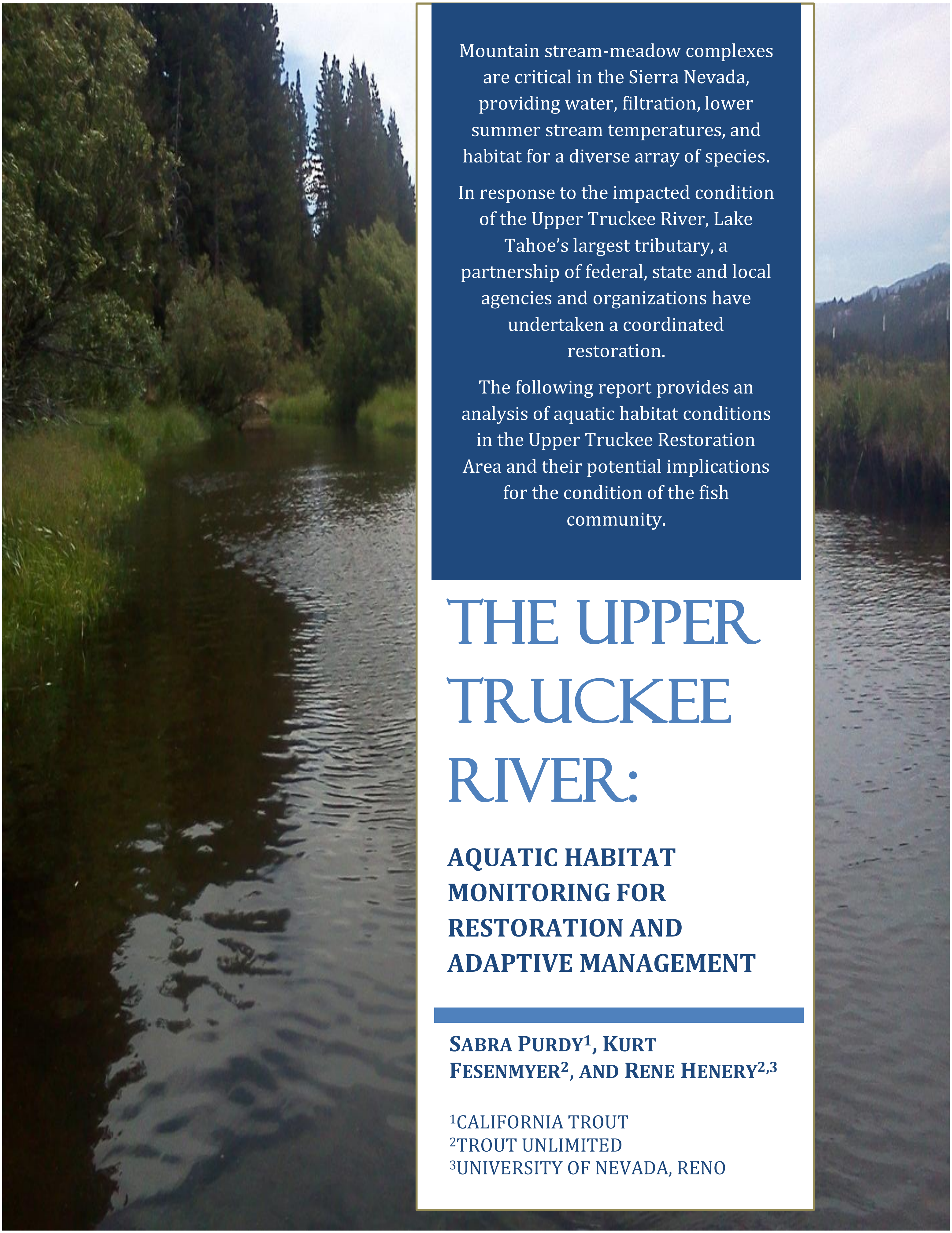

Mountain stream-meadow complexes are critical in the Sierra Nevada, providing water, filtration, lower summer stream temperatures, and habitat for a diverse array of species.

In response to the impacted condition of the Upper Truckee River, Lake Tahoe's largest tributary, a partnership of federal, state and local agencies and organizations have undertaken a coordinated restoration.

The following report provides an analysis of aquatic habitat conditions in the Upper Truckee Restoration Area and their potential implications for the condition of the fish community.

THE UPPER TRUCKEE RIVER:

AQUATIC HABITAT MONITORING FOR RESTORATION AND ADAPTIVE MANAGEMENT

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The Upper Truckee River: Aquatic Habitat Monitoring for Restoration and Adaptive Management

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Introduction

The opportunity of meadow restoration

Mountain stream-meadow complexes are critical habitats in the Sierra Nevada, providing water, shade, and cooling during the three to six month drought season, promoting lower summer stream temperatures, and supporting niches for a diverse array of species (NFWF 2009). In the Sierra Nevada, mountain streams and wet meadows have been identified as critical habitats for native fishes, including California's eight native trout species (Moyle et al. 2008, Williams et al. 2007). However, the vast majority of meadow systems in the Sierra Nevada have experienced more than a century of degrading influences. Cumulatively, these have resulted in a marked loss of the critical functions these meadows serve, including water filtration, flood attenuation, support of biodiversity, and water storage (Kattleman and Embury 1996).

Over the past twenty years a range of mountain stream and meadow restoration methodologies have become increasingly common approaches to bolster upper elevation water retention and slow runoff. Mountain stream and meadow systems, however, are heterogenous, differing across a range of criteria including soil type, hydrology, vegetation, slope, elevation, and size as well as history of human use (Kattleman and Embury 1996). As a function of this as well as the diversity of methodologies applied to meadow restoration, the range of restoration effects, still poorly understood, can also be diverse. Geomorphic restructuring approaches such as "Pond and Plug" have been shown to increase groundwater levels and storage (Cornwell and Brown 2008) but may have no or negative impacts on annual streamflow or baseflow in some cases (Hammersmark et al 2008) and positive effects on summer baseflow in others (Liang et al 2007). Meadow restoration along tributaries to the Feather River increased groundwater residence time and may have contributed to late summer streamflow duration (Loheide and Gorelick 2007). Other strategies such as grazing management and vegetation manipulation have been shown to reverse channel degradation (before it reaches critical degradation thresholds), and increase volume and duration of baseflow (Elmore and Beschta 1987), as well as restoring perennial flow to degraded stream networks (Klein et al 2007).

As awareness of the need and potential benefits associated with mountain meadow restoration expands, resource managers and restoration practitioners are increasingly looking to meadow restoration as a potential tool to serve a range of interconnected functions including a) promoting improved hydraulic retention and storage in the upper portions of watersheds, b) restoring channel forming geomorphic processes, and c) expanding and recovering habitat for aquatic and riparian fish, amphibians and bird species, as well as their invertebrate prey. Unfortunately, in addition to the varied results of meadow restoration projects to date, many of the restoration approaches applied are broad in design and may not incorporate the species- or habitat-specific needs of native fishes and other aquatic and riparian species. Few mountain stream-meadow restorations have been undertaken specifically to benefit fish, and in the cases where fish are a focus, lessons learned often do not get published, shared, or effectively integrated towards the progression of restoration science. Additionally, native fish species other than salmonids are seldom priority targets for conservation, and as a consequence, are often overlooked in restoration assessment and planning pre- or post-project.

Climate change impacts on Sierra Nevada fishes

Sierra Nevada aquatic and riparian ecosystems are already experiencing pressure from a changing climate. As a result of a decrease in snow pack and earlier snowmelt, the ability of California watersheds to store and slowly release water into stream systems is diminishing. Stream flows are expected to be lower during the summer months extending into the fall, and these changes are expected to be most significant in streams fed by the relatively lower north-central and northern Sierra Nevada (Mote et al. 2005; Null 2010). As a consequence of these climate driven changes in the Sierra Nevada, threats to California's mountain aquatic ecosystems and species include lack of habitat connectivity, reduced summer stream flows, increased stream temperatures, and reduced refuge areas.

For cold-water fish specifically, the lower baseflows resulting from reduced snowpack are expected to exacerbate rising air and water temperatures to levels that are potentially damaging (Hamlet et al. 2005; Stewart et al. 2004; Stewart et al. 2005). In a recent assessment of the status of California's inland fishes, 23% of 129 native species are currently listed as Threatened or Endangered, and an additional 54% were determined to be in decline (Moyle et al. 2011). Several of California's native inland trout taxa along with a suite of other impacted native species including Tahoe sucker, redside shiners, and speckled dace are primarily endemic to small, higher elevation stream systems vulnerable to climate change, and it is anticipated that future shifts will exacerbate pressure on those populations already in decline (Moyle et al. 2011). Coupled with a decrease in the timing and availability of cold water habitat, the extent of habitat for warm water species, such as bass (*Micropterus* spp.) and sunfishes (*Lepomis* spp.) of the family Centrarchidae, will increase (Mohseni et al. 2003) likely resulting in concurrent local declines in native fish abundance and increases in predatory non-native fishes (Marchetti & Moyle 2001).

Refining restoration: A novel approach

Mountain stream and meadow habitat function for aquatic and riparian species hinges on the interaction of landscape attributes and processes operating at scales ranging from the geomorphic and hydrologic interactions that define channel structure, surface and groundwater retention, and vegetation recruitment, to the substrate type, bank condition, and water quality in an individual riffle. Designing meadow restoration to meet the multi-scale goals of expanding high elevation groundwater retention, while improving habitat and providing a climate change buffer for native aquatic species, in a cost effective manner therefore necessitates a) a systematic and quantitative approach for evaluating restoration projects in terms of their effects on species and b) a targeted monitoring approach able to capture and quantify change in physical and biological habitat conditions resulting from the specific restoration actions, and their effect on target species.

With support under the NFWF Mountain Meadows initiative, Trout Unlimited (TU) California Trout (CalTrout), the University of Nevada Reno (UNR), and the University of California Davis (UCD) partnered to assess mountain stream and meadow restoration projects in terms of their potential benefit for native fish and aquatic habitat. Our coalition developed a novel tool called the Meadow Restoration Fish Analysis Tool (MRFAT) which quantifies benefits of past, existing, or future stream and meadow restoration projects for native fishes. We then applied MRFAT to review and analyze stream and meadow restoration projects within the ranges of eight native trout taxa that occur within California. The results of this process identified a variety of threats to native fishes that restoration projects were addressing to varying degrees, and provided the basis for development of restoration design refinements, enhancements, and adaptive management actions in the reviewed project areas (Henery et al 2011).

Monitoring is an essential component to any successful restoration project, providing critical information about a system that allows managers, researchers, and practitioners to identify problems, define and quantify successes, and make informed decisions about adaptive management. Building a cohesive monitoring program that is repeatable, provides scientifically credible data, and meets the critical information needs of a given project is a difficult task that requires considerable investment in planning and design. As an additional component of our effort, our coalition reviewed a broad range of existing monitoring approaches. Informed by our backgrounds in aquatic ecosystem analysis and restoration, our team developed a conceptual framework for monitoring (Purdy 2011), and assembled components of several existing methodologies into a robust monitoring approach for mountain meadows and streams[1]. We designed our approach specifically to a) quantify physical and biological effects from stream and meadow restoration, b) reveal the potential of that restoration to positively benefit native fish species, as well as the persisting threats to their populations in the restoration area, and c) be widely applicable and compatible with existing monitoring approaches already being implemented by resource managers and restoration practitioners.

[1] http://watershed.ucdavis.edu/pdf/Monitoring%20Approaches%20for%20Fisheries%20Restorations%20Final.pdf

The Upper Truckee River

The Upper Truckee River (UTR) is the largest of Lake Tahoe's tributaries. It originates at headwaters in Meiss Meadows, at an elevation of approximately 2750 meters, and flows some 40 kilometers north to its confluence with Lake Tahoe near the Tahoe Keys housing development. Draining over 87 square kilometers, the Upper Truckee is the largest watershed in the Lake Tahoe Basin and also the most heavily impacted by development. Over the last two centuries, the watershed has experienced severe degradation, primarily as a function of timber harvest, grazing, and, more recently, urbanization. The range of impacts associated with these pressures have included channel straightening, bank erosion and incision, disconnection between the river and the floodplain, loss of floodplain habitat to development, and an increase in turbidity and non-point source pollution. Channel impacts and alterations have also resulted in lower groundwater levels, desiccation or loss of important meadow and riparian habitat, and reduced groundwater storage potential. As a function of all of these factors, the aquatic habitat in the incised and straightened channel has lost a great deal of its underlying functionality, complexity and presumed associated value for native fish and other aquatic organisms.

In response to the impacted condition of the UTR, a partnership of federal, state and local agencies have undertaken a coordinated restoration effort that seeks to restore natural processes and functions, and improve water quality, terrestrial and aquatic habitat, and native vegetation using a variety of methods. The restoration approaches are being applied to a series of discrete but adjacent projects in the lower reaches of the UTR.

In 2010, in the course of evaluating meadow restoration and impacts on native fishes across CA, our coalition applied MRFAT to the analysis of restoration projects in the UTR watershed's Upper Truckee Marsh and Meiss Meadows. Results from this analysis are summarized in the report *Meadow Restoration to Sustain Stream Flows and Native Trout* (Henery et al. 2011[2]). A self-sustaining population of Lahontan cutthroat trout (LCT) has been restored in the headwaters of the UTR and efforts to expand that population and increase its range are under active consideration. Because it historically supported and currently supports LCT and other native species, as well as the potential for recovery of LCT in the future, the UTR was specifically selected for the analysis. Among the persisting, priority concerns for LCT and other native fish species in the UTR revealed by the MRFAT analysis was the presence of introduced fish species, and, in the absence of direct action to manage those species, the potential for restoration actions to promote their proliferation and expansion at the expense of native fishes.

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[2] https://watershed.ucdavis.edu/pdf/Meadow_Restoration_to_Sustain_Stream_Flows_and_Native_Trout_Final.pdf

UTR – Fish community

Over the last century and a half, a variety of non-native fish species have been introduced intentionally and unintentionally to the Tahoe Basin. Among these, five species of salmonid including rainbow trout *(Oncorhynchus mykiss)*, brown trout *(Salmo trutta)*, lake trout *(Salvelinus namaycush)*, brook trout *(Salvelinus fontinalis*), and kokanee salmon (*Oncorhynchus nerka*) continue to persist in the basin. While the larger among these continue to be sought after by anglers, there is a growing recognition of the impacts of these salmonids and other introduced species on the distribution and abundance of native species in Sierra Nevada streams (Moyle and Vondracek 1985; Moyle and Williams 1990; Moyle et al. 2008). Non-native warm water fish introduced into Lake Tahoe streams and near-shore include: brown bullhead (*Ameiurus nebulosus*), bluegill (*Lepomis macrochirus*), largemouth bass (*Micropterus salmoides*), smallmouth bass (*Micropterus dolomieu*), black crappie (*Pomoxis nigromaculatus*), and goldfish (*Carassius auratus*) (Lemmers and Santora 2013; Kamerath et al. 2008). Many of these species, as well as the introduced signal crayfish (*Pacifastacus leniusculus)*, have proliferated in the basin, altering the structure of the aquatic foodweb, reducing native fish presence and compromising the potential for recovery of native species, such as the Lahontan cutthroat trout, through restoration or other management actions (Lemmers and Santora 2013, MacRae and Jackson 2001; Betolli et al. 1992; Vander Zanden et al. 2003; Moyle and Nickols 1973).

In 2011, the USFS Lake Tahoe Basin Management Unit conducted a detailed survey of the fish assemblage in the Upper Truckee River from the mouth at Lake Tahoe upstream 20.4 kilometers. Through this effort, over 12,500 fish were sampled across 169 fish reaches ranging in length from 55 to 300 m. Their study documented twelve species with differing distribution and abundance across the sampled river segment, including seven native species (Lahontan redside (*Richardsonius egregious*), speckled dace (*Rhinichthys osculus*), Tahoe sucker (Catostomus tahoensis), mountain sucker (*Catostomus platyrhynchus*), Paiute sculpin (*Cottus beldingi*), mountain whitefish (*Prosopium williamsoni*), and Lahontan cutthroat trout (*Oncorhynchus clarki henshawi*)). With the exception of speckled dace and Paiute sculpin, native fish species were a small percentage of fish sampled while introduced brown and rainbow trout accounted for nearly 25% of the total fish sampled. Native species were limited in distribution and relative abundance, with the greatest species diversity found in the lower half of the UTR. (Lemmers and Santora 2013).

Monitoring conditions and quantifying effects in the UTR

Findings from our MRFAT analysis of the Upper Truckee Marsh restoration site highlighted a need for monitoring of the UTR both a) as a basis for quantifying restoration effects and change through time and b) to illuminate fish community dynamics, habitat relationships, and the specific risks associated with introduced species as well as potential for restoration actions to promote their proliferation. To address these needs and building on our conceptual approach for modeling as a foundation, in 2012 with support from NFWF and in cooperation with the USFS and other partners, we implemented a habitat monitoring and characterization effort for the UTR. We selected the design to facilitate applicability beyond the region and to make it compatible with ongoing efforts on the part of the USFS to describe stream habitat around the Tahoe basin. In addition to providing information about the UTR, an overarching goal of our effort was to field test and refine an applied monitoring approach for quantifying the effects of mountain stream-meadow restoration on physical habitat and aquatic species that could then be applied to other meadow sites, improving restoration success, adaptive management, and, more broadly, restoration science.

Monitoring Design

Beyond the broad goals described above, our UTR monitoring and data analysis approach was driven by the following research questions:

1. What is the nature and current condition of aquatic habitat in the UTR?
2. What effects might the suite of restoration projects on the UTR have on the nature, diversity, and distribution of riverine aquatic habitat?
3. What are the distributions of fishes in the UTR relative to specific habitat types?
    a. What if any strong correlations exist between species and habitat?
4. Based on the effects of restoration on habitat (current and future/ anticipated) and the distribution of the fish relative to habitat, what are some of the potential effects and/or opportunities for fish populations and community structure associated with restoration actions?

To address our research questions, in the context of our larger goals, we designed and implemented monitoring and analysis to target four primary objectives:

1. Based on the enhanced USFS Level II survey protocol, **characterize and map riverine habitat diversity and spatial distribution** during baseflow periods in the TR segment extending from the delta at the Tahoe Keys to Christmas Valley and including seven discrete restoration reaches/ projects.
2. **Model extent and variation in wetted habitat, including floodplain** as a baseline for quantifying potential restoration effects on aquatic habitat.
3. **Analyze fish distribution and abundance relative to habitat features** based on fish/ habitat correlations from reach specific fish data collected during the summer and fall of 2011.

4. **Interpret potential fish community response to restoration actions**, based on any species habitat relationships.

Methods

Selection and hierarchy of reaches within the Study Area

For management purposes, the Upper Truckee River had previously been split into seven reaches by agency and management groups. These reaches, here termed "Restoration Reaches" range from 1.5 to 4.2 km in length and were the largest unit used to subdivide the study area. Moving upstream (from north to south), they include The Upper Truckee Marsh, Middle Reaches 1&2 (Johnson Meadows), The Airport, Sunset Stables (5), Sunset Stables (6), Washoe Meadows Golf Course, and Christmas Valley (Figure 1, Appendix).

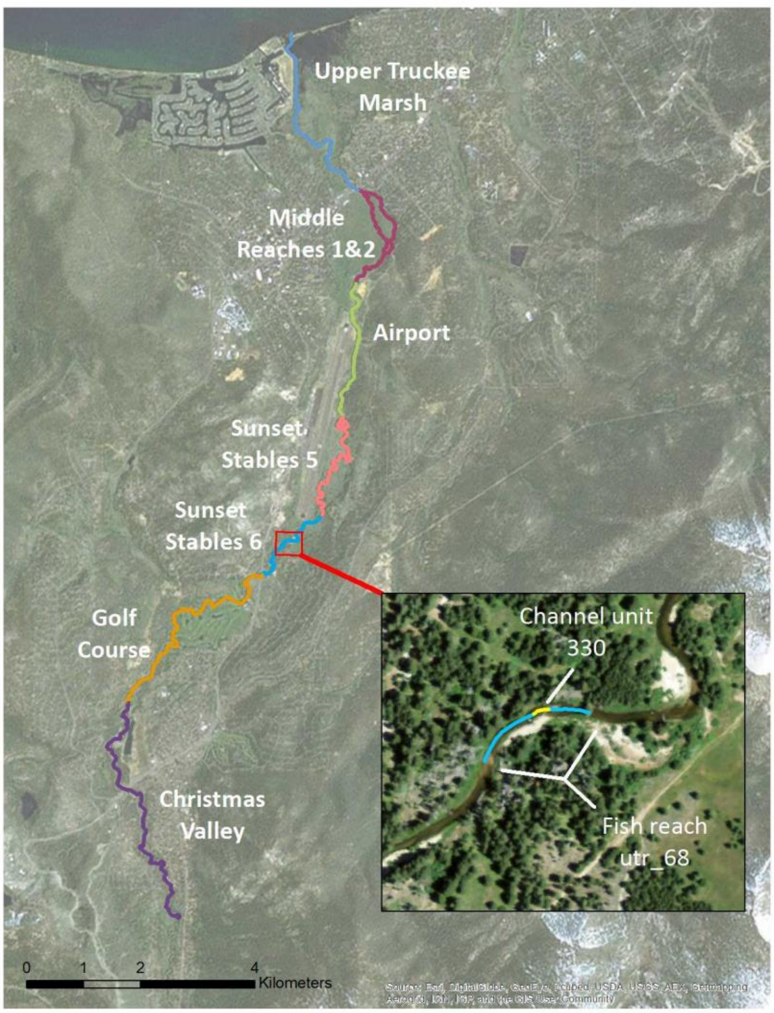

Figure 1. Locator map for the project area showing the seven restoration reaches, as well as an example of the smaller scale fish reach and channel unit (Inset).

In 2011, a US Forest Service (USFS) fish survey crew conducted surveys on all seven of the restoration reaches (see details below). Their methods sought to have fish reaches of approximately 100 meters that began or ended at obvious habitat breaks. This approach resulted in 169 smaller fish reaches nested within the seven larger restoration reaches. For the 2012 habitat survey, we followed USFS Stream Inventory Handbook Level I & II protocols and sampled habitats at the scale of channel units, which we identified based on habitat type (i.e., fast and slow water habitats separated into discrete units). Channel units represent the smallest unit in the hierarchy, and were additionally delineated to fit within fish reaches. For example, if a fish reach break was located in the middle of a channel unit, we broke the channel unit at the fish reach, continuing with a new channel unit of the same type in the new fish reach. Table 1 shows the nested hierarchy of restoration reaches, fish reaches, and channel units. Channel units ranged from 4m to 227m long, with a mean length of 31.4 m and a median length of 24 m. The number of channel units per fish reach ranged from 1 to 9. The number of channel units per restoration reach ranged from 51 to 162.

Hierarchy of Reaches							
Restoration Reaches	Truckee Marsh (2.7 km)	Johnson Meadows (2.9 km)	Airport Reach (2.3 km)	Sunset Stables (5) (2.7 km)	Sunset Stables (6) (1.5 km)	Golf Course (4.1 km)	Christmas Valley (4.2 km)
Fish Reaches	UTR_500-UTR_516	UTR_1-UTR_17	UTR_17-UTR_38	UTR_38-UTR_62	UTR_62-UTR_76	UTR_76-UTR_105	UTR_105-UTR_143
Channel Units	SO01-SO54	SO55-SO151	SO152-SO225	SO226-SO304	SO305-SO356	SO357-SO499	SO500-SO662

Table 1. Reach hierarchy (largest to smallest descending) including correlations across Restoration, Fish, channel Unit Scales.

Physical Habitat Surveys and Characterization

We conducted field surveys from June 26th to October 15th, 2012. We used a modified version of the USFS Stream Inventory Handbook Level I & II (USFS 2010) with the Lake Tahoe Basin Management Unit Supplemental protocol. We collected habitat data in accordance to the USFS protocol. Any differences in our methods or the data we collected are specifically noted below. We began surveying at the mouth of the Upper Truckee River (in the Upper Truckee River Marsh) at the edge of Lake Tahoe and continued upstream 20.4 km into Christmas Valley. As per the USFS Lake Tahoe Basin supplemental protocol, we surveyed 100% of the habitat from the edge of Lake Tahoe to the top of Christmas Valley.

Channel Units

We conducted detailed habitat surveys according to the USFS Stream Inventory Handbook (2010). Within the "channel unit" designation, the protocol further distinguishes between types of pools, riffles, rapids, runs, sheets, cascades, chutes, braids, tributaries, side channels, marshlands, and artificial structures. At each primary channel unit (fast or slow water), we quantified channel unit length, wetted width, bankfull width and depth, average and maximum water depths, woody debris counts, and bank instability (length and average height). In pools we measured the pool crest depth and noted what the pool was formed by (i.e., wood, beaver dam, scour pool, etc.). Tributaries, side channels and other "special cases" were processed according to the USFS (2010) protocol with less data collected than on primary channel units. All measurements were taken in metric units. We collected GPS waypoints at the bottom and top of each channel unit. Additionally, we photographed each channel unit as well as any important features associated with each unit.

Vegetation Surveys

In addition to the channel habitat measurements detailed above, for each primary channel unit we performed vegetation surveys for the inner riparian zone (~10 meters from the edge of the stream channel). We diverged from the original USFS protocol by separating vegetation surveys for the left bank and the right bank of each unit as well as by providing multiple vegetation classes for a given unit related in terms of percentage. We noted the dominant vegetation type/seral class for each bank according to the 7 seral classifications provided in the USFS protocol, based on diameter at breast height in inches (dbh) (Box 1). For each bank, we estimated the percent cover of understory and overstory species. The species codes use "H" to denote hardwood species, "C" to denote conifer species. Sedges and rushes were grouped together, grasses and forbs were grouped together, and woody shrubs were grouped together.

Diameter Class
NV = No Vegetation (bare rock/soil, dbh not applicable)
GF = Grassland/Forb Condition (dbh not applicable)
SS = Shrub/Seedling Condition (1.0-4.9 inches dbh)
SP = Sapling/Pole Condition (5.0-8.9 inches dbh)
ST = Small Trees Condition (9.0-20.9 inches dbh)
LT = Large Trees Condition (21-31.9 inches dbh)
MT = Mature Trees Condition (>32 inches dbh)

Box 1. Diameter class designations and vegetation types used during vegetation sampling and characterization. Dominant vegetation type/seral class was recorded for each bank according to the 7 seral classifications as well as based on diameter at breast height in inches (dbh). Vegetation types were also used to define the understory and overstory species as a relative percentage.

Vegetation Type
HA = Alder
HW = Willow
HC = Cottonwood
HQ = Aspen
HD = Dogwood
HE = Elderberry
HX = Unknown Hardwood
CP = Jeffery Pine
CQ = Western White Pine
CW = White Fir
CR = Red Fir
CL = Lodgepole Pine
CJ = Juniper
CC = Cedar
WS = Woody Shrubs
SR =Sedge/Rush
GF = Grass/Forbs
NV = No Vegetation

Shade

We used a handheld solar pathfinder to record the percent riparian shade at the top of each fast water channel unit. The data was taken in the center of the stream channel facing south with the unit held 0.5 meters off the surface of the water. We recorded percent riparian shade and percent artificial shade if there was some sort of non-natural structure such as buildings or bridges that created shade in a given channel unit. The handheld method was used in conjunction with the LiDAR data available for the Upper Truckee. The LiDAR shade data was used in the larger analysis because it was more comprehensive, and as a result of the degree of error when attempting to match the handheld GPS measurements associated with the pathfinder and the LiDAR.

Substrate, Wolman Pebble Counts, and Channel Alterations

We conducted Wolman Pebble Counts according to the USFS Stream Inventory Handbook (2010). We performed the counts twice in each restoration reach at a fast water unit approximately 1/3 and 2/3 of the way through the restoration reach. We began each count transect at the bankfull edge of the stream channel. We noted the first encountered substrate size at each step in a transect across the stream. If we did not get 100 or more measurements in the first transect, we surveyed a second transect.

Additionally, for each primary channel unit we noted dominant and secondary substrate types using the higher order Wolman categories. Within each channel unit, we also noted the presence of any bank stabilizing or substrate augmentation efforts such as riprap, gabions, introduced gravel or cobble, willow wattling or mattressing. In some sections of the Upper Truckee, it became difficult to identify introduced substrate because the overall size of the substrate was similar, so the reported number of stabilization/augmentation projects should be regarded as a minimum number.

Temperature

We launched HoboTemp temperature loggers at the bottom of each of the 7 restoration reaches to monitor, on a large scale, whether the reaches were gaining or losing net heat during the most thermally stressful (for fish and other aquatic species) portion of the season. The thermographs logged temperature in degrees Celcius every half hour from August 1st to October 15th. We would have liked to have monitored temperatures at the fish reach scale, but the high number of fish reaches coupled with equipment cost and time required made this prohibitive. Other entities have collected temperature data on the Truckee, but that data was not available to us at the time of our data analysis. Handheld temperature data was taken each day at the beginning and end of surveys. We did not take handheld temperatures at each channel unit due to the difficulty of interpreting the difference in temperatures taken at different times of day.

Water Quality

At the beginning of each survey day, we used a YSI handheld multi-meter to record beginning temperature, dissolved oxygen, percent oxygen saturation, and conductivity.

Flow and Discharge

USGS stream gage data for the UTR was a proxy for flow. In a limited subset of habitat units, additional flow data was collected using a Marsh-McBirney 2000 Flow meter.

Fish and Aquatic Biota

We did not perform timed visual encounter surveys (VESs) of fishes and other aquatic biota due to the availability of existing data on fish distribution from the USFS, time constraints as well as the difficulty of getting accurate data for fish using the VES method. We noted the presence and number of mussels in each channel unit where they were encountered. Birds and other terrestrial species were not included in our surveys.

Distribution, Abundance, and Density of Fish Species

Fish data used in this analysis was collected in 2011 as a component of the USFS Lake Tahoe Basin Management Unit's (LTBMU) Basin-wide Native Non-game Fish Assessment.

The Survey was initiated during the low flow period in August 2011 and continued through the end of September; flows for this period ranged from 150 – 17 cfs as measured by the USGS Upper Truckee River at Meyers gage. The effort sampled the UTR continuously from the mouth at Lake Tahoe (UTR_500) upstream approximately 20.4 kilometers to Christmas Valley (UTR_143), using a combination of backpack electro-fishers and an electro-fishing boat. The survey was conducted in sampling reaches of approximately 100m. Species and size classes (0-5cm, 5-10cm, 10-20cm, 20-30cm, 30+cm) were counted and recorded at the end of each survey reach. One hundred and sixty nine reaches were surveyed in the 2011 Fish Assessment, and >12,500 fish composed of 12 species were sampled during the eight week effort. The data was entered into the USFS corporate Natural Resource Information System (NRIS) geodatabase in Aquatic Surveys (AqS). Additional details on sampling methods are presented in *Revised Basin-wide Native Non-game Fish Assessment: 2011 Annual Report – February 2013* (Lemmers and Santora 2013).

Sampling data and results used in this analysis were quantified in terms of relative abundance by fish reach. Fish reaches delineations/ grouping were maintained, but were further categorized by restoration reach.

Additionally, in order to compare fish distribution during low flow periods in 2011 when the USFS sampling of the UTR occurred (average August flows: 52 cfs at Meyers gage) to the distribution during the much lower flows of 2012 when our habitat survey occurred (average August flows: 4.5 cfs at Meyers gage), we performed backpack electroshock sampling of fish in a limited subset of fish reaches.

Geospatial and Statistical Analyses

We created a master database that includes field measurements, variables derived from field measurements, and variables generated within a GIS by channel unit, fish reach, and restoration reach. Table 2 describes the variables we created at the fish reach scale, our primary scale of analysis.

Variable	***Description***
Fish_reach	Fish reach
Restor_reach	Restoration reach
Sum_hab_l	Sum of habitat survey lengths associated with fish reach
Ave_wet_w	Average wetted width of habitat surveys associated w/ fish reach
Max_wet_w	Maximum wetted width of habitat surveys associated w/ fish reach
Min_wet_w	Minimum wetted width of habitat surveys associated w/ fish reach
Pct_slow	Percent of fish reach typed as "slow"
Pct_fast	Percent of fish reach typed as "fast"
Pct_scour	Percent of fish reach typed as "scour"
Pct_turb	Percent of fish reach typed as "turbulent"

Pct_nonturb	Percent of fish reach typed as "non-turbulent"
Pct_side	Percent of fish reach typed as "side"
Pct_dam	Percent of fish reach typed as "dam"
Pct_trib	Percent of fish reach typed as "tributary"
Ave_depth	Average depth of habitat surveys associated w/ fish reach
Ave_max_dep	Average maximum depth of habitat surveys associated w/ fish reach
Max_max_dp	Maximum depth of habitat surveys associated w/ fish reach
Sum_unstab	Total length of unstable banks (left + right) of habitat surveys associated w/ fish reach
Pct_unstable	Percent of total length of habitat surveys associated w/ fish reach that are unstable (left + right)
Wood	Count of small/med/large woody debris of habitat surveys associated w/ fish reach
Pct_w_alt	Percent of total length of habitat surveys associated w/ fish reach flagged as altered
Max_poold	Maximum depth of pool formed by debris within habitat surveys associated w/ fish reach
Max_poolb	Maximum depth of pool formed by beaver dams within habitat surveys associated w/ fish reach
Pct_poold	Percent of fish reach typed as pool above debris
Pct_poolb	Percent of fish reach typed as pool above beaver dam
A_Unstab_len	Area of unstable banks (left + right) of habitat surveys associated w/ fish reach divided by habitat survey length (sq meters)
Ww_bfw	Ratio of the area of wetted surface (@20 cfs) to area of wetted surface at floodplain-accessing flows (600cfs) of fish reach within 20 meters of thalweg
Shade	Average % shading of water surface of fish reach
GIS_slope	slope of fish reach - GIS measurement from LiDAR (%)
GIS_sin	sinuosity of fish reach - GIS measurement
Dist_LT	distance of fish reach start from Lake Tahoe (miles)
Substr	Length weighted average of dominant substrate type converted to log of median grain size of habitat reach associated w/ fish reach

Table 2. Summary of fish reach scale variables

Field-based habitat measurements

We summarized the temperature data collected by the thermographs using HOBOware (Onset Computer Corp.). Maximum seven day average temperature, also known as maximum weekly average temperature, served as our primary summary statistic.

LiDAR-based habitat characteristics

LiDAR, or Light Detection and Ranging, data are a fine-resolution remotely sensed spatial dataset of elevation information that can be used to describe bare earth topography and vegetation structure and are increasingly used in ecological studies for habitat characterization and modeling (Vierling et al, 2008). LiDAR data for the Tahoe basin were acquired in mid-August, 2010 (flows ~ 15 cfs at USGS Upper Truckee River at Meyers gage) by a partnership of organizations, including the Tahoe Regional Planning Agency and US Geological Survey, and funded by the Bureau of Land Management through the Southern Nevada Public Land Management Act. As such, all LiDAR derived products describing the Airport reach refer to the pre-restoration condition (i.e. straight channel).

We used the bare earth and "highest hit" elevation models (0.5 m horizontal resolution) derived from the raw LiDAR data in a GIS to generate variables related to stream topography and riparian vegetation for channel units and fish and restoration reaches. Variables include stream slope as percent, sinuosity, and distance from Lake Tahoe.

Additionally, we used the solar radiation tools within ArcGIS 10.0 (ESRI, Inc) to model July direct solar radiation for both the bare earth elevation model for the Upper Truckee and the "highest hit" model that describes the vertical structure of vegetation. We approximated proportion of shading provided by riparian vegetation by dividing the direct solar radiation of the 20 CFS flow stream surface as affected by vegetation by the bare earth solar radiation of the same stream surface.

LiDAR-based hydrological modeling

Beyond describing and accurately mapping topographical features within riverscapes, LiDAR is also increasingly used as a tool for hydrological modeling (Murphy et al. 2007). To model water surface and floodplain inundation under a variety of flow scenarios, we used the US Forest Service's River Bathymetry Toolkit (http://essa.com/tools/rbt/; McKean et al. 2009) to create a detrended elevation model for the Upper Truckee. Detrended elevation models (DDEMs) remove downstream gradients within floodplain elevation datasets and have an arbitrary scale that reflects height above the predominant stream gradient trend in the elevation model. DDEMs are useful for predicting lateral inundation in a floodplain.

We generated a DDEM from a resampled bare earth LiDAR dataset (0.5 m horizontal resolution to 1.5 m horizontal resolution) for the lower 12 miles of the Upper Truckee River. We used the NAIP imagery described in the Land Cover Classification methods below to delineate the water surface for flows ranging between 15-20 cfs (USGS Upper

Truckee River at Meyers gage) by selecting an elevation of 98.9 in the DDEM. We improved upon this by digitizing the stream thalweg, or center line, and creating cost distance raster with slope as cost, a process that essentially finds the flat water surface in the LiDAR proximate to the center line. Using the archive of aerial imagery available in Google Earth (Google, Inc), we identified the DDEM elevation that corresponded with the water surface area of the mainstem lower Truckee visible in the photos. Based on imagery date, we related these flow conditions to observed flows at the USGS Upper Truckee at Meyers or South Lake Tahoe gages. Our range of imagery dates and flows included July 15, 2009 (20 cfs at Meyers), July 10, 2010 (120 cfs at Meyers), and June 14, 2011 (580 cfs at Meyers and 750 cfs at South Lake Tahoe). We developed a simple linear relationship between DDEM elevation and flow and used it to map the pattern of inundation and floodplain wetted area at flows ranging from 20 – 1670 cfs (Meyers gage). Flows of 600 cfs at Meyers corresponded to the flows at which water reached overbank condition and began to spread laterally across the floodplain. We generated a channel unit and fish reach scale variable related to the ratio of surface area at 20 cfs flows and at this overbank condition.

Land cover classification

High resolution aerial imagery interpretation and classification is increasingly used as a tool for monitoring riparian vegetation (Booth et al. 2007). We used USDA Farm Service Agency National Aerial Imagery Program (NAIP) photographs and the vegetation height information in the LiDAR dataset to characterize the existing vegetation type and structure within the floodplain of the mainstem Upper Truckee River to last upstream USFS fish sampling reach. NAIP images are color aerial photographs with a resolution of 1 meter and include spectral information for 4 bands – red, green, blue, and infrared. Upper Truckee images have an acquisition date of July 15, 2009, which had measured flows averaging 20 cfs at the Meyers gage.

To classify land cover type, we used the feature extraction tools within the Feature Analyst GIS software package (Overwatch Systems, Ltd) to identify patterns within the NAIP images and LiDAR dataset. These tools take the spectral information contained within multiple example polygons delineated by GIS technicians for each vegetation type and perform statistics on the NAIP and LiDAR data to cluster pixels within the entire image into land cover classes based on common statistics. Our classification is limited to the floodplain area and includes the following classes: water, bare ground/sand/rock, xeric-upland grasses/forbs/shrubs, wet herbaceous meadows, woody shrubs (< 6 m), woody trees (> 6 m), and lawn – golf course.

All land cover products are derived from aerial imagery that preceeds the recent restoration activities (i.e. added meanders).

Statistical analysis

We used a non-metric multidimensional scaling (NMDS) ordination to describe the fish community and the corresponding habitat gradients within the lower Upper Truckee. Ordinations are a statistical tool for data exploration and analysis that can reduce complex datasets into more discernable patterns based on similarities and correlations within the data. As applied to community and habitat studies in ecology, an NMDS plots species in 2 or 3 dimensional space in a way that maximizes the dissimilarities within a species dataset. Habitat variables can then be associated with the dimensions of the NMDS for describing the gradients associated with the distribution of species. Similar longitudinal studies of fish community structure and habitat relationships have highlighted the utility of the technique for analyzing datasets with multiple zero values (Torgersen, et al. 2006), as is the case with the fish relative abundance data; due to the uneven distribution of fish species within the lower Upper Truckee many reaches have zero abundance for many species. We analyzed the fish relative abundance data by fish reach first, and then overlaid the fish reach scale habitat data to describe habitat gradients that correspond to the fish community using the Vegan package in the R statistical software (R Foundation for Statistical Computing). We ran separate analyses with the entire fish community and another excluding mountain whitefish, brook trout, brown bullhead, and Lahontan cutthroat trout because they were present at less than 3% of fish reaches.

Results

Channel form and physical habitat attributes

Components of physical habitat structure varied considerably across the seven survey reaches comprised within our study area. A summary of the results from our analysis of stream habitat attributes for each of the reaches is presented in Table 3 and key attributes are mapped in the Appendix.

	Upper Truckee Marsh	Johnson Meadows	Airport	Sunset Stables (5)	Sunset Stables (6)	Golf Course	Christmas Valley
Stream length (km)	2.7	2.9	2.3	2.7	1.5	4.1	4.2
Ave. wetted width (m)	13.94	6.74	8.92	9.11	9.32	8.68	9.26
Max. wetted width (m)	60.0	25.0	18.2	22.6	15.9	19.0	23.6
% slow water	55.1	32.4	31.6	40.0	33.6	47.4	40.7
% scour pools	16.1	28.0	29.7	30.1	30.3	40.6	33.8
% riffle	17.0	33.5	40.0	18.8	28.2	19.8	34.8
% run	25.4	32.3	28.0	40.4	30.6	26.1	22.2
% side channel	1.1	2.4	1.9	5.2	2.1	10.7	6.2
% dammed pools	0.0	3.6	0.0	4.7	1.1	2.8	2.2
% dammed pools - debris	0.00	0.00	0.00	0.85	1.13	0.00	1.29
% dammed pools - beaver	0.00	3.63	0.00	3.86	0.00	2.80	0.93
Ave. depth (m)	0.80	0.41	0.42	0.48	0.35	0.62	0.42
Ave. max depth (m)	1.21	0.83	0.73	0.83	0.73	0.80	0.77
Max. dep. debris pool (m)	0.00	0.00	0.00	1.05	0.89	0.00	1.30
Max. dep. beaver pool (m)	0.00	1.60	0.00	2.00	0.00	1.40	1.20
% unstable banks	18.7	46.3	14.0	20.8	12.0	16.8	18.0
% altered	10.1	17.7	75.6	15.0	16.0	29.8	12.4
Woody debris count	28	50	15	102	39	92	259
Ave. ratio of channel width @ 20cfs to channel @ 600cfs	0.66	0.56	0.63	0.57	0.64	0.54	0.52
% shaded	11.4	18.5	15.8	11.8	17.1	18.1	32.9
Downstream 7-day max. Aug-Oct temp (°C)	21.6	18.9	21.5	21.3	20.8	20.2	18.9
Upstream to downstream temperature trend (°C)	2.70	-2.60	0.20	0.50	0.60	1.30	-
Ave. substrate diameter (mm)	2.8	4.1	32.0	30.0	25.4	74.9	105.8
Ave. gradient as %	0.06	0.11	0.10	0.10	0.10	0.20	0.52
Floodplain area per valley length (km) @ 1670 cfs (km^2/km)	1.08	0.77	0.25	0.38	0.28	0.27	0.11
Relative abundance non-native fish as % (all)	7.2	15.7	11.8	25.9	48.9	42.8	44.9
Relative abundance non-native fish as % (non-salmonids)	0.2	0.4	1.7	0.2	0.1	0.2	0.1

Table 3. Physical habitat attribute values, inundation estimates, and select fish abundance data summarized at the restoration reach scale.

Channel length, width, and depth

Stream length ranged across survey reaches with Christmas Valley (4.2km) and the Golf Course (4.1km), containing the greatest length of channel reaches and Sunset Stables 6 the shortest (1.5km), followed by the Airport (2.3km). Upper Truckee Marsh (2.7km), Middle Reaches 1 & 2 (2.9km), and Sunset Stables 5 (2.7km) were in between and of similar length.

We measured wetted width, bankfull width, water depths at 25, 50, and 75% of the channel, maximum depth, and the difference in elevation between the water surface and the bankfull indicator. Channel width, (both average and max wetted) was greatest in the marsh as the river joins Lake Tahoe. Moving upstream, average width decreased significantly in Johnson Meadows - Middle Reaches 1 & 2 (due to the flow being split into two channels), climbed again through the Airport and Sunset Stables reaches, decreased slightly at the Golf Course and increased again in Christmas Valley. The ratio of average width to max wetted width, indicative of the extent of incision, was lowest at the north end of the study area near the Lake (Marsh (0.23); Middle Reaches 1&2 (0.27)) and at the southern end in Christmas Valley (0.39). The largest value for ratio of average width to max wetted width was in Sunset Stables 6 (0.59); with the Airport (0.50) and Golf Course (0.47) similar, and Sunset Stables 5 more closely resembling Christmas Valley (0.40).

On average, the channel was deepest in the Marsh (0.80 m) and the Golf Course (0.62 m), and shallowest in Sunset Stables 6 (0.35 m). Average depth was fairly similar in Middle Reaches 1&2 (0.41 m), the Airport (0.42 m), and Sunset Stables 6 (0.48 m) and Christmas Valley (0.42 m). Average max depth was greatest in the Marsh (1.21 m) and fairly similar across other reaches; Middle Reaches 1&2, Sunset Stables 5, and the Golf Course were particularly close (0.83 m, 0.83 m, and 0.80 m respectively) as were the Airport (0.73 m), Sunset Stables 6 (0.73m) and Christmas Valley (0.77 m).

Physical habitat attributes

The extent and relative percentages of specific hydrologic and geomorphic habitat attributes (including: slow water, fast water, scour pools, dam pools, riffle, run, etc.) also varied significantly across the seven reaches. A more comprehensive look at trends in key habitat attributes is encompassed in the results of the NMDS analyses (below). Following are results summaries for select individual attributes.

Bank Stability

The percentage of unstable bank was highest in Middle Reaches 1&2 (46.3%), and lowest in Sunset Stables 6 (12.0%) and the Airport Reach (14.0%). Unstable bank percentage was similar in the Golf Course (16.8%), Christmas Valley (18.0%), the Marsh (18.7%), and Sunset Stables 5 (20.8%). Trends in unstable banks, measured at the channel unit scale, were summarized at the fish reach scale and mapped by restoration reach (Appendix).

Riparian Vegetation Associated Attributes

Several habitat attributes reported here a closely tied to the extent and condition of riparian vegetation, including extent of riparian cover types, riparian shading, and presence of woody debris. Results related to shading and percentage of woody debris are summarized below. Extent of habitat area for each riparian cover type is depicted in Figures 2 and 3 and in the Appendix for the southern and northern halves of the study area.

Land cover classification

Because we were able to merge 4-band aerial imagery and vegetation height information, our land cover classification appears to be very accurate. Based on a qualitative comparison with aerial imagery, the lone source of mapping error occurs in flat areas shaded by tall vegetation – these dark areas are mis-classified as water.

Shading

Percent shading was highest in Christmas Valley (32.9%). Middle Reaches 1&2 (18.5%), Sunset stables 6 (18.1%) and the Golf Course (18.1%) all had similar levels of shading. The Marsh and Sunset Stables 5 had the least shading (11.4% and 11.8% respectively), with the Airport exhibiting levels in the middle of the range (15.8%). Note, however, that the values reported for the Airport reach are derived from LiDAR and aerial imagery that preceded the recent restoration.

Presence of woody debris

Instream wood count was highest in Christmas Valley (259), Sunset Stables 5 (102), and The Golf Course (92), and lowest in the Airport (15) and Marsh (28), with Sunset Stables 6 (39) and Middle Reaches 1&2 (50) in between. Beaver presence tracked with large wood count, with Beaver dammed pools occurring only in the reaches with the four highest wood counts (Table 3).

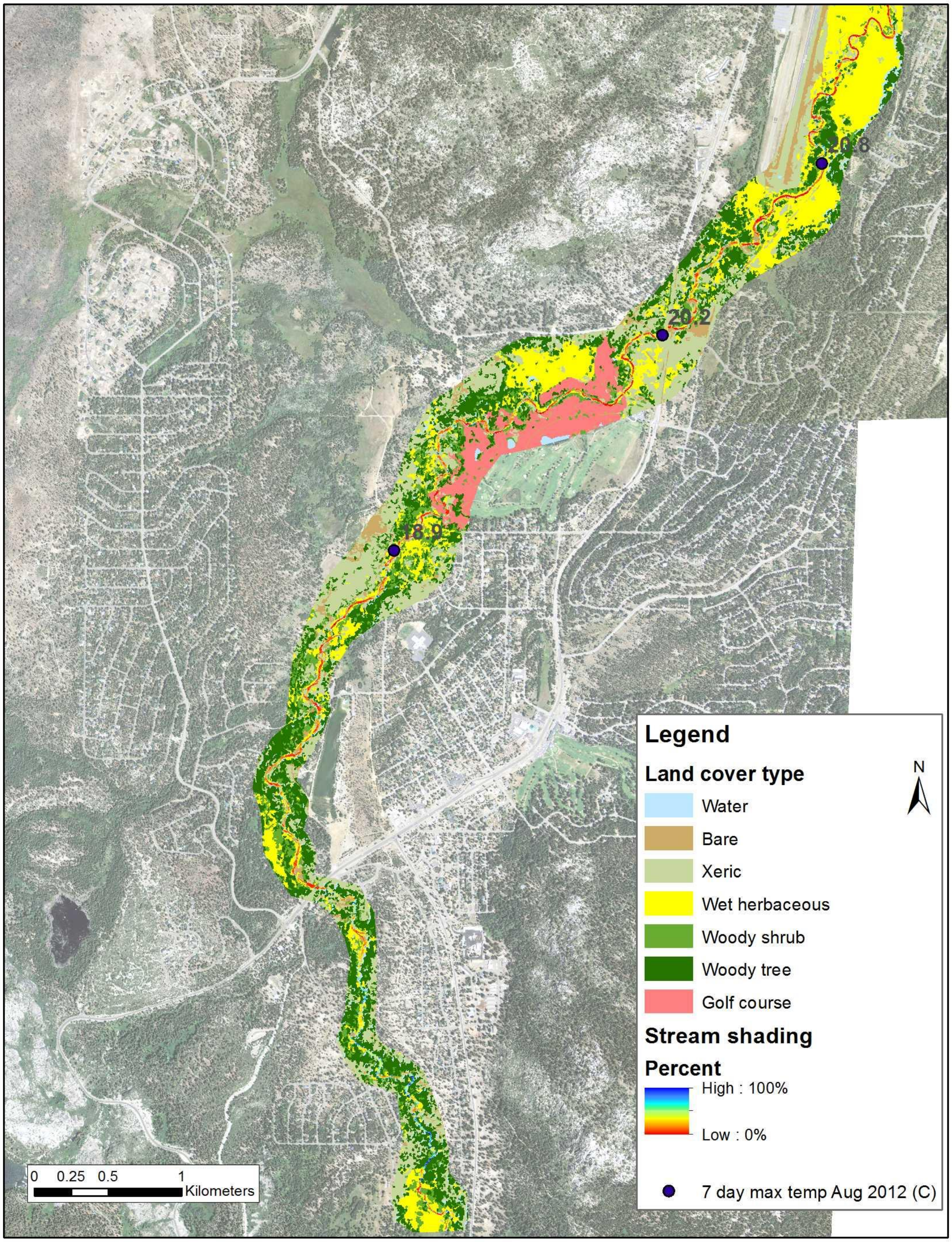

Figure 2. Vegetation distribution, along with shading and stream temperature, for the southern half of the study area (See Appendix).

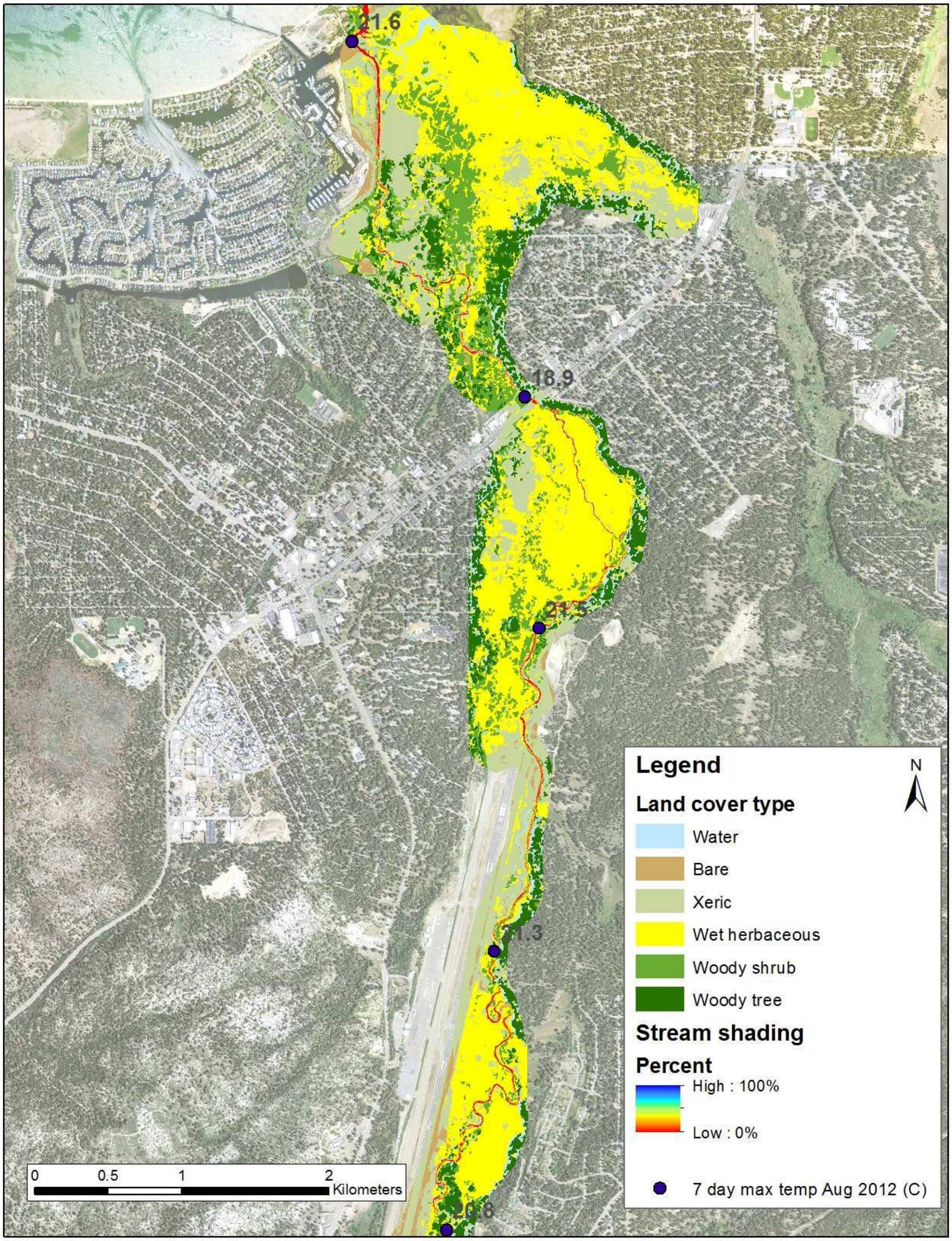

Figure 3. Vegetation distribution, along with shading and stream temperature, for the northern half of the study area (See Appendix).**Inundated habitat area**

A linear regression was sufficient for describing the relationship of DDEM elevation and observed flows ($r^2 = 0.93$). Patterns of inundation and inundated habitat area at high flows exhibited significant differences both in value between survey reaches and in trends across reaches (Figure 4, Figure 5, Figure 6, and Table 4). The ratio of channel width at 20cfs to channel width at 600cfs was similar across all seven reaches, but smallest in Christmas Valley (0.53) and the Golf Course (0.54). Middle Reaches 1&2 and Sunset Stables (5) exhibited similar, slightly higher values (0.56; 0.57), as did the Marsh, Airport, and Sunset Stables (6) (0.66; 0.63; 0.64) (Appendix).

Inundated floodplain area at high flow (1670cfs) per kilometer of the longest valley axis was highest in the Marsh (1.08 km2/km) and generally exhibited a decreasing pattern upstream: Middle Reaches 1&2 (0.77 km2/km); the Airport (0.25 km2/km); Sunset Stables (5) (0.38 km2/km); Sunset Stables (6) (0.28 km2/km); the Golf Course (0.27km2/km); and Christmas Valley (0.11 km2/km). The Airport reach is more similar to the furthest upstream reaches where total inundated floodplain area at high flow is more limited.

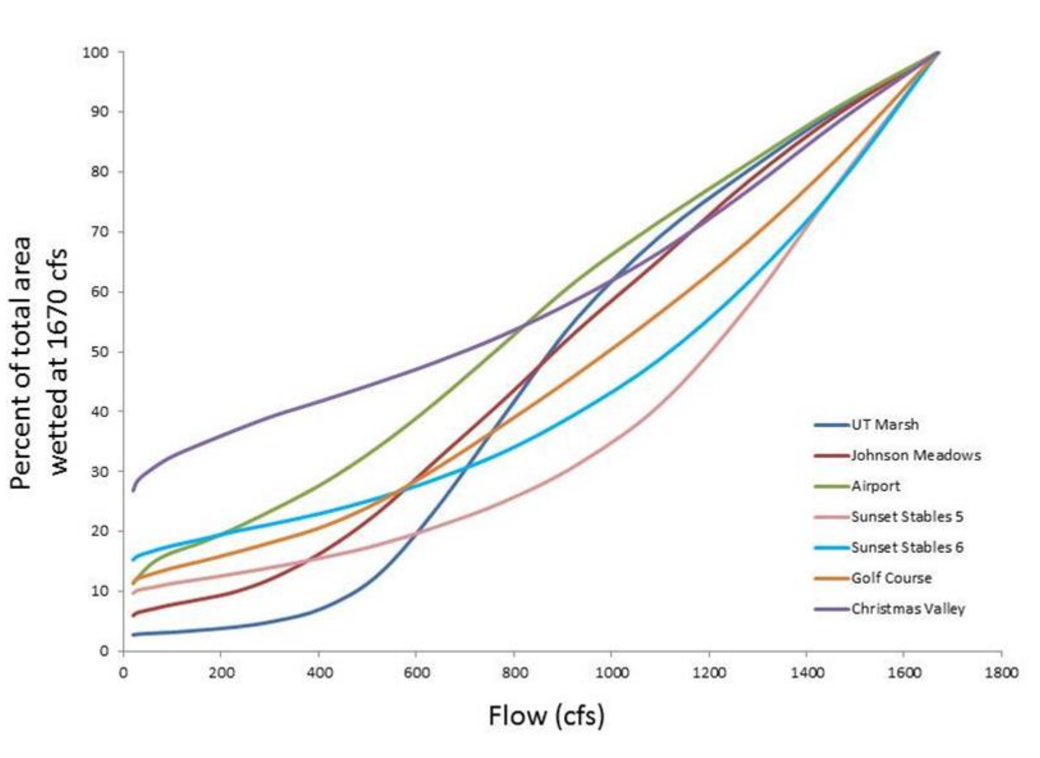

Figure 4. Percent of floodplain area inundated relative to flow (CFS) for the seven restoration reaches.

The nexus of habitat area for each riparian cover type, and inundated area can be used to define floodplain sub-habitat types and quantify them under a range of flows or inundation scenarios. Though a full analysis of vegetation and inundation based floodplain subhabitats is not presented, for each of the restoration reaches percent of inundated area at 1670 cfs occupied by each of the dominant vegetation or cover classes is presented in Table 4.

	Upper Truckee Marsh	Johnson Meadows	Airport	Sunset Stables (5)	Sunset Stables (6)	Golf Course	Christmas Valley
Bare ground	1.0	0.2	2.1	1.6	7.7	3.3	5.7
Xeric herbaceous/shrub	23.7	14.3	25.6	8.4	17.6	17.2	15.3
Wet herbaceous	55.3	68.6	47.3	72.9	37.8	39.4	29.6
Woody shrub	15.3	12.5	19.2	7.4	17.0	18.0	20.1
Woody tree	4.7	4.5	5.8	9.6	19.9	15.8	29.3
Lawn - golf course	0	0	0	0	0	6.4	0

Table 4. Percent floodplain occupied by vegetation type at 1670cfs (Meyers gage). Shrubs are defined by height < 6m; trees > 6m.

Figure 5. Vegetation distribution, along with shading and stream temperature, for the southern half of the study area (See Appendix)

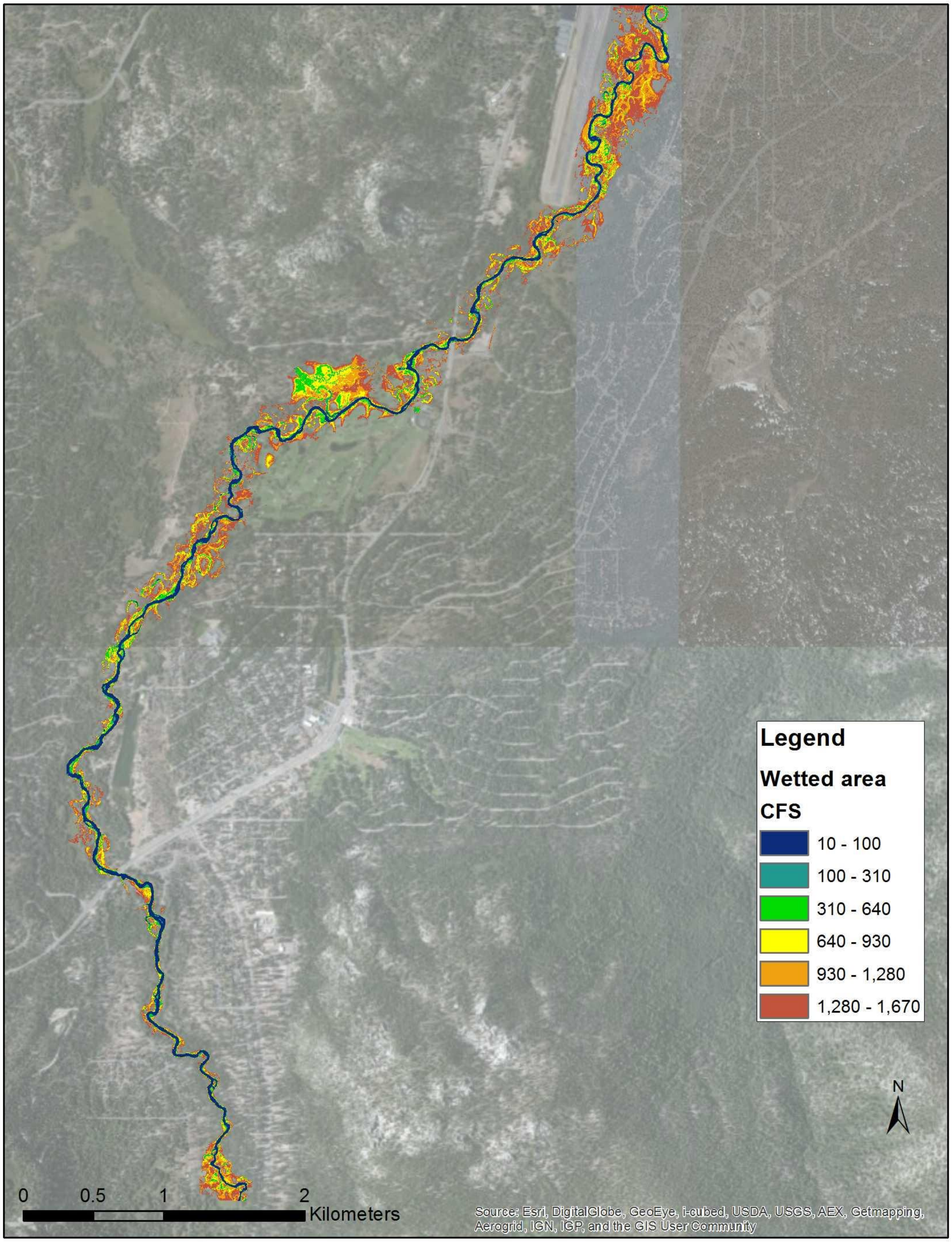

Figure 6. Inundated floodplain area relative to flow (CFS) for the southern portion of the study area (see also Appendix)

Fish Distribution and Relative Abundance

Additional information on fish distribution and relative abundance is available in the USFS Basin-wide Native Non-game Fish Assessment: 2013 Annual Report (Lemmers and Santora 2013). Relative abundance of non-native fish (including introduced salmonids) as a percentage of the total was highest in Sunset Stables 6 (48.9%) and lowest in the Marsh (7.3%) with reaches in between exhibiting a high degree of variability. Relative abundance of non-native-non-salmonids was highest in the Airport reach (1.7%) followed by the downstream Middle Reaches 1&2 (0.4%). All other reaches exhibited a similar, relatively low range of non-native-non-salmonid presence (0.1%-0.2%) with Sunset Stables (6) and Christmas Valley having the least (0.1%).

A more comprehensive description of trends in species and community specific distribution patters is included in the results of the NMDS analyses (below).

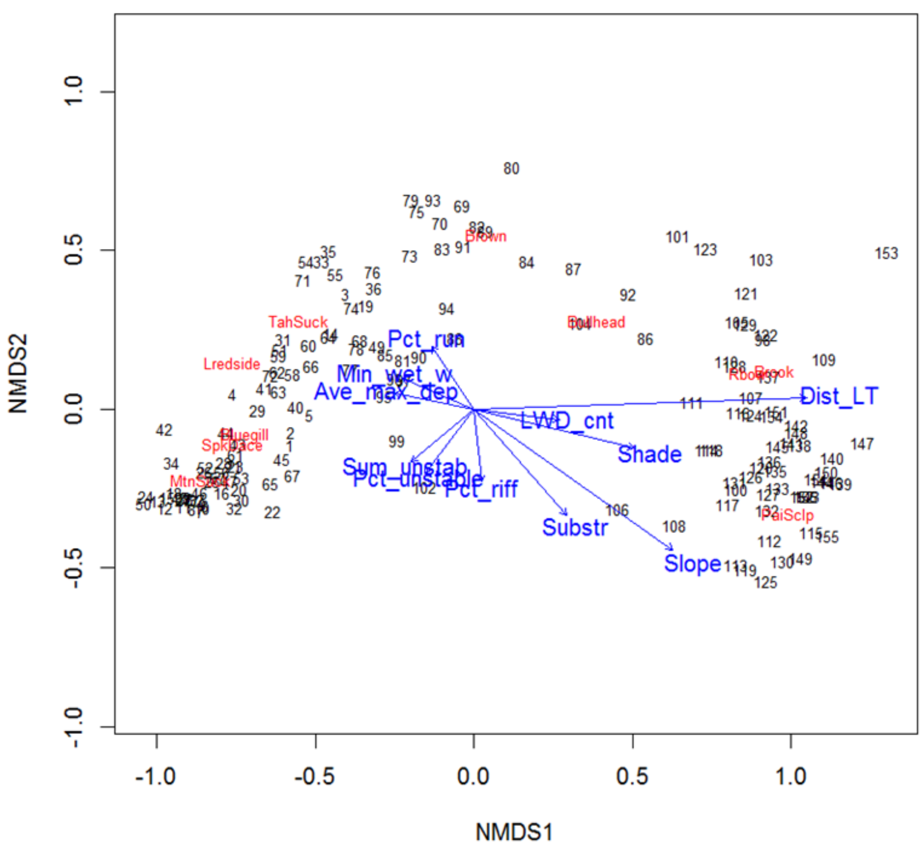

Figure 7. NMDS scaling of fish relative abundance with habitat variables overlaid. Species are arrayed within the two axes of the NMDS to reflect their difference in relative abundance at the fish reach scale. Fish reaches are labeled sequentially from Lake Tahoe.

Fish abundance relative to habitat gradients

NMDS scaling of fish relative abundance with habitat variables overlaid is presented in Figure 7 (2 NMDS axes with stress = 0.06). Relative to the habitat gradients, two distinct community structures are present: 1) a community ranging from mountain sucker/speckled dace/bluegill on one end to rainbow trout/Paiute sculpin/brook trout on the other and 2) a community ranging from Tahoe sucker/Lahontan redside shiner to Paiute Sculpin.

Several habitat gradients are significantly correlated ($P < =0.05$) to the fish community structure: distance from Lake Tahoe, large amounts of woody debris, and higher percentages of shade are strongly associated with the rainbow trout/Paiute sculpin/brook trout community. Proximity to Lake Tahoe, low woody debris counts, and lack of shade are strongly associated with the mountain sucker/speckled dace/bluegill community and weakly associated with the Lahontan redside shiner/Tahoe sucker community. Brown trout and are not associated with the distance/debris/shade gradient.

Higher slope, larger substrates, and fewer run habitats are strongly associated with Paiute sculpin and weakly associated with the rainbow trout/brook trout community. Lower slopes, finer substrates, and more run habitats are strongly associated with the Tahoe sucker/Lahontan redside shiner community and weakly associated with the brown trout/bluegill/speckled dace/mountain sucker community. Brown bullhead show no association to the slope/substrate habitat gradient. Due to the strong positive relationship between distance from Lake Tahoe and Axis 1, fish reaches generally align sequentially moving upstream and in a positive direction on the first NMDS axis. The farthest upstream reaches are aligned with the negative end of the second NMDS axis (Figure 7).

Fish and Habitat Gradients - Excluding rare species

Mountain whitefish, bullhead, and brook trout all occur infrequently in the study area (<3% of the fish reaches). Excluding these species from the analysis, fish community patterns (2 NMDS axes with stress = 0.06) and primary habitat gradients (i.e. distance from Lake Tahoe, woody debris count, and shade) remain constant. However, the secondary habitat gradient shifts to include steep and large substrate on one end and wider and deeper channel form on the other end. At less stringent significance levels ($P = 0.1$ rather than 0.05), a weak third habitat gradient is present, with percent riffle on one end to percent run and large ratio of channel width at 20 cfs to channel width at 600 cfs on the other. This analysis described brown trout as having the greatest association with the large ratios of 20 cfs to 600 cfs flows, which are often indicative of channel incision.

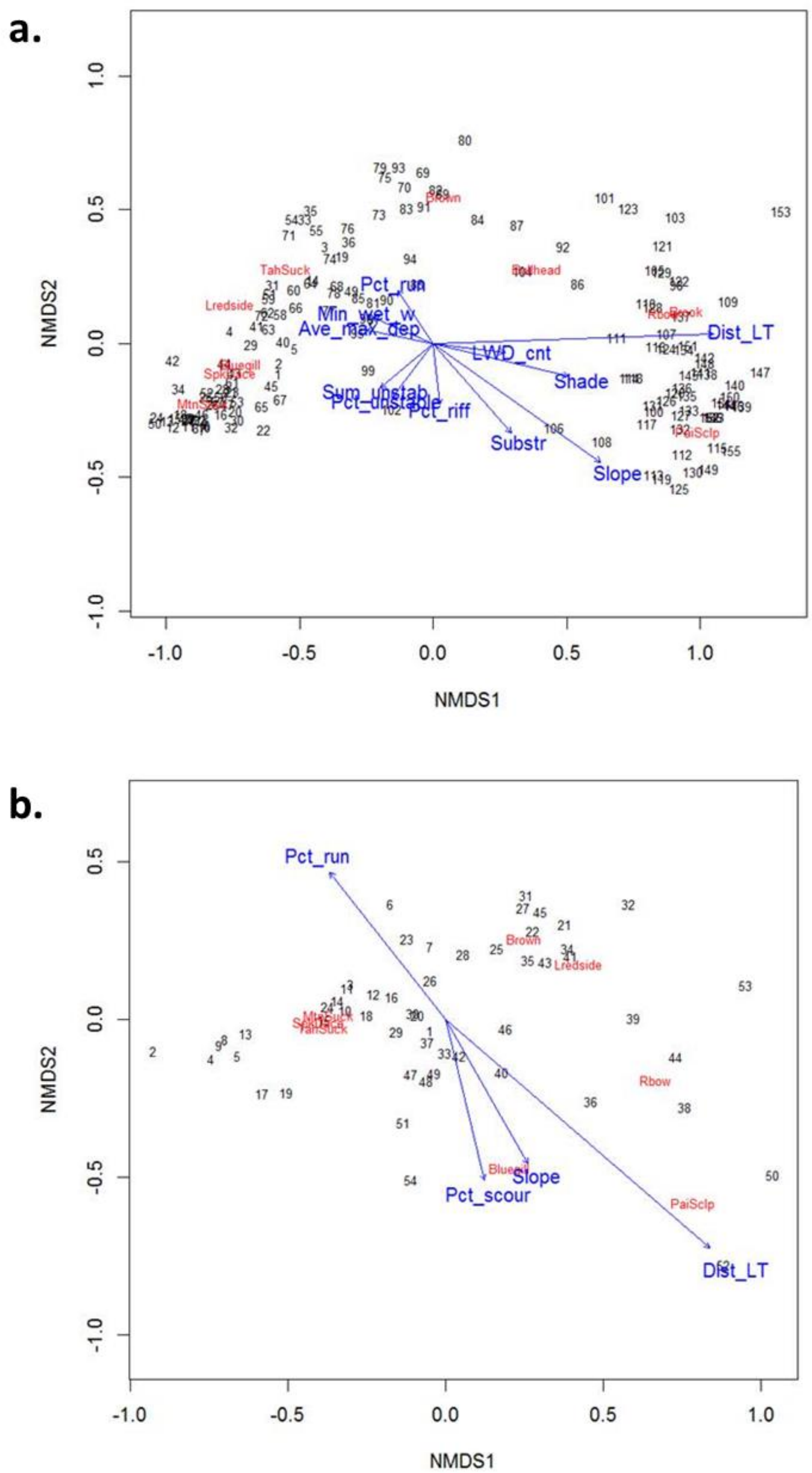

Figure 8. NMDS scaling of fish relative abundance with habitat variables overlaid (P= 0.05) a) excluding three most downstream fish reaches and b) for middle 50 fish reaches only. Species are arrayed within the two axes of the NMDS to reflect their difference in relative abundance at the fish reach scale. Fish reaches are labeled sequentially from Lake Tahoe.

Fish and Habitat Gradients – Middle Reaches (Zone of Transition)

In order to provide additional insight into the transition in the fish community with distance from the lake, an additional NMDS analysis was performed using only the middle 50 fish reaches, encompassing both Sunset Stables Restoration reaches and the golf course reach and excluding the rare species (2 NMDS axes with stress = 0.07) (Figure 8). Results from this analysis revealed more complex and varied fish and habitat relationships. The primary fish community structure and habitat gradient remained consistent with the analysis of the full study area, with a Paiute sculpin and rainbow trout community associated with increasing distance from Lake Tahoe and fewer run habitats and a sucker/dace community associated with run habitats closer to Lake Tahoe. Distinct from the habitat gradients for the entire lower river, the second habitat gradient shifted within these segments to describe higher slopes and more scour pools associated with Paiute sculpin and bluegill and lower slopes and fewer scour pools associated with brown trout.

Discussion

Habitat condition and gradients

Habitat conditions varied significantly at the full range of scales from channel unit to restoration reach. The following is a discussion integrating both observed and measured trends in habitat condition, restoration reach by restoration reach, across the project area.

Christmas Valley

At the Christmas Valley reach (UTR_105-UTR 143), the river goes down a steep cascade section above the surveyed reaches and enters a suburban-style housing development. This is the first area of significant development on the river and the upstream sections are predominantly USFS managed land in roadless areas. This section of the river is the most forested of all the reaches surveyed and has the most shading at 32.9% shaded (largely Jeffrey and Lodgepole pines) with a confined channel punctuated by smaller sections of meadow habitats (the smallest area of floodplain habitat per linear km of valley at 0.11 km^2/km). This section supports the highest amount of wood and woody debris inputs into the river (259 counted, more than twice that of any other reach) creating complex habitats for fishes. In some cases, there are houses right to the edge of the water. The meadow sections within this reach bear a similar level of instability to the meadow-dominated reaches downstream and riprap is a common tool for stabilizing eroding banks at the edge of properties. The percentage of unstable banks in this section is 18% and 12.4% of the channel units in this reach have bank stabilizing efforts such as riprap or gabions. The average substrate size in this section is the largest size of any of the restoration reaches

(105.8 mm) with some sections consisting predominantly of large boulders and cobble. Christmas Valley is the reach with the steepest gradient, averaging 0.52%. The reach had the coldest water of any of the reaches with a 7-day max downstream temperature (August-October) of 18.9˚C.

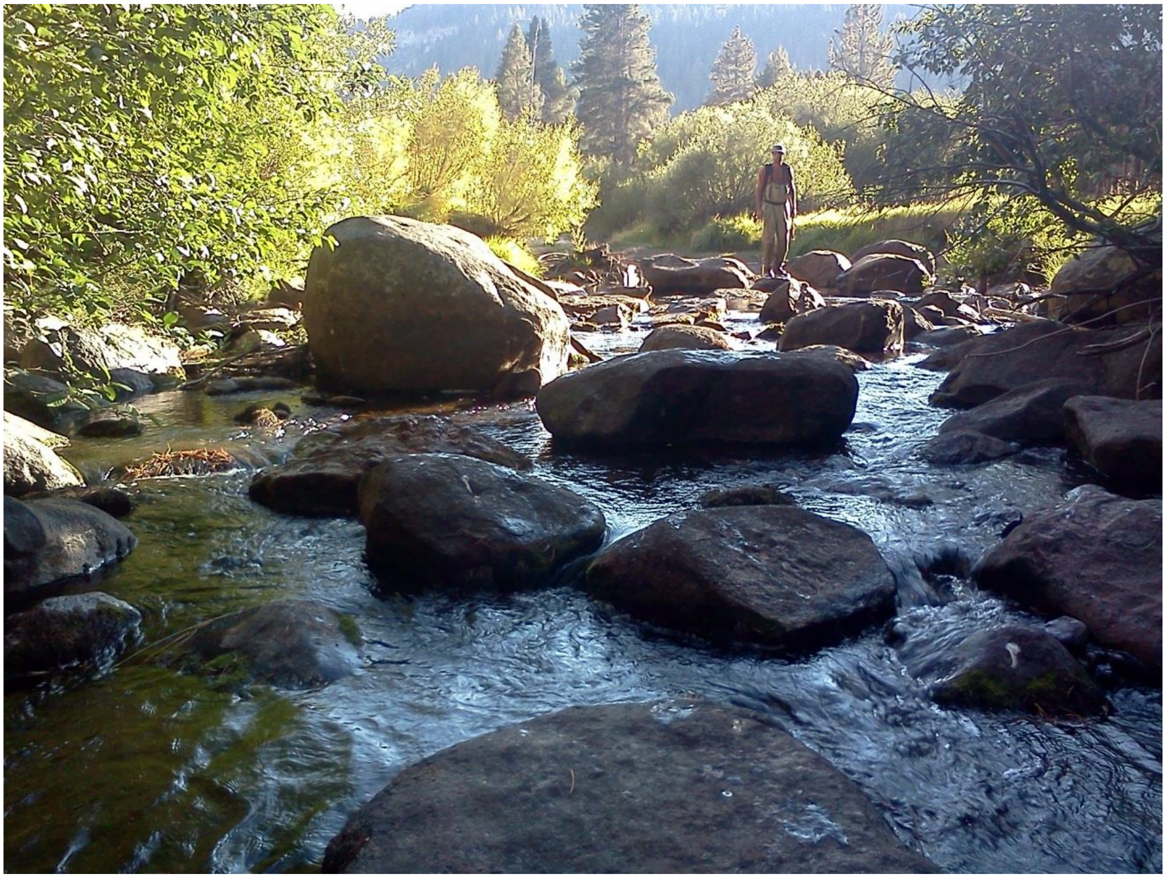

Figure 9. Boulder and cobble substrate, higher gradients, and denser forests characterize Christmas Valley reach. Photo: Sabra Purdy

Washoe Meadows Golf Course

Washoe Meadows Golf Course reach (UTR_76-UTR_105, 4.1 km) is characterized by a large, former meadow area that was developed as a golf course as well as more forested glacial outwash confined sections in a more natural state. The floodplain area per linear km of valley in this section is 0.27km^2/km. The Golf Course reach is one of the sites on the Upper Truckee that has had significant historical impacts from channel straightening, grazing, gravel mining, timber harvest, and sewer line construction. In the 1930's several meander bends were cut off to straighten the channel, reducing sinuosity and increasing slope and erosive power. This has led to incision and bank instability with profound and lasting effects on this reach. The water table is lowered and this resulted in drying of the meadow habitat. The channel had already downcut when the golf course was constructed in 1958 to

1962 on the former meadow area. Five undersized bridges were installed by the golf course over the UTR and they constrict the channel exacerbating erosion downstream. Average substrate size in this reach is 74.9 mm and consists largely of cobble. In many sections, the fairway comes right to the edge of the river creating an unbuffered source of nutrients and fertilizer and restricting the growth of riparian vegetation. We measured bank instability in this reach at 16.8% unstable banks with 29.8% of the channel units in this reach containing bank stabilization efforts such as riprap, root wads, and log barriers. These efforts have had limited success and there are several sections in this reach that have significant erosion zones that are eating into the fairway. At the upstream and downstream end of this reach STPU sewer lines cross the river and the lines are in the floodplain. The woody debris count in this section is 92, predominantly coming from upstream inputs above the golf course. The gradient changes in this section as it is a transition from the steeper glacial outwash reach in Christmas Valley and the lower gradient meadow and lake-influenced reaches downstream. The average gradient is .20 % and there is a grade control structure near the downstream end of the golf course for water intake. The percent of shaded habitats on this section is presumably lower than it was historically, due to lack of streamside vegetation in the golf course where the fairways extend to water's edge, and is around 18%. This reach gains 1.3˚C in temperature from top to bottom, which is probably a direct function of loss of riparian vegetation. California State Parks have put forward a major stream and meadow restoration proposal for this reach which has gone through significant environmental review but has not yet been implemented.

Figure 10. The uppermost of the golf course bridges has created significant downstream erosion problems. Note the heavy bank reinforcement and the fairway up to the edge of the stream. Photo: Sabra Purdy

Figure 11. The Golf Course Reach is characterized by frequent cases of bank instability or attempted bank stabilization projects and fairways that come all the way to the water's edge. Photo: Sabra Purdy

Sunset Stables 6

This small reach (only 1.5 km, UTR_62-UTR_76) represents the short section between the middle Highway 50 Bridge below the town of Meyers and the end of the Lake Tahoe airport runway. It has meadow habitat mixed with encroaching conifers and has been altered by the burial of the sewer line along the river right bank. The percentage of shaded areas in this reach is 17.1%. The bank stability in this small reach is the best of all of the restoration reaches at 12.0% unstable banks and 16.0% of the channel units contain riprap, gabions or other bank stabilization or substrate augmentation efforts. This reach gains 0.6˚C in temperature from top to bottom, which could potentially be improved with riparian revegetation efforts. The average substrate size in this reach is 25.4 mm and is predominantly gravel and small cobble with areas of fine sand. The average gradient is 0.1%, and the floodplain area per kilometer of valley length is 0.28 km^2/km. This area contained a large amount of non-native fishes mostly in the form of salmonid species (48.9%). This is the highest relative abundance of non-native species of the sampled reaches on the Upper Truckee.

Figure 12. Sunset Stables 6. Photo: Sabra Purdy

Sunset Stables 5

The Sunset Stables 5 reach (2.7 km long, UTR_38-UTR_62) parallels the upper end of the Lake Tahoe airport runway. This section is characterized by generally low gradients (0.10% average gradient), with gravel and sand substrates. The channel is confined here by the airport runway on river left and forested uplands on river right that contain housing developments. Despite the confining presence of the airport runway, there remains some floodplain habitat in this reach (0.38 km^2/km of valley length). This section is relatively exposed to solar radiation with only 11.8% shaded habitats and gains 0.50˚C over the course of the reach. The woody debris count is high in this reach at 102. This reach contains 20.8% unstable banks with some areas (near the bottom of the reach) that are highly incised, actively eroding, and will likely continue to unravel without intervention. There are bank stabilizing or substrate augmentation efforts in 15% of the channel units in this reach. This reach supports several active mussel beds. While it is not the most impacted reach on the Upper Truckee, the fact that some of the worst channel instability and deepest incision is immediately upstream of the recently completed Airport Reach restoration project means that those efforts are vulnerable if this section continues to degrade without intervention.

Figure 13. Example of badly incised and actively eroding meander bend at the base of Sunset Stables 5 reach. Note sod sloughing into the stream and the turbidity of the water. These meander bends are very tight and will likely be eroded though in the immediate future without intervention. Photo: Sabra Purdy

Airport Reach

The Airport Reach (2.3 km long, UTR_17-UTR_38) has a history of alteration. It was straightened in the 1960s to make way for the Lake Tahoe Airport runway which created scouring flows and contributed to downstream erosion and incision problems. A channel reconstruction project was completed here in 2011 and our survey was the first to conduct post-project monitoring. The new channel is heavily armored with extensive riprap and gabion structures as well as gravel and cobble augmentation in at least 75% of the channel units. The airport reach gains 0.2˚C from top to bottom and has an average gradient of 0.1%. There are several gradient control structures in this reach and the vegetation around the new channel is new and very tender. The areas where netting was implemented had the least observable erosion and highest recruitment of new vegetation. There are several places where newly constructed banks are unstable and rapidly eroding resulting in an overall percentage of unstable banks of 14%. These areas pose an immediate and acute risk and warrant further assessment and near-term action, particularly while vegetation has yet to take firm root and newly constructed banks are highly vulnerable. The average substrate size in this reach is 32 mm representing a lot of introduced cobble and gravel. The floodplain area in this section is 0.25 km^2/km of valley length, nearly identical to Sunset Stables 6 and is highly constrained by the airport runway on river left, and the forested upland on river right.

Figure 14. Restored channel in the Airport reach. Note heavily reinforced banks, gradient control structures, introduced cobble, and pipes for irrigation to encourage new vegetation growth. Photo: Sabra Purdy

Middle Reaches 1 &2 (Johnson Meadow)

This reach, also known as Johnson Meadow (2.9 km long, UTR_1-UTR_17) is one of the more complex reaches on the UTR. The channel splits into two channels at UTR_12. The right channel hugs the right edge of the meadow along a dense housing development. While there are some bank stability problems in the right channel, the habitat is as a whole in significantly better condition on that side than in the left channel. There are numerous active beaver dams in the right channel, with several new dams added this summer bringing the water table up and backing pools up to cover previously denoted habitat units. The left channel goes from a beaver dam through a riprapped channel to a large eroding pool. This pool is very deep (2-3 meters) and has very cold water (6-10˚C) indicating that it is likely draining groundwater through the meadow and negatively impacting hydrology. From the erosion pool downstream, the stream channel is uniformly incised and scoured with slick mud substrate and heavy algal growth. The water is shallow and the banks are highly unstable and support little in the way of riparian vegetation. Based on these characteristics, we would expect this to be a net warming reach, however, the extremely cold water inputs into this section result in a loss of 2.6˚C for the reach overall, which is a startling result for such a shallow and exposed reach. This reach is predominantly sand and fine gravel with an average substrate diameter of 4.1 mm and gradients typical of meadow streams at 0.1%. The overall bank instability in this reach is the highest of all of the restoration reaches at 46.3%. The number would be higher if the right channel were excluded, though it has areas of instability and downcutting as well, particularly in the area where the two channels reconvene at UTR_2. There have been bank stabilization and substrate augmentation efforts in 17.7% of the channel units in this reach. The much more forested right channel increases the overall shade values to 18.5%, though again, the two channels are very different and values for variables such as bank instability and shade should be examined separately.

Figure 15. The highly impacted left channel through Johnson Meadow. Note the deeply incised banks, scoured substrates, sod falling into the channel and the general lack of riparian vegetation and floodplain connectivity. Photo: Sabra Purdy

Figure 16. In contrast to Figure 15, the right channel contains sections of very stable banks, good connectivity to the floodplain, healthy riparian vegetation and coarser substrates. This section has an elevated water table due to recent beaver activity. Photo: Sabra Purdy

Upper Truckee Marsh

The Marsh Reach (2.7 km, UTR_500 to UTR_1), the lowest downstream reach, is adjacent to Lake Tahoe and contains the confluence of the Upper Truckee River and Trout Creek. It is characterized by low gradients (0.06%), fine substrates (average substrate diameter of 2.8 mm) and little riparian shade (11.4%). It has undergone tremendous development and conversion of wetlands in the Tahoe Keys area, but the delta around the confluence of Trout Creek has the highest floodplain area at 1.08 km^2/km of valley length. This area has undergone extensive reconstruction and restoration activities and has some of the best floodplain connectivity (particularly near the mouth of the lake where there is little incision possible). The percent unstable banks is 18.7% and the percent of channel units that have had bank stabilization efforts or substrate augmentation above the true marsh is 10.1%, which is probably a low estimate. This section is constrained by housing developments and the Tahoe Keys marina to the west and the water is generally slow and sluggish containing 55.1% slow water units. The area immediately downstream of the

Highway 50 Bridge suffers from erosion caused by the bridge design which increases water velocity below the bridge during high flow events. These impacts continue downstream throughout the reach.

While the Stream Inventory Protocol covers marsh lands, it is primarily designed for alluvial systems rather than many-branched deltaic systems without a primary channel. It is difficult to capture the variability and condition of such habitats using this protocol. While the Truckee Marsh is highly impacted and significant amounts of habitat have been lost, high functioning areas remain, particularly at the confluence of the Upper Truckee River and Trout Creek. Delta and marsh areas are ecosystems of critical importance to many species. They provide essential habitats for fishes, birds, and rare aquatic plant species (Kattleman and Embury 1996). The high water table, low gradient, and ample sunlight provide a rare and precious habitat that is disproportionately important compared to its extent in the landscape and supports a biodiverse community structure not found in other habitats (Kattleman and Embury, 1996, Loheide and Gorelick, 2007).

Figure 17. The Marsh Reach is characterized by low gradients, fine sediments and significant bank instability and loss of floodplain access. The lower reaches of the marsh have received considerable restoration efforts that have resulted in increased hydrologic connectivity and more stable banks. Photo: Sabra Purdy

Multi-scale relationships between habitat and fish community

Three of the five non-native fish species in the system are strongly associated with native species as well as the underlying habitat gradients in the sampled portions of the Upper Truckee. Rainbow and brook trout are associated with Paiute sculpin in upper portions of the river and bluegill are associated with the mountain sucker/speckled dace community. Brown trout and brown bullhead are not strongly associated with any native species or any of the underlying habitat gradients, suggesting they may be generalists.

Results from the habitat analysis and correlation of the fish and habitat data reveal trends at multiple scales with important implications for understanding system dynamics and planning future management and restoration actions. At a coarse scale, lower gradient habitat with finer sediments and less vegetation closer to the lake transitions to steeper gradient habitat with larger substrate and increased vegetation further from the lake. Similarly, native fish community dynamics, in terms of two dominant taxa, mirror this transition with speckled dace near the lake, declining and giving way to large numbers of Paiute Sculpin further upstream (Figure 18).

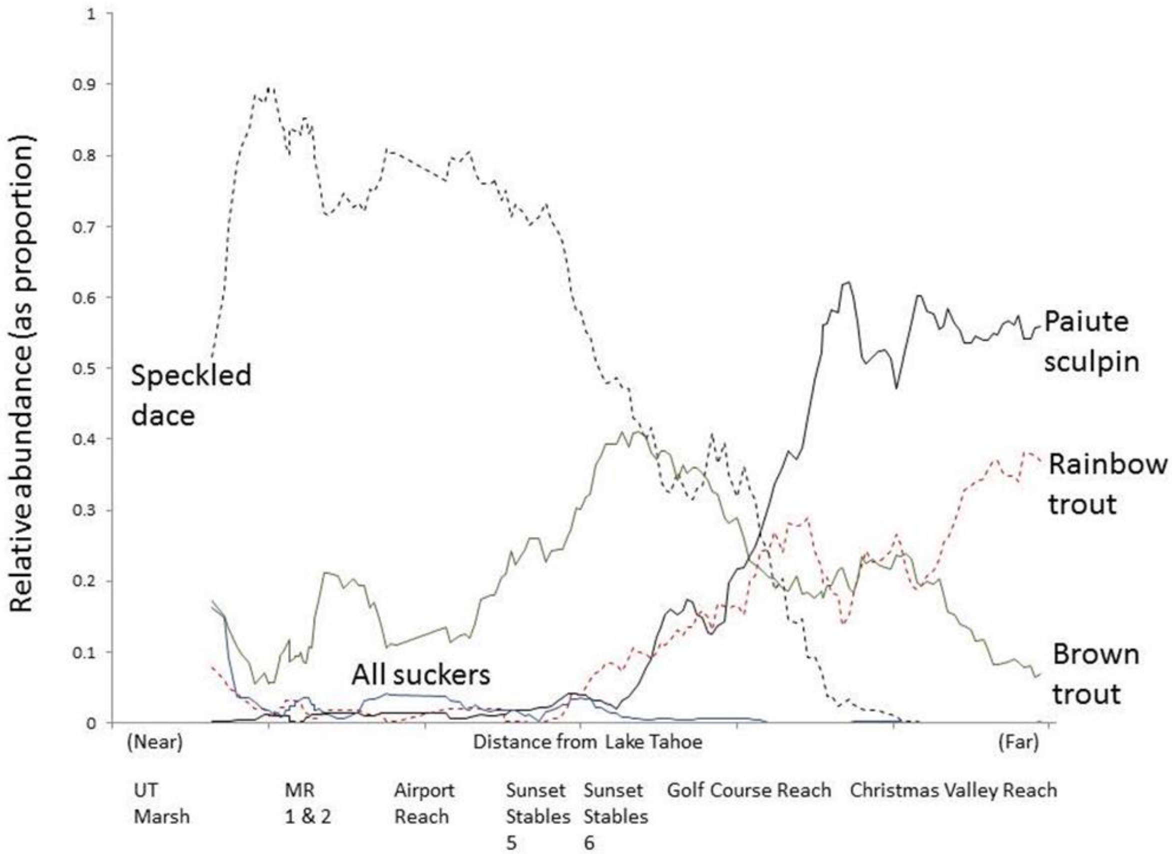

Figure 18. Fish relative abundance by species or species group (y-axis) and distance from Lake Tahoe (x-axis). Trend line is a 10 fish reach moving average. Mountain sucker and Tahoe sucker relative abundance are combined in the 'All Suckers' trend line.

At a finer scale, several distinct habitat types emerge including habitats with deeper scour pools and slow velocities, habitats with unstable banks, wide extended runs, and shaded habitats with stable banks far from the lake (Figure 19).

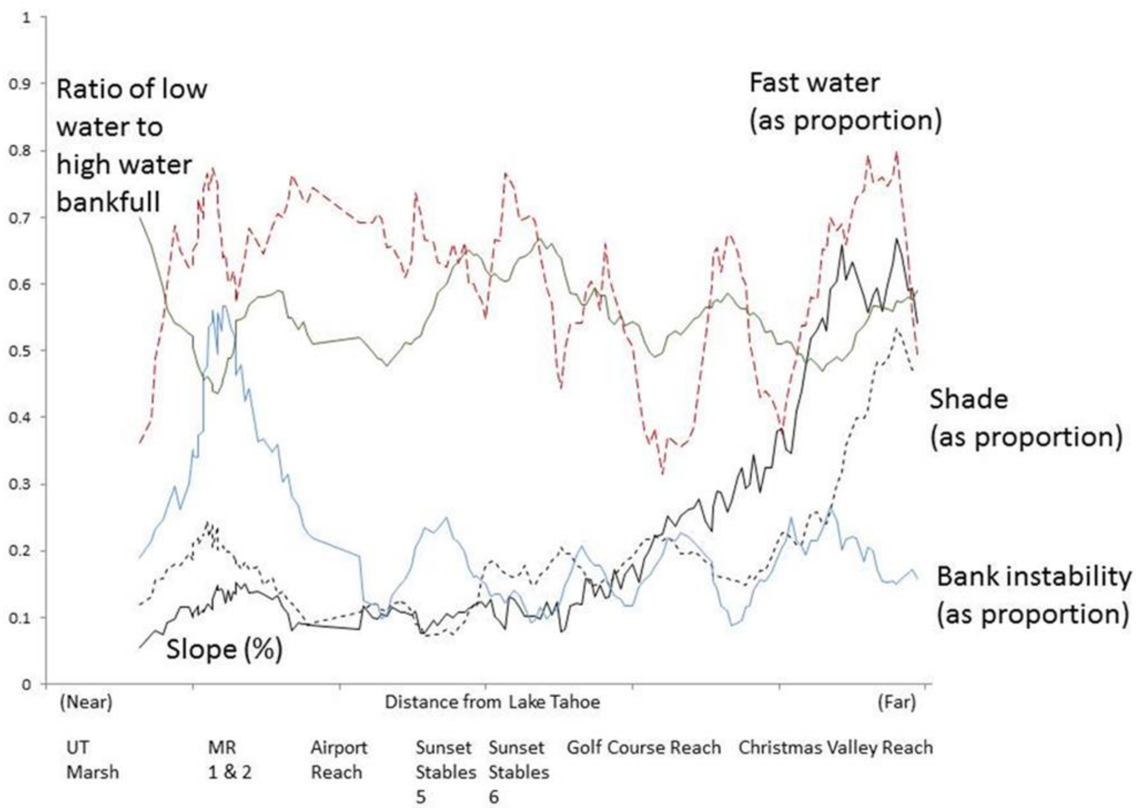

Figure 19. Patterns in select habitat variables as proportions (Y-axis) with distance from Lake Tahoe by restoration reach (X-axis).

Finer scale habitat features also have implications for the fish community. Closer to Lake Tahoe, habitats with low woody debris counts, and lack of shade are strongly associated with mountain sucker, speckled dace, and bluegill. Other features of these habitat associated with this fish community include lower gradients and fine substrates. Conversely, with greater distance from Lake Tahoe, larger amounts of woody debris, shade, and to a lesser extent steep gradients and larger substrate are strongly associated with the rainbow trout, Paiute sculpin, and brook trout community (Figure 18).

The observed trends comport with the known biological and ecological preferences and tolerances of the different species. While the lack of a strong association between brown bullhead and brown trout suggests that they function as generalists in the system, there is also some weak indication of an association between brown trout and areas with large ratios of channel width at 20 cfs to channel width at 600 cfs, which reflects incised channels. The relatively low numbers of bluegill and their association with the lower (northern) portion of the UTR where less vegetation and lower gradients also suggest warmer temperatures aligns with the preferred habitat of this typically warm-water species. The association with speckled dace, finer substrate, and less vegetation is consistent with their known tolerances as well as observations of their proliferation and dominance relative to other species in degraded meadow systems (Henery, unpublished; Purdy et al 2012). Rainbow trout, brook trout and Paiute sculpin all generally exhibit preferences for colder temperature habitat with riparian vegetation and large wood to buffer temperatures, provide cover for juveniles, and support cold water refugia during summer low flows, as well as coarser substrate to support invertebrate production, benthic foraging, and provide additional cover (Moyle 2002; Quist et al 2004).

Results from the NMDS ordination analysis reveal a distinct break in the fish community at the lower portions of the Golf Course restoration reach. These fish reaches are not strongly associated with the predominant communities found upstream and downstream, suggesting that this restoration reach falls in an important transition zone between the shadier, steeper, woodier habitat associated fish community at the south end of the study area and the lower gradient , less vegetated habitat associated fish community closer to the lake.

Implications for restoration and fish management

Of the habitat characteristics correlated with fish community composition, distance from Lake Tahoe and slope are inherent and therefore not likely to be affected by potential restoration actions. Other factors, however, including shading, woody debris in-stream (both of which are linked to riparian condition), and substrate size, can be significantly affected by restoration actions. Excluding rainbow trout, fine substrates were specifically correlated with non-native fish, and lack of woody debris and shading characterize much of the habitat closer to the lake where non-natives are more abundant. These habitat-fish relationships are supported by the biological characteristics, needs and tolerances of the species in question, and suggest a potential opportunity to exert influence over both introduced and native members of the fish community (e.g. rainbow trout, brook trout, Paiute sculpin (positively); speckled dace, bluegill (negatively)) through restoration actions that affect habitat by reducing fine sediment input, promoting riparian vegetation establishment and enhancement, increasing shading, and improving wood recruitment. By contrast, more generalist species with less apparent habitat affinity (e.g. brown trout and brown bullhead) are not likely to be affected by changes in habitat associated with restoration.

In the golf course reach specifically, the evidence of a transition zone suggests the potential for restoration driven changes in habitat characteristics to influence the fish community structure, potentially expanding the upper community (further from the lake) from the lake community downstream. The potential for restoration to shift the community dynamics in the Golf Course Reach, in-turn, has implications for fisheries management in the UTR going forward. Excluding introduced salmonids, non-native fish presence in the UTR (bluegill and brown bullhead) is relatively low and centered close to the lake, their presumed location of introduction. It is conceivable that a shift towards a cooler, woodier, coarser substrate habitat type in the Golf Course reach could help deter expansion of bluegill populations present in the Sunset Stables (6) reach, further upstream (see Appendix maps). Their relatively low numbers, however, in the presumably more suitable downstream habitat should serve to temper concern over their near-term upstream expansion.

By contrast, it is also possible that a transition to the upstream habitat type through the Golf course reach could promote the downstream expansion of brook trout populations. While rainbow trout distribution occurs throughout the lower reaches, climbing notably in SSR5 (Figure 18, Appendix), brook trout presence is limited overall and does not increase appreciably until the upper portion of the Golf Course reach (Figure 18, Appendix). From a recreation standpoint, improving habitat preferred by all salmonids, and with physical characteristics more closely resembling those in the upper part of the study area, could be positive for anglers, with whom the UTR is already a popular destination. The expansion of introduced salmonids, however, and most notably brook trout, the species least sought after by anglers, could have implications for native species currently present in the system, as well as for the potential reintroduction of Lahontan cutthroat trout.

Restoration and Lahontan Cutthroat Trout Reintroduction

Along with other introduced salmonids, brook trout have been implicated in the decline and localized distributions of LCT as well as the loss of native LCT from portions of their historic range in the Lahontan Basin of northeastern California, southeastern Oregon, and northern Nevada (Dunham et al 1999; Coffin and Cowan 1995). More recent research has highlighted a high degree of taxonomic dietary overlap between brook trout and Lahontan cutthroat trout, though it did not find specific evidence of direct predation on LCT or of LCT feeding being limited by brook trout (Dunham et al 2000).

Despite habitat correlations, the potential for increasing rainbow and brook trout populations in the golf course reach is speculative and open to a range of interpretation depending on management goals. Additionally, the potential challenge for LCT reintroduction posed by the widespread distribution of introduced salmonids in the UTR is universal to all the reaches included in this study. While certain habitat features, such as those associated with the upper river fish community might benefit LCT or introduced brook trout equally, others, such as increased floodplain connectivity that support habitat conditions and functionality more closely resembling historic conditions could provide specific benefits for LCT. In their investigation of dietary preferences in LCT and introduced brook trout, Dunham et al (2000) observed that both young of-year cutthroat trout and brook trout were most obviously abundant in off-channel habitats. However, LCT favored drift invertebrate prey whereas brook trout fed both on drift and benthos (Dunham et al. 2000). The pulse of invertebrate drift caused by floodplain inundation may therefore disproportionally favor LCT in a restored floodplain. Additionally, evidence for a range of other factors potentially limiting LCT including habitat fragmentation, stream temperatures, poor quality habitat including lack of over-summering and overwintering habitat, and climate (Dunham et al 1997; Dunham et al 2000; Elliot and Layton 2004) point to an even broader range of potential benefits from reintroductions in combination with habitat restoration (Elliot and Layton 2004).

Additional considerations for restoration and fish populations

Temperature data was taken at a fairly coarse scale; however, the thermographs revealed that all of the restoration reaches logged a number of hours of water temperatures above 22 degrees C. This number is widely regarded in the literature as a threshold temperature for salmonid species above which metabolism is impaired, fitness declines, and mortality increases. The more time a thermally sensitive fish such as a trout, salmon, or sculpin spends above its threshold temperature, the more likely they are to have decreased ability to eat, reproduce, defend territory, or move to less stressful habitats. During our limited sampling window, the hours above 22 degrees C varied by temperature logger/ location in the watershed. The number of hours above 22 degrees ranged by reach from 78.5 to 303 during the duration of the summer indicating that none of the restoration reaches were resistant to thermally stressful conditions. Interestingly, the two thermographs below the new restoration at the airport reach logged the highest number of hours above 22 degrees C at 290 and 303 hours respectively. Among the potential explanations for this is that the stream receives little shade in the Airport Reach (15%) because riparian vegetation is not yet established in the new channel; however there could be other causes as well. (i.e., irrigation return water from watering the new vegetation).

Also noteworthy was the widespread distribution of native species and the relative lack of striking dips in fish abundance from reach to reach, even in those fish reaches that were severely impacted. In part this may reflect the tolerance of many of the more ubiquitous introduced species, such as brown trout, bluegill, and, to a lesser extent, rainbow trout, as well as certain native species, most notably speckled dace. More likely, however, is that the overall fish community and native species specifically have been broadly impacted and their population numbers reduced from historic levels and the carrying capacity of the habitat uniformly lowered due to a long history of disturbance and multiple widespread impacts.

Both the presence of stress-producing temperature conditions across all of the reaches, as well as the condition of the fish community and possibility of lost carrying capacity with impacts over time point to the potential for extensive restoration to significantly benefit the native fish community of the UTR. In addition to rehabilitating geomorphic and hydrologic processes that in turn maintain flow, promote vegetation recruitment and establishment, and improve instream temperatures and habitat conditions, restoration of dynamic riverine processes such as floodplain inundation, fine sediment transport, and wood deposition allow native species to leverage evolutionary adaptations. As with off channel habitats and LCT, restored riverine processes often expand habitats preferred by native species. In certain cases, restoration may also benefit natives by resulting in increased stranding and higher mortality rates of bluegill or other introduces species not adapted to a dynamic inundation regime.

Hot Spots – opportunities for enhancement and remediation

Over the course of the 2012 habitat surveys we determined that sections of the Upper Truckee with channel incision, loss of riparian vegetation, and habitat degradation occurred throughout the 7 reaches. However there were certain areas within each of those reaches that pose more immediate threats to the stability and function of the river and meadow ecosystems than others. We highlight some of the most notable and pressing problem areas in this section. While this is not an exhaustive list of areas needing attention, these areas were noteworthy due to factors such as their proximity to infrastructure and property, the ramifications of not addressing them, and the trajectory of habitat degradation if they continue unabated.

Holistically, the Upper Truckee River has experienced significant channel degradation that stems from a variety of anthropogenic causes. Some of the problems are likely legacy issues from the nineteenth and twentieth centuries stemming from overgrazing of livestock and erosion problems from timber cutting and transport down the rivers. Other impacts to the system are more recent and come from bridges and road crossings that constrict the channel and create bank erosion downstream of the infrastructure. Additionally, the South Lake Tahoe wastewater system goes through the meadows and there is evidence of disturbance around buried pipes and there have been recent problems in the Golf Course reach where a sewer pipe crossing the river became exposed due to channel erosion. The straightening of the river along the airport in the 1960s created many downstream problems due to erosion of sediment, increased stream velocities, loss of floodplain access and area, and constriction of the channel. The same problems exist in the Golf Course reach where the channel was straightened and important meander bends were cut off. Simultaneously, undersized bridges create huge erosion problems and dump sediment into the river, which not only degrades in-stream habitat, but contributes to the loss of water clarity in Lake Tahoe. The development of the Tahoe Keys in the 1960s eliminated a huge portion of the Upper Truckee Marsh, which contributed to the precipitous decline of water quality in Lake Tahoe, not to mention loss of the ecosystem services associated with marsh and meadow habitats.

The cumulative effects of all of these impacts have significant implications for the function of the river, its ability to support fishes and other aquatic biota, and its impact on Lake Tahoe water quality.

Some of the observed impacts on the Upper Truckee River include:

- Significantly incised stream channel with actively eroding banks in all restoration reaches
- Loss of hydrologic connectivity to floodplain
- Loss of flood attenuation capacity in meadow habitats
- Drainage of groundwater through incised channels
- Increased sediment to Lake Tahoe
- Decreased ability to support fishes and other aquatic species
- Loss of biodiversity
- Habitat for invasive species
- Threats to infrastructure and property
- Water quality impacts from runoff, sediment, and fertilizer
- Reduced riparian vegetation

The Upper Truckee is not unique in terms of having significant and ongoing anthropogenic impacts to basic hydrological processes and ecological function. However, it is relatively unusual in the fact that it is the largest tributary to Lake Tahoe, it supports one of the highest human populations of the montane regions of the Sierra Nevada (~21,000 people), and it was historically one of the largest contiguous montane meadow systems in California.

Notable Problem Spots

Johnson Meadow

- Johnson Meadow, also known as Middle Reaches 1&2, is arguably the most impacted and unstable reach on the Upper Truckee. With the exception of the Truckee Marsh, it represents the one of the largest areas of undeveloped meadow habitat within the survey reaches. Our surveys indicated the highest percentage of unstable banks occurred in this reach (46.3%). The stream channel splits into two main channels at UTR_12. The right channel follows the edge of the meadow and is in considerably better condition than the left channel. However, the right channel is dangerously close to ~100 homes built right on the edge of the river. There are areas of significant bank erosion in this section that could threaten houses during flooding events and contribute sediments and nutrients to the river.

- The left channel at Johnson Meadow is badly eroded and incised. There is an erosion pool ~100 m downstream of the split that is actively eroding and has significantly increased in size over the past 20 years (visible via Google Earth). This section is so eroded and scoured that it supports very little riparian vegetation and the stream substrate is largely slick mud with the meadow serving as an isolated terrace. The erosion pool here is so deep that it appears to be leaching groundwater from the surrounding meadow. Our temperature loggers here indicate a temperature range of ~6-10˚C, about 10-15˚ colder than any other reach in the river. This has significant hydrological implications for the function of the remainder of the meadow and local groundwater dynamics. In addition to this actively eroding pool, the meander bend just downstream of this area (UTR_10) is eroding towards the right channel. There is just 30 m separating the two channels and without some sort of intervention, it seems inevitable that the left channel will capture the right channel, diverting the creek away from the right side and putting all of the water into the highly unstable left channel. This could lead to even more sediment being eroded into Lake Tahoe and the continued loss of meadow function, biodiversity, and ecosystem services in this section.

Figure 20.The problem starts here - deeply eroded and draining cold water from surrounding meadow, this pool represents the location where the left channel at Johnson Meadow becomes extremely degraded. Complete armoring of stream banks and bed for the ~100 m upstream to where the channel splits protects that section from erosion and incision until this point. Photo: Sabra Purdy

Airport Restoration Reach

- While all new restorations are vulnerable, there are a few key channel units in the Airport Reach that show signs of dangerous instability and erosion since the completion of the project. Much of the Airport Reach restoration involves highly armored banks, large gabions, and introduction of cobble and gravel. The areas that we observed to be the most unstable and in need of intervention were the channel units FTRF96, SSLS76, and FTRF97. The implications of not addressing these areas quickly could be continued erosion expanding into other areas, the loss of more sediment to Lake Tahoe, and negative impacts to downstream restoration efforts.
- There appeared to be a mix of bank stabilizing techniques used in the Airport Reach. From our observations, the sections that had jute netting overlaying

the banks appeared to have the highest recruitment of new vegetation and the least amount of observable erosion. Areas where willow mattressing was used (laying willow wands along the bank perpendicular to flow) showed signs of scouring underneath the willow wands and would probably be more successful when used in conjunction with netting over the top. The mix of highly armored sections of the project and those with soft, steep banks creates opportunities for erosion and may present increasing stability problems if not addressed.

Figure 23. Problem area in the Airport Reach restoration where right bank is unstable and actively eroding while downstream lateral scour pool is eating at the left bank as seen near the top of the photo. Early intervention could prevent this from worsening. Photo: Sabra Purdy

Sunset Stables 5 &6

- The meander bends between UTR_39 to UTR_44 are highly eroded, deeply incised and confined between the uplands to river right and the airport runway on river left. This is a likely place where, if left unattended, the river will cut through the meander bends eroding hundreds to thousands of cubic meters of sediment and increasing the channel size which would further reduce the river's access to the floodplain. This will result in increased stream velocities, which will negatively impact downstream areas and increase downstream erosion and the mobilization of sediments to Lake Tahoe.

Figure 24. The tightness of these meander bends coupled with deep incision leaves the river little option but to cut through, mobilizing tons of sediment, further reducing floodplain access, and negatively affecting aquatic habitat and hydrologic function. Photo: Sabra Purdy

- There are several large debris dams in the Sunset Stables reaches where the river goes through areas of dense Lodgepole forest. The huge tangles of dead trees impede flows, may negatively affect fish passage and divert the river around them, digging new channels that may have negative effects on erosion and bank stability. Conversely, these log jams may provide important shelter for aquatic species.

Figure 25. This large debris pile within the river channel alters flow dynamics and forces the river to cut a new channel. This may impact fish passage or conversely, it may provide good habitat.

Golf Course

- The problems associated with Washoe Meadows Golf Course are well documented and the proposed restoration has gone through significant environmental review. The historic straightening of the channel has led to incision and unstable bed and banks throughout the reach. The undersized bridges lead to localized erosion and instability where the bridges constrict flow. Additionally fairways are located up to the river's edge with no riparian buffer for habitat, shade or invertebrates. The proximity creates significant opportunities for fertilizer to enter the channel resulting in decreased water quality and impacting Lake Tahoe clarity. This section has particularly important restoration implications because of the relatively large size of the meadows here, the confluence of the previously restored Angora Creek with the significantly impacted Truckee channel, and for addressing bank instability and reconnecting the channel to its floodplain. In addition to the physical habitat characteristics, this reach is a transition zone for fish species and the ability for this reach to support fish could be significantly improved by restoration actions such as increasing riparian vegetation and addressing bank instability.

Considerations for Interpretation of Findings and Future Actions

Timing of Fish and Habitat Sampling

Habitat sampling occurred during the summer low flow period of 2012 (average August flows at Meyers gage: 4.5 cfs), while fish data from the USFS reported and used in analyses was collected during the low flow period of 2011, a wet year with higher summer flows (average August flows at Meyers gage: 52 cfs). While data collected in select reaches during the low flow period of 2012 suggests minimal inter-annual variation in fish distribution during low flow periods (Table 5), examining observed fish distribution and associated habitat relationships over multiple years would be helpful in determining the strength and year-to-year consistency of trends reported here. Additionally, while extent and specific characteristics of physical habitat can be inferred from modeling outputs under different flow scenarios, fish distribution and habitat use at higher flows cannot be reliably interpreted from low flow distribution data.

	Rainbow Trout	Brown Trout	Speckled Dace	Paiute Sculpin	Tahoe Sucker	Bullhead	Lahontan Redside Shiner	Mountain Sucker	Bluegill
UTR 508	0 (0)	0.32 (0)	0.59 (-0.08)	0 (0)	0.02 (0.02)	0 (0)	0.07 (0.07)	0 (0)	0 (0)
UTR 9a	0 (0)	0.08 (-0.13)	0.88 (0.13)	0.04 (0.04)	0 (-0.02)	0 (0)	0 (0)	0 (0)	0 (-0.01)
UTR 9-10	0.01 (-0.01)	0.04 (-0.01)	0.95 (0.08)	0.01 (-0.04)	0 (0)	0 (0)	0 (-0.02)	0 (0)	0 (0)
UTR 30B	0.085	0.043	0.830	0	0	0	0.043	0	0
UTR 46	0 (0)	0.32 (0)	0.59 (-0.08)	0 (0)	0.02 (0.02)	0 (0)	0.07 (0.07)	0 (0)	0 (0)
UTR 67	0.05 (-0.04)	0.24 (-0.28)	0.56 (0.22)	0.14 (0.12)	0.02 (0.02)	0 (0)	0 (-0.04)	0 (0)	0 (0)
UTR 78-79	0.06 (-0.11)	0.19 (-0.11)	0.36 (-0.09)	0.36 (0.27)	0.03 (0.03)	0.01 (0.01)	0 (0)	0 (0)	0 (0)

Table 5. Relative abundance of fish species (individuals collected for a species/total individuals collected) at fish reaches sampled in 2012. Parentheses show change from 2011 sampling at same locations. Because Reach UTR 30B is a new channel in the Airport restoration reach segment, it has no 2011 comparison.

Habitat variables

We were limited in our ability to measure habitat variables likely to influence fish community structure and distribution. Some of our measured and derived variables likely function as proxies for those missing variables. Our temperature data was collected continuously at the restoration reach scale and thus was too coarse to explain the variance found between fish reaches, however, distance from Lake Tahoe and shading are likely correlated with in-stream temperature. Examining temperature at a finer scale would be helpful to determine the specific dynamics of individual fish reaches. Though not continuous, temperature data collected in a subset of habitat units within each fish reach could be used to guide design for a finer scale examination.

Scale

Our analysis looked at very fine-scale information related to habitat and included these in associations drawn with the distribution of fish species. The fish community, however may be driven by even finer-scale factors that were beyond the scope of this project, including water quality factors, and prey availability and taxonomy.

Sampling Methodology

The results of our analysis suggest that the existing USFS Level 1, Level 2 habitat typing methodology is not, in and of itself, adequately robust to quantify restoration effects at the habitat scale, or to serve as the basis for evaluating fish community-habitat relationships. The methodology implemented in this study went beyond the existing protocol in a number of ways that were critical for the analysis presented. Most notable among these are:

- LiDAR – Availability and use of LiDAR allowed us to accurately capture slope, model solar exposure, and model flood inundation.
- Substrate – In addition to the Wolman counts required under the protocol at the reach scale, we performed substrate analysis to second level Wolman categories for each habitat unit.
- Channel bank erosion – In addition to measuring the length of area of bank instability as a component of the percentage unstable banks calculation, we also measured the average height of unstable bank area for each channel unit. Although the results of this calculation are not reported here, this was performed in the event that future research or remediation efforts focus on fine sediment supply in the system.
- Vegetation – We subdivided riparian vegetation in both inner and outer flood-prone areas by percentage for a more detailed depiction of vegetation classes and distribution.

In addition to the methodological refinements implemented for this study several other additions would further improve results, and are recommended for use in restoration monitoring and evaluation of species habitat relationships. These include:

- Cover – Calibrate and refine LiDAR based cover analysis using channel unit scale vegetation data.

- Temperature Data – Continuous temperature data collected at the fish reach scale, coupled with individual temperature measurements at the habitat unit scale.
- Time-lapse photography – Time-lapse photography at critical reaches over the course of one or multiple years, coupled with geo-reference points within images to allow flow/ habitat relationships and spatial extent to be estimated based on images.
- Invertebrates – Drift and benthic invertebrate distribution, abundance and diversity at the fish reach scale, and including a subset of samples at the habitat unit scale, measured quantitatively relative to area as a basis for density calculations.
- Fish Sampling - Fish sampling occurring in parallel or timed as close as possible to habitat surveys would increase confidence in observed and calculated fish-habitat associations. Additionally fish sampling during high flows when floodplain are inundated as well as during spring and fall spawning seasons would provide additional information about habitat relationships relative to specific life history stages.

  While additional fish sampling would support more specific fish-habitat relationships, in order to better plan restoration actions, it should be noted that fish sampling can be resource intensive and disturbing to both the species and the system. Additionally, specific species habitat relationship may vary widely between flow levels, seasons, and years. Physical habitat attributes and water quality parameters closely associated with habitat quality for fish may therefore be more appropriate 1) to monitor on a frequent basis, and 2) to use as a basis for developing hypotheses about fish recovery in response to restoration actions that when tested, can trigger adaptive management actions (*see Recommendations*).

Recommendations for future actions

It is our hope and intention that the monitoring data and analyses provided here will serve as a baseline against which to track change in the physical habitat of the UTR, quantify effects of restoration at the habitat scale, and plan future restoration actions and adaptive management based on aquatic species response. While the analyses and results reported here are designed to provide an initial perspective into conditions and trends in physical habitat and fish species throughout the study area, they are by no means exhaustive; there is an opportunity to integrate them with other existing data, as well as new data collection from ongoing monitoring, for a more nuanced analysis going forward.

In support of this monitoring approach and associated dataset and for maximizing its potential as the basis for understanding system change and quantifying the effects of restoration actions going forward, we have proposed a range of potential future actions for consideration:

- *Quantify restoration effects* – As a basis for designing future restoration projects and planning adaptive management actions, it is useful to quantify benefits to meadow habitats and species achieved through restoration and management efforts including:
    - Identifying specific metrics to measure change and characterize successes
    - Highlighting ongoing needs and prioritizing future actions

- *Post-Restoration Habitat Monitoring* - In order to quantify restoration effects and change in both the physical habitat and the distribution and abundance of fish and other target aquatic species, the monitoring approach used here (or some variant) should be repeated upon completion of restoration actions. Specific opportunities associated with post restoration monitoring include:
    - <u>Selection of representative reaches within each restoration reach</u>, based on initial findings, as the basis for ongoing monitoring
    - <u>Designation of floodplain habitat types</u>, as a function of a) inundation (frequency and duration at a range of flow levels) b) dominant vegetation type, to serve as the basis for quantifying the spatial and temporal effects of restoration in terms of floodplain habitat creation.
    - <u>Incorporation of detailed temperature and flow monitoring</u>, for representative reaches, as the basis for tracking subtle changes to habitat condition associated with restoration actions
    - <u>Sampling for water quality</u>, at regular intervals in representative reaches to capture seasonal and inter annual variability during and post-restoration.

- *Post restoration monitoring of fish and aquatic species* – In order to track response of fish species to restoration actions, as well as to refine species-habitat relationships as a basis for establishing and managing habitat targets to support conservation and recovery fish, monitoring should be repeated subsequent to restoration. Some of the specific opportunities include:
    - <u>Sampling fish distribution and abundance</u>, in the representative reaches, a regular intervals over the course of a year, in order to tack species-habitat relationships at different flow levels.

- Identifying indicator species and developing adaptive management triggers, based on known associations between particular species and components of the physical habitat anticipated to be significantly enhanced through restoration actions.

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