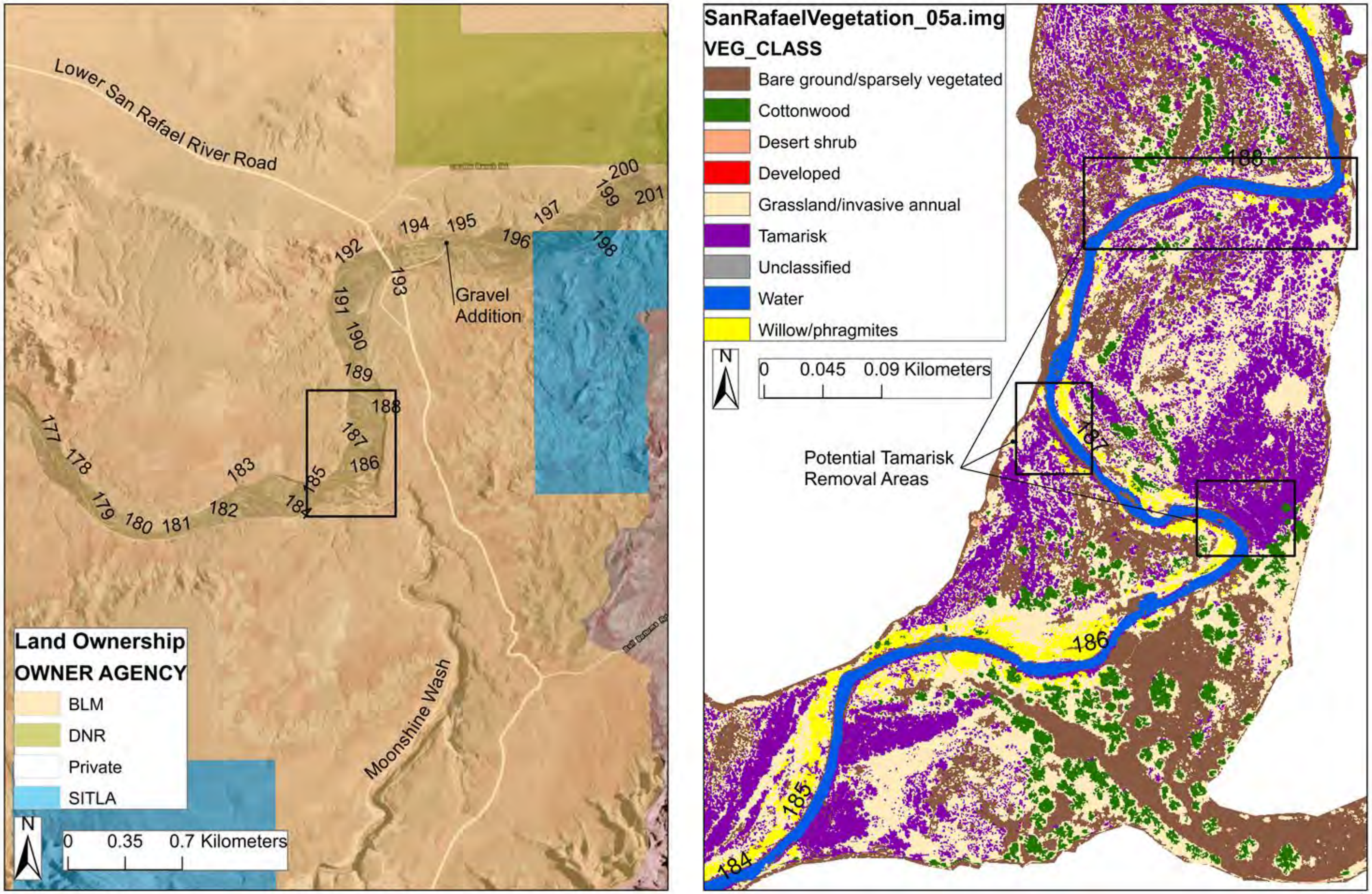

Figure 36. Map of the Canyon 3 section showing land ownership (left) and proposed locations for restoration treatments as well as a vegetation map (right). Box on the left figure shows location of vegetation map. Numbers mark the upstream end of reaches. Additional vegetation maps available at: http://bit.ly/1awJyOr.

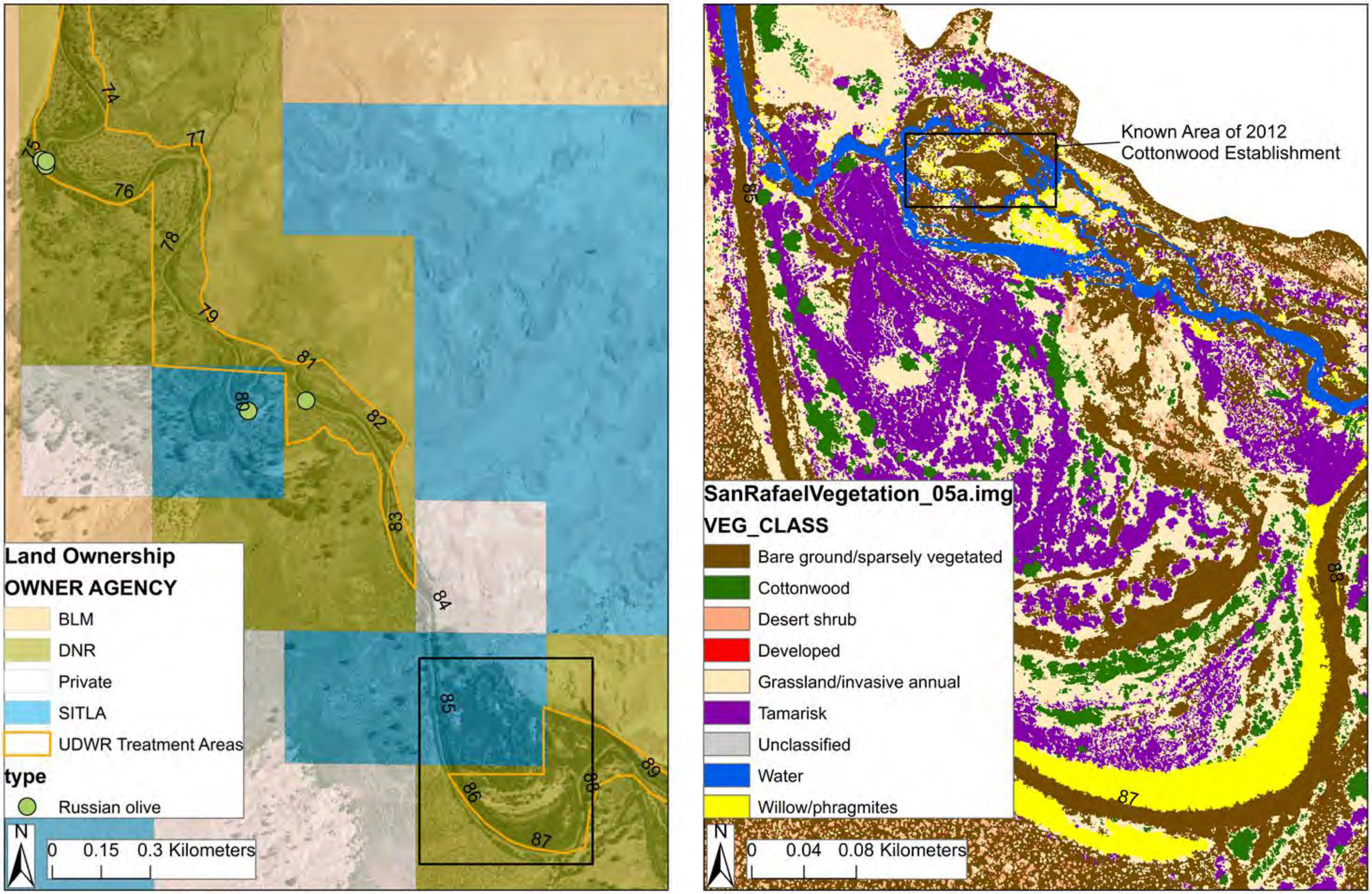

Figure 37. Map of Cottonwood Wash section showing land ownership (left) and a vegetation map (right). Box on the left figure shows location of vegetation map. Numbers mark the upstream end of reaches. Box in the vegetation map shows an area where cottonwood recruitment occurred in spring 2012 following the channel changes that occurred during the 2011 flood event (Fig. 38). Additional vegetation maps available at: http://bit.ly/1awJyOr.

Figure 38. Photograph showing cottonwood recruitment in the Cottonwood Wash section. Photo taken by B. Laub on May 2, 2013.

Lower Priority Restoration Reaches and Their Potential Restoration Treatments

Canyon 1 (reaches 147-160) and Dugout Wash (reaches 114-130)

These sections are prioritized for the second phase of restoration. Thus, there are no recommended actions at this time. However, the actions are likely to be similar to those employed in the Canyon 3 section. Monitoring of the Canyon 3 section should provide guidance on the most effective restoration techniques and those techniques should be applied to these two sections. Land use in these sections is entirely BLM except for one section of SITLA land which has been treated with tamarisk removal (Fig. 21). Removed tamarisk are currently piled on the floodplain in the SITLA parcel, and a potential restoration action in this section would be to place that woody material into the channel.

Frenchman's Ranch (reaches 50-67) and The Lower Wide-Valley (88-113)

These sections are prioritized for the third phase of restoration. Thus, there are no recommended actions at this time. However, the UDWR has removed tamarisk on most of these sections and thus this restoration could be supplemented with gravel additions, wood additions, and beaver structures, depending on how effective these techniques are found to be in the *Below SH-24* section.

I-70 to Hatt's Ranch

This section is prioritized for the third phase of restoration and is not discussed in detail at this time. However, much of this section is on BLM land, beetle-defoliated tamarisk is the dominant vegetation type, and there are very few existing cottonwood trees (Fig. 11). Thus, there is the potential for efficient large-scale tamarisk removal with fire in this section. Large-scale removal could potentially enhance channel changes and native vegetation recruitment in this section if a large spring snowmelt flood event occurred. The presence of native vs. non-native understory vegetation should be investigated in this section prior to any fire treatment to determine whether native vegetation is likely to colonize the area after fire treatment or whether treatment is likely to promote secondary weeds. Either way, such a treatment will likely require extensive follow-up weed treatments and may warrant cottonwood planting given the lack of available seed sources in this section. However, depending on plans for the Hatt's Ranch dam, the potential for significant tamarisk mortality due to continued beetle defoliation, and the efficacy of other treatment types, large-scale tamarisk removal may not be the preferred option. Different restoration actions should be reevaluated for this section as implementation and monitoring of other river sections proceeds. As more information becomes available, the prioritization of this section should be reevaluated as well.

Hatt's Ranch (reaches 1-13), Canyon 2 (161-176), and Chaffin's Ranch (reaches 200-210)

All three of these sections were prioritized for the fourth phase of restoration due primarily to their relatively high conservation weighting. Hatt's Ranch is in the wide-valley section of the San Rafael River and is entirely UDWR property, though leased by the Hatt's. Chaffin's Ranch is also a wide-valley section and is a mix of UDWR and BLM property (Fig. 21). UDWR has removed tamarisk on all the area they own in these sections. Restoration actions found to be effective in wide valley sections could be applied at Hatt's Ranch, but any restoration activities should be coordinated with the Hatt's. Conversion of the Hatt's Ranch property from flood to pressurized irrigation is one additional potential restoration action for this area (discussed below). Chaffin's Ranch and Canyon 2, which is in the narrow-valley section, could also be restored in the future with restoration techniques found to be most effective on other sections of the river.

Improving Passage for Native Fish

Improving the ability of native fish to move between the upper and lower San Rafael River and the Green River was identified in Objective 5 as an important aspect for ensuring the persistence of native fish populations. The only permanent man-made physical barrier to movement on the San Rafael River is the Hatt's Ranch dam, though dewatering may prevent fish movement temporarily during dry years (dewatering is addressed below). Therefore, providing fish passage at the Hatt's Ranch dam is recommended as a restoration action.

There are two options for providing passage at the dam: 1) construction of a manned weir at the existing dam, and 2) dam removal coupled with non-native fish removal and installation of a selective fish barrier near the Green River confluence. Under option 1, a weir would be installed at the current dam and would be manned during spring runoff to provide passage over the dam for upstream-migrating native fish. Option 2 would provide complete connectivity throughout the river for native fish, however, the Hatt's Ranch dam is currently a barrier to upstream migration of non-native fish and non-native fish are known to be a major factor contributing to low abundance of native species below the dam (Walsworth 2011). Thus, proceeding with dam removal is not recommended unless non-native fish can be removed or significantly reduced in the lower San Rafael River. Non-native removal will need to be coupled with installation of a barrier with selective fish passage near the Green River confluence to prevent recolonization of removal areas from the Green River by non-native fish. Dam removal would also likely cause significant incision upstream and sediment delivery downstream unless the channel is manipulated so that it stays on bedrock at the dam site (PSI 2009). Preventing incision may also involve some channel realignment up and downstream of the dam site, but there may be an opportunity to improve habitat conditions through this work, for example, reconnecting oxbows to the channel on the Hatt's Ranch property that were cut off from the channel during channel straightening operations. In addition, a selective fish barrier near the Green River confluence could become a complete barrier to fish passage without funding and staff availability over the long-term. Thus, option 2 comes with significant risks and will require a large investment in terms of cost, effort, and time. However, option 1 is also costly. Engineers from NRCS estimated that it would cost approximately $6 million to create an effective structure at the Hatt's Ranch dam and that it only had about a 30% chance of long term success given the large monsoonal floods which occur. The bypass structure would also require a number of grade control structures in the river to reduce velocities sufficiently to allow passage of all native species. Installation of such a structure at the Hatt's Ranch dam also has the same risks associated with long-term funding as a structure near the Green River confluence except that there is already a barrier at the Hatt's Ranch dam. The benefit to native fish would be much higher under option 2, if non-native fish can be removed and long-term funding reasonably assured. For example, a modeling study indicated that eradication of non-native fish would increase bluehead sucker abundance by 149-194%, flannelmouth sucker abundance by 35-52% and roundtail chub abundance by 16-29% even without habitat restoration (Walsworth 2011). In comparison, habitat restoration alone is predicted to increase native fish abundances on the order of 2-6% (Walsworth 2011).

To better inform decisions as to the best option, a more quantitative cost-benefit analysis should be conducted. Although such an analysis is beyond the scope of this plan, it is clear that the costs and potential effectiveness of different actions need to be determined. These include: 1) construction and operation of a barrier near the Green River confluence, 2) non-native fish removal, 3) dam decommissioning, and 4) consequences of non-native fish colonizing the upper river vs. benefits of connectivity for native fish species under dam removal. One component of such an analysis would be a pilot study on the effectiveness of non-native removal as discussed above in the non-native removal section. A formal cost-benefit analysis could also include alternative options such as dam removal without installation of a selective barrier at the Green River confluence and construction of a weir at the Hatt's Ranch dam coupled with periodic non-native fish control efforts on the lower San Rafael River. In any case, with the potential costs and risks involved, a final decision on an option for improving fish passage demands a more quantitative analysis than provided here.

Ecological Flows

As discussed in Objective 4, water users and resource managers need to develop and implement a suite of ecological flows that balance upstream water demands and provide baseflows and habitat-forming flood flows. A suite of flows are necessary to maintain a dynamic river system that provides sufficient habitat for native fish and vegetation. Maintaining baseflows will help prevent dewatering of the lower river, provide habitat for native fish, and keep water tables accessible for native riparian vegetation. Allowing periodic flooding during the snowmelt runoff season will be necessary to promote channel and floodplain processes that create habitat and provide establishment sites for native vegetation. Considerations and recommendations for baseflow and flood flow components are discussed here.

Baseflows needed for optimal habitat provision are difficult to recommend because they require an assessment of how habitat conditions change with flow level, and this information is not yet available on the San Rafael River. A physical habitat simulation model is currently being developed that may provide guidance with respect to these flows (Ian Gowing, USU Water Lab, personal communication). However, the relationship between habitat conditions and flow will vary with morphologic changes in the channel (Richter et al. 1997), such that physical habitat models may need to be updated over time. Given the lack of information for determining habitat provision flows at this time, a recommendation for minimum flows that maintain connectivity and high flows that promote habitat creation and channel changes are developed here. However, both minimum and high flow recommendations will need to be refined and validated over time through monitoring and adaptive management. Monitoring of fish habitat at varying flow levels will need to be done to recommend habitat provision flows. Further monitoring needed to refine flow recommendations is discussed below and methods for conducting this monitoring are provided in Section V of this report.

Minimum Flows

The goal of providing minimum flows is to maintain connectivity throughout the river, i.e., to prevent dewatering over significant stretches of the river. However, minimum flows may not provide optimal habitat conditions for native fish, because as flows decrease, useable habitat area shrinks and the potential for temperatures to increase and oxygen levels to decrease beyond tolerance limits for native fish increases (Lake 2003). Furthermore, as flows decrease and portions of the channel become dry, fish become concentrated in isolated pools and native fish may become especially susceptible to predation by non-native fish (Labbe and Fausch 2000). On the other hand, native fish in desert river systems are adapted to large variations in flow levels, whereas non-native fish are often adapted to more consistent flow levels (Olden et al. 2006). Thus, occasional river drying could potentially favor native over non-native fish, but current research indicates a strong negative impact of non-native fish despite occasional drying currently (Walsworth 2011). A minimum flow target range is recommended here for maintaining connectivity throughout the lower river, based on direct observations of connectivity in the lower San Rafael River at differing flow levels. Additional monitoring is needed to provide recommendations for habitat provision flows and to determine whether occasional river drying may shift the competitive balance in favor of native fish or increase predation by non-native fish on native fish.

<u>Direct observations of connectivity</u>. While there have been previous reports of drying on the lower San Rafael River (McAda et al. 1980, Bottcher 2009), these observations have not been sufficient to determine the precise flow level at which significant portions of the channel become dry. However, using recent observations, a range of flows can be provided that constrain the minimum flow recommendation. This range can be further refined over time by monitoring the river channel as minimum flows are implemented. On May 4, 2013, an observation of the state of connectivity of the channel was made over about 4 km of the lower San Rafael River between SH-24 and Frenchman's Ranch. Flow during this observation was about 7.5 cubic feet per second (cfs) at the USGS SH-24 gage and provided connectivity throughout this stretch of river, i.e., there were no dry sections. Furthermore, this flow did provide complex habitat where it was available, as measurements of pool habitat showed some pools had maximum depths > 1 m. On May 21-22, 2013 observations were made on sections of the river including Hatt's Ranch dam, Below SH-24, Dugout Wash, Spring Canyon, and Canyon 3. Discharge during this period ranged from 4-5 cfs at the USGS SH-24 gage and was also observed to provide connectivity at these locations, though measurements of habitat parameters were not made. On June 23, 2013 observations were made of flow in the channel at Tidwell Bottom, Moonshine Wash, the lower San Rafael River Road bridge. Mean daily flow at the USGS SH-24 gage was 3.2 cfs on this day, and connectivity was provided at Tidwell Bottom,

but the flow in the area of Moonshine Wash was restricted to a series of isolated pools (Fig. 39). A satellite image of the lower San Rafael River taken on 24 August 2004, when the mean daily flow at the SH-24 gage was 0.16 cfs shows that the channel is dry or nearly dry over significant stretches (available on GoogleEarth™). These observations provide bounds as a first attempt at defining a range of minimum flows for maintaining connectivity – that is, **7.5 cfs clearly provides sufficient flow to maintain connectivity and provides at least some quality physical habitat, 4-5 cfs provides connectivity throughout the river but the quality of habitat is unknown, 3.2 cfs provides connectivity above Hatt's Ranch but not in the area of Moonshine Wash, and 0.16 cfs clearly does not provide connectivity over large stretches of the river. Thus, a flow of 4-5 cfs at the USGS SH-24 gage is recommended as an absolute minimum flow value for maintaining connectivity at this time.**

Figure 39. Picture of the San Rafael River looking downstream from the Lower San Rafael River Road bridge showing an isolated pool in an otherwise dry channel. Photo taken by B. Laub on June 23, 2013.

Gain/Loss considerations. Water provisioned to the San Rafael River for maintaining minimum flows will come from flow releases from dams that are far upstream of the lower San Rafael River, because all the water storage in the San Rafael River watershed occurs on the three tributary streams of the San Rafael River (UDWR 2012). Thus, in considering whether minimum flows can reasonably be provided, the potential loss of water over the approximately 190 km course of the San Rafael River needs to be considered. The USU Water Lab was commissioned to study the gains and losses occurring over the lower San Rafael River, from the I-70 bridge to the Green River confluence. Results of this study showed no significant natural water losses over this approximately 70 km stretch (Gowing and Thomas 2012). However, the study was conducted during a colder weather period between September 2011 and March 2012 and thus did not take into account loss through evapotranspiration or irrigation withdrawls, which would be much higher in the summer. In addition, the study period followed a high-water year with a large magnitude spring flood event that likely affected groundwater interaction and recharge rates, and these interactions are likely to be different in low-water years. Thus, the scope of this gain/loss study is temporally limited and should be supplemented with additional monitoring. Analysis of USGS baseflow data (mean daily flow records when flow was ≤10 cfs) collected between 1 October 1947 and 30 September 1964 and between 1 October 1972 and 30 September 1986 at both the San Rafael River headwaters (i.e., just below the confluence of the three tributaries) and SH-24 reveals there is some loss of flow over this stretch, but the magnitude of loss is low considering the distance (about 5 cfs over approximately 135 km) (Fig. 40). In addition, the Hatt's Ranch dam is located upstream of the SH-24 gage and can draw as much as 7.5 cfs from the river, suggesting some of the losses on the San Rafael River could be attributable to this one source. The Hatt's Ranch dam was not captured by the USU Water Lab study, because the study was conducted during the winter period when flow was not being diverted (Gowing and Thomas 2012). Additional monitoring is needed to determine potential water losses in the lower river during the summer low-flow period, e.g., from evaporation, but preliminarily these studies suggest that providing minimum flows to the lower San Rafael River will not incur large water sacrifices to natural losses.

Recommended actions and monitoring. There are two actions that are recommended for providing minimum flows for the San Rafael River. The first is to present the recommended range of flows (4-7.5 cfs) to the San Rafael River stakeholders group as a first step toward working out an arrangement with water users to provide these flows. It is estimated that, at present, flows entering the San Rafael River downstream of water users need to be maintained at 11-16 cfs to achieve these minimum flows in the lower San Rafael River (Fig. 40). However, these target flows at the San Rafael River headwaters could be reduced by implementing the second recommended action, which is to convert Hatt's Ranch from flood to pressurized-pipe sprinkler irrigation. The NRCS has estimated this could save about 4-5 cfs of water during maximum irrigation periods (Keller 2012), which would reduce the required delivery to the river upstream to 6-12 cfs. The NRCS and UDWR will be taking the lead on any irrigation improvement projects at Hatt's Ranch, but efforts could be made to partner with these organizations to move irrigation improvements forward.

Ensuring the accuracy of a minimum flow recommendation is important, because water appropriated for minimum flows will not be available for use in agricultural, municipal, or industrial applications. To further refine the range presented here, monitoring during dry periods should be conducted to determine the flow level at which parts of the channel start to become dewatered. This assessment can be made by direct on-the-ground observations and by aerial photography of the length of the lower river.

Temporal considerations. Ensuring flow is maintained at or above a minimum level in the San Rafael River would greatly benefit native fish by providing connectivity and would benefit riparian vegetation by ensuring water tables remain accessible. Providing minimum flows will also benefit native fish by helping ensure that ecological functions such as primary and secondary production are maintained and are sustaining basal food resources such as algae and macroinvertebrates (Lake 2003). However, in drought years maintaining minimum flows may be difficult during periods of high agricultural demand. Given this, it is important to stress that maintaining minimum flows in years following a large spring flood event will be critical. A large spring flood season often promotes large recruitment events for native fish and vegetation (Braatne et al. 1996, Scott et al. 1997, Mahoney and Rood 1998, Brouder 2001, Balcombe and Arthington 2009). These large recruitment classes may be lost, however, if the river is dewatered in the following summer. Thus, providing minimum flow levels will be especially important 1-3 years after a large spring snowmelt flood to allow native fish and vegetation to grow to a less vulnerable stage and ensure that the benefits of spring snowmelt floods are maximized. If a large spring snowmelt flood event has not occurred within the previous 2-3 years of a drought year, failing to meet minimum flow requirements will be less detrimental.

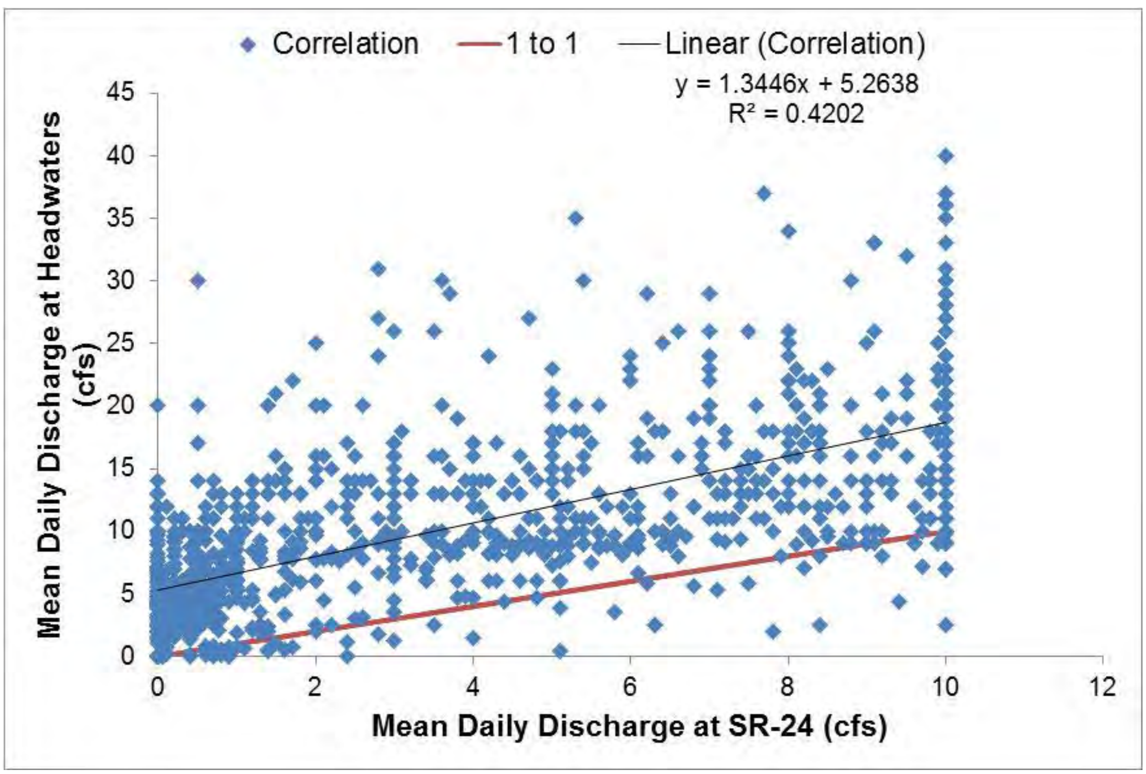

Figure 40. Correlation between mean daily discharge at the USGS SH-24 gage (09328500) and headwater gage (09328000) for flows ≤10 cfs at the SH-24 gage, with a three-day offset correction for estimated travel time between the two gages. Data cover the period from 1 October 1947 - 30 September 1964 and 1 October 1972 - 30 September 1986 (n = 1073). Data points for which flow at the headwaters was >50 cfs were removed from analysis as indicative of flood fronts and recession tails that had not traveled to the SH-24 gage (n = 4).

High flows

Restoration of parts of the snowmelt flood may alleviate some of the sediment loading that occurs under the present flow regime (see section I of this report), and thus, may help limit trends of channel narrowing and habitat loss that occurs under the current conditions of sediment surplus. Below, the historic trends of channel narrowing are linked to the hydrology in an attempt to quantify the magnitude, duration, and frequency of the snowmelt flood flows needed to aid in the rehabilitation of instream habitat and to help export fine sediment.

There have been two times over the historic record where trends in channel narrowing and habitat degradation have been temporarily reversed. The first was following the historic snowmelt floods of 1983 and 1984 (Fortney et al. 2011). Widening was measured on aerial photographs taken in 1974 and 1985 (Figs. 41 and 42), and was also measured from discharge measurement notes at the SH-24 gage (Fig. 43). The 1983 and 1984 floods had instantaneous peak discharges of 3,602 and 3,920 cfs, respectively, and were higher than the magnitude of the long-term 2-year flood (1,801 cfs) for 35 and 39 days, respectively. These floods widened the channel at the SH-24 gage by ~11%.

Reach-scale channel widening has also been measured after the 2011 snowmelt flood. The 2011 snowmelt flood peaked at 2,419 cfs (a 2.9 year recurrence interval), and was greater than the long-term 2-year flood magnitude for six days, and greater than the long-term 1.25 year flood magnitude (918 cfs) for 36 days. Aerial photograph analyses showed that the channel was widened by 32% over ~9.5 km where UDWR has removed tamarisk (downstream of SH-24), and the channel was widened by a little over 3% where tamarisk has not been removed. Habitat surveys conducted after the 2011 flood showed that in 18 of 19 reaches (300 m in length), the percent area of complex habitat increased. Of these 18 reaches, 14 of them had more than a 10% increase in percent complex habitat area (Fig. 44).

Conversely, the periods when channel narrowing and habitat loss has been most rapid were during the 1960s and 1970s, and during the 1990s and 2000s. Analyses and dating of floodplain deposits exposed within trenches showed that between 1961 and 1980, the channel at Hatt's Ranch narrowed by approximately 30%. Between 1990 and 2006, the channel narrowed by approximately 43% as measured in the Frenchman's Ranch trench (Fortney, 2013b).

A hydrologic metric that incorporates both flow magnitude and duration was used in order to correlate the historic patterns of geomorphic change to the size of the snowmelt floods. For every year, the mean-daily discharge for all days between January 1 and July 15 that were greater than the long-term 2-year flood of 1,801 cfs were summed, hereafter cfsdays. This metric thus shows all years where a single mean-daily discharge exceeded 1,801 cfs, and higher values indicate longer times during which this threshold was exceeded (Fig. 45).

During the 60s and 70s, and during the 90s and 2000s — the most rapid periods of channel narrowing — the long-term 2-year flood was rarely exceeded (Fig. 45). Between 1959 and 1979, the long-term 2-year flood was exceeded just once, and between 1987 and 2010, the long-term 2-year flood was exceeded just twice. Between 1980 and 1986, the long-term 2-year flood was exceeded four times, which was also the period when progressive channel narrowing was reversed and widening occurred. The long-term 2-year flood was exceeded for six days in 2011, and channel widening and increases in complex habitat occurred. In 1995, flows peaked at 1,960 cfs and the long-term 2-year flood was exceeded for 4 days. Although no significant geomorphic changes were measured in 1995, dendrochronology of cottonwood slabs, and vegetation mapping indicate that cottonwood establishment was extensive along much of the lower San Rafael River. Thus, although the occurrence of a snowmelt flood may not have translated into widespread habitat restoration, considerable riparian enhancement occurred following the 1995 snowmelt flood. Lastly, note that between 1910 and 1958 (21 years of data available) — a time period that pre-dates most of the channel narrowing — 1,801 cfs was exceeded nine times. In seven of these years, the spring snowmelt flood lasted longer than any of the floods since then, with the exception of the floods in 1983 and 1984.

Recommended actions and monitoring. Using historic geomorphic analyses, and hydrologic data, a relationship was constructed where cfsdays >1,801 cfs is ranked in terms of degree of 'positive' geomorphic change and/or ecologic change (i.e., channel widening, habitat creation, cottonwood establishment). Thus, the spring snowmelt flood that caused the greatest degree of 'positive' geomorphic change was ranked as 1, and the floods associated with a lesser degree of positive change were ranked in descending order (Fig. 46). Note that this is not a comprehensive analysis, and is merely an attempt to assign some degree of geomorphic/ecologic value to the hydrologic record. Future studies can help inform these relationships by replacing the rankings with some ecologic/habitat/geomorphic metric; however, data to construct this type of relationship is currently unavailable.

According to Fig. 46 and the other geomorphic and hydrologic data presented above, a spring snowmelt flood that exceeds ~1,800 cfs for approximately six days (i.e. 2011 snowmelt) provides greater geomorphic and ecologic benefit than a spring snowmelt flood that is smaller or shorter. It has been shown that habitat loss and channel narrowing occurs when there are extended periods without snowmelt floods exceeding ~1,800 cfs. Thus, without additional data, the threshold of 1,800 cfs, and a duration of six days should be used as an initial recommendation for the high-flow portion of an environmental flow program.

Stage-discharge relationships from Fortney (2013b) show that near Hatt's Ranch, this discharge is the approximate channel-filling discharge, and thus the maximum shear stress occurs on the bed and banks without inundating the adjacent floodplain and causing vertical floodplain formation. Near Frenchman's Ranch, the stage-discharge relationship is slightly different, whereby the target discharge of 1,800 cfs inundates the floodplains immediately adjacent to the channel. Even though floodplain inundation promotes vertical floodplain accretion and disconnection of the floodplain from the channel, limited floodplain inundation in this reach may be beneficial. Healthy cottonwood stands are present, and cottonwood seed germination may occur if the high flow occurs in early to mid-June, the period when cottonwoods produce their seeds. Furthermore, cottonwood seeds generally require fresh alluvium for germination, and alluvium is provided by deposition on the floodplain during out-of-bank flow. High flows significantly larger than this target discharge may not provide any additional benefit because vertical floodplain accretion and disconnection of the floodplain from the channel would occur. **The frequency of this recommended high-flow pulse should be less than once every five years, and ideally would occur every 3 years.**

Given the importance of water for all stakeholders in the San Rafael River basin, whether for utilitarian uses or for environmental purposes, an extensive monitoring and adaptive management program should be conducted to evaluate the validity of the above high-flow recommendation. Comprehensive measurements of geomorphic change, and the presence of desirable aquatic habitat, should be conducted before and after any flow that is of similar discharge and duration of the recommendation. Additionally, vegetation surveys should be conducted to determine the effectiveness of any spring high flow in the promotion of cottonwood seedling establishment and survival.

In addition to measurements of geomorphic changes, a suspended-sediment monitoring program at two locations on the lower San Rafael River (e.g., at the current USGS gage at SH-24 and at the lower San Rafael River Road bridge) would be beneficial in constructing a suspended-sediment budget to inform adaptive management activities. Suspended-sediment measurements would help determine the volume of sediment that is exported during any spring snowmelt flood, and would also help determine the amount of sediment input to the lower San Rafael River during the monsoon season. Ideally, adaptive management efforts could be implemented so that when sediment inputs exceed a certain threshold, and key water availability criteria are met, a spring high-flow pulse could be implemented to reduce sediment loading in the lower San Rafael River. This could be done in a similar manner to the Glen Canyon Adaptive Management program that implements high-flow releases based on sediment inputs from the Paria River (see Bureau of Reclamation and National Park websites for more information – www.usbr.gov/uc/rm/amp/ and www.gcdamp.gov).

Gain/loss considerations. A gain and loss study was conducted by the USU Water Lab in 2011 and 2012 (Gowing and Thomas 2012); however, measured discharges during this study never exceeded 111 cfs. Thus, there is little understanding of gains and losses at high flow, and this remains a key information gap concerning the use of high flows for environmental management purposes. The target discharge of 1,800 cfs applies to the lower San Rafael River downstream from the San Rafael Swell. If high-flow releases were ever to be used for environmental purposes, additional work would be needed to know the magnitude of high-flow attenuation between the water source areas and the lower San Rafael River. The proportion of high-flow attenuation that was later contributed to baseflow would also be critical to monitor to determine overall water gains and losses during flood flows.

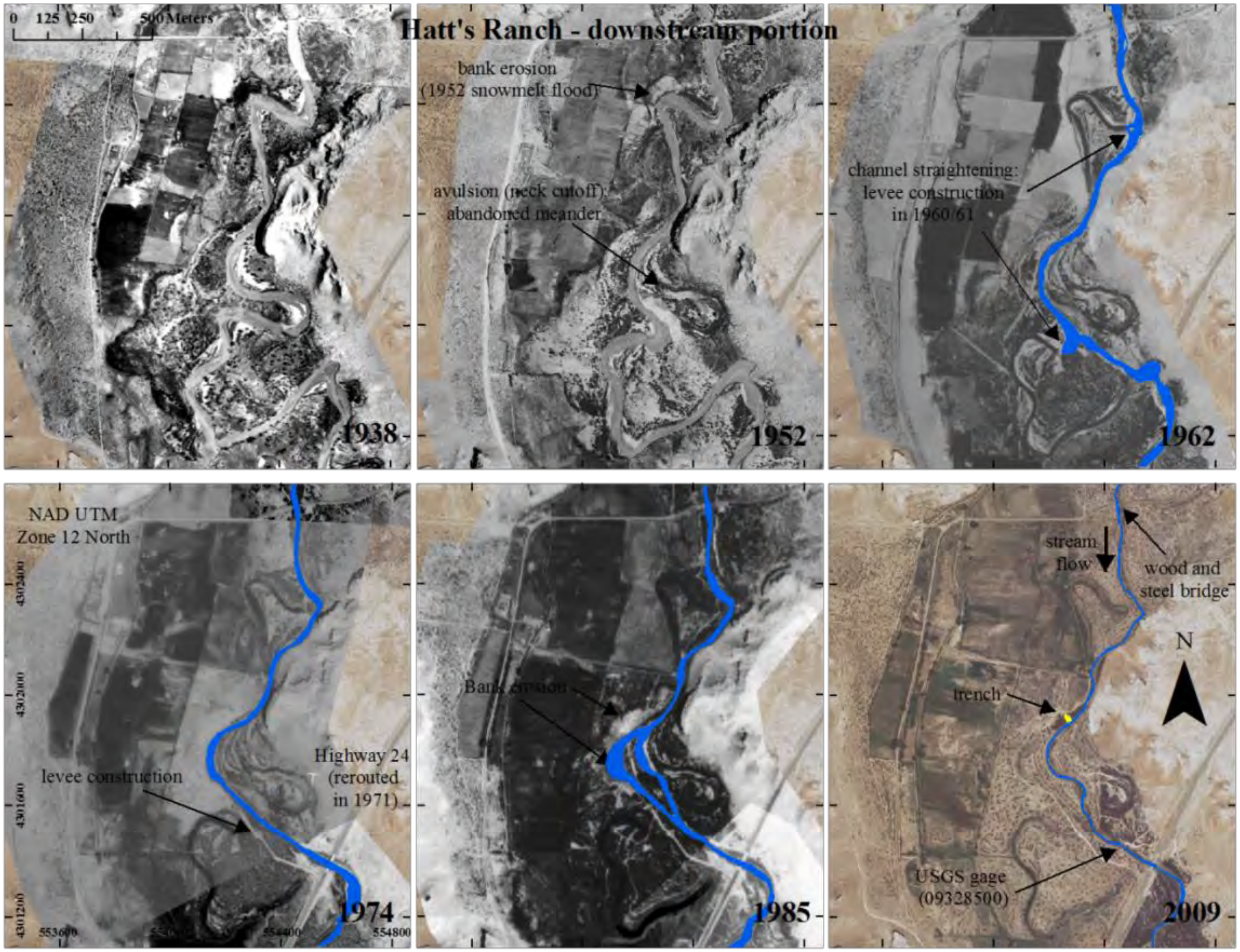

Figure 41. Aerial photographs of the channel at Hatt's Ranch depicting changes to channel planform between 1938 and 2009. Note the increase in channel width, and the creation of a secondary channel depicted in the 1985 aerial photograph following the snowmelt floods of 1983 and 1984.

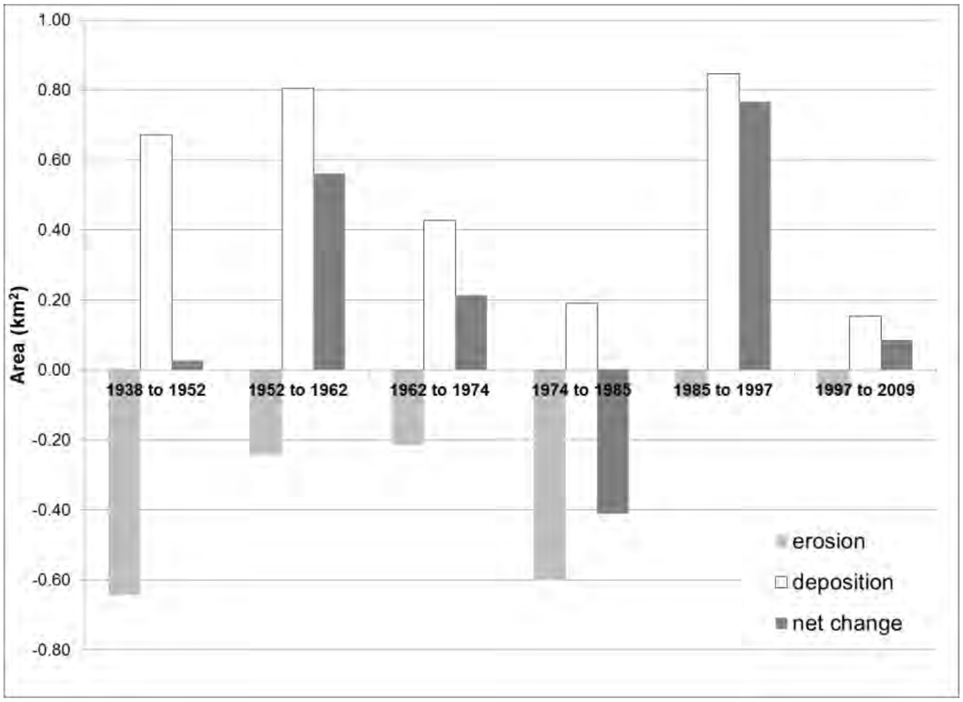

Figure 42. Graphical results from spatial union analysis performed in GIS, of sequential historic aerial photographs**.** White columns represent the area of floodplain constructed between each photograph series. Light gray columns represent area of floodplain erosion. Dark gray columns represent net change (difference between light gray and white). The only time where net erosion occurred was between 1974 and 1985, which incorporates the historic snowmelt floods of 1983 and 1984. Note that this analysis only extends to 2009, so the impacts of tamarisk removal and the 2011 flood event are not captured.

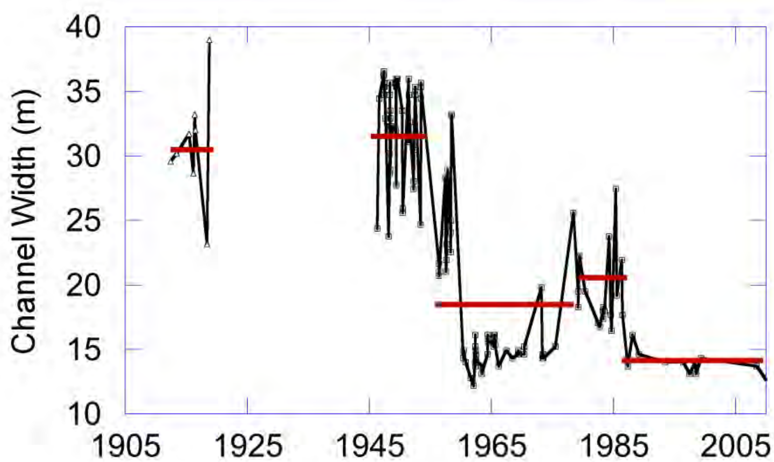

Figure 43. Time series of channel width taken from measurements of discharge at the USGS SH-24 gage (09328500) on the Hatt's Ranch. Data only incorporates measurements when flows were not overbank. Only data measured during flows that were between 247 cfs and 988 cfs are used in this analysis. Horizontal lines show the mean over the different time periods. See Fortney (2013b) for description of time periods.

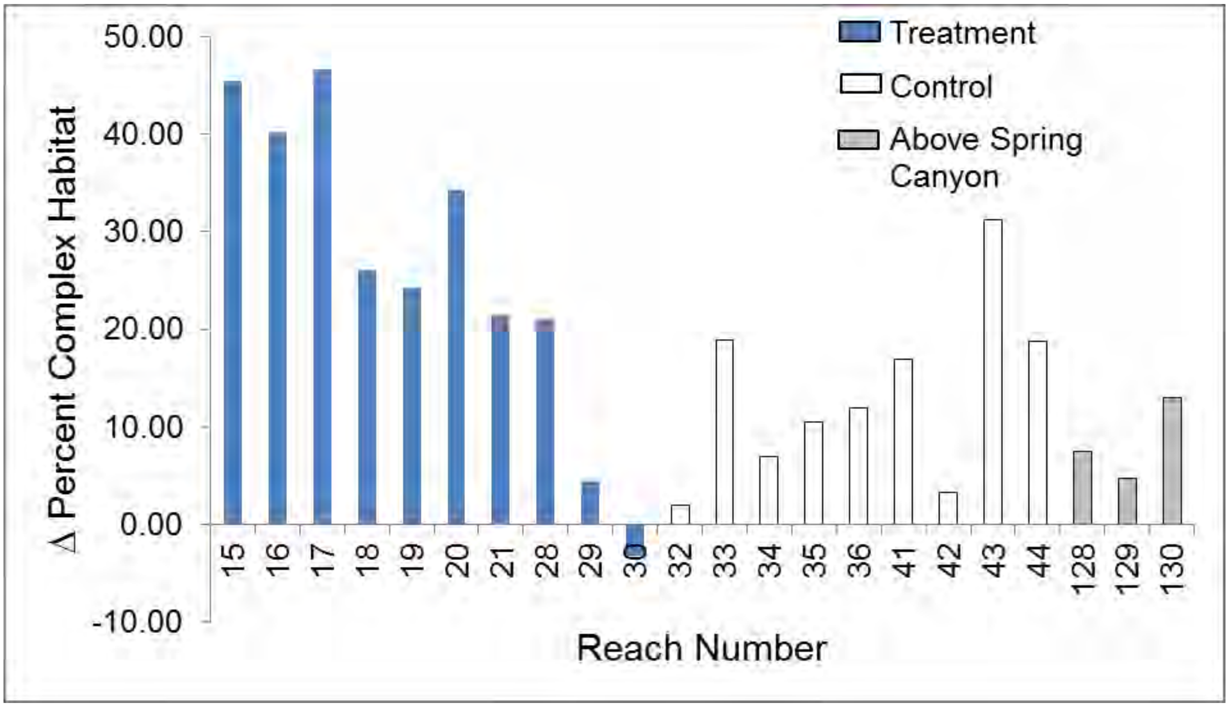

Figure 44. Difference in percent habitat complexity in 300-m reaches between 2010 and 2013 or 2012 (reach 15). Positive numbers indicate an increase in habitat complexity. The treatment and control reaches are located in the area where the UDWR removed tamarisk in 2009 below SH-24 (treatment) and the area below this removal area where tamarisk was not removed (control; see Keller 2012). Three reaches were also surveyed immediately upstream of the Spring Canyon confluence.

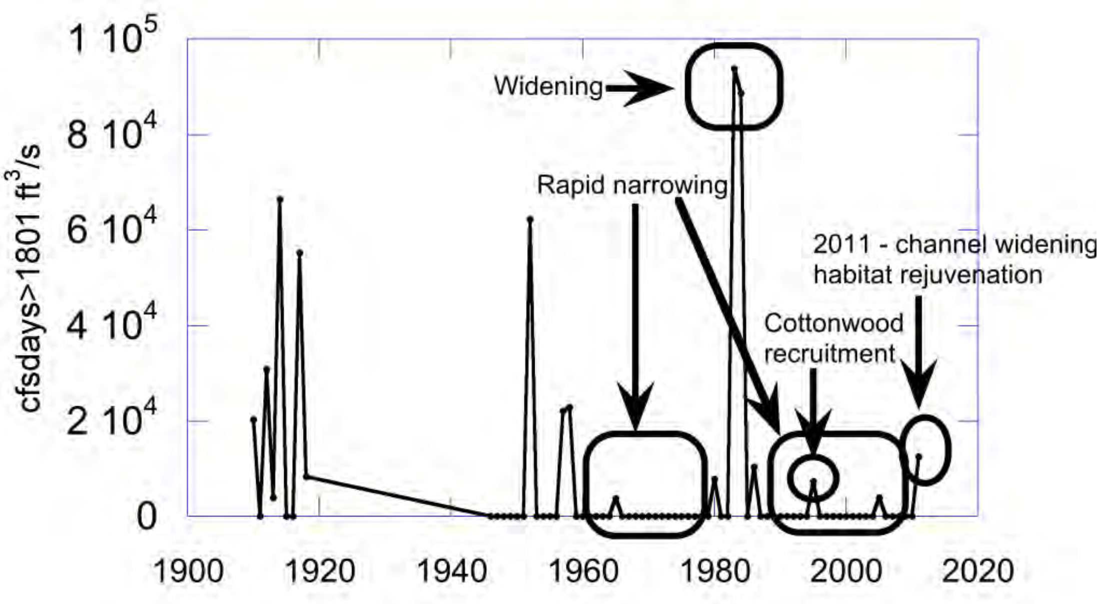

Figure 45. Peak mean-daily discharge and duration (cfsdays) greater than the long-term 2-year flood of 1,801 cfs over the period of record at the USGS SH-24 gage (09328500).

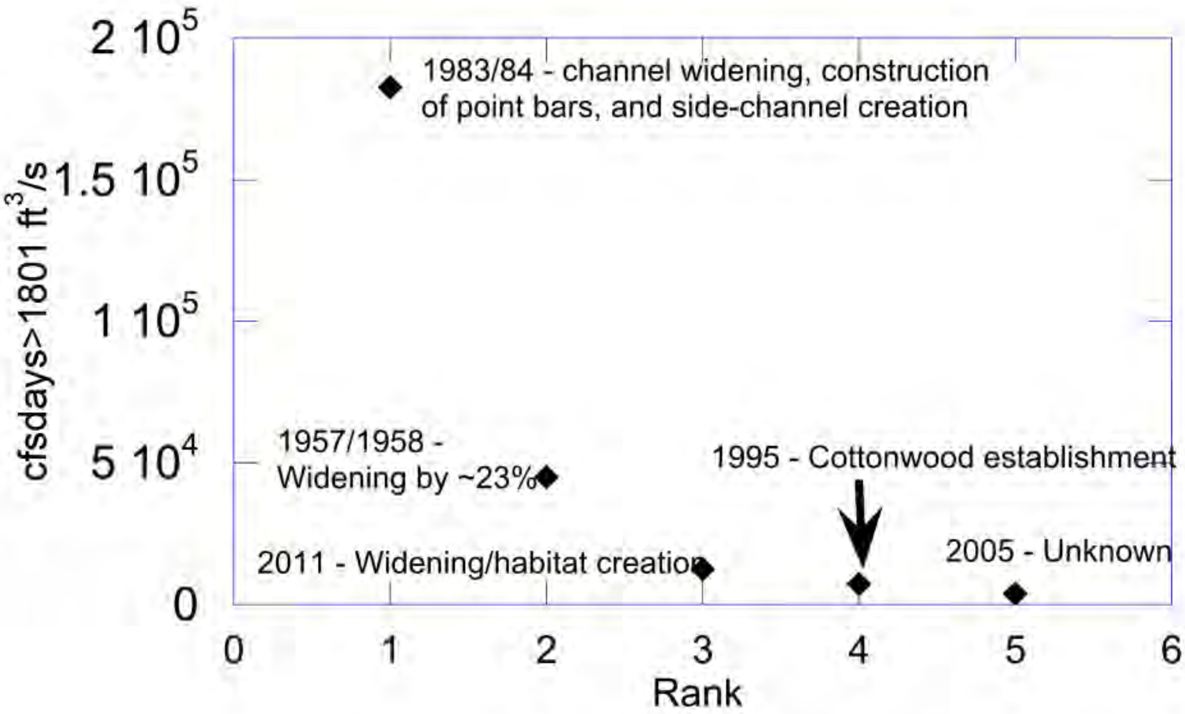

Figure 46. Ranking of snowmelt floods according to geomorphic/ecologic benefit, with 1 = greatest benefit and 5 = least benefit.

Water Quality

Previous studies have demonstrated that restoration of hydrologically connected river-floodplain systems can increase sediment retention, reduce delivery of dissolved solids downstream, and generally improve water quality (Kronvang et al. 2007, Kaushal et al. 2008, Richardson et al. 2011). The San Rafael River currently exists in a confined channel with tall banks and limited floodplain connectivity over large stretches (see section I of this report). In this geomorphic configuration, there is reduced opportunity for flows to access the floodplain and floodplain depressions where sediment retention and water-filtering can occur. Instead, in many flood events, water is routed directly through the confined channel with little potential for retention of sediments and water filtering on the floodplain. Therefore, the recommended action for accomplishing Objective 6 - reducing concentrations of total dissolved solids (TDS) – is to reestablish river-floodplain hydrologic connections. Reconnection of river-floodplain connections will be targeted through implementing the actions recommended above, specifically, working with upstream water users to reestablish a more natural hydrologic regime combined with strategic vegetation removal, and facilitating establishment of beaver dams in select locations.

Combined, these efforts are predicted to allow greater channel movement and bank erosion, which will help create instream habitat for fish and help reconnect the river to the floodplain. Work on the UDWR tamarisk removal project has shown that a combination of vegetation removal and high flow events can increase the amount of channel movement relative to areas where vegetation has not been removed (Keller 2012). There may be a short-term increase in TDS through these recommended actions, because erosion of bank sediments was identified as a contributing source to TDS loads in the San Rafael River (MFG, Inc. 2004). However, the contribution of bank erosion to TDS loads was found to be a small component of TDS loading relative to upstream irrigation return flows and natural loading (MFG, Inc. 2004). In addition, over the long term, TDS loading is predicted to decline due to reestablishment of river-floodplain connections and development of water retention in newly created meander cutoffs and oxbows.

Beaver establishment in selected areas is recommended, because research has demonstrated that beaver dams and associated ponds can store large quantities of sediment (Naiman et al. 1986, Butler and Malanson 2005, Pollock et al. 2007), which should help reduce delivery of TDS downstream. In addition, by promoting aggradation and backing up water, beaver dams can reduce channel entrenchment and help reestablish river-floodplain connections (Westbrook et al. 2006, Andersen et al. 2011, DeVries et al. 2012), something that has been directly observed on the San Rafael River (Fig. 14).

V. Monitoring Recommendations

Introduction

Monitoring is an essential component of successful ecological restoration and adaptive management (Palmer et al. 2005), because it provides information on the effectiveness of restoration actions, and if done properly, information on why actions were or were not effective. Restoration can be viewed as an ecological experiment (Palmer et al. 1997), and proper monitoring thus advances river science and the practice of river restoration in general. Thus, in this section, an extensive monitoring plan for the San Rafael River restoration project is developed to understand whether the restoration objectives are being met by the recommended restoration actions and why objectives are or are not being met (see Table 4 for a summary). Development of this monitoring plan is intended to accomplish Objective 7 of the restoration plan, that is, to 1) provide information on the effectiveness of restoration actions that can be used to adapt and improve the restoration plan over time, and 2) extend lessons learned through restoration implementation to management and restoration of other desert river systems in the region. The protocol recommends specific methods and sites for conducting monitoring, but does leave some detail to be filled in such as the specific number of replicated sites or samples needed to ensure sufficient statistical power for different variables.

To best understand whether restoration actions are achieving their intended effects and the reasons for success or failure, the recommended restoration actions should be implemented and monitored using an experimental approach (Block et al. 2001) For example, a before-after control-impact (BACI) design presents one effective design well-suited for monitoring restoration impacts (Stewart-Oaten et al. 1986), and randomized intervention analysis (RIA) might also work well (Carpenter et al. 1989). The monitoring protocol is developed by identifying for each variable of interest – i.e., those variables that were targeted in the restoration Objectives – the existing data (the before condition), the necessary data to collect post-restoration (the after condition), sites where the restoration action will be implemented (the impact sites) and geomorphically and ecologically-similar sites where no restoration actions will occur (the control sites). However, not all variables will be amenable to a BACI design. For example, it will not be possible to have control and impact sites for fish movement between the upper and lower San Rafael River and the Green River. Variables that deviate from a BACI design will be identified and the rationale explained. Implementation of an experimental approach to restoration does not require that only one restoration action can be implemented at a time. In many cases, it is preferable to implement multiple alternative restoration actions simultaneously for two reasons: 1) to determine whether the combined effects of multiple actions are greater than individual actions, and 2) to improve efficiency over evaluating one action at a time.

Table 4. Summary of the proposed monitoring plan, listing response variables to monitor, a summary of recommended procedures and their frequency, existing data for each variable, and recommended control sites for comparing to restoration sites.

Variable	**Recommended Method (Recurrence Interval)**	**Pre-Restoration Data**	**Control Sites**
Fish Habitat	Reach-based surveys (5 years and after major flood events) Aerial imagery (5 years and after major flood events)	Habitat survey between Hatt's Ranch dam and Green River confluence in 2010 (Walsworth 2011) NAIP imagery collected in 2009 and 2012	Non-restored sections
Fish Populations	Reach-based abundance, size distribution, habitat use, and spatial distribution assessments (2-3 years)	Surveys of fish abundance conducted in 1977 and since 2007 (McAda et al. 1980, Bottcher 2009, Walsworth 2011, Keller 2012)	Non-restored sections Upper San Rafael River Price and White River
Native fish movement	PIT-tagging and PIT-tag readers (ongoing)	PIT-tag antennas have been in place since 2008	Price and White River
Ecological Flows	USGS SH-24 gage, potential new gage near Green River confluence (ongoing)	Flow monitored from 1910-1918 and 1946-present by USGS	NA – compare flows to historical flows and recommended targets
Suspended sediment	Install samplers at USGS SH-24 gage and a new gage near Green River confluence (ongoing)	Suspended sediment monitored by USGS at SH-24 gage from 1949-1957	NA – compare pre and post monitoring
Water quality	Install samplers at USGS SH-24 gage and a new gage near Green River confluence (ongoing)	Some spot measurements of TDS (see MFG, Inc. 2004) but no estimates of changes in concentrations or load through the lower San Rafael River	NA – compare pre and post monitoring

Table 4 cont.

Variable	Recommended Method	Pre-Restoration Data	Control Sites
Geomorphic changes	Reach-based surveys (2-3 years and after major flood events) LiDAR or equivalent technology (5-10 years)	Cross-section surveys from USGS and Fortney (2013b) LiDAR flown in April 2013	Non-restored sections
Riparian vegetation	Reach-based surveys (Initially 2-3 years and after major flood events) Vegetation mapping (5-10 years)	Vegetation map based on 2012 aerial imagery	Non-restored sections
Wildlife	Reach-based surveys (2-3 years)	Estimate of bird diversity and community composition at Hatt's Ranch in 2008, 2010, and 2012 (Wright 2012)	Non-restored sections
Stream temperatures	In-situ loggers (ongoing) Thermal imagery (2-3 times per year in low water years)	Spot measurements at USGS SH-24 gage from 1950-1977 In-situ loggers and thermal imagery currently being collected by USU Water Lab	Non-restored sections
Beaver dams	Ground and aerial-based surveys (2-3 years in association with other surveys)	Survey of active and inactive beaver dams between Hatt's Ranch and Green River confluence in 2010 (Walsworth 2011)	Non-restored sections
Implementation	Track implementation methods and costs (ongoing)	NA	NA

In addition, for many variables it will be important to evaluate their response to site-specific restoration actions but also their response to the cumulative impacts of restoration actions that will be implemented throughout the lower San Rafael River. In these cases, the monitoring protocol identifies both local scale measurements that will be taken and methods for scaling the local measurements up to monitoring at the whole-river scale. Finally, the timeline over which monitoring will need to occur to assess the impacts of restoration activities is identified. In many cases, long-term monitoring is needed as there may be a different predicted response in the short term (i.e., within 1-2 years) as compared to the long term (i.e., over decades). For example, as detailed in the *Wildlife* section below, there may be a short-term shift of bird communities in tamarisk-removal areas due to altered vegetation structure, and over the long-term communities are likely to change further as cottonwood stands are established and grow.

Fish Habitat

Pre-existing condition

Surveys of fish habitat on the San Rafael River conducted in 2007-2008 and 2010 found that habitat complexity (pools, riffles, backwaters) was low throughout large stretches of the lower river (Bottcher 2009, Walsworth 2011 – see also Fig. 15). The 2010 survey in particular provides a good benchmark with which to compare post-restoration changes. In 2010, the entire length of the San Rafael River between Hatt's Ranch dam and the Green River confluence was surveyed for percent habitat complexity in 300-m reaches (Walsworth 2011). The survey revealed that about 70% (150 of 213) of these 300-m reaches had habitat complexity below 10%, suggesting that nearly 45 km of the lower river was providing very limited habitat for the three species. A resurvey of 21 of these 300-m reaches in 2013, plus one in 2012, suggested that the 2011 flood event increased habitat complexity in many areas of the lower San Rafael River, as all but one of the resurveyed reaches showed increased habitat complexity (Fig. 44). This resurvey in 2013 shows that the 2010 survey can be used as the benchmark data to determine if restoration activities are improving habitat complexity over time.

Monitoring protocol

Fish habitat will be surveyed using two methods: an on-the-ground survey method and an aerial imagery method. The on-the-ground method should follow standard protocols (e.g., Archer et al. 2012) as used by previous researchers on the San Rafael River (Bottcher 2009, Walsworth 2011, Keller 2012). In general, a team of two people walk the channel and mark with a GPS and measure the area of channel occupied by each pool, riffle, and backwater identified. Pools are usually deep areas with a maximum depth at least 1.5 times the pool tail depth that span the thalweg and at least 50% of the wetted channel width at one location. Deep areas above and below beaver dams and boulder and bedrock outcrops that may not have a defined tail crest are also considered pools (Archer et al. 2012). Riffles are swift-flow areas over coarse substrate, and backwaters are areas with flow circulating opposite to the main direction of flow. The area of all pool, riffle, and backwater habitat features within established 300-m reaches (see Bottcher 2009, Walsworth 2011, and Keller 2012) are summed and divided by the total reach area (computed by obtaining an average width from at least 5 cross-sections) to give an estimate of percent habitat complexity. Areas not classified as pool, riffle, or backwater habitats are considered run or glide habitat by default, and this is the most common type of habitat on the lower San Rafael River. Wolman pebble counts are also conducted within each 300-m reach to provide an estimate of mean grain size and variability in grain size. On-the-ground surveys should be carried out in established restored and control sites once every 5 years. The aerial imagery method involves delineating the area of each habitat feature on aerial photos for the entire length of the lower San Rafael River. The aerial images will be obtained every 5 years or after significant restoration activities or flow events. Determination of habitat complexity using aerial images should be calibrated with on-the-ground data and corrected for differences in flow level between photographs and between photographs and on-the-ground surveys. Aerial photographs can also be used to provide a census of woody debris accumulations throughout the lower San Rafael River. The combination of detailed on-the-ground measurement and a survey of the entire lower river with aerial imagery will provide an estimate of whether the objective established for habitat complexity on the lower river is being met (Objective 1a and proposed outcomes 3 and 4 identified in the original NFWF proposal). Surveys should also be compared to the 2010 data to determine which sections of the river have experienced changes in habitat complexity over time and to gage whether different restoration techniques were more or less effective in improving habitat complexity.

Control sites

There are two major types of geomorphic reaches on the lower San Rafael River – wide valley reaches and narrow, canyon-bound reaches (see Fortney 2013a and Fig. 3). Thus, control sites are identified for each of these geomorphic reaches. Reference sections that represent the desired condition in the two major geomorphic reaches were identified in the prioritization section of the plan as Iron Wash for the wide valley sections and Spring Canyon for the canyon-bound sections. If individual reaches are needed within these two sections, reach 68 is recommended for the Iron Wash section and reach 134 is recommended for the Spring Canyon section, because these reaches have been surveyed previously for habitat conditions and fish populations (Bottcher 2009).

The only large area of the wide-valley reach below Hatt's Ranch dam that has not been treated by UDWR for tamarisk removal is reaches 32-45 in the Below SH-24 section. Much of this section was prioritized for restoration; however, the reaches in this section on private land (34-37 and 39-41) can be used as control sites. In particular, reach 35 is within this section and has been previously sampled for native fish. Reaches that currently have only tamarisk removal are widely available and reaches 8, 15, 27, 62, 90, 95, and 109 have been previously sampled for fish populations. Tidwell Bottom could also be used as a control reach for the wide valley reaches if it is not subject to restoration in Phase 1.

The only section of the canyon-bound reach that has been treated with tamarisk removal is in the Dugout Wash section (reaches 117-123), thus any other locations with the canyon-bound section could serve as control areas. Reaches 120, 126, 146, 158, and 173 are recommended because they have been previously sampled for native fish populations.

Predicted Response

The combination of on-the-ground restoration activities and work toward securing spring flood flows is predicted to increase habitat complexity throughout the lower river over time, with higher magnitude changes predicted for areas where on-the-ground restoration activities occur relative to control sites (Fig. 47). Survey data collected in 2012 and 2013 in the UDWR tamarisk removal and control areas was compared to the survey data collected in 2010 to give an estimate of the predicted response of habitat complexity to securing the recommended spring snowmelt flood events in areas with on-the-ground restoration and in control areas (Fig. 44). All else being equal, if the high-flow flood recommendation can be obtained, the objective for habitat complexity (Objective 1a) should be achievable within 5-10 years.

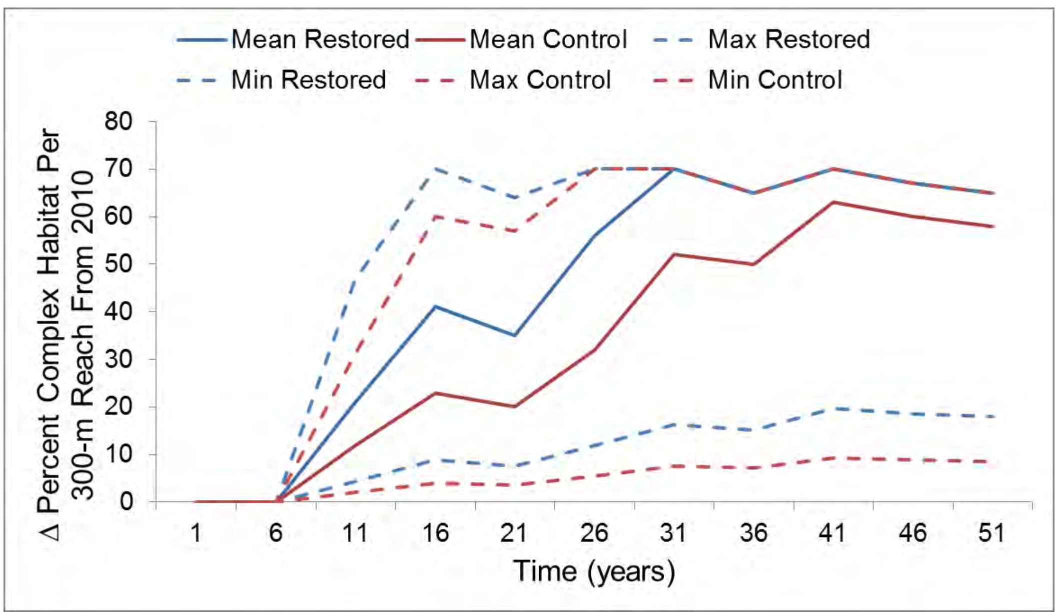

Figure 47. Predicted mean and range of change in percent complex habitat per 300-m reach from 2010 surveys for restored and control areas where restoration has not occurred. Prediction assumes that the high flow recommendation can be achieved, with increases in percent complex habitat representing spring snowmelt flood events and decreases representing years between flow events. The mean and ranges are based on the mean, maximum, and minimum values of change in percent complex habitat observed between 2010 and 2013 surveys for treatment (tamarisk removal) and control areas (no tamarisk removal) (Fig. 44). Maximum percent change of 70 is based on the highest value of percent complex habitat seen in any reach in 2010 surveys.

Fish Populations

Pre-existing condition

Surveys of the three species in the San Rafael River have found that densities are consistently higher above Hatt's Ranch dam than below, although the three species have been captured below Hatt's Ranch dam in isolated reaches where habitat complexity is high (see section I of this report and McAda et al. 1980, Bottcher 2009, Walsworth 2011, Keller 2012). One exception has been age-0 fish, which are often at higher abundance in individual reaches below Hatt's Ranch dam than above (Bottcher 2009, Walsworth 2011). Non-native fish are found in low abundances upstream of Hatt's Ranch dam but often dominate the fish assemblage below Hatt's Ranch dam. Even in the upper San Rafael River (above Hatt's Ranch dam), populations of the three species in most places are considered low-moderate abundance based on definitions established in the three species agreement, though flannelmouth sucker were considered to be at high abundance in one location in the upper river based on recent sampling (UDNR 2006, Keller 2012).

Monitoring protocol

Surveys of fish populations in the San Rafael River should be conducted to determine abundance, spatial distribution and habitat use, diversity, and population size and age structure of native fish. Several intensively monitored reaches should be coupled with numerous less-intensively monitored reaches over a wide spatial distribution. Intensively monitored reaches should be sampled using a combination of multi-pass electrofishing and seining for small size classes to provide abundance estimates for native species and to determine the size and age structure of local populations. The location of each captured fish should be marked so that an estimate of habitat use compared to habitat availability can be developed (see Bottcher 2009, Walsworth 2011). Less-intensively monitored reaches should be sampled using single-pass electrofishing or seining depending on conditions. Sampling numerous less-intensive reaches throughout the lower river will provide an estimate of the spatial distribution of native fish and their relative densities (catch per unit effort) in different sections of the river. In both intensive and less-intensive reaches, all native fish should be counted and measured for length and weight and all native fish of sufficient size should be tagged to determine movement patterns (see next section). Sampling should be undertaken once every 2-3 years at monitoring sites established by previous researchers (see Bottcher 2009, Walsworth 2011). These sites are Fuller Bottom, Buckhorn Draw, and Tidwell Bottom upstream of Hatt's Ranch dam and reaches 8, 15, 27, 35, 48, 62, 68, 90, 95, 109, 120, 126, 134, 146, 158, 173, 182, 193, 196, 205, and 213 downstream of Hatt's Ranch dam. All sites upstream of Hatt's Ranch dam should be sampled intensively every 2-3 years. Reaches 48, 182, 193, and 213 are in the restoration reaches prioritized for Phase 1 and thus should also be sampled intensively. Other intensively-sampled reaches should be those identified as reference and control reaches, including reaches 68 and 134, which are located in the reference areas. Remaining reaches can be sampled less intensively.

Control Sites

Control sites will be those identified in the *Fish Habitat* section above and the Fuller Bottom, Buckhorn Draw, and Tidwell Bottom sites in the upper San Rafael River. However, because fish are highly mobile and subject to population regulation by regional factors such as precipitation and climate patterns, comparing control and treatment sites may not give a full understanding of whether restoration activities are increasing abundances of native fish populations. In fact, it is possible that native fish populations could decline due to broader regional scale forces such as climate change or disease even if restoration actions are successful at recovering fish habitat. Therefore, comparison of population trends of the three species in the San Rafael River should also be compared to population trends in nearby watersheds that also harbor populations of the three species, primarily the Price River and the White River. The Price River watershed is the adjacent watershed north of the San Rafael River and thus serves as a control river in a similar geologic and climate setting but that will not be subject to the same intensity of restoration efforts, at least in the immediate future. The White River is also a tributary to the Green River but is located several hundred kilometers upstream from the San Rafael River confluence. However, the White River is known to have some of the healthiest populations of three species and greatest abundance of complex habitat of any Green River tributary in the region. The White River can therefore serve as a general reference for targeting three species abundances and in determining whether population trends in the San Rafael River follow regional trends or may be a result of restoration actions.

Predicted response

The combination of high flows, minimum flows, non-native removal, increasing connectivity, and habitat restoration efforts should increase populations of native fish in both the lower and upper San Rafael River. Ideally, abundances of the three species will increase from absent or low to medium to high abundance in all sampled reaches due to provision of flows and increasing connectivity. However, the increase in abundance of the three species is predicted to be greater in treatment areas subject to habitat restoration. Non-native species are predicted to decline to low abundances, such that native species are numerically dominant in all sampled reaches (i.e., proposed outcomes 5 and 6 of the original NFWF proposal; Fig. 48).

Native Fish Movement

Pre-existing condition

In February 2008 a PIT-tag reader that detects directional movement by tagged fish was installed on the San Rafael River near the Green River confluence (Bottcher 2009). In April 2009 a second PIT-tag reader was installed near the USGS SH-24 gage, just downstream from Hatt's Ranch dam (Bottcher 2009, Keller 2012). These PIT-tag detectors were operating from their installation date until spring 2011, when they sustained damage from a large flow event. The detectors were re-installed in fall 2012. An analysis of the data from these PIT-tag detectors prior to 2011 and recaptures of tagged fish provides an estimate of the current level of fish movement between the upper and lower San Rafael River and the Green River. Flannelmouth suckers are moving throughout the lower San Rafael River and into the Green River, primarily in early May, with most suckers detected moving at least several tens of kilometers (Bottcher 2009). Endangered fishes of the Colorado River are also moving into and out of the San Rafael River from the Green River in the spring, as evidenced by 15 detections of Colorado pikeminnow, 20 detections of razorback sucker, and 17 detections of bonytail chub. Two of the Colorado pikeminnow detections occurred at the upstream PIT-tag reader, suggesting that at least some of these fishes are attempting to move into the upper San Rafael River. However, Hatt's Ranch dam prevents upstream movement of fish (Budy et al. 2009). Research has also indicated that downstream drift of age-0 fish from the upper river to the lower river is occurring and helps maintain the lower river population by providing a source of colonists (Bottcher 2009). Overall, this data from the San Rafael River suggests that both the three species and endangered fishes are moving throughout the San Rafael River system, and this is supported by previous work on the three species in other river systems (e.g., Chart and Bergersen 1992, Robinson et al. 1998, Compton et al. 2008).

Monitoring protocol

Determination of the impacts of restoration on native fish movement patterns should be carried out by continuing to operate the PIT-tag detectors and continuing to implant and monitor for PIT-tags in individuals of the three species captured during fish population surveys. The UDWR currently operates the PIT-tag detectors and conducts population surveys and will continue to do so for the forseeable future (Dan Keller, UDWR, personal communication). If Hatt's Ranch dam is removed or passage provided at the dam as part of restoration efforts, it would be worthwhile to install a third PIT-tag detector upstream of the dam or reposition the PIT-tag detector currently at SH-24 above the dam. Doing so would help determine whether native fish begin to move into the upper San Rafael River from the lower river after passage is provided.

Control Sites

The three species are known to be highly mobile, and flannelmouth suckers have been found to move throughout the lower San Rafael River. Thus control sites are not applicable within the San Rafael River. The main assessment as to the impact of restoration on fish movement will be to compare movement patterns over time to determine whether native fish continue to move throughout the lower San Rafael River and the frequency, distance, and timing of these movements.

Although the main indicator of changes in fish movement will be pre-post restoration comparisons on the San Rafael River, similar to fish population assessment, the Price River and White River can serve as comparison rivers because PIT-dag detectors are installed within these river systems as well. The detectors and tagging of fish in these and other river systems also provide an opportunity to determine whether fish that use the San Rafael River migrate between different tributaries to the Green and Colorado Rivers. There is some indication that this is the case already because at least one Colorado pikeminnow detected in the San Rafael River was tagged in the White River (Budy et al. 2010).

Predicted response

Efforts to improve native fish habitat, control non-native fish and provide minimum and high flows should increase populations of native fish and provide increased connectivity throughout the lower San Rafael River and to the Green River. Thus, over time, detections of native fish movement within the lower San Rafael River should increase, including continued detections of endangered species. Movement between the upper and lower San Rafael River is unlikely to increase without removal of Hatt's Ranch dam or provision of passage at the dam. However, if either of these activities is accomplished, movement between the upper and lower San Rafael River is likely to increase (i.e., proposed outcome 2 of the original NFWF proposal).

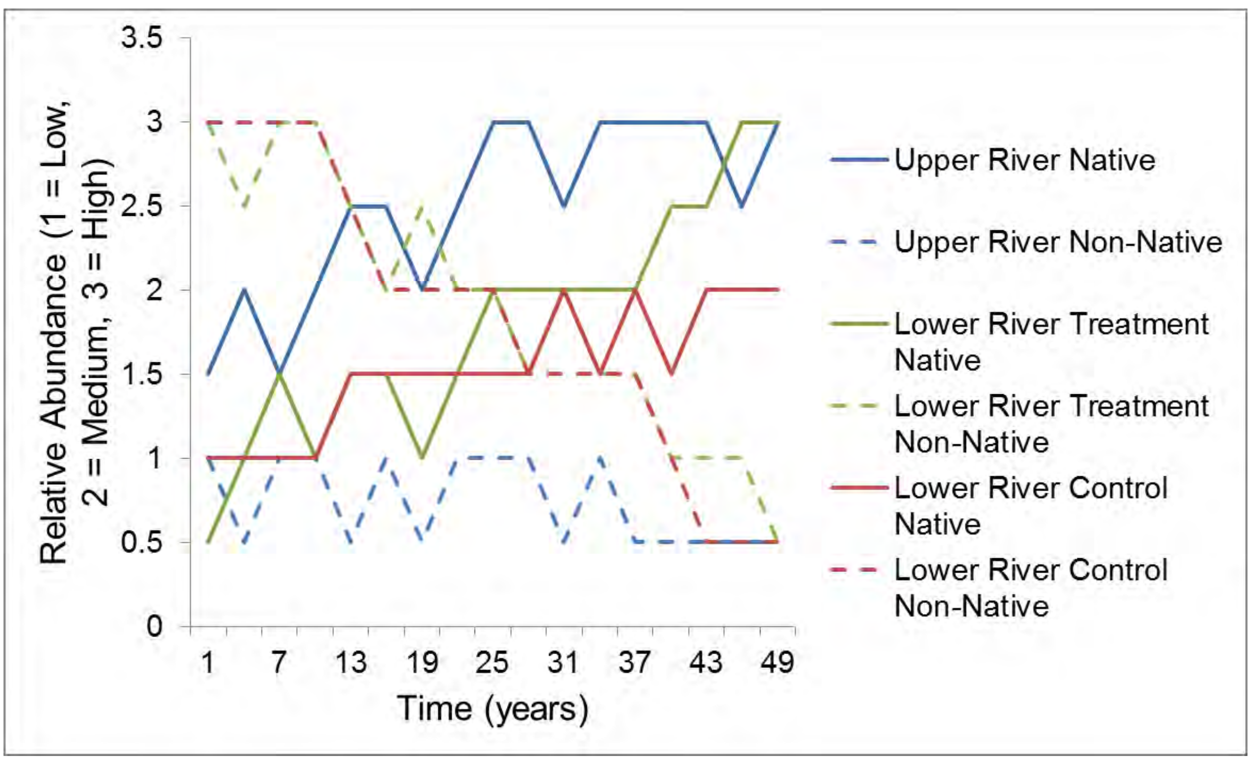

Figure 48. Predicted response of native and non-native fish populations to restoration activities.

Ecological Flows

Pre-existing condition

The current hydrological regime, and how it has been altered by water development in the basin, has been well documented by analysis of flow data collected by the USGS at various locations on the San Rafael River since 1910 (Fortney et al. 2011). The magnitude and duration of spring snowmelt flood events has been reduced during this time by a combination of altered rainfall and snowmelt patterns and water development in the basin (see section I of this report). In addition, large reaches of the lower river can become dewatered for several months at a time during dry periods (Fig. 49**,** McAda et al. 1980, Bottcher 2009).

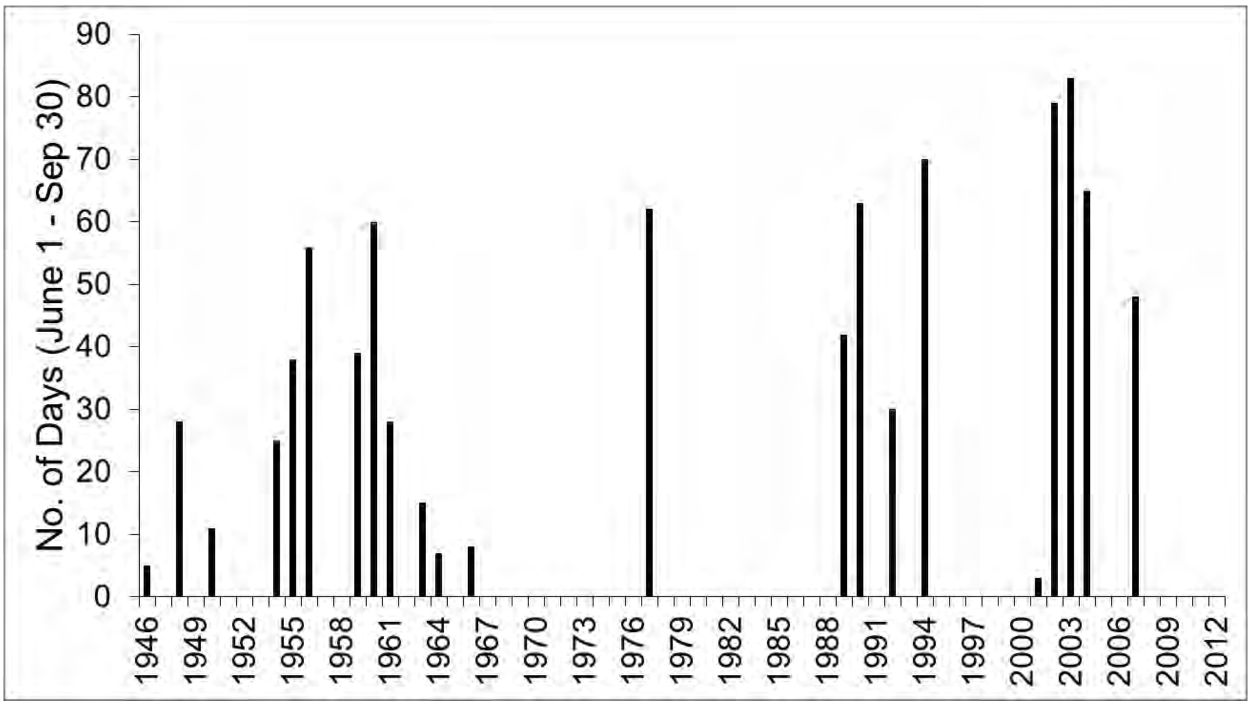

Figure 49. Number of days per summer (June 1- Sep 30) that flow at the USGS SH-24 gage was <1 cfs for years 1946-2012.

Monitoring protocol

Monitoring of flow patterns in the lower San Rafael River by the U.S. Geological Survey will continue at the SH-24 gage (gage 09328500). The gage provides real-time information on water level and flow and this information will be used to determine whether the range of minimum flows is being maintained and whether the recommended high flows are being achieved over the specified time period. Further refinement of the range of minimum flows should be done by observing the channel at flows between 7.5 and 0.16 cfs to determine when portions of the channel start to become dry and prevent fish movement. Some of these observations could be provided by aerial imagery associated with collection of habitat and vegetation data, but on-the-ground observations should be carried out opportunistically when flows are within this range and personnel are working on the river for other purposes. Installation of continuous-recording pressure transducers at different locations throughout the lower San Rafael River would also help inform at what flows the channel begins to dry and the spatial pattern of drying (e.g., does it dry from the Green River upstream, from the Reef downstream, or patchily from multiple locations?). Developing rating curves for installed pressure transducers would also help refine gain/loss estimates for the lower San Rafael River.

Control sites

Control sites are not applicable in assessing ecological flows, because the flows are provided for the whole river. The main comparison will be before and after restoration and also to compare flow records to recommended flow criteria.

Predicted response

By working for arrangements for minimum flows and improving irrigation efficiency at Hatt's Ranch, it is predicted that dewatering of the lower river will be eliminated except during exceptional drought conditions. Arrangements with upstream water users will also likely be sufficient to achieve the recommended high flow scenario. Implementing these flow recommendations is predicted to improve both habitat and native fish populations on the lower river (i.e., proposed outcome 1 of the original NFWF proposal).

Suspended Sediment

Pre-existing condition

Suspended sediment concentrations were measured at the USGS SH-24 gage between 1949-1957. However, this gage information is not sufficient to provide a sediment budget for the lower river, which will require measurement of suspended sediments and flow at two gages.

Monitoring protocol

Assessment of the impacts of restoration and flow on suspended sediment concentrations and sediment storage or erosion from the lower river channel and floodplain will require measurement of suspended sediment concentrations and discharge over a range of discharge values at an upstream and downstream location on the lower San Rafael River. Such monitoring will be critical for refining high-flow recommendations because it will provide an estimate of loads brought into the system during summer and fall monsoon events and moved through the system during spring snowmelt flood events. Currently, there is a gage at SH-24 that monitors discharge but not suspended sediment. Thus, in order to monitor suspended sediment loads, the current gage at SH-24 needs to be equipped with a suspended-sediment sampler. In addition, a second gage should be installed near the confluence with the Green River, with the most appropriate location being the lower San Rafael River Road bridge. Although the gage at SH-24 is not at the ultimate upstream end of the lower San Rafael River (the San Rafael Reef) it is located above the majority of BLM land on the lower river where restoration actions are planned. In addition, this length of river will be sufficient to estimate sediment budgets and thus help refine high flow recommendations.

Control Sites

Control sites are not applicable in assessing suspended sediment concentrations and loading, because the assessment is made over most of the length of the lower San Rafael River. The main comparison will be before and after restoration. Therefore, the gages should be installed as soon as possible to begin collecting pre-restoration data.

Predicted response

Many of the recommended restoration activities aim to promote lateral channel scour and migration through erosion and transport of bank material. Such activities may promote export of sediment from the lower river; however, this will be critically dependent on occurrence of spring snowmelt floods. If the frequency and duration of spring snowmelt floods can be increased through implementation of a flow plan, there is likely to be less storage of sediments within the lower San Rafael River over time. The concentration of suspended sediments is driven primarily by sediment delivery from the landscape and rainfall and snowmelt patterns, and thus is unlikely to be significantly impacted by restoration actions applied within the river channel and floodplain.

Water Quality

Pre-existing condition

The mean and ranges of total dissolved solids (TDS) concentrations and annual loadings have been established for the period of 1990-2001 through water-quality monitoring by DEQ and Emery Water Conservancy District (EWCD) combined with flow monitoring by the U.S. Geological Survey (USGS). Three locations on the river have been sufficiently sampled to provide means and ranges of TDS: near the headwaters (i.e., just below the junction of the three tributaries), Buckhorn Wash, and the SH-24 bridge. However, only the site at the SH-24 bridge is currently gaged and thus, this site is the only site on the San Rafael River where enough information was provided to demonstrate current seasonal trends in TDS concentrations. A relationship between TDS concentration and flow has been developed for the SH-24 site and allows annual load estimation for this site, although the relationship does not extend above 500 cfs. Estimation of loading or reductions in TDS loads through the lower San Rafael River has not been done due to the limited data on flow and concentrations upstream of the SH-24 site. The current available data to 2001 are summarized in MFG, Inc. (2004): average concentrations at the headwaters, Buckhorn Wash, and the SH-24 bridge are: 2,549, 1,803, and 2,170 mg/L respectively and the average annual load at the SH-24 bridge is 137,521 tons. In comparison, the loading capacity based on a TMDL target concentration of 1,200 mg/L and the mean annual flow is estimated at 101,524 tons (MFG, Inc. 2004).

Monitoring protocol

Assessment of the impacts of river restoration on TDS concentrations and annual loads will be difficult due to implementation of other BMPs throughout the watershed and natural variability. To isolate the effects of restoration on TDS it will be necessary to monitor the change in concentration and change in flow throughout the lower San Rafael River. This means there would ideally be measures of TDS and flow at the start of the restoration reach (i.e., just downstream of the San Rafael Reef) and at the end of the restoration reach (i.e., just above the confluence with the Green River). Measures will have to be taken over a range of discharges to develop a rating curve between flow and TDS to estimate loads. Neither of these locations is currently gaged, however, measurement of TDS can be done using the same sampling equipment and gages as used in suspended sediment monitoring. Thus, TDS measurements should be taken at both the SH-24 gage and near the Green River confluence in association with suspended sediment measurements. In addition, it would be helpful to monitor input sources of TDS such as ephemeral tributaries and seeps over a range of flow conditions to understand inputs through the lower San Rafael River.

Control sites

Control sites are not applicable in assessing reductions in TDS concentrations and loading, because the assessment is made over the entire reach. The main comparison will be before and after restoration. Therefore, the gages should be installed as soon as possible to begin collecting pre-restoration data.

Predicted response

The recommended restoration activities may increase loads of TDS within the project reach in the short-term (the next 5-10 years) due to destabilization and erosion of bank materials, a known, albeit minor, component of TDS loading in the San Rafael River (MFG, Inc. 2004). However, over the long term (> 10 years), loads are expected to decline through the project reach due to increases in river-floodplain connectivity and retention of water and sediments in beaver ponds, oxbows, and floodplain depressions. The expected reduction in loads as a result of restoration will likely be small in magnitude but nonetheless significant (Fig. 50), due to the major sources of TDS loading to the San Rafael River being irrigation return flows and natural loading from groundwater and monsoon-derived sediment inputs.

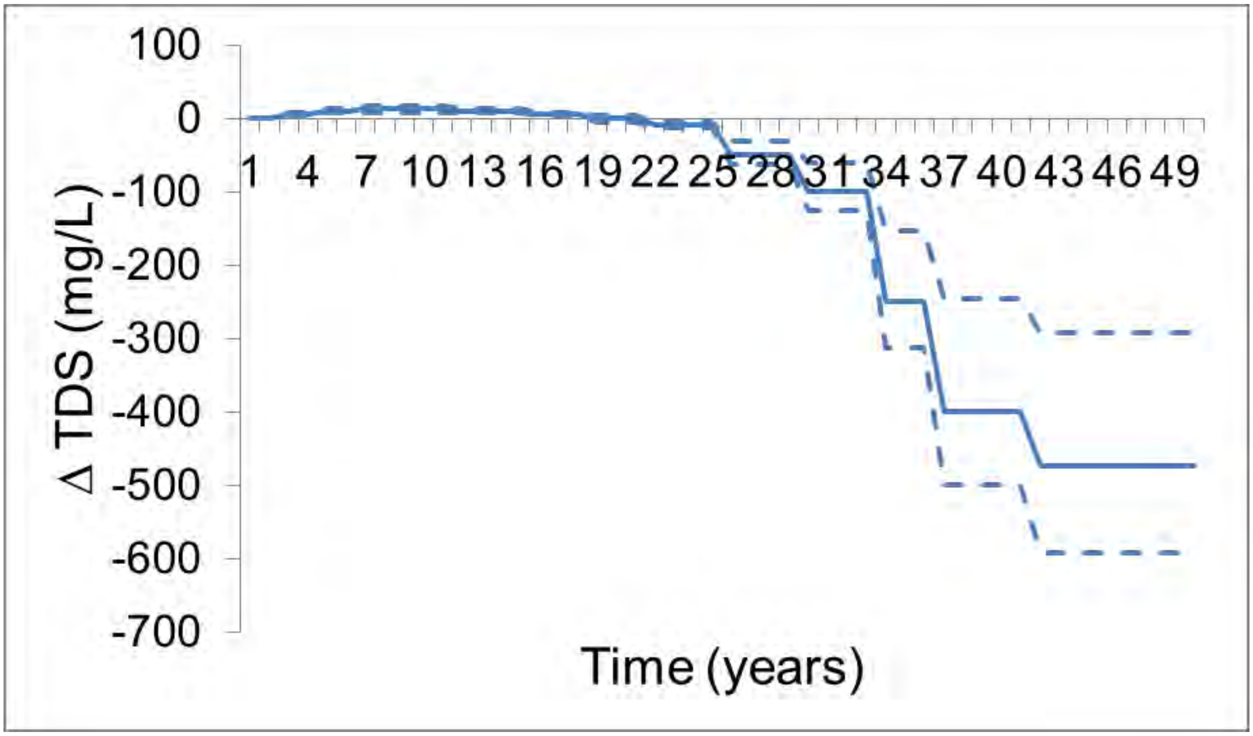

Figure 50. Predicted response of TDS to restoration actions over time. The graph displays the mean (solid line) and ranges (dashed lines) of the predicted difference between TDS concentrations upstream and downstream of the project reach. The predicted increase in the short-term is based on the proportion of the load that streambank erosion was estimated to contribute in the lower San Rafael River (MFG, Inc. 2004). The predicted decrease over the long term is based on applying the average proportional reduction of specific conductance reported in a river-floodplain and wetland restoration project in North Carolina (Richardson et al. 2011) to the mean TDS concentration of the San Rafael River at SH-24 for the period prior to restoration (MFG, Inc. 2004). Ranges for the short-term increase are based on the 95% confidence intervals for the mean TDS concentration in the lower San Rafael River as reported in MFG, Inc. (2004). Ranges over the long term are based on the mean and maximum differences in reaches seen in the study in North Carolina (Richardson et al. 2011). A difference of 0 is assumed prior to restoration.

Geomorphic Changes

Pre-existing condition

Detailed investigation of changes in channel and floodplain morphology since the early 20th century have shown that the San Rafael River has transitioned from a wide, active channel with a connected floodplain to a narrow, confined channel over this time (see section I of this report, Fig. 41, and Fortney 2013b). The current channel and floodplain morphology is captured in a few cross-section surveys conducted in 2009 and 2010 in the vicinity of Hatt's Ranch and Frenchman's Ranch (Fortney 2013b) and by discharge measurements taken at the USGS gage at

SH-24. In addition to these cross-sections, detailed topographic information in the form of LiDAR was captured for the entire lower San Rafael River valley in April 2013.

Monitoring protocol

Changes to channel and floodplain morphology as a result of restoration activities should be assessed by repeat surveys of channel and floodplain topography using both repeated on-the-ground and aerial-based surveys such as LiDAR. On-the-ground surveys using RTK-GPS instruments should be conducted in treatment and control areas both prior to restoration and, at a minimum, every 2 years after implementation to determine geomorphic changes at the reach-scale attributable to restoration activities. Surveys should be conducted in areas where vegetation monitoring transects are established (see below), so that any changes in vegetation can be linked to geomorphic changes. Surveys should also be conducted in the summer following a major spring snowmelt flood event to gage the impacts of the flood on channel and floodplain morphology. Established protocols for monitoring geomorphic changes through repeated on-the-ground surveys are readily available and should be followed (e.g., the Columbia River Habitat Monitoring Program, Bouwes et al. 2011). In the case of gravel additions, geomorphic surveys should also include grain size analysis and a search for gravel tracers within the study reach. LiDAR or an equivalent digital elevation mapping technology should be resurveyed at longer intervals because it will capture broad-scale changes in channel morphology across the entire lower river that are unlikely to be significant over 2-3 years. Comparison of high-resolution digital elevation models between years will allow determination of areas of erosion and deposition of sediment within the lower San Rafael River and with this information, it may be possible to estimate volumes of sediment eroded or deposited within the lower river channel and floodplain. Areas of erosion and deposition should also be compared with vegetation changes obtained through repeated vegetation mapping (see below), so that large-scale vegetation changes can be linked to large-scale geomorphic changes. Software for making calculations of erosion and deposition with associated error estimation is available and should be used (Wheaton et al. 2010). Digital elevation data should be resurveyed every 5-10 years as a method for understanding the cumulative impacts of restoration activities over a broad spatial scale.

Control sites

Control sites are the same sites identified above in the *Fish Habitat* section. In addition, comparison of survey data before and after restoration will be important to determine whether channel morphology has changed over time.

Predicted response

Many of the recommended restoration techniques are designed to promote lateral scour, bank erosion, and movement of the channel across the landscape. If these actions are successful, the increased channel movement should help reduce channel entrenchment, create a wider active channel, and provide increased connectivity between the channel and floodplain (see Fig. 51 for predicted response). This prediction is based on understanding the processes that have caused channel changes over the last 100 years (Fortney 2013b). In addition, examination of channel response to the 2011 flood event demonstrated that given the proper conditions, large flood events can cause significant lateral scour and erosion (Keller 2012), and can also drive significant changes to channel and floodplain morphology including channel avulsions and meander cut-offs (Fig. 52). It is predicted that these types of channel changes will occur throughout the San Rafael River through efforts to provide habitat-forming flood flows, however, the magnitude of the changes are predicted to be greater in treatment areas compared to control areas (Fig. 51).

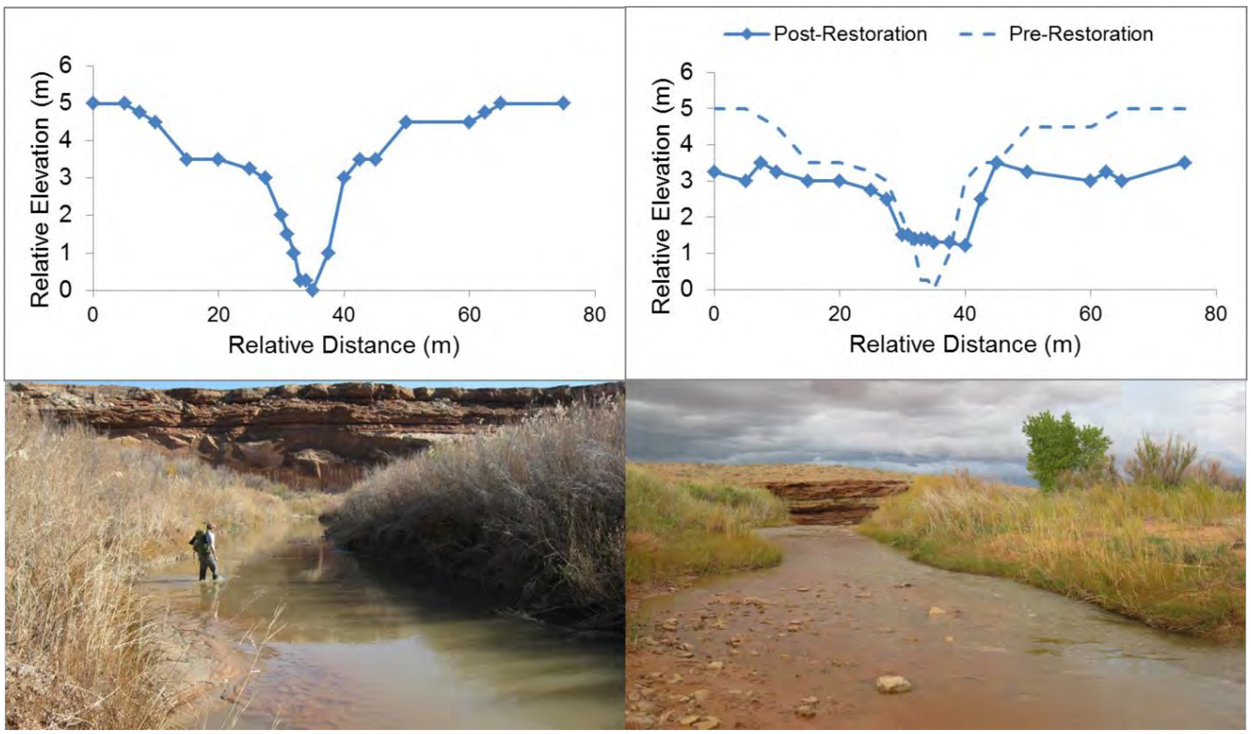

Figure 51. Predicted response of channel morphology to restoration actions and large spring snowmelt floods. The top row shows a representative cross-section before (left) and after (right) restoration actions and series of large spring snowmelt floods. The bottom row shows representative pictures of the predicted response with the left picture showing pre-restoration (photo looking downstream at about reach 158, taken by B. Laub on November 8, 2012) and the right picture post-restoration (photo looking downstream below Spring Canyon confluence, taken by B. Laub on October 12, 2012). Note the gentler-sloping channel banks, decreased entrenchment, and greater channel-floodplain connectivity predicted to occur as a result of restoration activities.

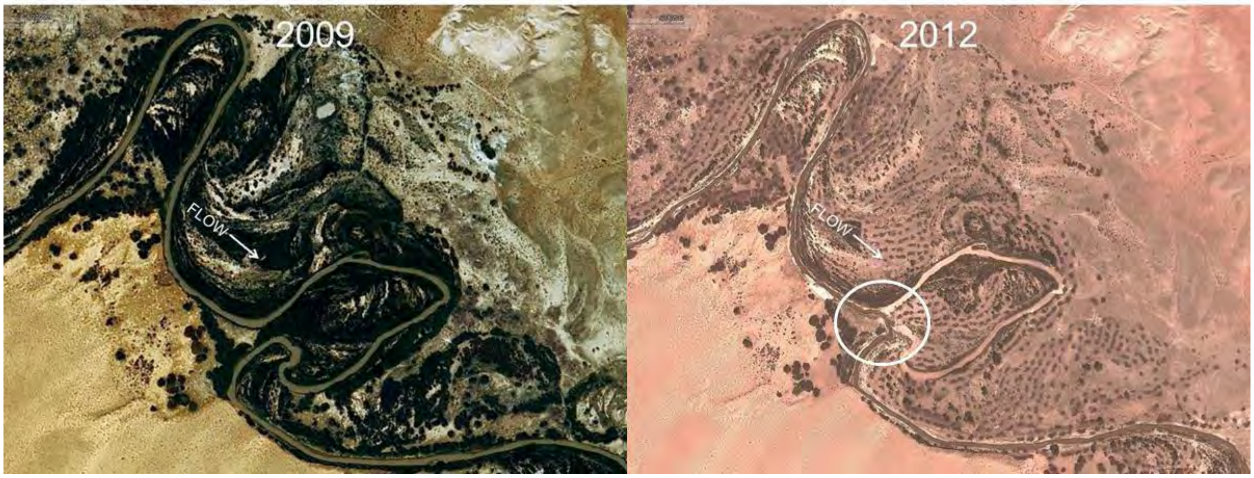

Figure 52. Aerial photographs of a reach of the San Rafael River taken in 2009 and 2012. Dots on the floodplain in the 2012 photo are piles of tamarisk that were removed by the UDWR in 2009-2010. In 2011 a large magnitude, long duration spring snowmelt flood occurred and caused a channel avulsion and meander cutoff event, seen in the circle on the 2012 photograph.

Riparian Vegetation Changes

Pre-existing condition

Fine-scale riparian vegetation mapping over the entire lower San Rafael River corridor was conducted in 2013 using object-based image analysis techniques and 0.5-meter multi-spectral GeoEye satellite imagery. The mapping effort involved extensive on-the-ground vegetation data collection for the generation of training site data and accuracy assessment data (Macfarlane and McGinty 2013, attached as Appendix VII). This map serves as a detailed representation of the pre-restoration state of riparian vegetation on the San Rafael River, though the mapping was completed after tamarisk removal on UDWR lands. Mapping indicated that about 5% of the lower San Rafael River riparian corridor was covered by native woody vegetation (cottonwood and willow/pharagmites stands), and 25% was covered by beetle-impacted tamarisk stands, though compositions varied between the different geomorphic sections (see Fig. 21-26 in Macfarlane and McGinty 2013). Willow and native phragmites are found primarily on riparian berms throughout the lower river (e.g., Fig.13). Herbaceous grasses, both native and non-native, were the most prevalent cover class on the lower San Rafael River (34%), followed by bare ground/sparsely vegetated cover (25%). Russian olive, another non-native woody plant found commonly along rivers in the desert southwest (Friedman et al. 2005a) is present in the lower San Rafael River but at much lower abundance than tamarisk. However, field plot data and aerial imagery indicated that nearly all tamarisk on the San Rafael River is defoliated by the tamarisk leaf beetle (*Diorhaba* spp.). The tamarisk beetle was initially released at Fuller Bottom by the Emery County Weed Department in 2005 and was subsequently released at Hatt's Ranch. Thus, the beetle has been present in the lower San Rafael River for several years and may start to induce tamarisk mortality in the next few years, depending on the root mass of plants and the intensity of defoliation (Dudley et al. 2006). Monitoring of vegetation response to tamarisk removal on UDWR property has found limited resprouting of tamarisk plants, in part due to beetles attacking resprouts. The reduction in tamarisk through removal and beetle-induced mortality could open up areas for colonization by Russian olive, non-native herbaceous vegetation, or native vegetation if spring flood flows and associated channel movement can be provided.

Monitoring protocol

Similar to fish habitat monitoring, it will be useful to perform detailed field monitoring of vegetation cover in treatment and control areas and combine these on-the-ground measures with future vegetation mapping over the whole river corridor. Field monitoring should be conducted using the protocol developed for assessing the response of vegetation to tamarisk treatments on the Colorado River (BLM 2011). At each monitoring site, at least 3 permanent transects should be established running perpendicular to the channel from the active channel margin to the edge of the riparian corridor. The permanent transects should coincide with transects used for monitoring geomorphic changes (see below), so that any vegetation changes can be interpreted in terms of geomorphic changes or stasis. Additional transects along defined geomorphic surfaces such as the riparian berms would also be beneficial to link vegetation changes to geomorphic changes. At 50 evenly spaced points along each transect the line-intercept method is used to estimate vegetative cover. In this method, a 36-inch pin flag is dropped in the ground and every plant species that intercepts the pin is recorded. In addition, cottonwood and tamarisk density can be estimated along these transects by counting the number of trees with greater than 50% of the tree occurring within 1-m on each side of the transect. Densities should be determined for different size classes of tamarisk and cottonwoods. Measurements of stem density will be most useful as an assessment of wildlife habitat, so this data should be directly linked to bird count data (see below). The presence of seedlings of cottonwoods and tamarisk should be noted and the extent recorded if observed. However, estimating density of seedlings is not necessary, because determination of whether recruitment of cottonwoods is occurring at a higher rate than tamarisk or other non-native woody vegetation will be determined by repeated vegetation mapping. If densities are high enough that counting all trees within the transect is impractical, densities should be determined within sub-sampling quadrats. The extent of defoliation by the tamarisk leaf beetle should also be recorded for each belt transect. Photographs should be taken at the permanent transect markers in each cardinal direction during vegetation sampling. Field plots should be surveyed 1, 3, and 5 years after treatment and then once every 5 years and in years following a high flow event. Vegetation mapping should be repeated every 5-10 years following restoration to provide a large-scale view of cumulative vegetation changes over the entire San Rafael River riparian corridor. Vegetation mapping should be linked to high-resolution topographic data (e.g., LiDAR), which should also be resurveyed every 5-10 years (see *Geomorphic Changes* section above), so that large-scale vegetation changes can be linked explicitly to large-scale geomorphic changes. Mapping every 5-10 years should be sufficient because large-scale mapping is unlikely to detect significant changes on finer time-scales than several years. Vegetation mapping should follow protocols established during mapping of the baseline vegetation dataset (Macfarlane and McGinty 2013, attached as Appendix VII**)**.

Control sites

Control sites are the same sites identified above in the *Fish Habitat* section.

Predicted response

The recommended restoration actions are intended to increase the establishment of native vegetation over time, and while not directly targeted at reducing prevalence of non-native vegetation, non-native vegetation is predicted to decline through direct removal methods and through replacement by native vegetation. In particular, cottonwood establishment is predicted to increase following high-flow years (Fig. 53).

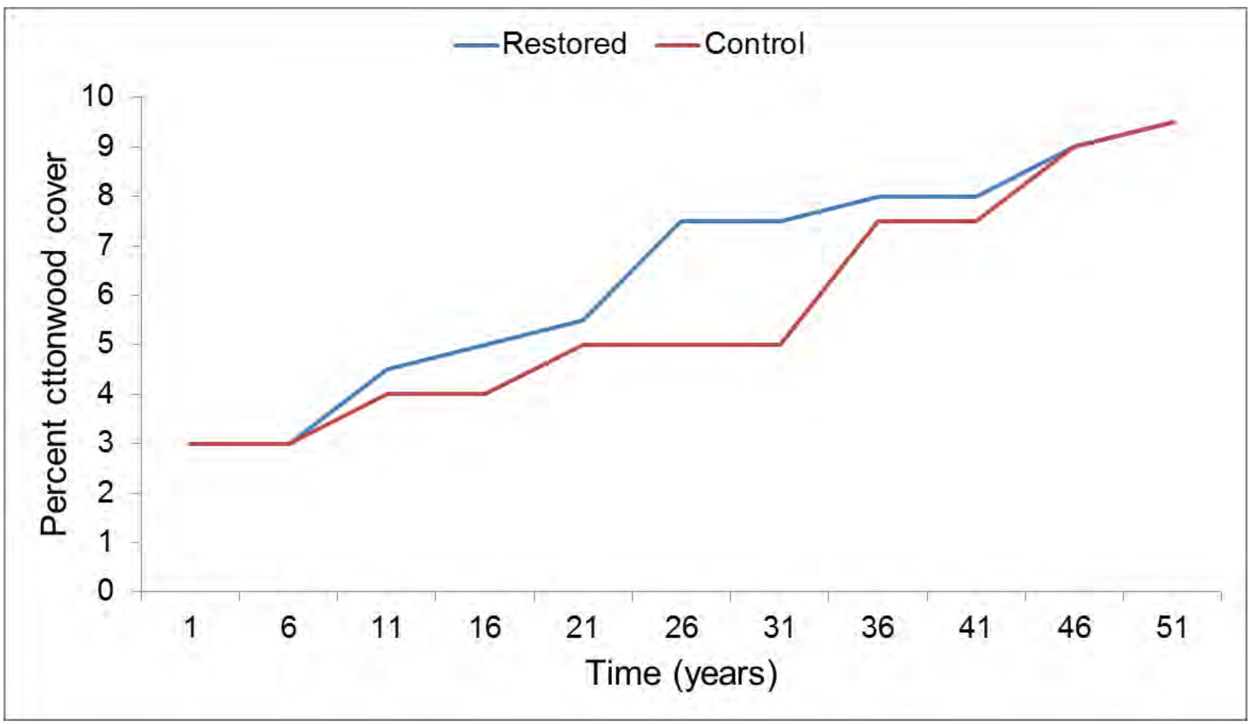

Figure 53. Predicted response of cottonwood cover to restoration actions over time. The predicted increase is due to a combination of flow events, tamarisk removal, gravel addition, and promotion of beaver dam building activity. Restored sections are predicted to respond quicker in the short term due to tamarisk removal, gravel additions, and promotion of beaver activity, but control sites are predicted to increase over time due to recovery of favorable flow patterns. Current cottonwood cover is 3% for the entire lower San Rafael River based on vegetation mapping (Macfarlane and McGinty 2013), and 9.5% is the median target cover for the lower river.

Wildlife

Pre-existing condition

Little information exists on the populations of birds or other vertebrates on the lower San Rafael River. The UDWR conducted a study on bird response to their tamarisk removal project at Hatt's Ranch, and thus there is a list of bird species present and their relative abundances available for this site (Wright 2012). However, collection of data on bird populations at proposed treatment and control sites is recommended prior to restoration activities to better establish the pre-existing condition of bird populations. Birds are selected as a group to represent wildlife, because many species are known to require or make use of riparian habitats (UDWR 2005), and thus should be representative of any changes in riparian habitat quality as a result of restoration efforts.

Monitoring protocol

At each treatment and control site, the protocol used by the UDWR at Hatt's Ranch should be implemented (Wright 2012). The UDWR protocol consists of three point counts of birds at 10 locations in each site. Point counts are conducted during the breeding season (May 1-June 30) between sunrise and 10:00 AM avoiding days with significant precipitation or strong winds. Point counts consist of an 8 minute observation time broken into three sections (0-3, 3-5, and 5-8 minutes), during which all birds seen or heard are identified and time, location, age, sex, and distance from observer are recorded if possible.

Control sites

Control sites are the same sites identified above in the *Fish Habitat* section. However, similar to fish populations, counts of individual bird species should be compared to regional count data to determine whether any increase or decrease in numbers may be attributable to broader regional population trends, as done in Wright (2012).

Predicted response

The recommended restoration activities are intended to increase establishment of native vegetation species and increase abundance of native riparian vegetation communities over time, which should beneficially impact wildlife species through improvement in habitat conditions. In the short-term there may be a decrease in habitat quality as a result of tamarisk removal due to the disturbance caused by removal activities and the loss of vegetation structure associated with tamarisk removal. The study by the UDWR at Hatt's Ranch suggests that there will be a shift in the community of bird species but no overall change in diversity in the short term. However, over the long-term, the predicted response is an increase in richness of bird species through increased establishment and abundances of native vegetation communities (Fig. 54). Riparian obligate species, such as the willow flycatcher are also predicted to increase in abundance over the long-term if riparian habitat objectives are met.

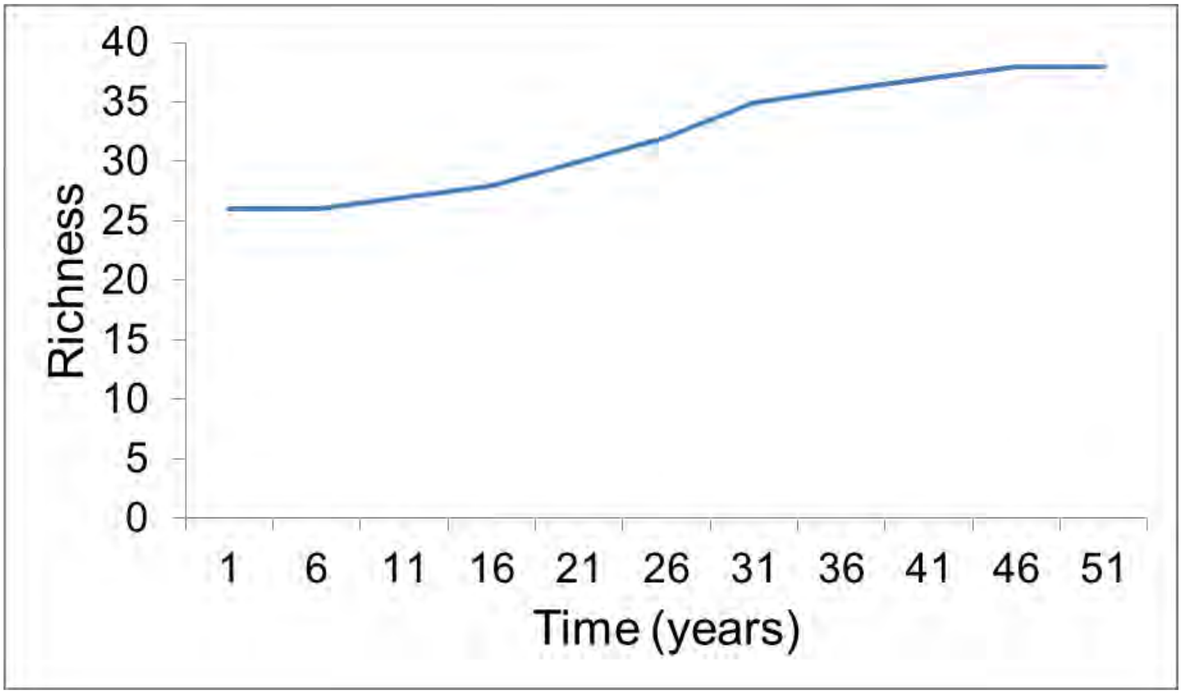

Figure 54. Predicted response of bird species richness to restoration actions over time. The graph displays the mean richness predicted in restored sites over time. The current richness is based on the average richness seen at Hatt's Ranch over three sampling years by the UDWR, while the maximum predicted richness is predicted as the total number of species observed over the three year sampling program at Hatt's Ranch (Wright 2012).

Stream Temperatures

The three species inhabit desert river systems and thus do persist in systems where temperatures fluctuate from 0-30°C over the course of a year; however, studies have shown that 30°C is at the high end of preferred temperatures for each species (Bezzerides and Bestgen 2002). In periods of low flow during the summer, particularly in isolated pools, temperatures may increase beyond these preferences, potentially limiting native fish populations (Bottcher 2009). Even temperatures below 30°C can be limiting during low-water periods because metabolic demands increase with temperature, and fish will require increased food resources compared to lower temperatures. Research on the San Rafael River has found that productivity of macroinvertebrates is generally low due to the lack of coarse substrate and complex riffle habitat (Walsworth 2011), suggesting that increased temperatures could interact with low habitat complexity and low productivity to limit growth and persistence of native fish. Understanding this potential limitation is critical, because if temperatures are often limiting for fish, habitat restoration and non-native fish removal may not be sufficient to recover native fish populations.

Pre-existing condition

The U.S. Geological Survey took spot measurements of temperature at the SH-24 gage consistently between 1950 and 1977, and from this data it is clear that temperatures in the San Rafael River consistently approached and sometimes exceeded 30°C during summer (Fig. 17). Temperature monitoring since then has not been conducted, except for a few observations of high temperatures (about 35°C) in isolated pools during low water periods (Bottcher 2009). Given the relatively consistent yearly temperature patterns between 1950 and 1977, summer temperatures likely approach and exceed 30°C in many years currently. However, whether such temperatures occur over the entire length of the lower San Rafael River and whether certain habitat types such as deep pools provide lower temperatures during summer is unknown. To provide more detailed information on water temperatures, the USU Water Lab has initiated a study on stream temperatures on the lower San Rafael River that will be conducted over the next 6-12 months that should provide a better understanding of whether temperatures can become limiting for the three species over large sections of the lower San Rafael River (UWRL 2012). In this study, the USU Water Lab will be installing a continuously-recording temperature sensor about every 1.6 km on the river between Tidwell Bottom and the Green River confluence, with increased densities of sensors around several beaver dams. In addition to continuously recording temperature, the sensors will allow calibration of thermal imagery of the entire lower river captured with an unmanned aerial vehicle. This thermal imagery should provide a snapshot of surface temperatures during the summer and should provide another indicator of the potential for thermal limitation for native fish. Thus, although currently there is limited pre-existing data on spatial variability in temperature patterns in the river, this data will likely be available for at least one year prior to restoration.

Monitoring protocol

Temperatures can vary substantially in different areas of a river due to upwelling groundwater, shading effects, and presence of deep pools. Thus, monitoring whether temperature regimes are altered by restoration activities will require measuring temperature in different habitat features. Temperature sensors are relatively inexpensive and should be installed in several pools, runs, and riffles in each study reach. Alternatively, the main focus of interest in monitoring temperatures is to determine if temperatures become limiting during the hottest periods of the year, such that measurements could be taken by hand in several habitat features during other field work conducted during low-flow periods in the summer. In addition, reflying the thermal imagery of the entire lower San Rafael River should be done in low-water years after restoration begins in order to provide an understanding of whether temperatures are limiting over large stretches of the lower San Rafael River or whether limiting temperatures are restricted to particular reaches.

Control sites

Control sites are the same sites identified above in the *Fish Habitat* section.

Predicted response

Habitat restoration will ideally provide pools that can serve as thermal refugia during low-water periods and provision of minimum flows should help prevent temperatures from becoming limiting in these habitat features. Thus, temperatures in the lower San Rafael River are predicted to exceed critical tolerances for the three species less often than prior to the initiation of restoration activities.

Beaver Dams

Pre-existing condition

Beaver are present on the lower San Rafael River and were likely present historically, based on old beaver cut-marks. However, the presence of beaver is not always indicative of the presence of beaver dams in desert rivers, because beaver often live in bank dens and may not construct dams everywhere they are present (Baker and Hill 2003). Surveys of the entire lower San Rafael River channel in 2010 identified only 8 active beaver dams and many of these were likely washed from the river by the high spring flows in 2011 (Keller 2012). Numerous dams have been built since the 2011 flood as observed during field visits in 2012 and 2013 (Fig. 26), and there are currently at least 10 active dams throughout the lower San Rafael River.

Monitoring protocol

To determine whether beaver activity and the number of beaver dams are greater in restoration sections, the presence of beaver dams and whether the dam is currently active should be noted at study sites during habitat monitoring. Whether beaver are using installed beaver assist structures should also be determined for all installed structures during habitat monitoring trips. On-the-ground monitoring of beaver dams can be facilitated by using a smart phone app developed by the Utah State University's Ecogeomorphology & Topographic Analysis Laboratory (ETAL). Finally, if beaver dams can be identified on aerial imagery, they should be censused by counting the total number of dams seen on aerial imagery for the entire lower San Rafael River.

Control sites

Control sites are the same sites identified above in the *Fish Habitat* section.

Predicted response

Analysis of potential beaver dam capacity on the San Rafael River using the Beaver Restoration Assessment Tool (Macfarlane and Wheaton 2013) indicated that the current beaver dam density is below potential capacity throughout much of the lower river. The analysis was run using LandFire vegetation data and thus should be rerun prior to restoration implementation using the newly developed vegetation map (Macfarlane and McGinty 2013, available at http://bit.ly/1awJyOr). Nonetheless, based on the current low density of beaver dams relative to the estimated potential, the number of beaver dams is predicted to increase in the short term. A short-term increase should occur due to the installation of beaver assist structures that will facilitate persistence of beaver dams through high flow events. Dam density should continue to increase over the long term as well due to efforts to establish cottonwood and willow and reduce confinement of the river channel. Dams are not predicted to remain in place indefinitely. Instead, beaver are likely to shift activity over the San Rafael River due to availability of food resources and beaver population density changing over time. However, the predicted increase in food resources and dam-building materials over time should allow greater densities of dams over long time scales (Fig. 48).

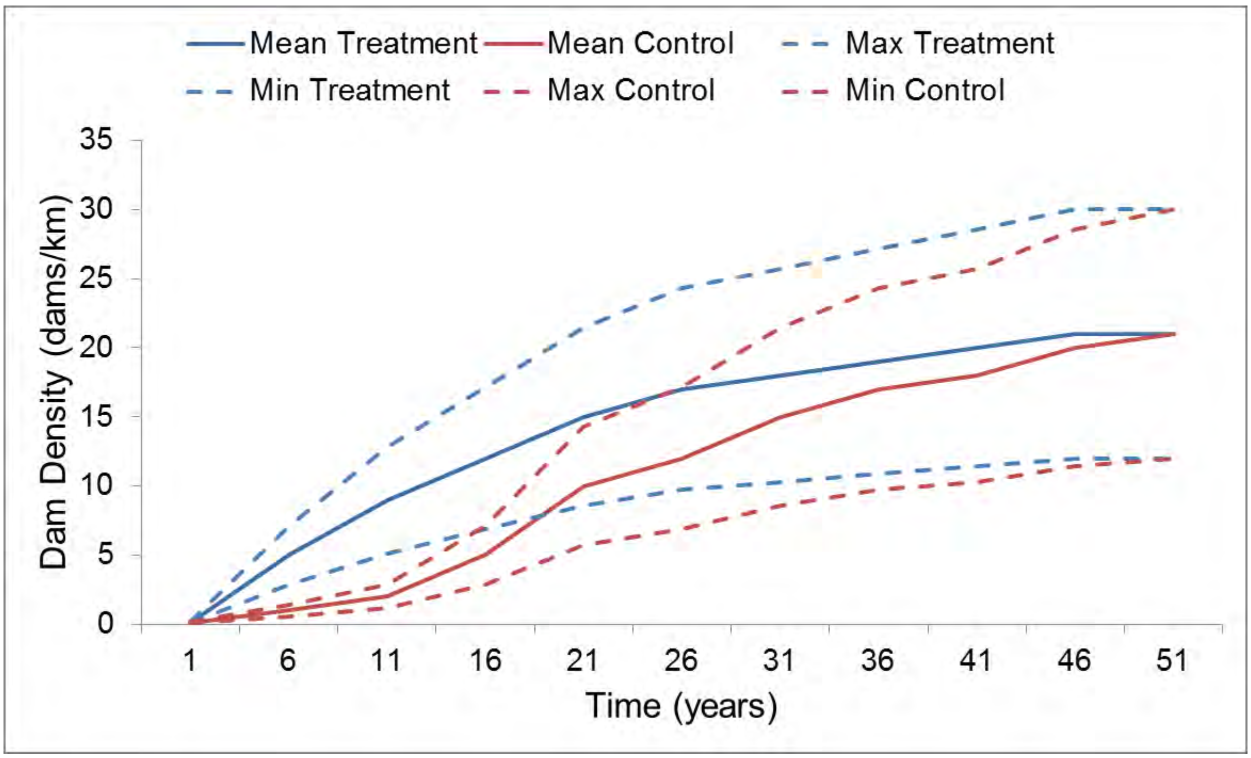

Figure 55. Predicted response of beaver dam density to restoration activities over time. Dam density is predicted to increase more rapidly in treatment sites due to installation of beaver assist structures, however, control sites are predicted to have similar density over the long term due to establishment and growth of cottonwood trees and decreasing channel entrenchment. The current density is based on surveys of active beaver dams in 2010 and the plateau values are based on the maximum values predicted for the San Rafael River using the Beaver Restoration Assessment Tool (Macfarlane and Wheaton 2013). Ranges were predicted by dividing the range of predicted dam densities into 5 categories and applying the minimum and maximum values from the highest category.

Implementation

Monitoring whether changes were made to the planned restoration actions during implementation, for example, due to access issues or altered conditions from the planning phase, is critical because understanding how a restoration action impacted the stream ecosystem is dependent on understanding exactly how the restoration action was implemented. Thus, when each action is implemented, whether design specifications were followed should be checked immediately and any changes recorded. In addition, the costs of all implementation and monitoring actions should be recorded, so that an assessment of cost-benefit can be obtained. Such information will be critical for managers looking for efficient restoration techniques to employ on other sites on the San Rafael River and on other river systems.

VI. Conclusion: Adaptive Management and Broader Implications

The plan presented herein is intended to guide restoration and management of the lower San Rafael River over the next several decades. However, the plan in its current form should not be viewed as the final blueprint for restoration over the next 30-50 years. Instead, periodic review of the plan should be conducted every 5-10 years as monitoring data become available. Based on response of the river to restoration and potential changes in climate or land use, site prioritization, restoration actions, and the monitoring methods may need to be altered or adapted. By incorporating flexibility into the plan, future efforts to restore the San Rafael River can be adapted to changing conditions and new information as progress is made toward achieving the restoration vision.

The plan presented here was developed with an experimental design so that lessons can be learned from efforts to restore the San Rafael River and extended to management of other desert river systems in the area. The San Rafael River is one tributary of the upper Colorado River, and many of these tributaries face similar threats as the San Rafael River (e.g., Price, Muddy Creek, Escalante). In addition, native fishes of the Colorado River basin including the three species move between the Colorado River mainstem and associated tributaries, and in this way the San Rafael River is connected to the larger Colorado River system. Therefore, it is important that restoration on the San Rafael River be viewed in terms of larger efforts to manage the ecosystems of the upper Colorado River Basin (e.g., Dauwalter et al. 2011). Extending the resources invested in restoration on the San Rafael River to other Colorado Basin tributaries through experimental restoration and monitoring will help ensure the restoration plan presented here contributes to these broader efforts.

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VIII. List of Appendices

Appendix I: Original NFWF project proposal

Appendix II: Fortney, S. 2013a. Geomorphic organization of the lower 90 kilometers of the San Rafael River. Masters Thesis, Chapter 2. Utah State University, Logan, Utah, USA.

Appendix III: Fortney, S. 2013b. Channel change on the lower San Rafael River, UT. Masters Thesis, Chapter 3. Utah State University, Logan, Utah, USA.

Appendix IV: Keller, D. L. 2012. Effects of flooding and tamarisk removal on habitat for sensitive fish species in the San Rafael River, Utah: Implications for future restoration efforts. Non-thesis Masters Report. Utah State University, Logan, Utah, USA.

Appendix V: Bottcher, J. L. 2009. Maintaining population persistence in the face of an extremely altered hydrograph: Implications for three sensitive fishes in a tributary of the Green River, Utah. Masters Thesis. Utah State University, Logan, Utah, USA.

Appendix VI: Walsworth, T. E. 2011. Analysis of food web effects of non-native fishes and evaluation of restoration potential for the San Rafael River, Utah. Masters Thesis. Utah State University, Logan, Utah, USA.

Appendix VII: Macfarlane, W. W. and C. M. McGinty. 2013. Fine scale riparian vegetation mapping: Lower San Rafael River, Utah. Fish Ecology Lab and RS/GIS Laboratory, Utah State University, Prepared for Department of the Interior, Bureau of Land Management, Logan, Utah, 52 pp.