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HISTORIC CHANNEL CHANGE AND POST-PROJECT ANALYSIS OF A HABITAT RESTORATION PROJECT ON THE UPPER STRAWBERRY RIVER, UTAH

by

Marshall Bruce Baillie

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Watershed Science

Approved:

John C. Schmidt Major Professor	Joe Wheaton Committee Member
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UTAH STATE UNIVERSITY

Logan, Utah

2011

ABSTRACT

HISTORIC CHANNEL CHANGE AND A POST-PROJECT ANALYSIS OF A HABITAT RESTORATION PROJECT ON THE UPPER STRAWBERRY RIVER, UTAH

by

Marshall B. Baillie

Utah State University, 2011

Major Professor: Dr. John C. Schmidt
Department of Watershed Sciences

Restoration of the upper Strawberry River included bank stabilization techniques because it was assumed that excessive bank erosion was degrading spawning habitat for Bonneville cutthroat trout (*Oncorhynchus clarki Utah*)(BCT). Using a long-term aerial photograph record, we determined the historic range of variability in bank erosion rates and channel geometry, and used this information to assess present-day conditions and the rationale for restoration. Relative to historic variability, bank erosion rates were low and channel morphology was stable in the decade prior to restoration. Although a historic loss of riparian vegetation coincided with a shift to a wider and more sinuous channel, lateral migration rates declined to lowest levels in the period-of-record and the channel narrowed as riparian cover increased in the decades prior to restoration. Additionally, the percentage of fine

sediment in the streambed prior to restoration was insufficient to impact BCT spawning success. Furthermore, using a 1-D hydraulic model we examined pre- and post-restoration channel morphology and hydraulic variables related to habitat conditions for BCT. The results of the historical analysis suggest that bank erosion and fine sediment did not affect the quality of spawning habitat or the abundance of BCT on the upper Strawberry River. Furthermore, the 1-D hydraulic model shows that the physical in-channel manipulations made little improvements in achieving marketed changes in habitat and as such may have little effect on BCT spawning and resident population success. Our results highlight how a historic analysis can be used to identify the sources of habitat degradation and inform the selection of restoration goals and strategies as well as how surveyed cross-sections coupled with a 1-D hydraulic model can examine initial success of in-stream manipulation for habitat enrichment of a restoration project.

ACKNOWLEDGMENTS

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I would also like to thank Nira Salant for a constant supply of guidance and direction and Jack for the persistent boot in the backside, as well as the Fluvial Geomorphology lab cohorts for their support with my graduate endeavors. Lastly, a special set of thanks goes to my family; Finn, Maggie and Jill and my parents for always smiling politely when I would say that I am “almost done”.

TABLE OF CONTENTS

ABSTRACT ii

ACKNOWLEDGEMENTS iv

TABLE OF CONTENTS v

LIST OF TABLES viii

LIST OF FIGURES ix

Chapter 1-Introduction 1

1.1 Introduction 1

1.2 References 6

Chapter 2-Background 8

2.1 Historical analysis 8

2.2 Post-project analysis 12

2.3 References 18

Chapter 3-Strawberry River historical and post-project analysis 22

3.1 Watershed characteristics and reach boundary conditions 22

3.2 Climate 23

3.3 Geology 24

3.4 Land use history of the upper Strawberry River 25

3.5 Hydrology and the history of water use in the upper Strawberry River 26

3.6 Riparian vegetation 28

3.7 Beaver 29

3.8 Upper Strawberry River restoration 30

3.9 References....34

Chapter 4-Methods....35

4.1 Aerial photograph analysis and interpretation....36

4.1.1 Aerial photographic rectification....37

4.1.2 Image interpretation....39

4.2 Channel Reach Surveys and HEC-RAS....42

4.2.1 Reach and site surveys....42

4.2.2 Bed material composition....44

4.3 HEC-RAS 1-D hydraulic modeling....45

4.4 Site measurements of discharge and temperature....46

4.5 Regional analysis of hydrology....47

4.5.1 Developing a time series of hydrology from Strawberry Reservoir inflows47

4.5.2 Flow-Duration analysis....49

4.5.3 Flood Frequency analysis....50

4.6 References....51

Chapter 5-Results, Discussion and Conclusions....53

5.1 Aerial Photograph analysis and interpretation of historical geomorphic planform change....53

-Lateral channel migration....53

-Sinuosity, active channel width, and the ratio of radius of curvature to channel width....54

-Riparian vegetation....55

5.2 Channel reach surveys and HEC-RAS....55

-Streambed samples and composition....55

-Comparison of pre- and post-restoration channel planform and hydraulics using HEC-RAS....56

5.3 Site measurements....58

-Site measurements of Q and T, frequencies and duration of observed flows....58

5.4 Regional analysis of high flow years and LCM rates....59

Chapter 6 Discussion and Conclusions....60

6.1 Discussion....60

6.2 Conclusions....63

6.3 References....67

Tables-....69

Figures-....73

Appendix-....95

Baillie, M.B., Salent, N.L., and Schmidt, J.C., 2011. Using a historical aerial photograph analysis to inform trout habitat restoration efforts. *Earth Surface Processes and Landforms*, DOI: 10.1002/esp.2196. 95

LIST OF TABLES

Table 1: The upper Strawberry River record of post-colonial human influences 1776 to 2009.....69

Table 2: Aerial photograph attribute table: B/W – black and white, CI – Color Infrared, and C - Color 70

Table 3: Aerial photograph period and associated root mean square error (RMSE) per year and per period.....70

Table 4: Percentages of fine sediment <1 and <10 mm from riffle locations on three reaches of the Strawberry River, Utah, in October 2009 and June 2010. Values are the mean (SE) of three riffles. 71

Table 5: Results of the HEC-RAS analysis for three discharges of 26 surveyed cross-sections pre- and post-restoration of variables left to right; 1) mean water surface slope, 2) mean velocity, 3) mean flow area per modeled discharge, 4) mean cross-sectional shear stress, 5) mean cross-sectional depth, 6) water surface width across channel and, 7) width to depth ratio. The percent change reflects the differences for the "Restored 2009" reach pre- and post-restoration.....71

LIST OF FIGURES

Figure 1: a) Location of study site in Utah, b) Study reach on the upper Strawberry River and, c) three degrees of restoration to consider when selecting a restoration strategy. 74

Figure 2: Upper Strawberry River watershed and trans-basin water diversions....75

Figure 3: Photograph of U.S. Army barracks on the upper Strawberry River valley in 1888. The Strawberry River flows along the far section of the valley right to left (USFS 2004)....76

Figure 4 a & b: Photographs comparing riparian vegetation(circle) of the Strawberry River in 1908 (top image) and 2002 (bottom image). Both pictures are pointed northward up the valley near Telephone Hollow. Pictured are Strawberry District Ranger George Fisher (top) and Heber District Ranger Julie King (bottom) (from USFS 2004). 77

Figure 5 a & b: Photographs showing reduction in willows(circle) from 1888 (top image) to 2002 (bottom image). Both photographs look down-valley (southwest) towards U.S. Highway 40. The upper Strawberry River runs along the butte on the far side of the floodplain (from USFS 2004)....78

Figure 6: Study site showing Restored 2008 & 2009 reaches as well as the unrestored reach. The forth reach, Control 2 (above) was not overly effective for this study. Much of the reach was inundated with backwater from beaver dams built towards the end of the reach....79

Figure 7 a& b: a) Restoration techniques on the Restored 2009 reach: log vanes to deflect bankfull flows towards the center of the channel, coconut matting to reduce bank erosion and create a better environment for willow establishment, and pools deepened to create refugia for resident fish; b) flow patterns around log vanes (flow direction indicated by arrows)....80

Figure 8: Cross-sections on Restored 2008 reach....81

Figure 9: Cross-sections on Restored 2009 reach....81

Figure 10: Cross-sections on Control 1 reach....82

Figure 11: Cross sections on Control 2 reach 82

Figure 12: The top line is a longitudinal profile of the water surface elevation at baseflow or 0.41 m^3/s. Shown longitudinally are the US Route 40 Bridge, Hobble Creek inflow, Unrestored reach, spring inflow, restored reach 2009 and restored reach 2008. The lower scatter plot is all of the calculated lateral channel migration rates for the entire period of record. The trendline is a simple moving average with a period of 10, which approximately represents mean every 100 meters longitudinal distance of the previous 10 LCM calculations. Areas of lateral instability are readily observable longitudinally along the 7 km reach. 83

Figure 13 a-d: A) Lateral channel migration, B) sinuosity, C) mean channel width, and D) riparian vegetation cover of the Strawberry River, Utah, from 1938-2009. Box plots show the distribution of values for the full record (1938-2009) and periods of time within the record (demarcated by dashed vertical lines). Vertical arrows in (D) indicate high flow years. Photographs in (D) are from USFS (2004), showing the change in vegetation cover between 1908 (top image) and 2002 (bottom image), looking up-valley towards Bald Knoll Peak. 84

Figure 14: Pre- and post-restoration mean cross-sectional velocity (m^3/s) at a surveyed bankfull discharge of 4.1 m^3/s. Each point represents cross-sections 1 through 26, upstream to downstream. 85

Figure 15 a-c: a, b and c: Pre- and post-restoration mean cross-sectional depths in meters at a discharge of 0.4 m^3/s, 1.93 m^3/s, and 4.1 m^3/s. Each point represents cross-sections 1 through 26, upstream to downstream.....87

Figure 16: Pre- and post-restoration mean cross-sectional flow area in square meters at a discharge of 4.1 m^3/s. Each point represents cross-sections 1 through 26, upstream to downstream. 88

Figure 17: Percent changes in channel morphology metrics for the Restored 2009 reach pre- and post- restoration, for three discharges modeled in HEC-RAS. 89

Figure 18: Mean daily discharges for the Upper Strawberry River at U.S. Route 40 Bridge for water year 2009 and 2010. 90

Figure 19: Flow Duration Curve created using 43 years of flow data from USGS gage # 09312600, White River below Tabbyune Creek, Utah in conjunction with 2 years of flow data from the upper Strawberry River at US Route 40. Shown are the percent exceedence values for three flows of interest; $Q_{max-2009}$, $Q_{max-2010}$ and $Q_{bankfull}$. 91

Figure 20: Flood frequency curve created with flow data from USGS gage # 09312600, White River below Tabbyune Creek. Shown are the flood recurrence intervals for three flows of interest; $Q_{max\text{-}2009}$, $Q_{max\text{-}2010}$ and $Q_{bankfull}$. 92

Figure 21: Temperature in Celsius recorded at U.S. Route 40 Bridge for 2009 and 2010 water years. The dashed line represents a zone of temperature where Bonneville cutthroat trout begin to show signs of stress and higher mortality rates (e.g., 18°C to 25°C) as a result of high summertime temperatures (Johnstone and Rahel, 2003).....93

Figure 22: Total annual streamflow record of the Strawberry River from 1949-2001, reconstructed from records of Strawberry Reservoir water storage, inflows, and outflows, compared with the lateral channel migration rate for time periods from 1938-2009 and a long-term discharge record from USGS gaging station #10128500 on the Weber River at Oakley, Utah. High flow years (greater than one standard deviation above the mean) are labeled. Vertical dashed lines separate the periods for which lateral channel migration rate was calculated. 94

Chapter 1-Introduction

1.1 Introduction

Many rivers and streams which were able to follow untamed courses now have altered physical and biological trajectories as a direct result of human influences. The Environmental Protection Agency states in a report in 2000 that > 33% of rivers were listed as impaired or polluted (USEPA, 2000). Consequently, the number of restoration projects over the past two decades has increased exponentially resulting in nearly $1 billion per year being utilized to mitigate and re-direct altered rivers (Bernhardt et al., 2005). The greatest concentrations of these projects are located in the Pacific Northwest, Chesapeake Bay watershed, and in California. The most common goals of restoration projects are to; enhance water quality, manage riparian zones, improve in-stream habitat, provide fish passage, stabilize eroding banks, with a median cost of ~ $45,000 dollars per project (Bernhardt et al., 2005).

River restoration practice, in many instances seeks to reintroduce conditions prior to human influence. To accomplish these objectives there are many of differing techniques that attempt to accomplish restoration goals over a short time span. As a result many of these techniques have good intent but lack adequate development and design resulting in potentially higher rates of failure (Frissell and Nawa, 1992; Williams, 1997; Kondolf, 2001). Sources of failure stem from the lack of; understanding physical/biological history of the system, examining proper scale, treating correct sources of degradation, integrating ecological principles, developing

proper goals, pre- and post-project monitoring for adaptive management, and focusing on a particular physical state rather than underlying processes (Angermeier, 1997;Williams, 1997; Wohl et al., 2005).

Many contemporary river restoration projects are often based on trial and error methodologies with little understanding of historical context. A well-established planning process facilitates the creation of clearly defined goals that produce more effective use of resources as well as increase the probability of project success. Projects such as these are rare in modern river restoration practice (Woolsey, 2007). Consequently, developing a perspective of the past through a historical analysis of a degraded river system can be useful in evaluating restoration and management alternatives in river systems. A historical analysis has many benefits in the planning process which include; an understanding of the underlying problem, development of realistic objectives and in-turn allow for the selection of appropriate strategies and techniques, as well as a better understanding of the natural hydrogeomorphic variability of the system (Kondolf, 1995; Schmidt et al., 1998; Downs and Kondolf, 2002; Wohl, 2005; Woolsey, 2007). While a historic analysis elucidates the past and assists in the creation of a more robust restoration design, a post-project analysis or PPA can aid by informing future river restoration projects through learning from past projects success and failures. Utilizing the data and knowledge from these successes and failure iteratively aids in the advancement of future river restoration design practice. While both of these components are not

a “smoking gun” they increase redundancy while decreasing uncertainty and therefore should be employed more often as part of restoration practice.

The purpose of this thesis is to present a historic analysis and a post-project assessment of a habitat restoration project on the upper Strawberry River, Utah. First, we investigate perceived sources of degradation in the system (i.e., excessive bank erosion) using a historic analysis, thereby providing a context for assessing the underlying reasons for restoration. Our assessment is based on several sources of historic information as well as the construction of a geographic information system (GIS) dataset using a suite of aerial photographs from 1938 to 2009. We calculate historic channel widths, sinuosity, amount of riparian vegetation and lateral channel migration rates. Along with this GIS dataset we construct a synthetic hydrograph for the region based on inflows to the Strawberry Reservoir below the reach to delineate historically wetter and drier periods in the flow record and thus mechanisms for channel change for the period-of-record. The historical analysis is an attempt to characterize the recent past of the upper Strawberry River and explore historical geomorphic context and variability in the system.

Secondly, we investigated the percentage of fine material in the riffle zones in-order to assess the gravels viability for spawning of Bonneville cutthroat trout. If there is excessive bank erosion in the system then it would be reflected in bed sediment composition with high contents of fine sediments. Moreover, high fine sediment content in spawning gravels would limit BCT fry emergence and would therefore limit BCT population viability and sustainability on the upper Strawberry

River. Together, the GIS and riffle grain size distribution investigations examine whether the perceived sources of degradation are in-fact the limiting factors for a sustainable fishery for the target species.

Thirdly, we attempt to characterize the how restoration has changed channel morphology and salmonid habitat using a 1-D hydraulic model. The model attempts to scrutinize changes in channel form as a result of physical in-stream modification techniques. Moreover, using current flow data and surveyed water surface elevations we attempt to characterize changes in hydraulic flow variables to describe channel change as an outcome of the restoration. Of the four study reaches in the investigation one has pre- and post-project data at twenty-six surveyed channel cross-sections along with water surface elevations for two separate discharges. Using the results of the hydraulic model we then examine how the initial physical in-stream modifications are successful or not at achieving the project goals.

Together, the historical analysis of lateral channel migration along with present-day channel surveys and spawning gravel grain size distributions illustrate how a targeted analysis of sources of degradation prior to restoration could prevent unnecessary and ill-conceived restoration projects. Furthermore, a post-project analysis can provide information whether the as-built restoration structures are performing as anticipated and are benefiting a positive or negative system-wide response.

Lastly, the Appendix of this Thesis contains a published article outlining the importance of a historical analysis with regards to habitat restoration for adfluvial

salmonids. The article has been published in a British geomorphology journal *Earth Surface Processes and Landforms.* The article stresses the need for understanding geomorphic processes prior to restoration and how a post-project analysis enables iterative and adaptive advancement of restorative techniques for river ecological form and function.

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Chapter 2-Background

2.1 Historical analysis

A historical analysis is the basis for understanding key system processes and can therefore aid planning and design for restoration projects. The analysis can establish an understanding of the underlying problem, help create realistic restoration objectives and formulate appropriate strategies to achieve those objectives (Kondolf, 1995a). Historical perspectives can also help increase our understanding of the dynamic nature of landscapes and provide a reference for assessing modern patterns and processes (Wissmar, 1997; Swetnamet al., 1999; Marcucci, 2000). Many argue that reference conditions for a system may not be attainable and the futility of attempting to re-establish pre-disturbance conditions may be unattainable (Kondolf, 1995a; Ward et al., 2001; Jacquette et al., 2005; Wohl, 2005; Florsheim et al., 2006; Stein et al., 2010). Although many obstacles may hinder a perfect picture of past history it is difficult to understand stream condition and design effective restoration measures without understanding their temporal and spatial contexts, the nature of habitat-forming processes, and a disturbance history (Montgomery and Bolton, 2003). While many researchers have emphasized the potential role of historic geomorphic and ecological data in the selection of restoration goals (Sear et al., 1994; Kondolf and Larson, 1995; Wissmar, 1997; Schmidt et al., 1998; Kowalski and Wilcox, 1999; Swetnam et al., 1999; Ward et al., 2001; Downs and Kondolf, 2002; Bohn and Kershner, 2002; Montgomery and

Bolton, 2003; Collins et al., 2003; Pess et al., 2003; Florsheim and Mount, 2003; Brown and Pasternack, 2005; Wohl, 2005; Woolsey et al., 2007; Surian et al., 2009; Stein et al., 2010) the application of such data to restoration project planning has not been widely adopted.

In order to understand the past geomorphic and ecological history of a system there are several resources of information with which to draw from. Kondolf and Larson (1995) pursue several sources of data in order to merge information needed to generate a historic analysis. The initial step attempts to understand the position of the channel in the watershed and what may be sources of influence on flow and sediment. Additionally, examination of the hydrology via gages or adjacent basin gages may provide context within which to interpret channel changes on aerial images or from field evidence. Understanding hydrology can also have implications concerning riparian and biological resources. Additionally, historical maps and aerial photographs can provide important information regarding channel morphology and can also be correlated with hydrologic records to examine temporal channel change. Moreover, aerial photographs and historical maps can provide information on riparian and ecological processes. Additionally, oblique photos can be used to document historical channel and riparian change by re-photographing the original site from known points-of-reference. Additional prospects for historical information are surveyed channel cross-sections or any information concerning channel planform of a site. Therefore, the main focus of a historical analysis is to combine and link many different sources

of disparate data into a picture that is clear enough for substitutive conclusions of past history in order to provide insight into present as well as potential future trajectories.

There are several, but not many, examples where a historical analysis was utilized in restoration planning, design, and post-project analysis. Kondolf and Larson (1995) examined previous floodplain uses and channel conditions in two reaches of the San Luis Rey River to document riparian resource loss, to assess the degree of historical dynamic change, and to establish the potential for riparian restoration. Kowalski and Wilcox (1999) used historical and geospatial data to identify the relationships between water levels, wetland vegetation, littoral drift of sediments, and the condition of a protective barrier beach on a coastal wetland in western Lake Erie, to guide a joint federal and state wetland restoration project. Warne et al. (2000) used a historic geomorphic analysis to determine reference conditions for ecological restoration along the Kissimmee River, Florida. Ward et al. (2001) demonstrated how the use of a historical analysis in several degraded European river systems provided landscape-level indicators for assessing the status of the river corridors, as well as serving as reference conditions for restoration goals. Bohn and Kershner (2002) used a historical watershed analysis of Grave Creek, Montana to guide restoration planning for determining the status of habitat conditions for bull trout and westslope cutthroat as well as identify and prioritize restoration objectives. Brown and Pasternack (2005) used paleo-environmental reconstruction to augment historical perspectives along the Sacramento and San

Joaquin river deltas with the aim of improving adaptive management and restoration procedures. Sear et al. (2006) utilized historical and documentary evidence coupled with field surveys and sediment modeling to provide a comprehensive picture of fluvial processes on a river in the United Kingdom. A simple sediment budget was calculated and the results were used to develop practical restorative options that address sources of the instability. Stein et al. (2010) utilized a historical analysis of the San Gabriel River watershed in California to describe historical wetland extent and distribution and compare historic wetlands to contemporary conditions to calculate wetland losses and reveal areas conducive to future wetland re-establishment and restoration.

River restoration has many possible objectives and goals, ranging from habitat improvement to flood control and water quality enhancement. These objectives need to be clear and as such are critical for success of a project. Clearly stated goals, that are consistent with geomorphological and ecological processes; aid designers in choosing, identifying, and prioritizing the restoration endeavor while also providing improved planning and design (Angermier, 1997; Kondolf, 1998; Bohn and Kershner, 2002).

An important component of a historical analysis and pre-project planning analyzes watershed versus local scale drivers of stream condition. Frissell et al. (1986) describes a nested hierarchical model of physical organization where geo-ecological associations are nested. Features that vary over small spatial and temporal scales (e.g., microhabitats, hydraulic units) are nested within boundaries

established by features that vary over large scales (e.g., vegetation, geology). Not taking into account larger scale drivers of stream condition may potentially lead to design failure. Much of river restoration focuses on small spatial and temporal scales (e.g., reach) and therefore does not provide a clear view of larger scale governing physical and biotic interactions. Consequently, restoration which is focused on an individual spatial and/or temporal scale may fail to notice the accurate source(s) of degradation in a system which may have originated from a larger scale influence. For example, watershed scale vegetation has indirect influences on stream flow and sediment transport, whereas; reach scale vegetation directly influences channel morphology, floodplain and hillslope connectivity as well as hydraulic resistance.

2.2 Post-project analysis

While a historic analysis provides a glimpse of the past physical and biological characteristics of a system a post-project analysis (PPA) examines restoration design and implementation, evaluates the degree of attaining restoration objectives/goals, examines unanticipated effects of restoration, and contributes to improved designs in the future. Despite many arguments to increase post-project monitoring and performance evaluations (Kondolf and Micheli, 1995; Bernhardt et al., 2005; Palmer and Allan, 2006) and ideas for standardizing assessments (Downs and Kondolf, 2002; Montgomery and MacDonald, 2002; Palmer et al., 2005), widespread post-project monitoring and evaluation in river restoration

is the exception and not the rule (Smith and Prestagaard, 2005; Tompkins and Kondolf, 2007). Consequently, many river restoration projects success or failure remains subjective and therefore provides little guidance for future projects.

There is a small community of researchers who have conducted a post-project performance analysis and performance evaluation of river restoration projects. These examples mostly examine channel and floodplain geomorphology which constitute the framework within which aquatic habitat and riparian conditions exist, therefore an understanding of geomorphological processes and conditions is the prerequisite to successful restoration design (Kondolf, 1995a).

Frissell and Nawa (1992) evaluated rates and causes of physical impairment or failure for 161 fish habitat structures in 15 streams in southwest Oregon and southwest Washington and found that 60% were somewhat impaired following a $Q_{2\text{-}10}$ return interval floods. They also found that commonly prescribed structural modifications were inappropriate and counterproductive in streams with high or elevated sediment loads, high peak flows, or highly erodible bank materials. Overall, processes of failure and impairment were dominated by changes in channel morphology that, apparently, had not been anticipated by project designers. These changes often were related to dynamic conditions at a watershed-scale and not reach-scale.

Kondolf (1998) used a PPA to evaluate a restoration project on Rush Creek in the eastern Sierra Nevada, California. The project examined riparian revegetation, bank erosion mitigation techniques and, aquatic enhancement efforts including

flushing flow releases. They found that bank mitigation and protection reflected a choice of objectives inconsistent with geomorphological and ecological processes, and that the project attempted to control channel form rather than permit channel processes to create and maintain habitat.

Kondolf and Smeltzer (2001) investigated a restoration project on a reach of Uvas Creek, California, that was washed out just one year post construction. The project was designed using a popular stream classification system, based on which the designers assumed that a "C4" channel (e.g., meandering gravel-bed channel) would be stable at the site. Their study cast doubt on several assumptions common in many stream restoration projects: that channel stability is always an appropriate goal; that channel forms are determined by flows with return periods of about 1.5 years; that a channel classification system is an easy, appropriate basis for channel design; and that a new channel form can be imposed without addressing the processes that determine channel form.

Smith and Prestegaard (2005), like Kondolf and Smeltzer (2001), examined a rehabilitation project conducted in a reach of Deep Run, Maryland. There, they monitored commonly used approaches to channel design that rely on classification systems to describe channel form, empirical relations to predict channel dimensions, and a single design discharge to evaluate the hydraulic conditions. The Deep Run rehabilitation project was intended to reduce the sediment supplied to downstream areas by stabilizing the active channel. The monitoring and subsequent PPA of the Deep Run project documented that the constructed channel

reach was morphologically and hydraulically different from the original channel and other previously documented Piedmont streams and therefore the constructed form was unsustainable resulting in failure. Furthermore, the observations in Deep Run illustrate how processes operating at four spatial scales (i.e., physiographic region, watershed, project reach, and channel feature) influence the stability of a channel reach. While channel rehabilitation designs typically focus on the average conditions of the project reach, the problems experienced with the Deep Run project were attributed to processes operating at the other three larger scales.

Goetz (2008) utilized a PPA to examine a physical assessment of the Provo River Restoration Project (PRRP), Utah in order to investigate the design and construction of a large-scale stream restoration project. Goetz provided a context for assessing project performance in terms of reestablishing geomorphic processes that connect the channel and floodplain. Goetz found that the PPA demonstrated that many assumptions were made along the route from the perception of a problem, to the eventual construction of the PRRP. Furthermore, these assumptions were made based on a scientific understanding of naturally functioning river systems although no data was collected to quantify the nature of physical impairment. The PPAs measurements suggest that what was constructed was often very different from the design, and that the functional response of the river to its channel and floodplain re-alignment was therefore not predictable.

Miller and Kochel (2009) examined 26 stream restoration projects in North Carolina utilizing site assessment and post-project monitoring data of channel

reconfiguration projects. An analysis of site and basin geomorphology revealed that large post-construction adjustments were associated with highly dynamic stream channels characterized by a combination of high sediment transport capacity, large sediment supply, and/or easily erodible bank materials. In-stream structures along reconfigured channels exhibited high incidences of damage. Their analysis suggested that attempts at channel reconfiguration may be extremely difficult along dynamic rivers which are often targeted for restoration. Furthermore, they suggest that allowing the channel to self-adjust (e.g., enhanced natural recovery) can be combined with other less aggressive methods to improve the rivers overall condition.

Lastly, Buchanan et al. (2010) evaluated a stream restoration project completed in the fall of 2005 on Six Mile Creek, New York. Using a variety of evaluation approaches, they documented both successes (e.g., enhanced in-stream habitat) and failures (e.g., channel avulsions) of in-stream physical channel manipulation. Overall, they concluded that the project was marginally successful in achieving its stated goals and that future prospects remain uncertain based on the current trajectory.

Together these examples provide evidence for effective practice in pre- and post-project restoration procedure. Effective pre-project monitoring and subsequent post-project analysis/evaluation practice are as follows: 1) generate a defined list of stakeholders, 2) establish a list of clear goals and objectives, 3) establish and initiate a pre-project monitoring program which assembles a present

geomorphic and ecological baseline context, 4) establish and initiate a historical analysis which assembles a past geomorphic and ecological context . These four basic steps can provide ample information for effective pre-project planning and design. In addition, after project completion, a post-project monitoring and evaluation program can provide future adaptive management possibilities and subsequent strategies for restoration success.

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Chapter 3-Strawberry River historical and post-project analysis

3.1 Watershed characteristics and reach boundary conditions

The study area is located on a reach of the Strawberry River upstream from Strawberry Reservoir near Heber City, Utah (Figure 1). The topography of the watershed varies from steep mountain ridges to foothills and wide valleys. Elevations in the watershed range from 2320 m at the reservoir to 3200 m on the headwater ridges. The upper Strawberry River valley is approximately 0.67 km wide and is surrounded on either side by mountainous terrain ranging from 100 m to several hundred meters in height. The watershed is located on the southwest edge of the Uinta Mountains and flows from its headwaters in the north southward into Strawberry Reservoir.

The study reach is located in a transitional zone between the partially confined mid-catchment zone and the unconfined alluvial valley of the watershed. Much of the active channel in the study reach is unregulated with little hillslope-channel connectivity and is laterally unconfined. The valley floor shows evidence of single-thread, meandering paleochannels and the existing channel is meandering. Channel type follows a combination of asymmetrical and compound shapes which are associated with lateral migration and large flow variation respectively. The asymmetrical channels are found in the more sinuous reaches, and are characterized by meanderbends, while the compound channels are can be found in straighter reaches and are characterized by a smaller inset channel within a larger

macro-channel. In asymmetrical channels, secondary flow circulations promote deposition of associated point bars on the convex bank. This type of channel behavior lends to an assemblage of point and lateral bars, pools, as well as riffles with alternating deep pool and shallow riffle sections. The alternating riffle-pool sequences are characteristic of bedload or mixed-load transport regimes (Brierley and Fryirs, 2005). In normal flow stage the secondary flow circulation, deposits sediments at the toe of the point bar. However, as the flow increases, sediment deposition occurs around the bend and on top of the bar surface. This situation, depending on the flow angle, can stimulate avulsive channel behavior in meanderbends that are late in their development through extension and translation. Additionally, chute cutoffs are formed during high flows circumventing meanderbends, and initiating new channels that are straighter and have greater slopes, thus larger erosive power. There are numerous instances of avulsive channel behavior along the reach. Both conditions have the potential to reintroduce large amounts of sediments into the existing channel.

3.2 Climate

The mean annual precipitation for the watershed is approximately 68.5 cm per year. From 1931 to 1960, 72% (50.5 cm) of annual precipitation fell as snow between October and April and the remaining 28% (19.8 cm) occurred between May and September, falling primarily as rain (USFS, 2004). From 1931 to 1960, daytime temperatures in the valley are generally below freezing from the end of

November through the end of March and there are commonly periods when temperatures fall below -17 C. Average maximum and minimum July temperatures are about 27°C and 8°C, respectively. Most of the valley is covered by 0.6-1.2 m of snow from November through March and snow depths at higher elevations may exceed 2.1-2.4 m in some years (Jeppson et al., 1968).

3.3 Geology

The dominant geologic formations are the Duchesne, Uinta, and Green River formations each of which consists of continental sedimentary rocks deposited during the Oligocene to Paleocene approximately 66 to 24 million years ago. Cretaceous and older formations (e.g., more than 66 million years old) occur in the north end of the upper Strawberry River valley. Structurally, these rocks are more folded and faulted than rocks of the younger Duchesne River, Uinta, and Green River formations. Within this zone of older rocks, the two formations of most interest are the Permian Kirkman limestone and the Pennsylvanian-Permian Park City formation. Both formations locally have beds high in phosphorus and appear to be sources of phosphate to the upper Strawberry River and Reservoir and therefore are of interest to water quality and fisheries managers (USFS, 2004, UDWQ, 2007). Excess phosphate in the system is believed to be a potential source of water quality problems in the river as well as the reservoir.

3.4 Land use history of the upper Strawberry River

Much of the upper Strawberry River watershed has been used for livestock grazing by Heber Valley settlers since the early 1860's. In 1864, the area was under the jurisdiction of the Uinta Tribal Reservation which was located in Fort Duchesne, nearly 80 km to the southeast and consequently hindered effective management of grazing on the lands. With the need for water to be delivered to the growing Utah and Salt Lake counties to the west, the federal government began the creation of a water delivery and storage system known as the Strawberry Valley Project. The lands immediately surrounding the future reservoir were put under the jurisdiction of the Bureau of Reclamation and the upland areas were put under the jurisdiction of the Uinta Forest Reserve later to become the Uinta National Forest.

In his diaries, Albert Potter then the associate Chief of the Forest Service examined the land that would eventually become the Uinta National Forest and made these observations (Potter, 1902):

> August 7, 1902: Left Heber for a trip south to Strawberry and Hobble Creek– took road leading up Daniels Canyon. The farming lands extend along the creek for about 2 miles and then beyond there are grazing lands on the ridges for about 2 miles farther until the line of the proposed reserved lands have been bought from the State by the stockmen. As soon as the unsurveyed lands are entered, a difference can be noticed in the feed and the farther up the canyon you go the more heavily grazed the country is, the head of the canyon being just about tramped out (i.e., Daniels Summit- the edge of the upper Strawberry River watershed). As soon as the line of the Uintah Indian Reservation is crossed (i.e., approximately US Route 40 bridge at the Strawberry River) a marked change is again noticed. There is good grass and plenty of woods and browse. The country shows the difference restriction of grazing makes in range condition.

Potter's observations demonstrate that prior to land reallocation in the Strawberry Valley, from the Uintah Valley Reservation to what is today the Uinta National Forest, much of the land was relatively undisturbed.

Heber Valley ranchers who had previously leased grazing from the Uintah Indian Office in Fort Duchesne now petitioned the Bureau of Reclamation to continue grazing on the reallocated lands. Consequently, on March 10, 1906, the Secretary of the Interior leased the withdrawn lands to several Heber Valley ranchers for grazing purposes. It wasn't until the 1970s that grazing pressures were reduced by 20% through implementation of rotational grazing management and segregated (e.g., sheep and cattle) stocking. Grazing on the mainstem of the upper Strawberry River was completely removed in 1990, however grazing in the upper headwater reaches continues to the present. Historically, much of the watershed has scars from human influence in the region over the past 200+ years (Table 1). In the past these influences stemmed from grazing, flow diversions, and logging. In modern times, while grazing still occurs in the upper headwater areas, the largest influence would be recreationists, on the system of dirt roads using off-road vehicles. These forms of recreation were noted in the USFS (2004) report as large sources of degradation to the local stream system.

3.5 Hydrology and the history of water use in the upper Strawberry River

The upper Strawberry River watershed is characterized by a snowmelt-driven flow regime. The higher elevations of the upper Strawberry River are > 3000 m and are snow-covered throughout the winter, resulting in flows that typically peak between mid-May and early June as temperatures warm and recede to base flow levels by mid- to late July. Summer precipitation is characterized by convective thunderstorms from July through September, resulting in locally heavy precipitation for short durations. Historic stream-flow records for the upper Strawberry River are limited. The only local gage records are for Hobble Creek at Daniel's Summit Ditch from 1963 to 1984 (USGS gage #09280400) and the Strawberry River and Willow Creek Ditches from 1949 to 1960 (USGS gage #09280000). Both of these gages measured flow diversions from the upper Strawberry River into Daniels Creek and then onto the Provo River for use on the Wasatch Front. For this study, a pressure transducer was installed in August 2008 on the upper Strawberry River at the U.S. Route 40 crossing to measure discharge and temperature for use in this study and future monitoring efforts.

The upper Strawberry River is part of the greater Strawberry Reservoir watershed which contains several diversions. These diversions were part of Reclamation's Upper Colorado Region Central Utah Project (CUP), which was created to develop water for irrigation, municipal use, and power generation. Consequently, the Strawberry Reservoir was created after several years of feasibility studies as part of the Strawberry Valley Project. Begun in 1906 and completed in 1915, the project stored and then distributed water to both valleys via

a series of tunnels and canals for agricultural and municipal uses. The main trans-basin diversions affecting the upper Strawberry River were built in 1872; two canals, Hobble Creek Ditch and the Willow Creek Ditch, diverted water from the tributaries of the upper Strawberry River to Daniels Canyon in Wasatch County. Water quantities were insufficient for this diversion to be driven by gravity flow, so a 330-m tunnel was excavated through the mountain which allowed additional water to be diverted from the upper Strawberry River drainage to Daniels Canyon (UDWQ, 2007; Figure 2). Approximately 70% of the diverted water was from the upper Strawberry River and the remainder from smaller tributaries resulting in the dewatering of ~26 km on the upper Strawberry River (USFS, 2004). The natural system hydrology was restored when the diversions were decommissioned in 2001.

3.6 Riparian vegetation

The dominant vegetation type of the floodplain is characterized by sagebrush and grassland with willows interspersed along the riparian corridor. There are several wet meadow areas along the river corridor which have sedges, grasses, and forbs resulting from emergent ground-water springs from associated side canyons. Much of the willows along the upper Strawberry River were extirpated due to over-grazing (1861 to 1989), herbicide treatments (1965 to 1973), and reduced flows as a result of the Daniels and Hobble Creek diversions (1872 to 2001 and 1890-1955 respectively). A series of oblique photographs compare historic and current

riparian corridors along the upper Strawberry River and illustrate the reduction in riparian cover since the late 1800s (Figures 3, 4 a & b, 5 a & b).

3.7 Beaver

The American beaver (*Castor canadensis*) historically had a strong presence along the upper Strawberry river corridor. There is evidence of buried dams, lodges, and debris in many of the bare banks along this corridor overlain with a meter or more of floodplain deposits. Examining the woody outcrops provides evidence of beaver mastication on the individual pieces of debris as part of their dam and lodge building activities. The beaver uses the surrounding vegetation to create dams, raise the associated water-table, and provide refugia from predators while providing forage for food. By raising the surrounding water-table they provide a suitable environment for recruitment of riparian vegetation (Pollock et al. 2007, McKinstry MC., 2001).

A major aspect of managing at larger spatial scales is recognizing that many stream fishes require access to a variety of habitat conditions to fulfill their life history requirements, a phenomenon known as habitat complementation. Management efforts will need to consider providing the full range of habitats needed by all life history stages if populations are to thrive (White and Rahel, 2008). The populations of beaver along the upper Strawberry River have fluctuated from 1938 to the present. From 1938 to the mid 1960's there were a total of 13 colonies and 24 dam structures evident in aerial photographs. The number of colonies and

dams then plummeted to 5 colonies and 6 dams respectively, from 1965 to 2001(USFS, 2004). It would appear the loss of riparian habitat through extirpation of the willows from 1965 to 1971, led to loss of beaver habitat, resulting in a decline of beaver populations in the past several decades.

3.8 Upper Strawberry River restoration

In the decades since its construction, the Strawberry Reservoir has grown into the most popular recreational fishery in Utah and today receives over 2 million visitors per year (USFS, 2004; UDWR, 2007). In the early 1980s, the Bureau of Reclamation brought together stakeholders to examine resource concerns in the Strawberry Valley. These meetings illustrated the need for better management and restoration of many of the inflows to the Strawberry Reservoir. The concerns of the stakeholders focused on the desire for a sustainable and thriving sport fishery of adfluvial salmonids (i.e., Bonneville cutthroat trout and Kokanee salmon). Throughout its range, the Bonneville cutthroat trout (*Oncorhynchus clarki utah*) (BCT) has been the focus of restoration activities aimed at improving habitat for the various life stages of these species. However, BCT are not native to the upper Strawberry River. The Strawberry River is a headwater tributary of the Green River and ultimately flows to the Colorado River; thus, it was never connected to Pleistocene Lake Bonneville. Nevertheless, because of its value as a sport fish, BCT was introduced by the Utah Division of Wildlife Resources (UDWR) to Strawberry Reservoir in the early 1990s following the rotenone eradication of the reservoir's

existing fish populations. Today, Strawberry Reservoir is managed as a premier trout fishery.

Low BCT populations in the upper Strawberry River have been attributed to several causes, including high bank erosion rates, large fine sediment loads, high width-to-depth ratios, limited vegetative cover, and high summer daytime temperatures (UDWR, 2007). As a result, many of the restoration efforts in the Strawberry Valley have focused at remediating these perceived sources of habitat degradation.

The upper Strawberry River is the largest inflow to the Strawberry Reservoir and thus offers the greatest potential for increasing the quantity of spawning and rearing habitat. Restoration of the upper Strawberry River has included several projects that have targeted the alleged problem of excessive bank erosion. In the early 1990s, juniper revetments and willow plantings were placed along the outside of meander bends to stabilize the banks. This large-scale effort encompassed 32 km of the upper Strawberry River channel and some tributaries, using roughly 50,000 willow cuttings (USFS, 2004). The success of this earlier effort at reducing bank erosion rates and increasing the riparian corridor biomass has not been adequately assessed; no comprehensive pre- and post-project monitoring data are available to assess restoration effectiveness. Furthermore, these activities appear to have had little effect on the BCT recruitment and reproductive success, which remains the primary goal of the stakeholders. As a result, in 2008, the Utah Division of Wildlife Resources (UDWR), in conjunction with the Uinta-Wasatch-Cache National Forest,

began an in-stream habitat restoration project along the upper segments of the upper Strawberry River to address these concerns. This restoration project focuses on a 7 km section of the river from Bull Springs upstream to US Route 40 (Figure 6). According to the project proposal (UDWR, 2007), the stated objectives of the project are to:

- Restore and maintain the natural dimension, pattern, and profile of the upper Strawberry River
- Improve upstream fish migration from Strawberry Reservoir
- Stabilize eroding banks
- Reestablish a more natural riparian plant community
- Reduce stream temperatures
- Reconnect the river to its historic flood plain
- Improve and increase complexity of aquatic habitat
- Reduce fine sediment and improve spawning habitat

The methods used by the restoration designers to achieve desired results were as follows: the proper alignment and placement of rock and log vanes, root wads, and other structures which attempt to stabilize the channel. In addition, only structures suitable for this stream type based on the Natural Channel design developed by Rosgen (1994) were employed. A single thread channel with meanders and proper channel sinuosity was maintained. Rock and log vanes were placed at critical locations to protect stream banks and allow riparian vegetation to reestablish. Vertical banks were sloped to allow vegetative cover to establish. Willow clumps were transplanted from other Strawberry Valley locations to positions along the

newly sloped stream banks. Root wads and logs were also be used to protect stream banks and provide cover for trout. Coconut fiber was be used on outside bends of meanders to provide additional bank protection until vegetation becomes established. Sloped banks and other disturbed areas were reseeded with species currently found in the area that are appropriate for the site including water requirements. Channel realignment was necessary where excessive degradation had occurred, in order to reconnect the stream with the floodplain. When channel realignment was necessary, the old channel was converted into oxbow ponds whenever possible, thereby increasing habitat heterogeneity (UDWR, 2007, Figures 7 a & b).

Other than a two-page proposal describing in broad terms the goals and techniques of the project, no material plans, pre-project monitoring data or historical analysis was developed to guide project design and implementation (Justin Robinson, UDWR, personal communication, July 2010). Restoration planning (e.g., structure placement and riparian planting locations) was based entirely on qualitative field observations of flow angle of attack and perceived "eroding banks" during peak annual discharges. Consequently, this study seeks to inform the historical context and evaluate in-stream restoration techniques and their effect on the project goals.

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Chapter 4-Methods

The main goals of this thesis were to use historical, hydrological, along with contemporary survey data to examine the perceived sources of degradation as well as the performance of a restoration project on the upper Strawberry River, Utah. The historical database examines historical changes of the perceived source of degradation-bank erosion and whether the perceived problem is factual or an expected component in this system. The hydrological analysis attempts to characterize the upper Strawberry Rivers mean daily flow durations and annual flood frequencies. Furthermore, the 1-D hydraulic models can evaluate channel performance by comparing pre- and post-restoration change channel morphology and hydraulics. In order to accomplish these goals, the study obtained and analyzed historic aerial photographs, hydrological data, and present-day channel surveys to understand the system's historic variability and sources of degradation.

To address these goals, this study specifically uses four types of analyses to investigate changes in channel form prior to and following restoration: 1) measurement of changes in planform channel geometry and riparian cover from a decades-long record of historical aerial photography in a Geographic Information System (GIS) and 2) hydraulic modeling using surveyed cross-sections, analysis of longitudinal channel surveys as well as streambed sampling of spawning gravels, 3) site measurements of discharge and water temperature, and 4) a regional analysis of hydrology and hydraulics.

4.1 Aerial photograph analysis and interpretation

For the first analysis, completed GIS coverage's were developed from aerial photographs taken in 1938, 1946, 1956, 1963, 1978, 1987, 1993, 1997, 2006 and 2009 (Table 2). This GIS database was used to quantify changes in planform geometry, lateral migration rates, and the distribution of riparian vegetation over time.

Imagine and ArcInfo were used to georeference aerial photographs and create a GIS for analysis of the study area. The aerial photographs came from several sources including the U.S. Department of Agriculture Aerial Photography Field Office, the U. S. Geological Survey Earth Resources and Science Center, and the Utah State Geographic Information Database. In this study, co-registration was achieved using a 2006 digitally ortho-rectified quarter quadrangle (DOQQ) as a base layer. Of the six photographs that needed rectifying, only two (e.g., 1978 and 1987) had associated calibration reports. In each case, the calibration report was missing focal length, principal point, and at least one of the fiducial coordinates. As a result, these images were rectified using the same protocols as the images without calibration reports. The aerial photographs from 1993, 1997, 2006, and 2009 were all previously registered DOQQs. A second-order polynomial georectification model was used as the mode for rectifying the 1938 through 1987 historical image collection.

4.1.1 Aerial photographic rectification

The 2006 DOQQ was used to georeference the unregistered aerial images in Imagine. There are three main steps to do this: (i) matching of ground-control points (GCPs) on the scanned photo image and base layer (ii) transformation of the GCP coordinates on the scanned image from a generic raster set to a geographical projection and coordinate system and (iii) pixel resampling (Leys and Werrity, 1999, Hughes et al., 2006). Identification of adequate GCPs to increase positional accuracy was difficult in the study area because there were few anthropogenic features and the natural features change position over time. These GCPs were located using a Real-Time Kinematic (RTK) survey-grade GPS. These GCPs included road intersections, rock outcrops, and bridges and were not on the river corridor. GCPs that were part of the river corridor were unidentifiable in many of the early photographs. In combination with the surveyed GCPs, GCPs were located on the photographs for use in the rectification process. Many of the GCPs located on the images were immobile objects such as rock outcrops whereas others were old ranch and Forest Service Ranger cabins. Each co-registration was exhaustively combed for matching GCPs. Better accuracy and therefore lower error can be established by concentrating the GCPs in the target area (e.g., the river channel), but, in this study, objects were not readily available near the river channel. An alternative technique is to spread the GCPs over the entire image in the shape "X" which more evenly distributes the skew in the transformation and thus tends to reduce the amount of error in the resampled image (Hughes, 2006). In this study, a combination of an "X"

and an "O" pattern most efficiently minimized the overall error. In all, each image utilized approximately 30 GCPs for rectification purposes.

Once the GCPs were entered for both the base layer (i.e., the 2006 DOQQ) and the unregistered raster image, a polynomial transformation was applied to resample the image. There are two basic types of polynomial transformations that can be used for rectification. The first is linear and consists of a polynomial function with a numerical value of the highest exponent in the expression. As a result, 1st order, 2nd order, and 3rd order transformations are linear. In this study, 2nd order transformations were used because they tend not to excessively warp digital images and thus make the photograph unusable for data topographic extrapolation (Leica Geosystems, 2006). During a polynomial transformation, a least-squares function is fit between GCP coordinates on the unregistered image and base layer. This function is then used to assign coordinates to the entire photograph. After transformation, GCPs on the photo and base layer have slightly different coordinates, depending on the degree to which the overall transformation affects the positional area of each GCP. The difference in location between the GCPs on the transformed layer and base layer is represented by the total root-mean square error (RMSE), a metric based in the Pythagorean Theorem and calculated for a coordinate pair by the equation:

$$\boldsymbol{RMSE} = [(\boldsymbol{x_s} - \boldsymbol{x_r})^2 + (\boldsymbol{y_s} - \boldsymbol{y_r})^2] \quad (1)$$

where x_s and y_s are geospatial coordinates of the point on the source image; and x_r and y_r are coordinates of the same point on the transformed aerial photograph. The RMSE for the whole image is the sum of the RMSE for each coordinate divided by the square root of the number of coordinate pairs (Hughes 2006). In this study, the RMSE was relatively low for most of the images rectified with an average of 2.51m for all the images. Each time period (e.g., 1938 to 1946) had a calculated RMSE based on GCPs used for the transformation. The resulting RSME was then calculated per year for the time period. The largest RMSE was 0.58 m/y for the 1946 to 1953 period and the lowest was 0.16 m/y for the1963 to 1978 period (Table 3).

Once the image was georeferenced, a resampling step was utilized to normalize the pixel size throughout the image (Hughes et al. 2006). In many cases, the transformed image had pixels that differed in size depending upon the order of the transformation. To rectify this problem, there are three main techniques used to resample an image; nearest neighbor, bilinear interpolation, and cubic convolution. Cubic convolution smoothes the surfaces, whereas nearest neighbor tended to coarsen the images and bilinear interpolation is a combination of the two. Through successive iterations, it was determined that bilinear interpolation would be the best resampling method resulting in pixel sizes of 1m x 1m and of the best clarity of the three techniques.

4.1.2 Image interpretation

Rectified aerial images were overlain and then used to compute rates of lateral channel migration (LCM), as a proxy for bank erosion rates, as well as

average channel width, channel sinuosity, and the percent of riparian cover at different time steps in the record. Rates of LCM were computed using the following steps. First, the left and right active channel boundaries were digitized. In many of the earlier images, these boundaries were not evident due to upstream water diversions that left a dewatered channel. In these cases, the edge of the vegetation on the bed was used as a surrogate for the active channel boundary. Secondly, using the newly created active channel boundaries and the midpoint tool in the GIS software, a centerline was created for the channel. The midpoint tool generated a line that paralleled both left and right channel boundaries for the entire reach. In meander bends, the number of centerline points generated was increased to provide for a more accurate representation of channel curvature. Thirdly, channel centerlines for each time step were superimposed to define polygons that represented the area of floodplain that was eroded in each time period. Following the method of Micheli and Kirchner (2002), the average migration rate (m/y) for each eroded-area polygon was computed by dividing the polygon area by one-half its perimeter and then by the number of years elapsed between time steps. Mean annual LCM rate for the entire reach in each time period was taken as the average migration rate of all polygons in that time period; the number of polygons used in computing this average ranged from 46 (1953 to 1963) to 230 (2006 to 2009). Summing the error from the digitization and image rectification produced a total error of 22.6 m for a polygon formed from two centerlines. When divided by the time interval of 71 years, the result is an error of ±0.16 m/y for the average period

migration rate calculated for a polygon (Micheli and Kirchner, 2002). Polygons with annual migration rates smaller than this error were thus considered undetectable within the range of expected error and were excluded from the calculation of average LCM for a given time period (Constantine et al., 2009). In this way, georectification error was incorporated into the estimates of LCM rates.

While analyzing the images, it became evident that some of the polygons were the result of a meander neck or chute cutoffs. In some instances, it was also obvious that these cutoffs were the result of beaver activity. Beaver dams create low velocity zones around the beaver lodge that provide protection against predators and a winter feeding ground. Sediment deposition and accumulation in these low velocity zones cause channel aggradation, which eventually induces a change in river course that could be construed as channel migration. All polygons that were created as a result of a meander cutoff were therefore also excluded from the LCM calculation.

In addition to LCM, several other metrics of historical channel planform geometry were calculated for each period, including active channel width (b), sinuosity (p), and radius of curvature (R_c). Active channel width (b) was calculated along the entire study reach at each time step by dividing the area of a polygon between left and right channel banks by one-half the perimeter of the polygon. Computed widths for each polygon were then averaged to determine the mean channel width for the study reach at a given time step. Sinuosity (p) (the ratio of channel length to valley length) was determined from the digitized channel

centerline and the distance between reach endpoints. Radius of curvature (R_c) was measured in each image to examine the relationship of bend geometry and channel curvature (R_c/width) to channel width and to lateral migration rates. Prior to the extirpation of willows in the 1960s, many of the cutoffs appear to be as a result of beaver activity. However, in the photographs with little riparian vegetation, the mechanism for cutoffs is different. By examining the ratio of radius of curvature and channel width, Hicken and Nanson (1975, 1984) demonstrated that the rate of lateral migration reaches a maximum when $2 < R_c/\text{width} < 3$, with a decrease below 2 and above 3. Hooke (1975) also found that uniform down-valley migration, resulting in stable planform geometry, required a ratio in the range of 2 to 3. The ratio of radius of curvature and channel width can be used to evaluate channel stability and the tendency for meander-cutoffs. To measure radius of curvature (R_c), a circle was drawn on each meander bend that best fit the shape of the bend defined by the channel centerline. The radius of each circle was then calculated and taken to represent the radius of curvature for each bend (Nicoll et al., 2010).

4.2 Channel Reach Surveys and HEC-RAS

4.2.1 Reach and site surveys

Channel surveys were conducted to examine channel cross-sectional and longitudinal channel morphology. The ground-based surveys used a Real Time Kinematic Global Positioning System to measure the bed and water surface longitudinal profiles and channel cross-sections. The longitudinal water surface

profiles were surveyed at left-edge-of-water locations, whereas bed surface elevations were surveyed at the channel centerline. The main 7-km reach had four distinct restored and unrestored reaches for cross-section surveys at two different discharges, following the procedure of Harrelson et al. (1994). These surveys were then used in a 1-D hydraulic model to compare reach channel morphological and hydraulic characteristics among pre- and post-restoration reaches.

In September 2008, a channel survey was conducted following restoration of a 198-m long reach, hereafter known as the "Restored 2008" reach (Figure 8). Thirty-five channel cross-sections were surveyed on this reach in 2008, and again in 2009 and 2010. In 2009, 26 cross-sections were established on a 178 m-long reach upstream of "Restored 2008", hereafter known as "Restored 2009"(Figure 9). Cross-sections were surveyed on this reach prior to restoration in July 2009, following restoration in September 2009, and again in June 2010. Surveys were also conducted in 2009 and 2010 on two upstream unrestored reaches. Ten cross-sections were surveyed on the 105 m-long "Control 1" (Figure 10), immediately upstream of "Restored 2009) and slated for restoration in July 2010. Twenty cross-sections were surveyed on the 205-m long "Control 2" (Figure 11), the farthest upstream reach that will not be restored. Cross-sections were spaced at approximately 10m intervals or two bankfull widths.

A longitudinal survey of the active channel bed centerline and water-surface elevations was surveyed for the main 7 km reach. The survey was then plotted and examined longitudinally for areas of instability which may better explain excessive

channel widths, lateral channel migration, and sinuosity as calculated using a GIS as well as providing a general slope of the reach which was then used in the HEC-RAS model.

4.2.2 Bed material composition

Pebble counts (Wolman, 1954) were conducted as part of a habitat study (Nira Salant, personal communication) to examine the suitability of substrate for spawning salmonids and other aquatic organisms. Collection consisted of two evenly spaced samples from three riffles along each reach; the two samples per riffle were combined in order to amass a large enough sample to meet the criteria of Church et al. (1987). A MacNeil sampler because it allowed for retainment of the very fine sediment suspended during collection (MacNeil and Ahnell, 1984); the base of the sampler was capped to hold water and suspended material, which was then filtered through a < 4 μm mesh. All particles > 8 mm were sieved into standard size classes and wet-weighed in the field; all sediment < 8 mm, including the filtered suspended material, was bagged and returned to the lab for particle size analysis. The percentage of fine particles < 1 and 10 mm was then calculated for each riffle and computed the mean (±SE) fine sediment content for each reach. Due to longitudinal connectivity among reaches, substrate conditions on different reaches cannot be considered independent, violating a necessary assumption of an analysis of variance. Therefore, a test for significant differences in fine sediment content (< 1 and < 10 mm) was used among reaches or between sampling dates using a repeated measures model (Maindonald and Braun, 2003), treating reach or sampling date as

a fixed factor ("treatment") and riffle (sample location within reach) as a random factor. A repeated measures model was used because samples were taken ("repeated") at different streambed locations (riffles). Comparisons were made among reaches on a single sample date and between sample dates on each reach. We considered a p-value < 0.01 to be significant (Salant 2010-unpublished data).

4.3 HEC-RAS 1-D hydraulic modeling

The one-dimensional hydraulic model HEC-RAS was created in order to estimate water-surface elevations, flow depths, channel geometries, and hydraulic conditions for observed baseflow and bankfull as well as modeled BCT spawning discharges. After calibration, the models were then used to evaluate the effects of in-stream channel habitat restoration on morphology and hydraulics at three different discharges. Such information is valuable to initial success of the restoration project.

Hydraulic models of each study reach were calibrated by varying the Manning's *n* roughness coefficient until the computed water-surface elevations matched the surveyed water-surface elevations. Water-surface elevations were surveyed at baseflow 0.4 m^3/s (Q_b) and bankfull of 4.1 m^3/s (Q_{bf}). A third modeled discharge or BCT spawning flow of 1.93 m^3/s (Q_{spawn}) was also analyzed to examine habitat change amongst pre- and post-restoration channel alterations.

The focus of the modeling analysis was on the 'Restored 2009' reach which was the only surveyed reach with pre- and post-restoration survey data. Hydraulic outputs for the three modeled discharges were analyzed and included; cross-

sectional channel-average boundary shear stress, cross-sectional flow area, cross-sectional hydraulic depth, cross-sectional mean velocity, and water-surface active channel width for cross-sectional and longitudinal channel morphology adjustments. Restored 2008, Control 1, and Control 2 reaches have data which will be used for future monitoring of the project.

4.4 Site measurements of discharge and temperature

A pressure transducer along with discharge measurements was used in conjunction to establish a rating relation for the gage at the bridge on US Route 40. The rating relation and measured water surface elevations from the pressure transducer were used to compute associated discharge values. The pressure transducer collected data every 15 minutes. For the period-of-record the mean daily discharge was then calculated. The mean daily values were used to create a time series of discharge flows for 2009 and 2010 and were analyzed for information on; mean annual stream flow, expected timing, magnitude and frequency of annual peak flows, and flow variability. The pressure transducer also measured water temperature and was used to analyze maximum summer water temperatures.

4.5 Regional analysis of hydrology

4.5.1 Developing a time series of hydrology from Strawberry Reservoir inflows

The upper Strawberry River has no flow data other than 2009 and 2010. Stream flow records are scarce for Strawberry Valley streams. The U.S. Geological Survey operated a stream gage on Indian Creek between 1909 and 1911 and only partial records are available from this period. The only local gage records are for Hobble Creek at Daniel's Summit Ditch, Utah from 1963 to 1984 (USGS gage #09280400) and the Strawberry River and Willow Creek Ditches, Utah from 1949 to 1960 (USGS gage #09280000). Both of these gages measured flow diversions from the upper Strawberry River into Daniels Creek and then onto the Provo River.

Total stream flows from Strawberry Valley can therefore be interpreted from records of the Strawberry Reservoir storage for 1949-2001, created by the U.S. Bureau of Reclamation and kept by the Strawberry Valley Water Users Association. This information is then used to describe why rates of lateral channel migration, channel width, sinuosity along with changes in riparian cover affect the system as a result of hydrologic variation. Reservoir records include monthly and annual reservoir water surface elevation, water storage, measured outflow to the Strawberry River downstream from Soldier Creek Dam and through the Strawberry Tunnel and (since 1990) inflows from the Strawberry Aqueduct and Collection System (SACS). The resulting record can be used to calculate total stream inflow from the equation:

$$\Delta S = flow\ (in) - flow\ (out) \quad (2)$$

where ΔS is the change in water storage in the reservoir and *flow(in)* is inflow to the reservoir and *flow(out)* is flow out or water losses from the reservoir. Excluding stream flow, all of the main inflows and outflows from the reservoir are measured and includes: releases to the Strawberry and Syar tunnels, releases to Soldier Creek, and SACS inflows. Two important components are not measured - evaporation and seepage losses - but these are accounted for by the change in reservoir water surface elevation (USFS, 2004, Bob Gecy,USFS Hydrologist, personal communications).

The reconstructed inflow records to the Strawberry Reservoir were from 1949 to 2001 and consequently did not cover the first and last periods of the aerial photographic analysis. Consequently, another regional basin with longer temporal resolution was analyzed and plotted along with the inflow data to corroborate high flow events. The Weber at Oakley, Utah (USGS gage # 10128500) was analyzed using mean daily discharge data from 1938 to 2009. The Weber River watershed is roughly 40 kilometers north of the upper Strawberry River watershed and is located on the western edge of the Uinta Mountains. High years for recorded inflows to the reservoir were 1952, 1983 to 1986, 1995, and 1997 to 1998. Whereas, the Weber River gage reflected high flow years as; 1952, 1965, 1975, 1983 to 1986, 1995, 1997 to 1998, 2005 and 2009. These large flow years reflect a larger snowpack which

potentially reflect higher hydraulic and scour forces resulting in potentially greater changes in channel morphology.

4.5.2 Flow-Duration analysis

A flow duration curve (FDC) was created to show the percentage of time that flow in a particular stream is likely to equal or exceed a specified value of interest. To do this, data was again used from the White River below Tabbyune Creek near Soldier Summit, Utah (USGS gage # 09312600, 1968 to present or 43 years). The mean daily discharge of the upper Strawberry River at US Route 40 was plotted versus the White River below Tabbyune Creek mean daily for the same time period to quantify correlation (i.e., October 1st, 2008 to September 31st, 2010). The discharge data was plotted and a least squares linear regression trendline was computed from the data which provided an $r^2 = 0.83$ and an equation where $y = 0.301(x)^{0.666}$. Imputing the discharge data (i.e., 'x') into the regression equation resulted in a discharge value (i.e., 'y'). The calculated discharge values were then normalized based on the ratio of the drainage area for the upper Strawberry River at US Route 40 (i.e., 73.8 km^2) and the White River below Tabbyune Creek gage (i.e., 184.1 km^2). The calculated discharge value and the associated exceedence probability were used to create a synthetic FDC for the upper Strawberry River. This curve was then used to describe the percent of time the surveyed and modeled flows for the upper Strawberry River were equaled or exceeded.

4.5.3 Flood Frequency analysis

A flood frequency analysis was created using flow data from an adjacent watershed to understand the relationship between flood magnitude and its recurrence interval on the upper Strawberry River of surveyed and modeled flows. The analysis utilized gaging records (i.e., 1968 to 2011 or 43 years) from the White River below Tabbyune Creek near Soldier Summit, Utah (USGS gage # 09312600) which has basin attributes which are similar to that of the upper Strawberry River. To do this a Log-Pearson Type III distribution was used to fit the annual maximum of the mean daily discharge data for $Q_{2\text{-}100}$ floods. This data was then normalized using the ratio of basin area for the two watersheds.

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Chapter 5-Results, Discussion and Conclusions

5.1 Aerial Photograph analysis and interpretation of historical geomorphic planform change

-Lateral channel migration

Lateral channel migration (LCM) is a natural process where-by the outside of a meanderbend represents erosional surfaces while the inside of the meanderbend represents an area of deposition. Restoration on the upper Strawberry River relied on the perceived belief that excessive bank erosion was expediting disproportionate amounts of fine sediments to the channel. These fine sediments were then being deposited in BCT spawning gravels contributing to low recruitment and unsustainable resident populations of BCT. The study examined LCM rates for the entire 7km reach for the period-of-record in two ways. First, the calculated rate per longitudinal distance downstream for each time period was lumped together then plotted upstream to downstream to examine lateral instabilities longitudinally without regard to time. Secondly, LCM rates were calculated for each period in the record to examine where present rates compare to historical rates.

Lateral channel migration rates are distinctly different among three sections of the 7 km reach, corresponding to distinct differences in channel slope (Figure 12). From the upstream-most river-station (RS) 0 to RS 3217, the slope is 0.005, from RS 3217 to RS 3769 the slope is 0.002, and from RS 3769 to the bottom of the reach at RS 6970 the slope is 0.0035. These three different regions of slope correspond to LCM rates of 0.56 m/yr, 0.42 m/yr, and 0.49 m/yr, respectively. As seen in Figure

12, the lateral migration rate varies along the channel profile, showing regions of higher lateral instability.

The study sought to examine if modern LCM rates were excessive as compared to historical rates. LCM rates from 1938 to 2009 were on average 0.54 m/yr (Figure 13a). The period of the greatest lateral channel migration was from 1946 to 1953 (0.77 m/yr) and the two lowest rates occurred in the two most recent periods, 1997 to 2006 and 2006 to 2009 , 0.32 m/yr and 0.36 m/yr, respectively.

-Sinuosity, active channel width, and the ratio of radius of curvature to channel width

Mean sinuosity of all images in the record was 1.91 (Figure 13b). From 1938 to 1978, the mean sinuosity was 1.87 ± 0.03. From 1953 to1987, mean sinuosity increased by 7% from 1.83 to 1.96. From 1987 to 2009, mean sinuosity was 1.93 ± 0.003.

Active channel width increased from 1938 to 1987 by ~39%, followed by a 23% decrease from 1987 to 2009 (Figure 13c). Mean channel width from 1938 to 1987 was 4.71 ± 0.93 m. From 1987 to 2009, mean width was 6.25 ± 0.2 m.

In general, the ratio of radius of curvature and channel width (R_c/b) – which represents meander bend tightness – ranges from 2 to 3. Because the shape of the meander bend affects bank erosion rates (Knighton, 1998), R_c/b draw a parallel with lateral channel migration rates. On the upper Strawberry River from 1938 to 1978, the number of cutoff channels and the ratio of R_c/b increased from 4 to 14 and

from 2.67 to 3.07, respectively. After 1987, the number of cutoff chutes and R_c/b decreased.

-Riparian vegetation

The loss of a riparian area may increase bank erosion and lateral channel migration which were perceived sources of degradation in the system prior to restoration activities. For this study a 75-m buffer was created in the GIS which encircled the channel centerline. The buffer attempts to encompass and take account of the riparian area prior to its extirpation starting in the 1940's as a result of ranchers needs to the late 1960's with the USFS chemically treating the system which fully eradicated most riparian vegetation. The amount of riparian vegetation decreased from 62% in 1938 to 27% in 1963 (Figure 13d). Detailed examination of the aerial photographs from 1978 to 1997 revealed no discernible riparian vegetation along the river corridor. Recolonization of riparian vegetation began in the early 2000s as the amount of riparian vegetation was 4 and 5.5% in 2006 and 2009, respectively.

5.2 Channel reach surveys and HEC-RAS

-Streambed samples and composition

The percentages of fine sediment < 1 and 10 mm did not differ significantly among reaches for either sampling date (Oct09, 1 mm: p = 0.96; Oct09, 10 mm: p = 0,21; Jun10, 1 mm: p = 0.39; Jun10, 10 mm: p = 0.46) (Table 4). Furthermore, the

percentage of particles < 1 mm was not significantly different between sampling dates for any reach (R08: $p = 0.06$; R09: $p = 0.75$; Unrest: $p = 0.17$). However, the percentage of particles < 10 mm was significantly greater in June 2010 than in October 2009 on all reaches ($p < 0.01$). On average, the percentage of particles < 1 mm was 8.8 (±0.15) % in October 2009 and 12.6 (±0.44) % in June 2010; the percentage of particles < 10 mm was 10.7 (±0.07) % in October 2009 and 40.4 (±0.7) % in June 2010(Nira Salent, personal communication).

-Comparison of pre- and post-restoration channel planform and hydraulics using HEC-RAS

Because the main goal of the hydraulic modeling analysis was to evaluate the effects of habitat restoration on channel morphology and hydraulics, only the Restored 2009 reach was focused on in the analysis, since this reach was surveyed several weeks before and after restoration. The restoration along the upper Strawberry sought to provide suitable habitat for BCT as well as other sport fish. In-stream modifications associated with habitat enhancement may be a source of positive as well as negative change. For example, a reduction in width: depth ratios (i.e., deeper and narrower channel) would also reduce potentially lethal summertime water temperatures for resident BCT, whereas making a meanderbend laterally static (i.e., coconut matting to prevent bank erosion) may reduce recruitment of riparian vegetation (Noble, 1979). In this study several hydraulic variables are analyzed via a 1-D hydraulic model to examine how in-stream modifications assist or hamper habitat metrics for success.

Channel shape and planform and geometry were relatively unchanged by restoration, given that the channel was not reconfigured. The main difference between the pre- and post-restoration channel was the construction of greater pool depths and drop log bank flow deflectors anchored by large boulders or concrete blocks. Along the banks, which were deemed excessively eroding coconut matting was installed and willow cuttings were introduced to help with recruitment.

The Restored 2009 pre-and post-restoration reach-averaged channel dimensions are presented in Table 5. At the bankfull discharge (Q_{bf}), the mean cross-section velocity decreased by 12% from 0.65 m/s to 0.58 m/s after restoration, likely due to the increased depth along the reach as a result of restoration activity. Most of the decrease in channel velocity occurred from XS 1 to 10, corresponding to a decrease in the water-surface elevation by nearly 16.2 cm (Figure 14). The reach-averaged hydraulic depth increased after restoration for all of the modeled discharges, with the greatest increase occurring for the Q_{bf} discharge, 13 % from 0.73 m to 0.84 m, corresponding to a decrease of the water-surface elevation by 9.2 cm. Hydraulic depth increased the most from XS 7 to 10 for the baseflow discharge (Q_b) (30 %) and from XS 17 to 20 for the spawning discharge (Q_{spawn}) (16 %) (Figures 15 a-c). Flow area decreased after restoration for the Q_b discharge by 6% and by 8.7% for the $Q_{4.1}$ discharge, but increased by nearly 7% for the Q_{spawn} discharge. The flow area for the three modeled discharges changed relatively little, with the Q_{spawn} discharge having the greatest increase from XS 18 to XS 26 (20% or 0.84 m^2) (Figure 16) For the Q_{bf} discharge, the calculated shear stress

for the entire reach decreased by 57 % (21.4 to 8.4 N/m^2) with most of the reduction occurring between XS 1 and 10. After restoration, width to depth ratios decreased on average 5.1% (2.6 m) from a mean of 16.1 to 15.3 for the three modeled discharges (Figure 17).

5.3 Site measurements

-Site measurements of Q and T, frequencies and duration of observed flows

Based on continuous discharge measurements at the installed pressure transducer, in the 2009 water year, the mean annual flow was 0.71 m^3/s with a maximum recorded instantaneous peak discharge of 5.64 m^3/s on May 24, 2009 which based on the flood frequency analysis is a $Q_{2.5}$ recurrence-interval (RI) flow and is equaled or exceeded 0.38% of the year or 1.4 flow days per year. For the 2010 water year the mean annual flow was 0.47 m^3/s with a maximum recorded instantaneous peak discharge of 3.68 m^3/s on June 6, 2010, which based on the flood frequency analysis, is a $Q_{1.7}$ RI flow and is equaled or exceeded 1.8 % of the year or 6.5 flow days per year. The bankfull flow (Q_{bf}) was surveyed on May 18, 2009, at 4.1 m^3/s and was a $Q_{1.9}$ RI flow and is equaled or exceeded 1.3% of the year or 4.7 flow days per year (Figures 18, 19 and 20).

Recorded temperatures at the US Route 40 bridge gage site never increased to thresholds (e.g., = or >25^o C) which may have led to fatality amongst BCT populations (Figure 21). However, from June 31st to July 5th, 2010 were above 18^{o}C,

which is a level that researchers describe as “stressful” for BCT populations (Johnstone and Rahel, 2003).

5.4 Regional analysis of high flow years and LCM rates

Comparing records of the yearly total streamflow record (1949 to 2001) with LCM rates, channel widths and riparian vegetation over the period of record reveals clear relationships between hydrology and channel conditions (Figure 22). Furthermore, another regional basin with a longer temporal resolution was analyzed and plotted along with the inflow data to corroborate high flow events. The Weber at Oakley, Utah (USGS gage # 10128500) was analyzed using mean daily discharge data from 1938 to 2009. The Weber River watershed is roughly 40 kilometers north of the upper Strawberry River watershed and is located on the western edge of the Uinta Mountains. High years for recorded inflows to the reservoir were 1952, 1983 to 1986, 1995, and 1997 to 1998. Whereas, the Weber River gage reflected high flow years as; 1952, 1965, 1975, 1983 to 1986, 1995, 1997 to 1998, 2005 and 2009. These large flow years reflect a larger snowpack which potentially reflect higher hydraulic and scour forces resulting in potentially greater changes in channel morphology.

Chapter 6 Discussion and Conclusions

6.1 Discussion

The foundation for restoration on the upper Strawberry River rested on qualitative observation that bare banks meant the system had high erosion rates resulting in degraded habitat conditions for Bonneville cutthroat trout (BCT). However, observations of bare banks do not indicate information about lateral channel migration, channel stability or biologically relevant geomorphic conditions. A historical analysis provides information about temporal variations in channel conditions and processes, which can be used to evaluate whether current conditions warrant concern or are within range of historic natural variability (Kondolf et al., 2006, Wohl, 2005). The assumption, that on the upper Strawberry River excessive bank erosion was degrading BCT habitat had no historical context. Furthermore, there was no established link which illustrated that fine sediments were degrading BCT spawning gravels. On this assumption restoration designers moved forward to manipulate channel flow dynamics through drop log structures, root wads, pool depths to stem sources of degradation. However, the study illustrates that bank erosion rates in the last decade are at their lowest level in 71 years and that fine sediment was not inhibiting egg growth and subsequent fry emergence in spawning gravels.

In the absence of bank stabilizing vegetation, the series of high flows in the early to mid-1980s likely triggered channel widening and increased sinuosity

(Thorne, 1990; Simon and Darby, 1999). Although vegetation loss and bank destabilization may have temporarily increased bend growth and curvature, it was possibly the lack of vegetation that caused sinuosity to subsequently decline in the late 1980s and early 1990s, due to either installation of juniper revetments and/or the formation of chutes and cutoffs (Murray and Paola, 2003; USFS, 2004; Tal and Paola, 2007, 2010). Thus, the loss of riparian vegetation and high flow years did cause a short-term increase in bank erosion rates, by which the channel adjusted its width and sinuosity. However, the constant channel width and sinuosity of the past two decades suggests that the channel has achieved a new quasi-steady state. Lateral migration rates were the lowest in the 71 year period of record prior to restoration, despite only modest increases in riparian cover and the return of natural flows to the river in 2001.

The percentage of fine sediment in spawning areas was insufficient to have the potential for a significant biological impact on BCT spawning success. Historical bank erosion and channel widening does not appear to have affected present-day habitat conditions. Furthermore, the amount of streambed fine sediment was similar among restored and unrestored reaches, indicating that bank erosion was not contributing to local or reach-scale differences in bed composition. Relative channel stability, low migration rates, and small quantities of streambed fine sediment indicate that bank erosion was not causing habitat degradation in this system, a finding that runs counter to the assumptions of project designers.

Temperatures recorded on the upper Strawberry River had roughly 5 days with high mean daily temperatures above 18^{o} C which is considered a lower threshold value for stress of Bonneville cutthroat trout (BCT). Although the system would benefit from an increase in riparian biomass, which would help maintain lower daily maximum temperatures, the temperatures recorded are not a major limiting factor for BCT recruitment or sustainability along the upper Strawberry River.

1-D hydraulic modeling of the Restored 2009 reach found modest declines in velocity, shear stress, and width:depth ratios with an increase in hydraulic depth following restoration activities. While most of these variables (i.e., water surface slope, top channel width and width:depth ratios) demonstrated a shift towards project objectives, they constituted <10% change in channel morphology. The greatest change for the three modeled discharges was reduction in cross-section shear stress ranging from 9% to 57% respectively. It should be noted that 1-D models, such as HEC-RAS, are insufficient to capture the full hydraulic effect of in-stream structures (Minor, 2007; Shen and Diplas, 2007). Hence, the 1-D hydraulic models indicate small initial success of the objectives; however project success at this point in time is difficult to measure. The need for future monitoring will provide better insight into success or failure of the in-stream restoration techniques used on the upper Strawberry River.

The restoration designers utilized a restoration techniques based on the popular Rosgen (1994) classification system. This classification system attempts to

predict a rivers behavior from its appearance and thereby recommends techniques which will provide a stable channel form among other results. The upper Strawberry River is not laterally confined and as such should be allowed to follow a natural course. Additionally, the analysis suggests that the system has already reached a more stable setting. Utilizing the results of a historical analysis would have provided a substantive link to solutions which could have provided project designers with viable alternatives to restoration for BCT.

6.2 Conclusions

Taking into account the results of the historical analysis, sediment sampling and 1-D hydraulic modeling which found; present lateral channel migration rates were at a historical low, stable channel width and sinuosity, a riparian corridor that is recovering, and a lack of fine sediments in BCT spawning gravels, and little change in channel morphology as a result of physical manipulation measures, many of the restorative techniques on the upper Strawberry River may have been unnecessary and/or inadequate.

The bank stabilization techniques may be detrimental to system stability in the future as was the juniper revetments installation in the late 1980s and early 1990s (USFS 2004). Furthermore, bank stabilization may have potentially detrimental effects on the function and structure of the riverine environment in the future. The placement of boulders and drop log structures in the stream banks was intended to constrain lateral migration and maintain a static channel condition. Lateral channel migration, however, has important effects on in-stream and

floodplain habitat for fish and other aquatic organisms. In a meandering river, cut bank erosion leads to the deposition of point bars, which provides sediment suitable for the establishment of pioneer plant species such as willow and cottonwood (Read, 1958; Everitt, 1968; Wilson, 1970; Johnson et al., 1976; Noble, 1979). Consequently, revegetation efforts on the upper Strawberry River may therefore be limited in the future if there is insufficient bank erosion and sediment deposition for willow recruitment and establishment. Although lateral channel migration rates were relatively high in the 1940s and 1950s, vegetation cover declined during this period because of intense grazing pressure and chemical/mechanical willow removal (USFS 2004). Some vegetation growth has been possible in recent years with the removal of livestock grazing in 1989, but may be constrained in the future without natural bank erosion and sediment deposition.

Channel migration enhances the physical complexity of in-stream and floodplain habitats. Meander migration and chute cutoffs create valuable off-channel spawning and winter rearing habitat for salmonids, including overflow channels, sloughs, and wetlands (Beechie et al., 1994). Erosion of vegetated banks can also supply woody debris to the stream, which enhances habitat complexity by creating pools, trapping sediment, and redirecting flow (Montgomery et al., 2003). Although accelerated bank erosion and channel widening can degrade in-stream habitat, cut bank erosion and lateral migration are essential components of a meandering river ecosystem. A historical comparison can help assess whether contemporary erosion rates are accelerated relative to past conditions; the period-of-record low migration

rates and stable channel form of the upper Strawberry River in recent decades indicate that bank erosion is an unlikely cause of habitat degradation in this system. Furthermore, it is important to consider that BCT are not native to the upper Strawberry River and did not live in the river until the 1990s. As such, historical river characteristics (e.g., geography, habitat, and hydrology) may never have been suitable for a resident population of BCT. Additionally, utilizing present-day surveys of channel morphology can provide a baseline dataset with which to model and adaptively manage the objectives of the restoration in the future.

Reestablishing historical physical conditions appears impractical and returning the system to its pre-disturbance condition would require reversing a century of human alterations, including the Strawberry Reservoir and associated diversions. Nevertheless, despite being altered from its pre-disturbance condition, the present-day channel is stable and bank erosion is not degrading spawning habitat. As such, the maintenance of suitable spawning habitat for BCT does appear to be a feasible management strategy. The study would recommend refocusing restoration efforts on other potential sources of degradation (e.g., riparian cover). Furthermore, concentrating on a healthy riparian corridor may assist in expansion of beaver habitat which may have positive and lasting effects for BCT habitat. Beaver allow for the development of pools and woody vegetation that provide cover for older trout as well as maintain hydrologic refugia for episodic low flow years (White and Rahel, 2008). Consequently, beaver habitat compliments riparian

growth and assists the sustainability of resident populations of fish and other aquatic organisms.

The study illustrates how restoration efforts on the upper Strawberry River not only inaccurately targeted bank erosion as a source of degradation, but may also inhibit riparian recovery and habitat improvement in the future by limiting natural channel migration. Additionally, using surveyed data of channel morphology coupled with a hydraulic model can provide an enhanced understanding of in-stream restoration techniques and their success or failure at creating habitat for target species. These results illustrate how a historical analysis and current channel surveys can be used to identify sources of degradation and assist the development and management of a more effective restoration design plans in the future.

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Tables-

Table 1: The upper Strawberry River record of post-colonial human influences 1776 to 2009

Key moments in the upper Strawberry River history	
1776	Dominguez and Escalante-Dominican Friars/explorers search for a new route to California, move through the upper Strawberry Valley.
1820 to 1840	European fur trappers enter region on permits from Spanish government to trap. One of the main targets for these traders was beaver that by many accounts was scarce by the late 1820s
1844	John C. Fremont-explorer and surveyor of region
1859	Settlement of Heber Valley
1861	President Lincoln authorizes establishment of Ute Indian Reservation in Uinta Basin
1874 to 1889	1st Water diversions from upper Strawberry River to Heber Valley leading to skirmishes with Ute tribe over water rights with Heber Valley pioneers. U.S. government sends troops in 1888 to occupy the upper Strawberry River region and quell conflicts
1902	Reclamation Act establishes U.S. Reclamation Bureau (later became the Bureau of Reclamation) and funds Federal water projects in 12 western states
1905	Strawberry Valley Project approved pending negotiation of water rights
1905(December)	Congress approves water rights, withdraws "project" lands from Reservation
1912	Strawberry Dam, Reservoir, and tunnel completed
1925	USBR leases grazing rights to Strawberry Water User's Association (SWUA)
1934	Currant Creek feeder canal delivers water from Currant Creek to Co-op Creek
1973	Soldier Creek Dam completed; reservoir expanded from 8,800 surfaces acres to 17,160 surface acres via the Central Utah Project
1989 to 1990	Juniper revetment placed along 20 km of Strawberry River to mitigate perceived excessive bank erosion
2001	Diversions along the headwaters of the Strawberry River decommissioned allowing natural flows.
2007 to 2009	In-stream active restoration along the Strawberry River to stem excessive bank erosion and provide suitable habitat for BCT

Table 2: Aerial photograph attribute table: B/W – black and white, CI – Color Infrared, and C - Color

Acquisition date	Agency	Office	Scale(m)	Attributes
9/2/1938	USBR	U.S. Bureau of Reclamation Salt Lake Aqueduct Project.	1:11600	B/W
8/4/1946	USGS	EROS Data Center	1:11000	B/W
8/6/1953	USGS	EROS Data Center	1:19500	B/W
9/5/1963	USGS	EROS Data Center	1:11600	B/W
10/6/1978	USDA	Aerial Photography Field Office	1:19500	B/W
9/17/1987	USDA	Aerial Photography Field Office	1:7500	CI
8/24/1993	USGS	EROS Data Center	1:8500	B/W
9/30/1997	USGS	EROS Data Center	1:8501	B/W
6/1/2006	USDA	Utah Automated Geographic Reference Center	1:7500	C
8/13/2009	USDA	Utah Automated Geographic Reference Center	1:7500	C

Table 3: Aerial photograph period and associated root mean square error (RMSE) per year and per period.

Period	RMSE per year (m)	RMSE per period(m)
1938-1946	0.30	2.38
1946-1953	0.58	4.06
1953-1963	0.44	4.38
1963-1978	0.16	2.34
1978-1987	0.30	2.68
1987-1993	0.35	2.12
1993-1997	0.39	1.96
1997-2006	0.22	1.95
2006-2009	0.25	0.76
MEAN	0.33	2.51

Table 4: Percentages of fine sediment <1 and <10 mm from riffle locations on three reaches of the Strawberry River, Utah, in October 2009 and June 2010. Values are the mean (SE) of three riffles.

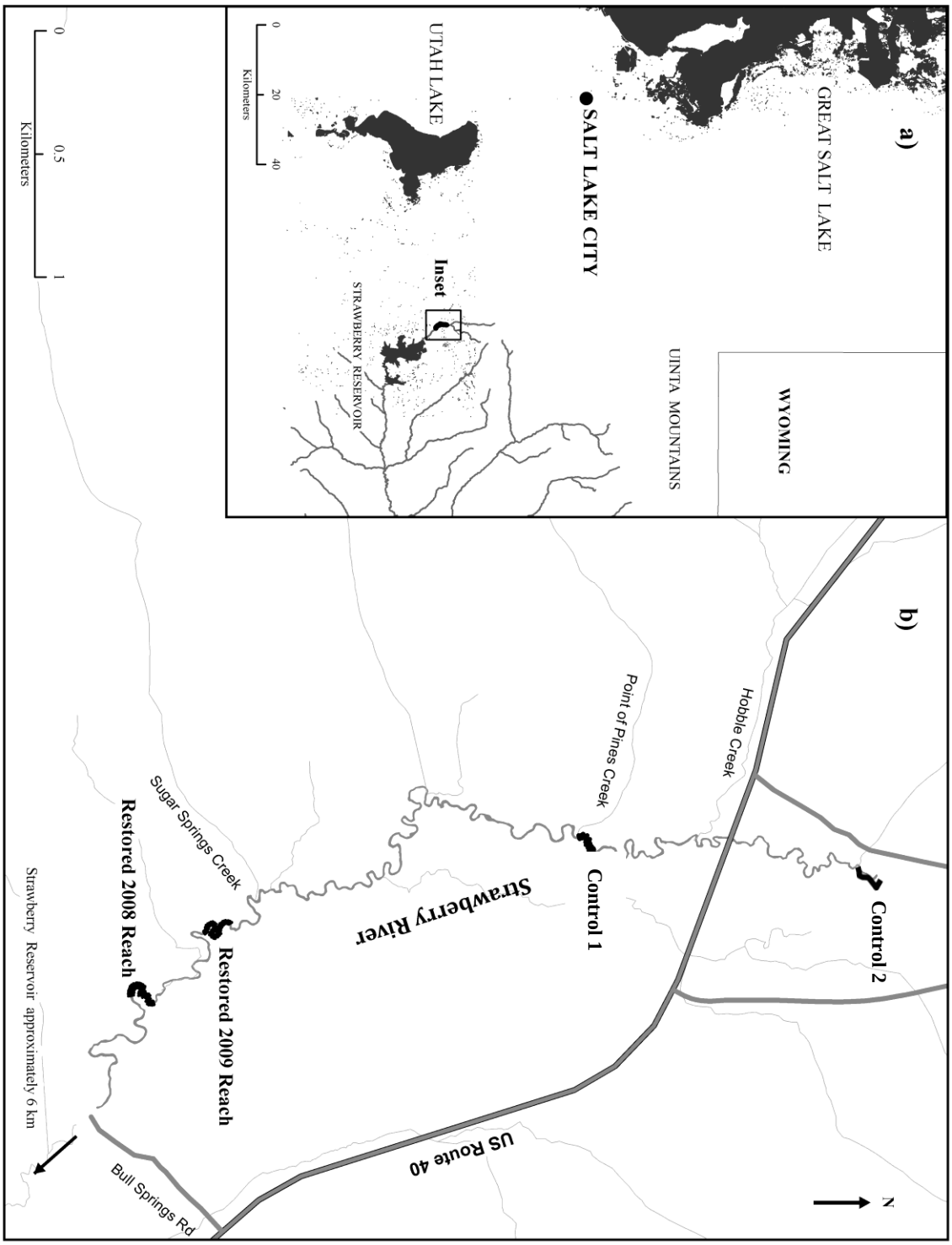
Reach	October 2009		June 2010	
	< 1mm	< 10 mm	< 1mm	< 10 mm
Restored in 2008	8.93(1.4)	10.9(0.29)	9.92(2.6)	36.7(4.7)
Restored in 2009	8.46(1.5)	10.2(0.43)	14.6(1.8)	41.0(2.3)
Unrestored	9.00(1.9)	10.5(0.44)	13.2(2.5)	43.5(3.7)
Mean	8.79(0.17)	10.5(0.25)	12.6(1.4)	40.4(2.0)

Table 5: Results of the HEC-RAS analysis for three discharges of 26 surveyed cross-sections pre- and post-restoration of variables left to right; 1) mean water surface slope, 2) mean velocity, 3) mean flow area per modeled discharge, 4) mean cross-sectional shear stress, 5) mean cross-sectional depth, 6) water surface width across channel and, 7) width to depth ratio. The percent change reflects the differences for the "Restored 2009" reach pre- and post-restoration.

Discharge	reach	water surface slope	U	flow area	shear	hydraulic depth	top width channel	b:h ratio
(m^3/s)			(m/s)	(m^2)	(N/m^2)	(m)	(m)	
0.4	Control 1	0.07	0.38	1.29	6.81	0.23	5.94	25.8
	Restored 2008	0.02	0.26	1.94	6.79	0.3	6.38	21.3
	Restored 2009-Pre	0.02	0.27	1.77	5.44	0.3	5.87	19.6
	Restored 2009-Post	0.02	0.27	1.67	4.98	0.3	5.57	18.6
	pre-/post change	**-9%**	**0%**	**-6%**	**-9%**	**0%**	**-5%**	**-5%**
1.93	Control 1	0.06	0.7	2.92	18.06	0.37	8.01	21.6
	Restored 2008	0.02	0.49	4.27	14.59	0.5	8.02	16.0
	Restored 2009-Pre	0.02	0.51	4.1	12.63	0.53	7.68	14.5
	Restored 2009-Post	0.01	0.46	4.4	9.29	0.55	7.63	13.9
	pre-/post change	**-17%**	**-11%**	**7%**	**-36%**	**4%**	**-1%**	**-4%**
4.1	Control 1	0.05	0.95	4.85	23.22	0.48	11.07	23.1
	Restored 2008	0.02	0.64	6.7	18.86	0.7	11.17	16.0
	Restored 2009-Pre	0.01	0.65	7.87	16.31	0.73	10.54	14.4
	Restored 2009-Post	0.01	0.58	7.24	10.38	0.84	11.41	13.6
	Pre-/Post change	**5%**	**-12%**	**-9%**	**-57%**	**13%**	**8%**	**-6%**

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Figures-


a)
GREAT SALT LAKE
WYOMING
UINTA MOUNTAINS
SALT LAKE CITY
UTAH LAKE
Inset
STRAWBERRY RESERVOIR
0
20
40
Kilometers
b)
Control 2
Hobble Creek
Point of Pines Creek
Control 1
Strawberry River
Sugar Springs Creek
Restored 2009 Reach
Restored 2008 Reach
US Route 40
Bull Springs Rd
N
0
0.5
1
Kilometers
Strawberry Reservoir approximately 6 km

c)

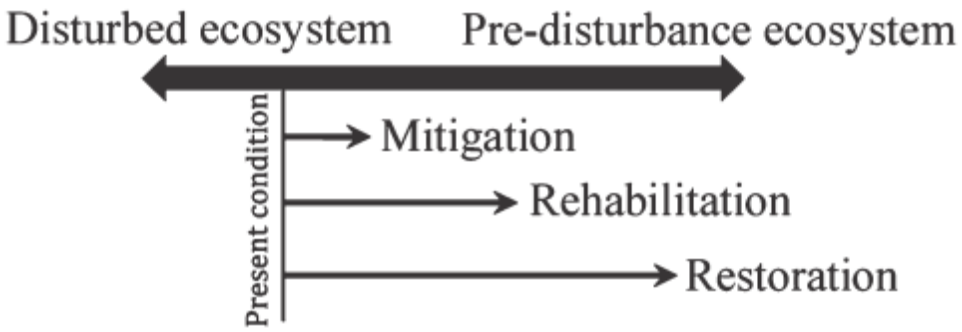


Figure 1: a) Location of study site in Utah, b) Study reach on the upper Strawberry River and, c) Three degrees of restoration to consider when selecting a restoration strategy.

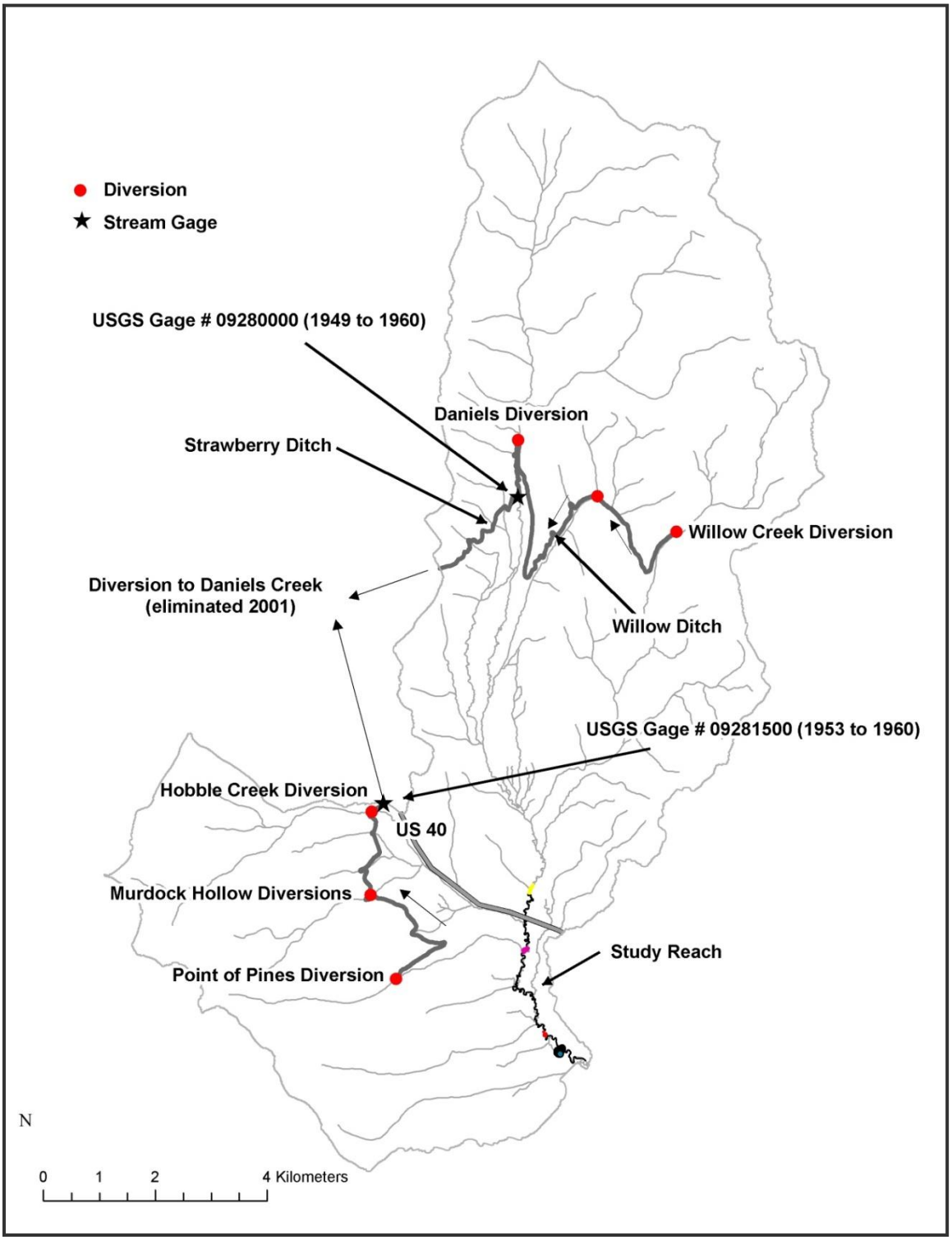


Figure 2: Upper Strawberry River watershed and trans-basin water diversions

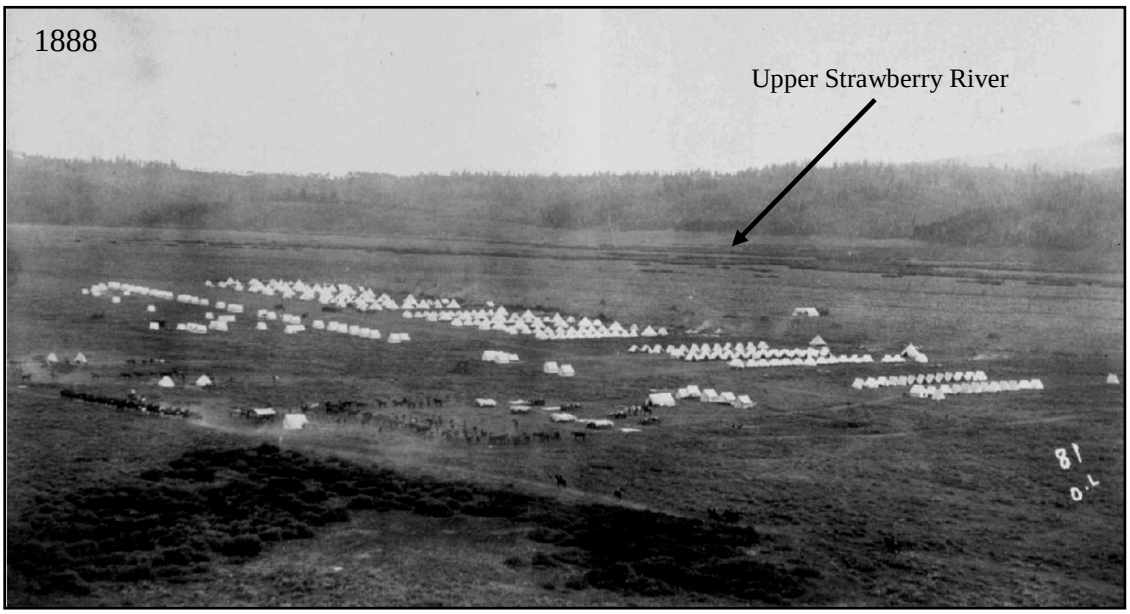


Figure 3: Photograph of U.S. Army barracks on the upper Strawberry River valley in 1888. The Strawberry River flows along the far section of the valley right to left (USFS 2004).

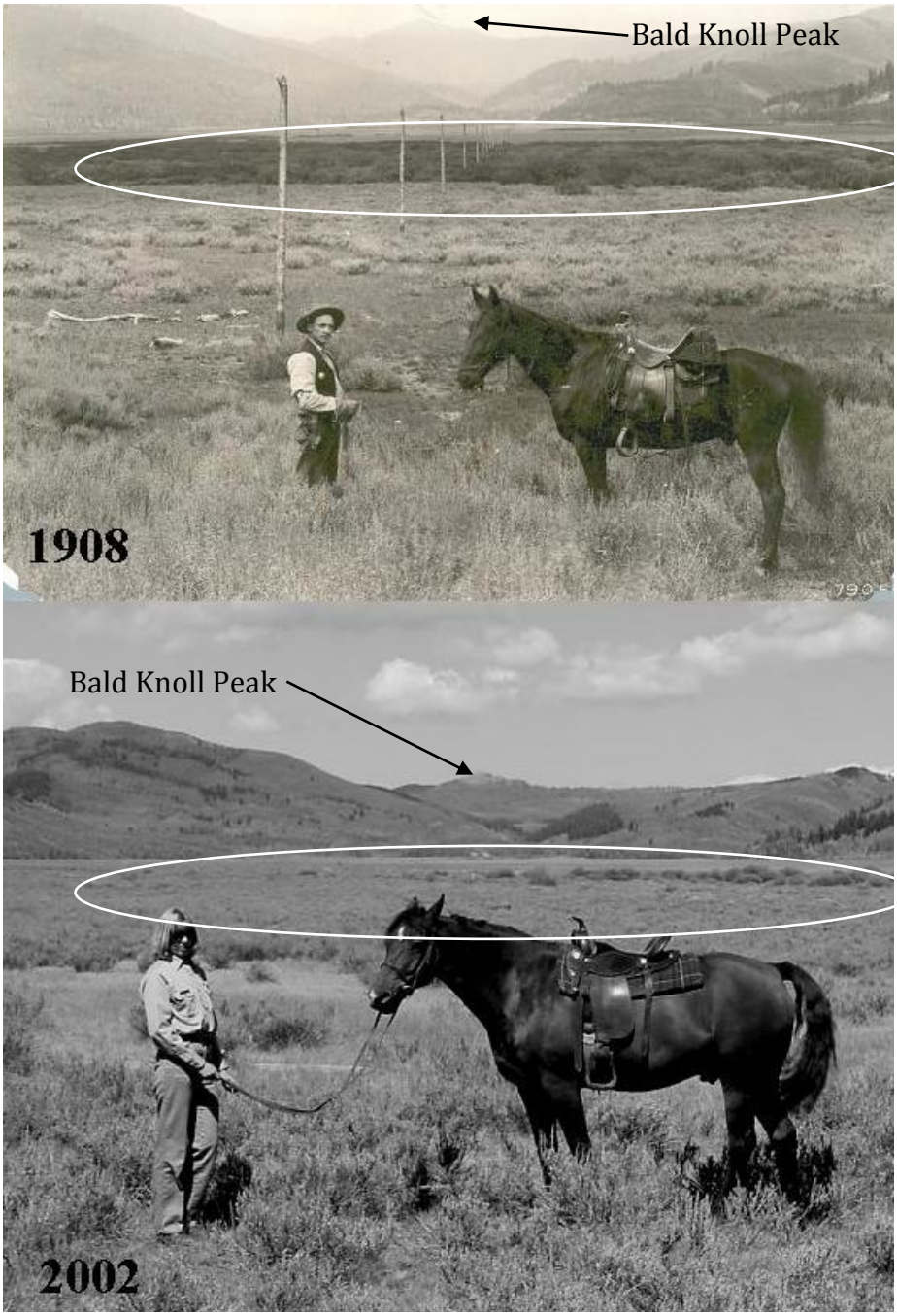


Figure 4 a & b: Photographs comparing riparian vegetation(circle) of the Strawberry River in 1908 (top image) and 2002 (bottom image). Both pictures are pointed northward up the valley near Telephone Hollow. Pictured are Strawberry District Ranger George Fisher (top) and Heber District Ranger Julie King (bottom) (from USFS 2004).

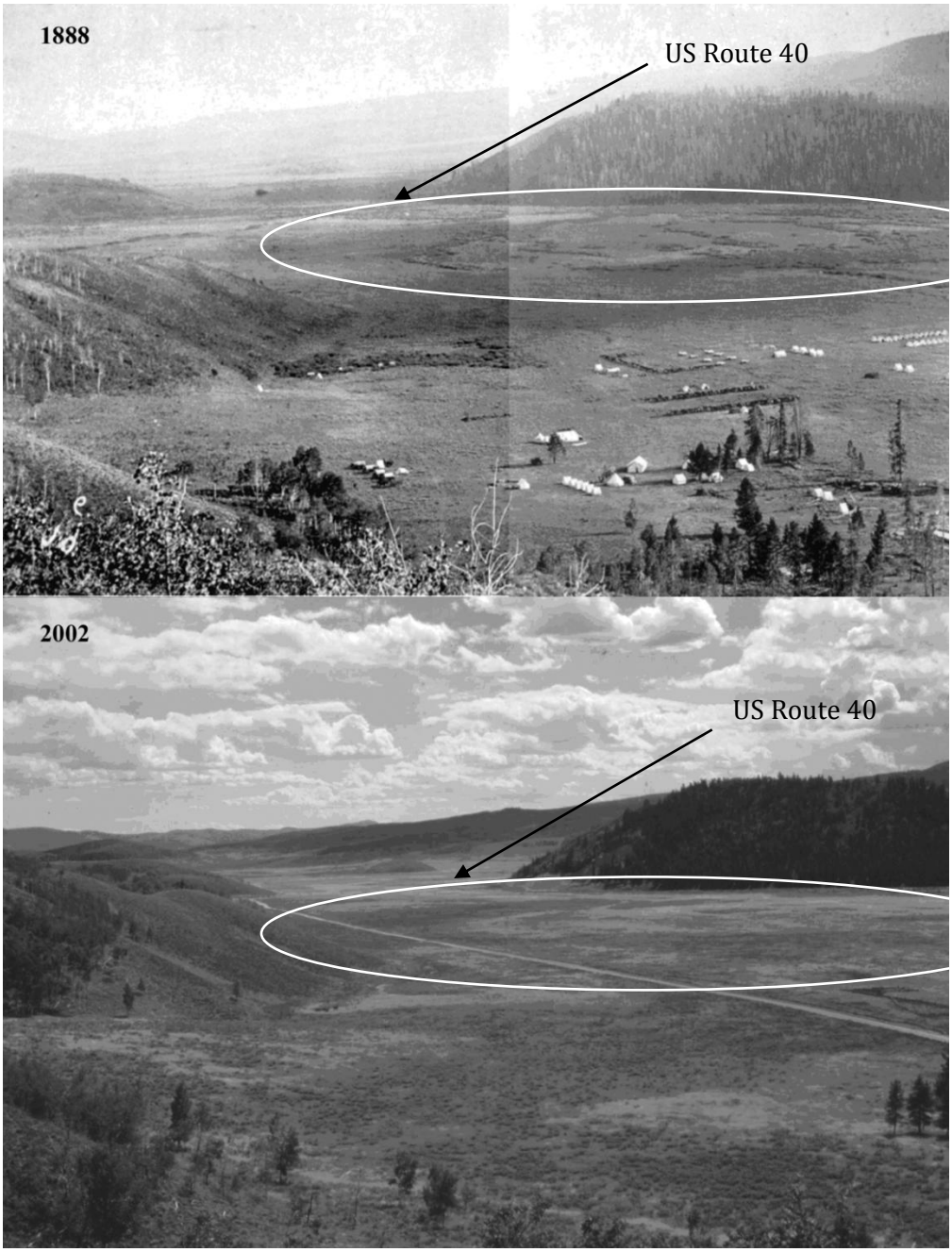


Figure 5 a & b: Photographs showing reduction in willows (circle) from 1888 (top image) to 2002 (bottom image). Both photographs look down-valley (southwest) towards U.S. Highway 40. The upper Strawberry River runs along the butte on the far side of the floodplain (from USFS 2004).

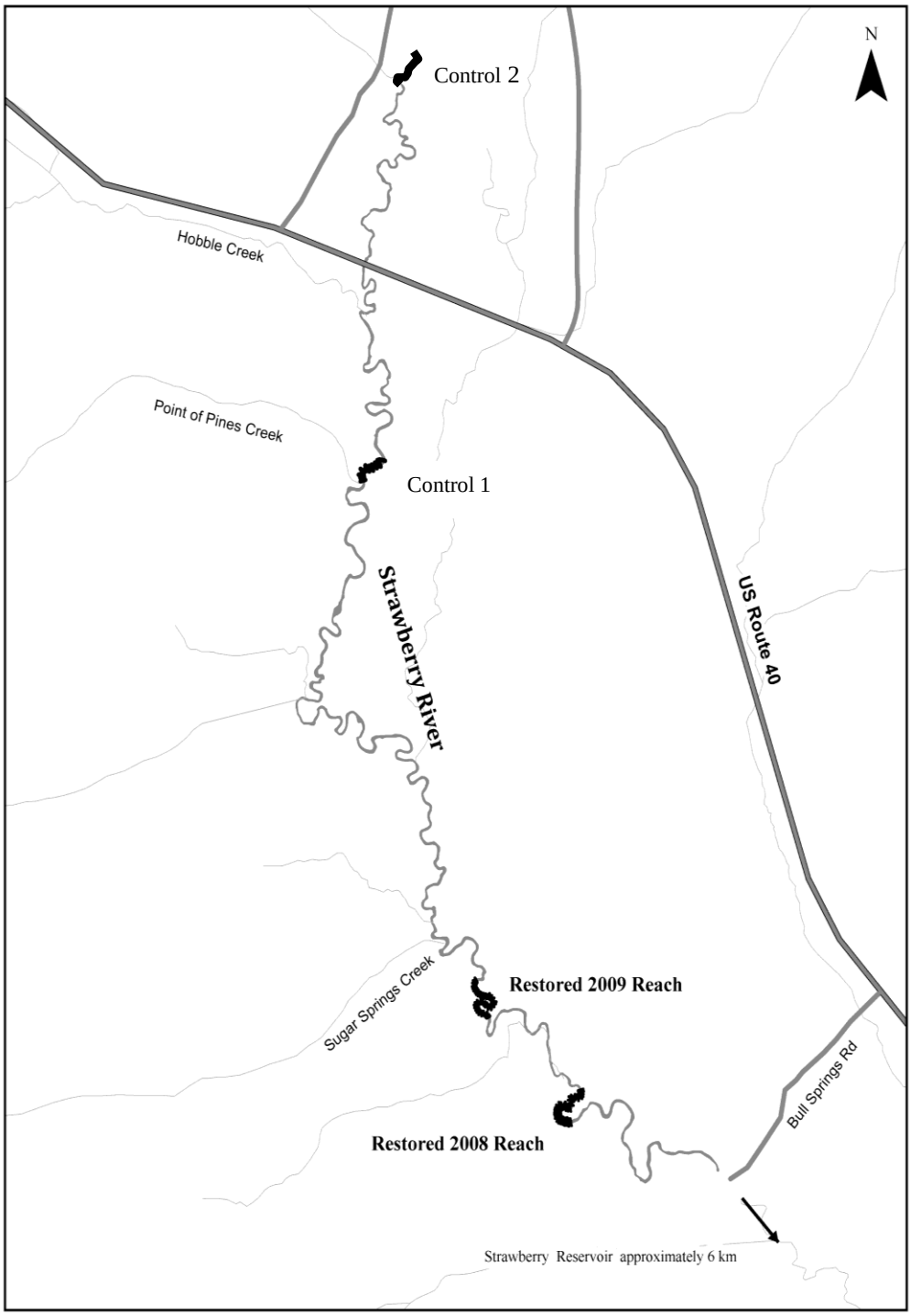


Figure 6: Study site showing Restored 2008 & 2009 reaches as well as the unrestored reach. The forth reach, Control 2 (above) was not overly effective for this study. Much of the reach was inundated with backwater from beaver dams built towards the end of the reach.

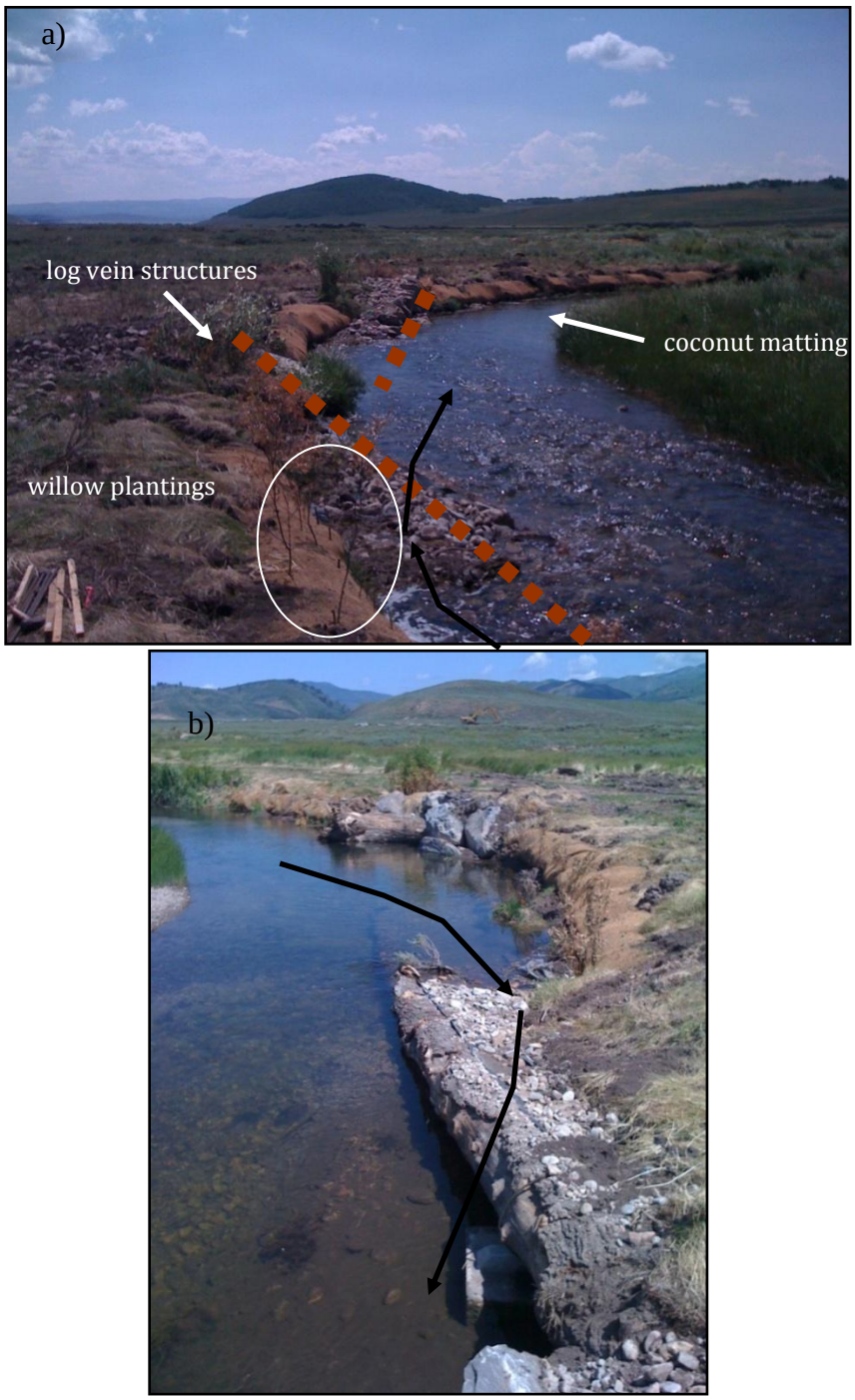


Figure 7 a& b: a) Restoration techniques on the Restored 2009 reach: log vanes to deflect bankfull flows towards the center of the channel, coconut matting to reduce bank erosion and create a better environment for willow establishment, and pools deepened to create refugia for resident fish; b) flow patterns around log vanes (flow direction indicated by arrows).

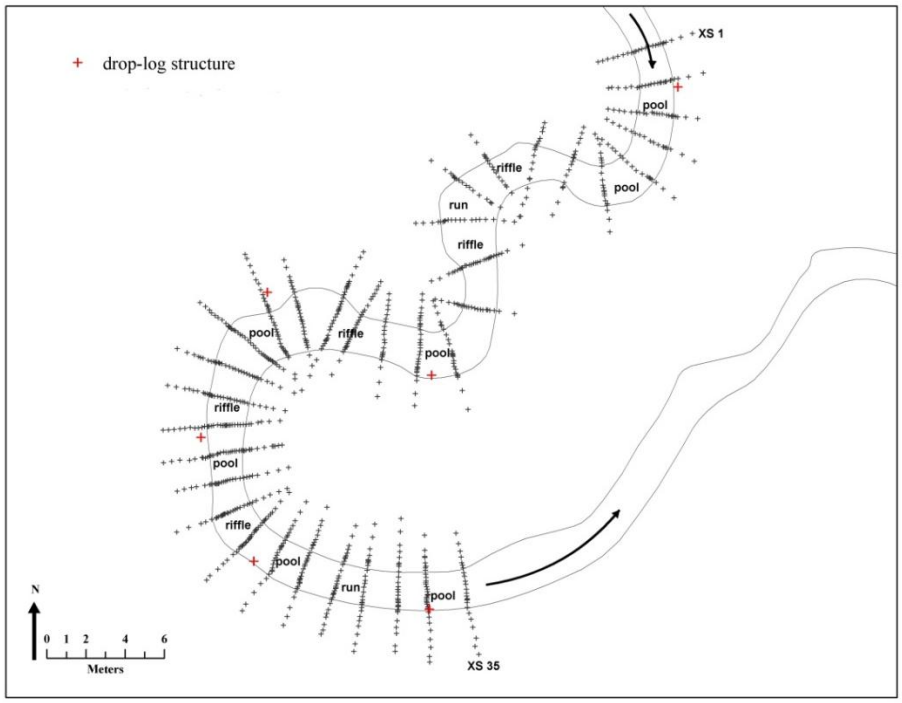


Figure 8: Cross-sections on Restored 2008 reach

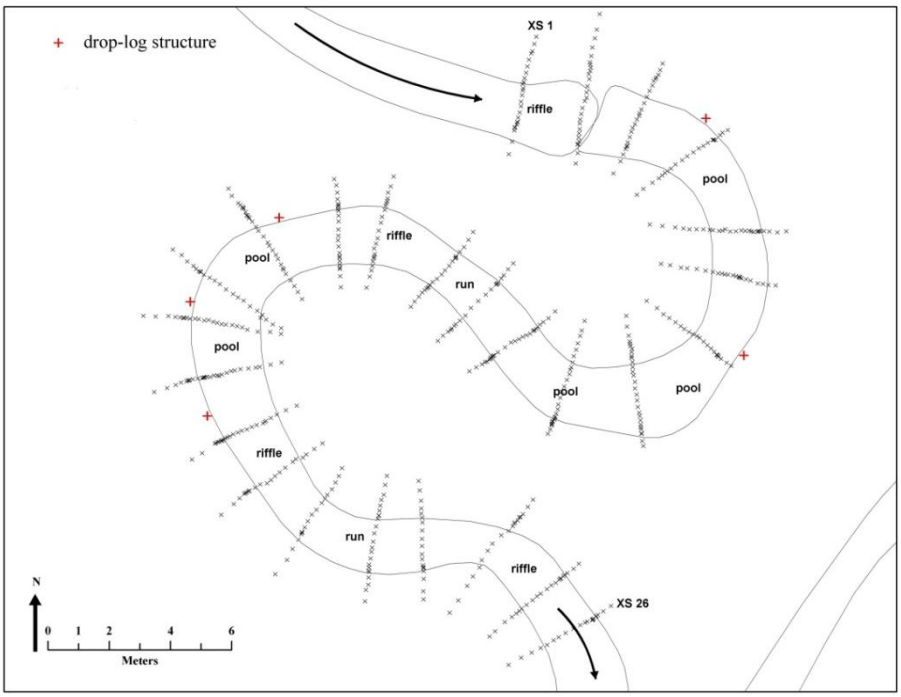


Figure 9: Cross-sections on Restored 2009 reach

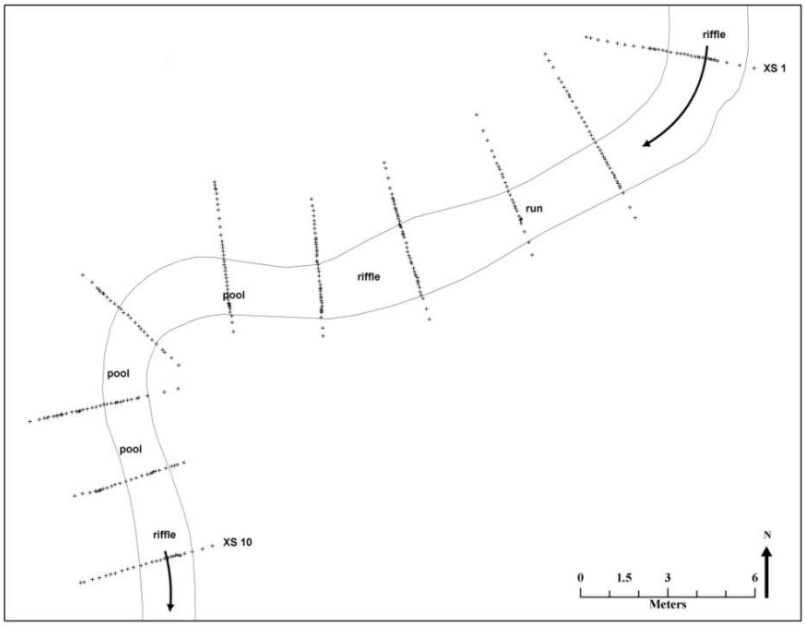


Figure 10: Cross-sections on Control 1 reach

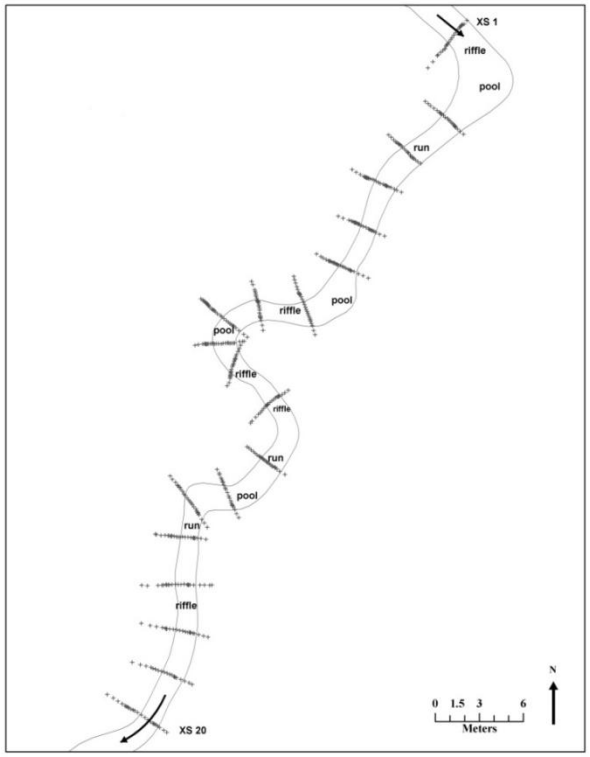


Figure 11: Cross sections on Control 2 reach

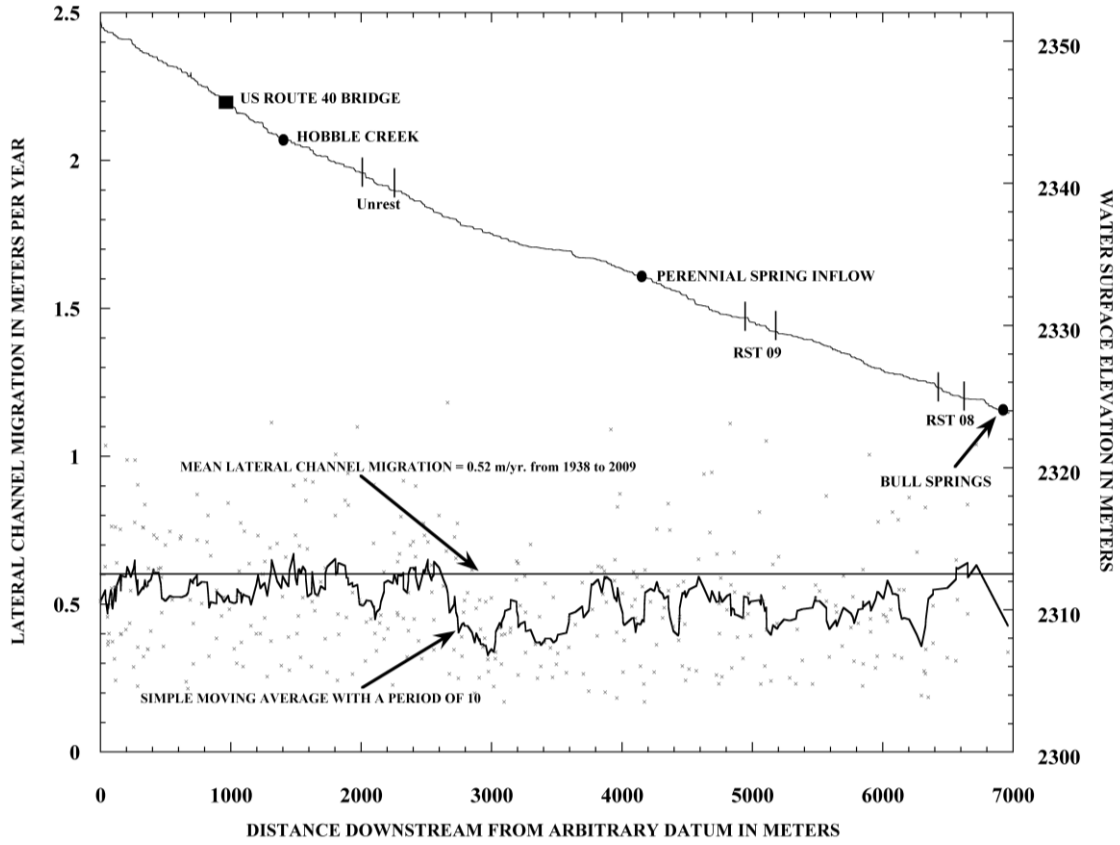


Figure 12: The top line is a longitudinal profile of the water surface elevation at baseflow or 0.41 m^3/s. Shown longitudinally are the US Route 40 Bridge, Hobble Creek inflow, Unrestored reach, spring inflow, restored reach 2009 and restored reach 2008. The lower scatter plot is all of the calculated lateral channel migration rates for the entire period of record. The trendline is a simple moving average with a period of 10, which approximately represents mean every 100 meters longitudinal distance of the previous 10 LCM calculations. Areas of lateral instability are readily observable longitudinally along the 7 km reach.

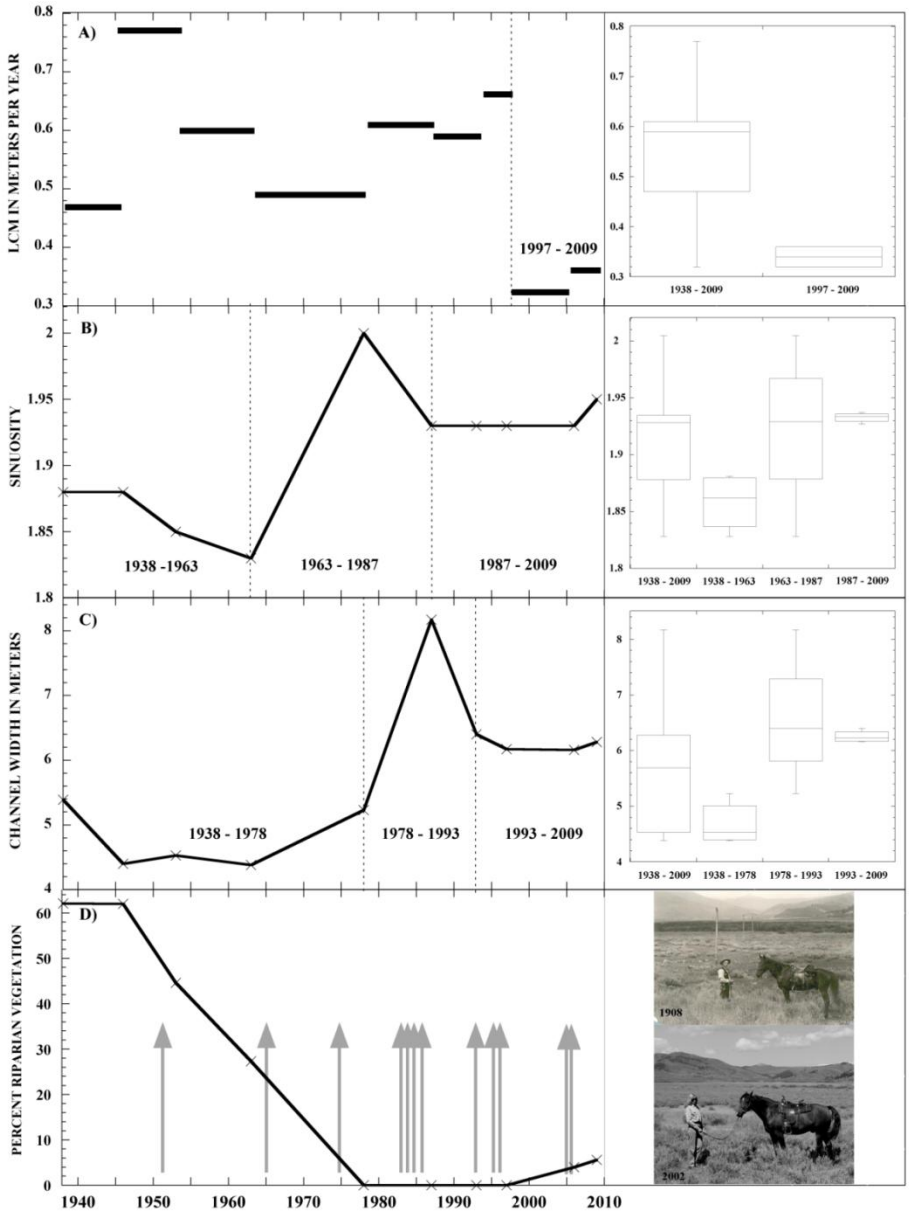


Figure 13 a-d: A) Lateral channel migration, B) sinuosity, C) mean channel width, and D) riparian vegetation cover of the Strawberry River, Utah, from 1938-2009. Box plots show the distribution of values for the full record (1938-2009) and periods of time within the record (demarcated by dashed vertical lines). Vertical arrows in (D) indicate high flow years. Photographs in (D) are from USFS (2004), showing the change in vegetation cover between 1908 (top image) and 2002 (bottom image), looking up-valley towards Bald Knoll Peak.

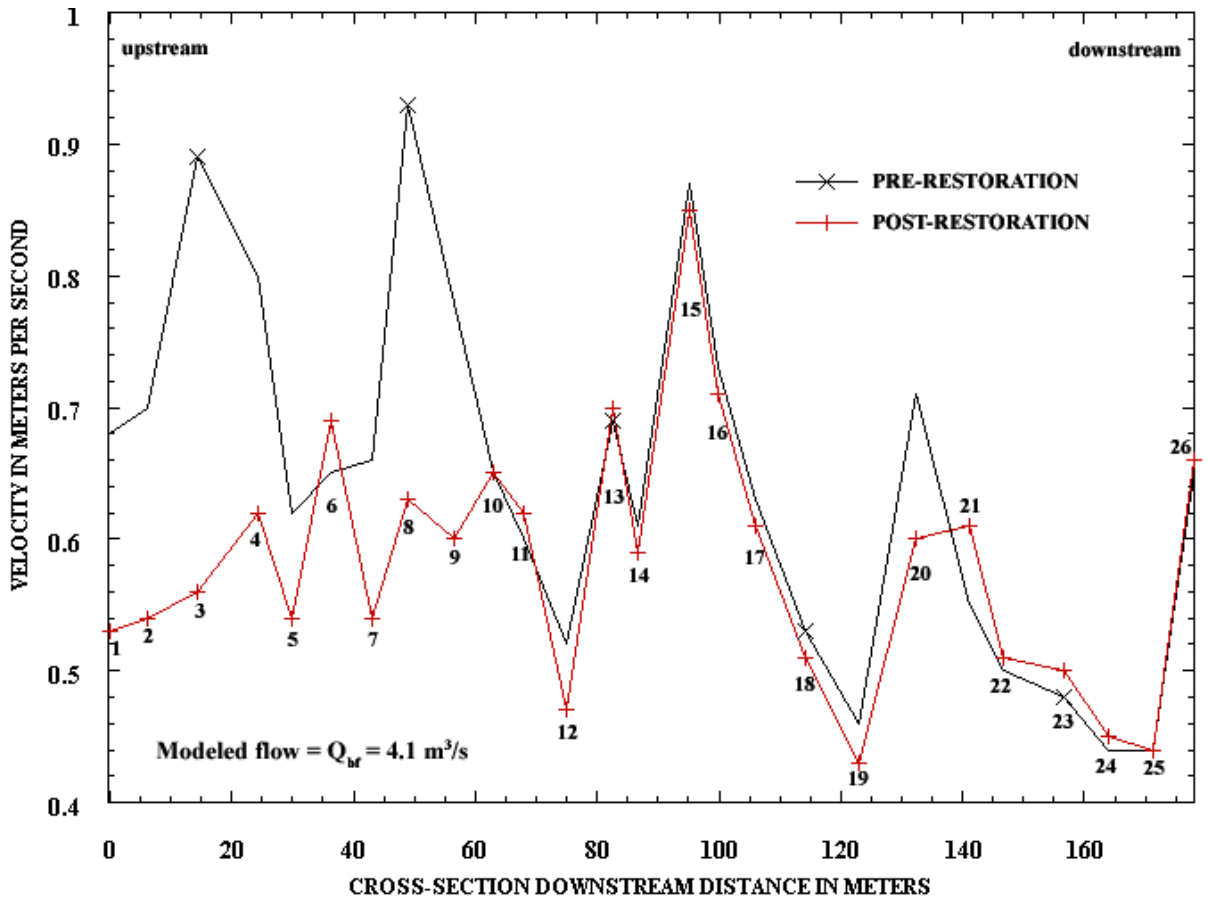
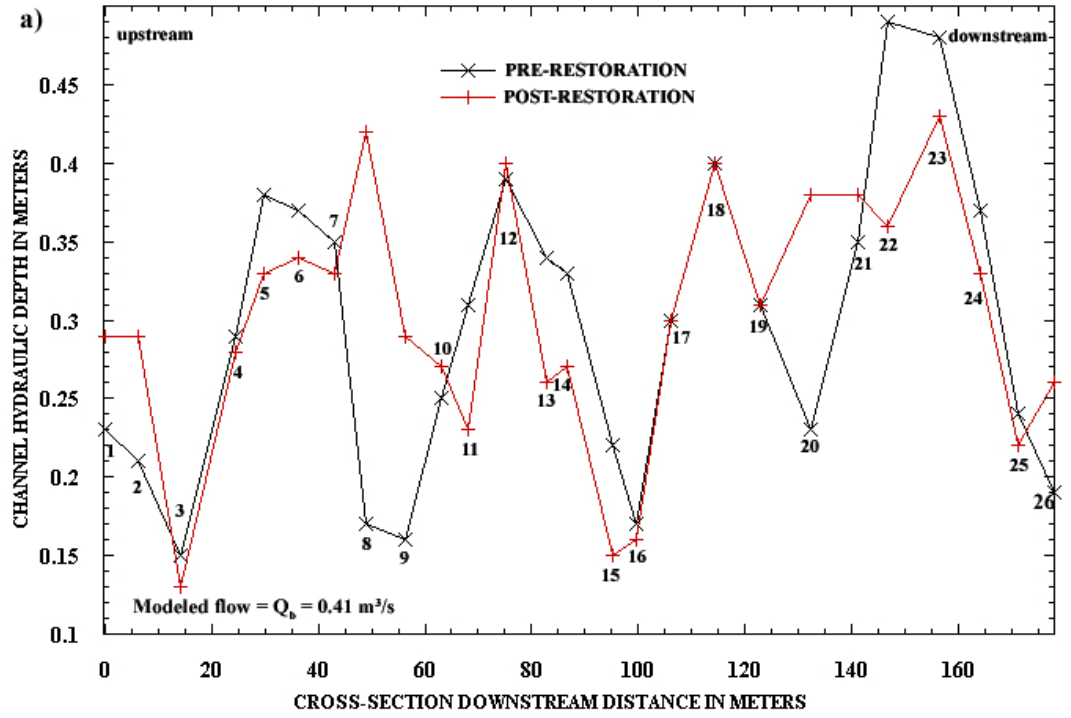
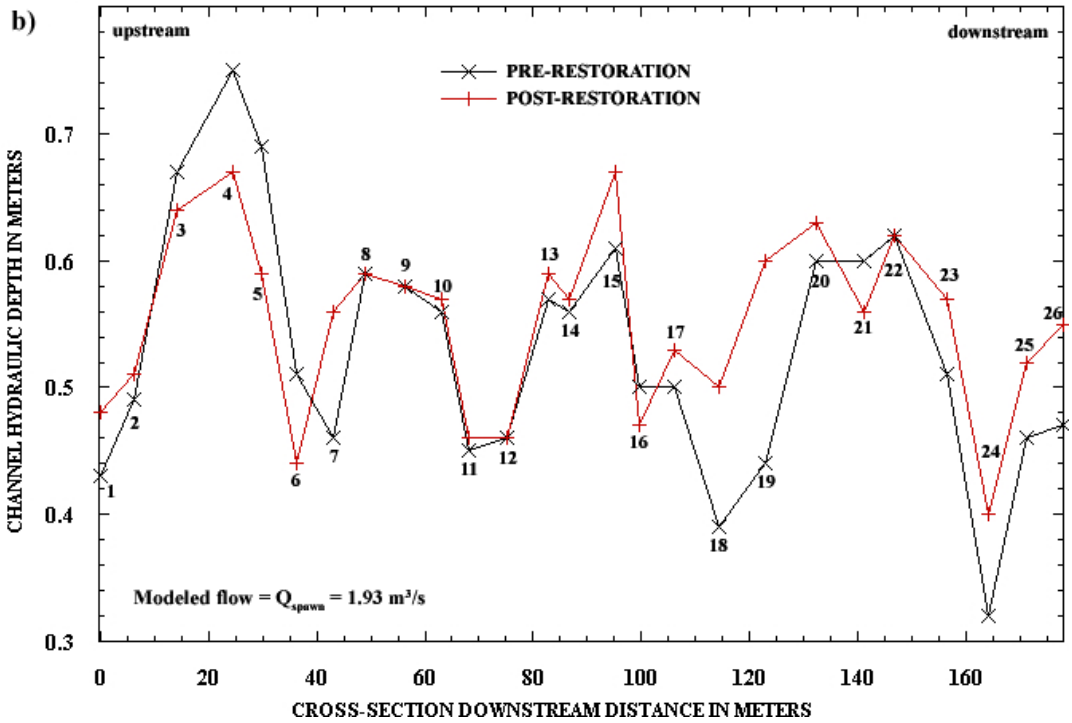


Figure 14: Pre- and post-restoration mean cross-sectional velocity (m^3/s) at a surveyed bankfull discharge of 4.1 m^3/s. Each point represents cross-sections 1 through 26, upstream to downstream.


a)
upstream
downstream
PRE-RESTORATION
POST-RESTORATION
CHANNEL HYDRAULIC DEPTH IN METERS
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
Modeled flow = Q_b = 0.41 m³/s
0
20
40
60
80
100
120
140
160
CROSS-SECTION DOWNSTREAM DISTANCE IN METERS


b)
upstream
downstream
PRE-RESTORATION
POST-RESTORATION
CHANNEL HYDRAULIC DEPTH IN METERS
0.7
0.6
0.5
0.4
0.3
Modeled flow = Q_{spawn} = 1.93 m³/s
0
20
40
60
80
100
120
140
160
CROSS-SECTION DOWNSTREAM DISTANCE IN METERS

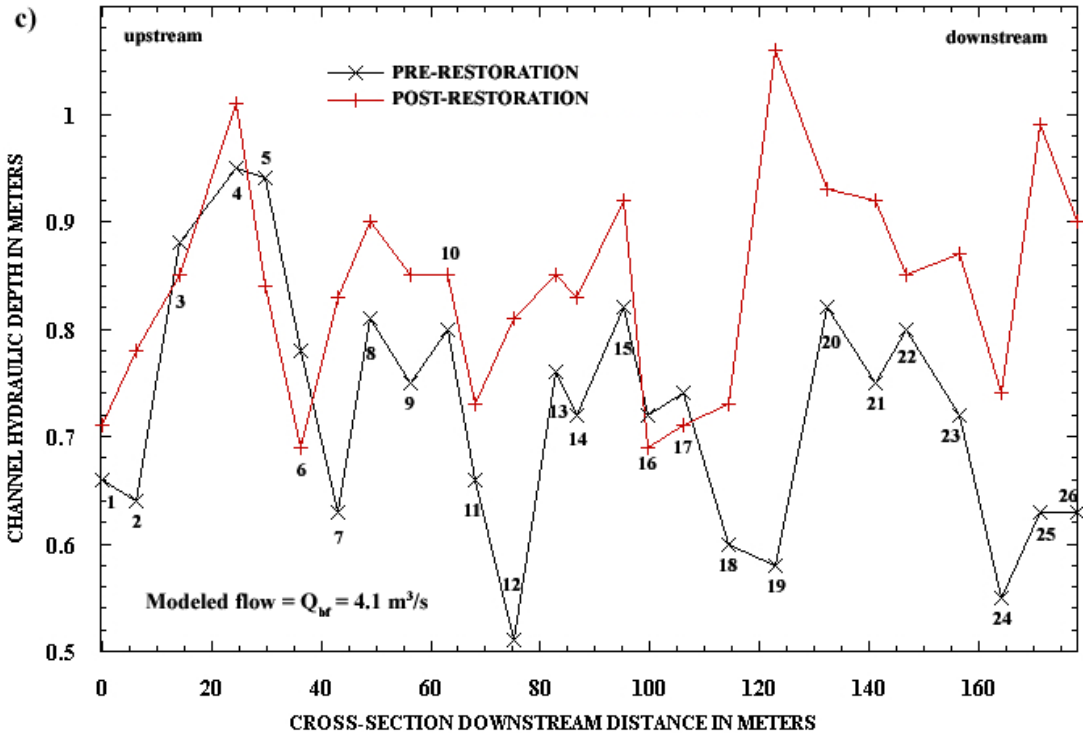


Figure 15 a-c: a, b and c: Pre- and post-restoration mean cross-sectional depths in meters at a discharge of 0.4 m^3/s, 1.93 m^3/s, and 4.1 m^3/s. Each point represents cross-sections 1 through 26, upstream to downstream.

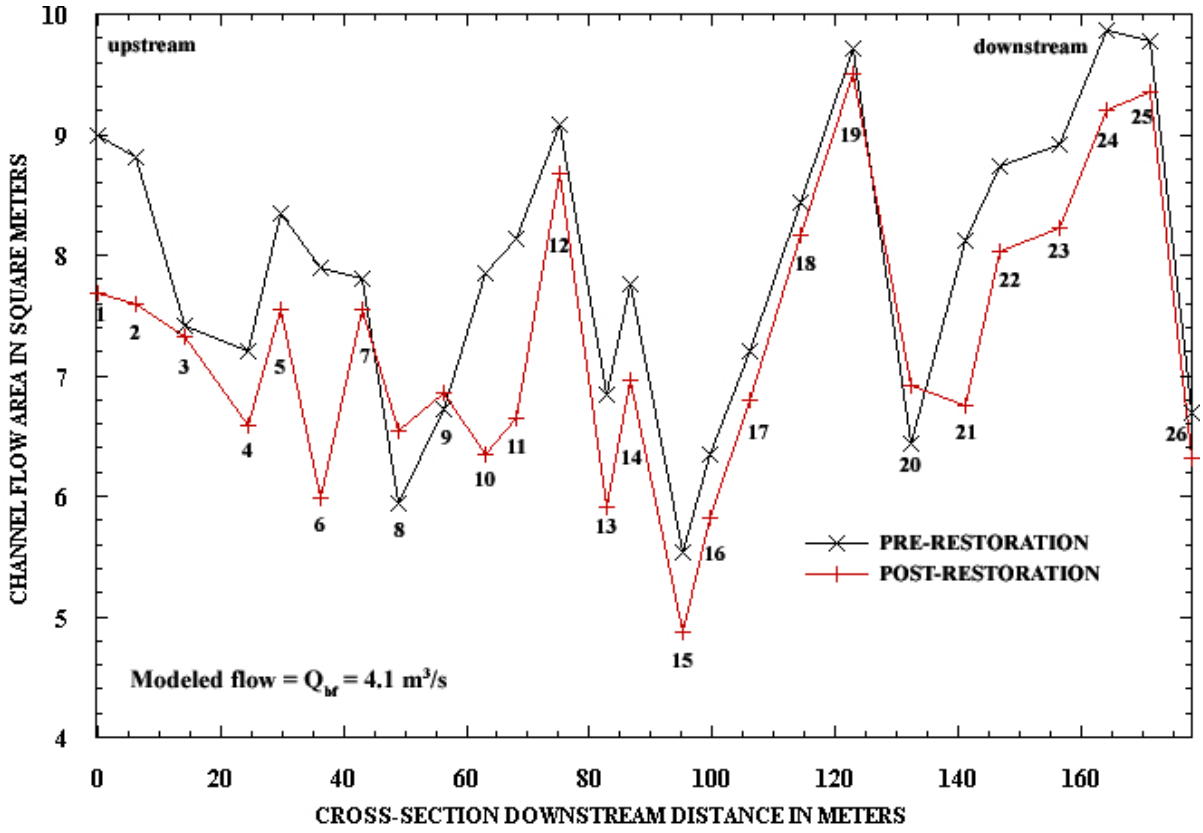


Figure 16: Pre- and post-restoration mean cross-sectional flow area in square meters at a discharge of 4.1 m^3/s. Each point represents cross-sections 1 through 26, upstream to downstream.

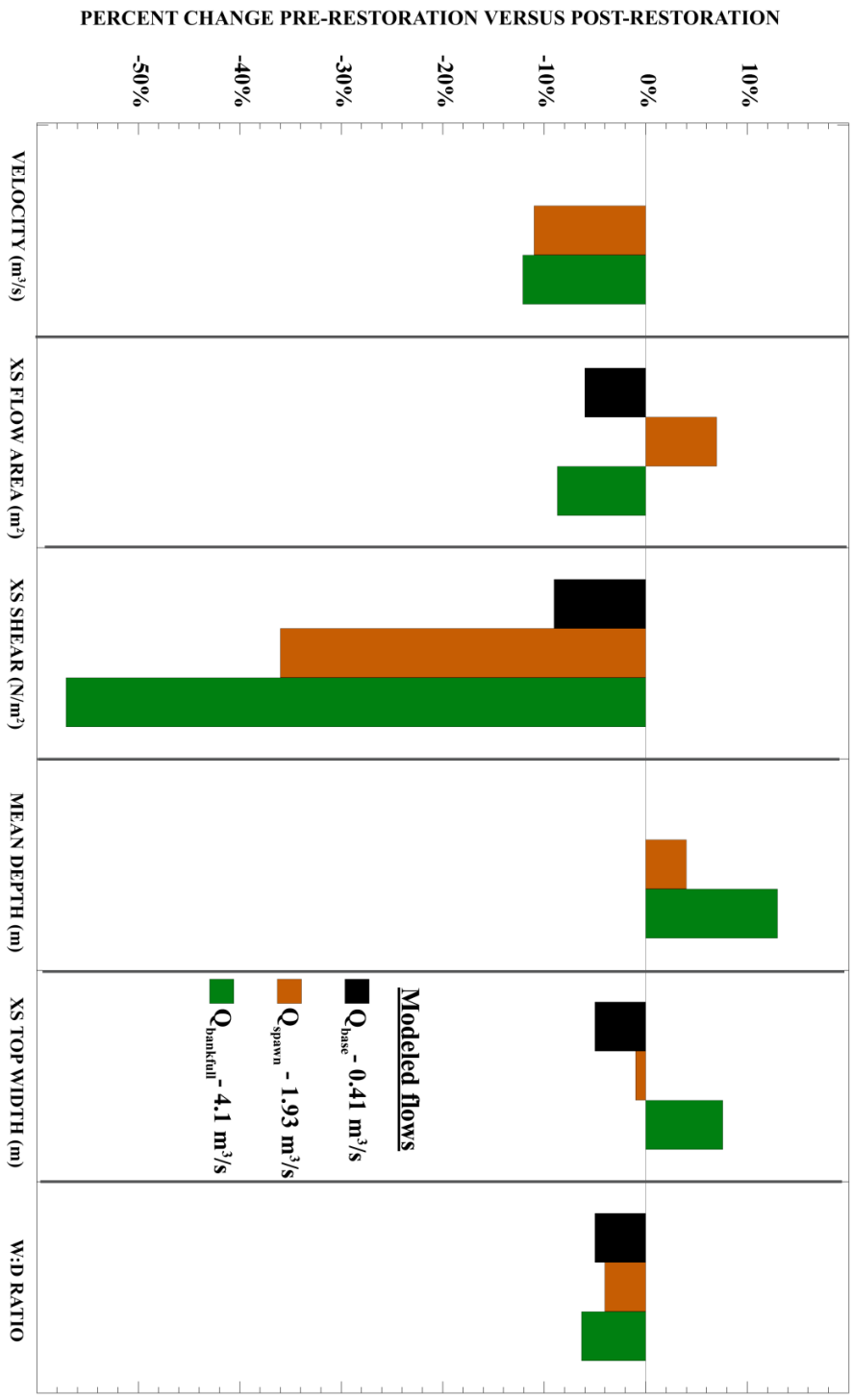


Figure 17: Percent changes in channel morphology metrics for the Restored 2009 reach pre- and post- restoration, for three discharges modeled in HEC-RAS.

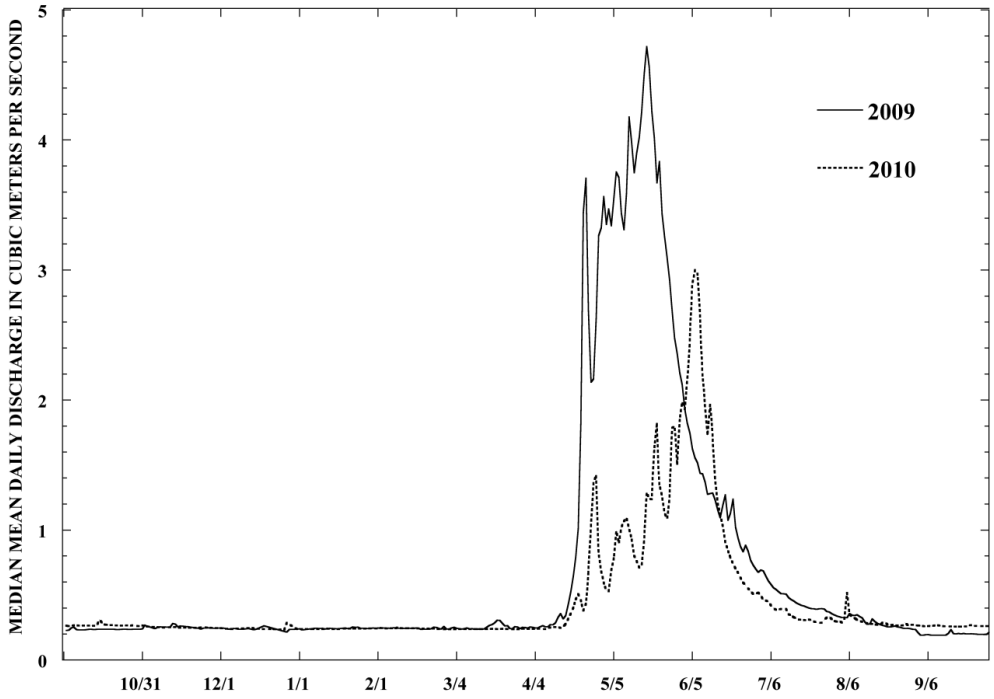


Figure 18: Mean daily discharges for the Upper Strawberry River at U.S. Route 40 Bridge for water year 2009 and 2010.

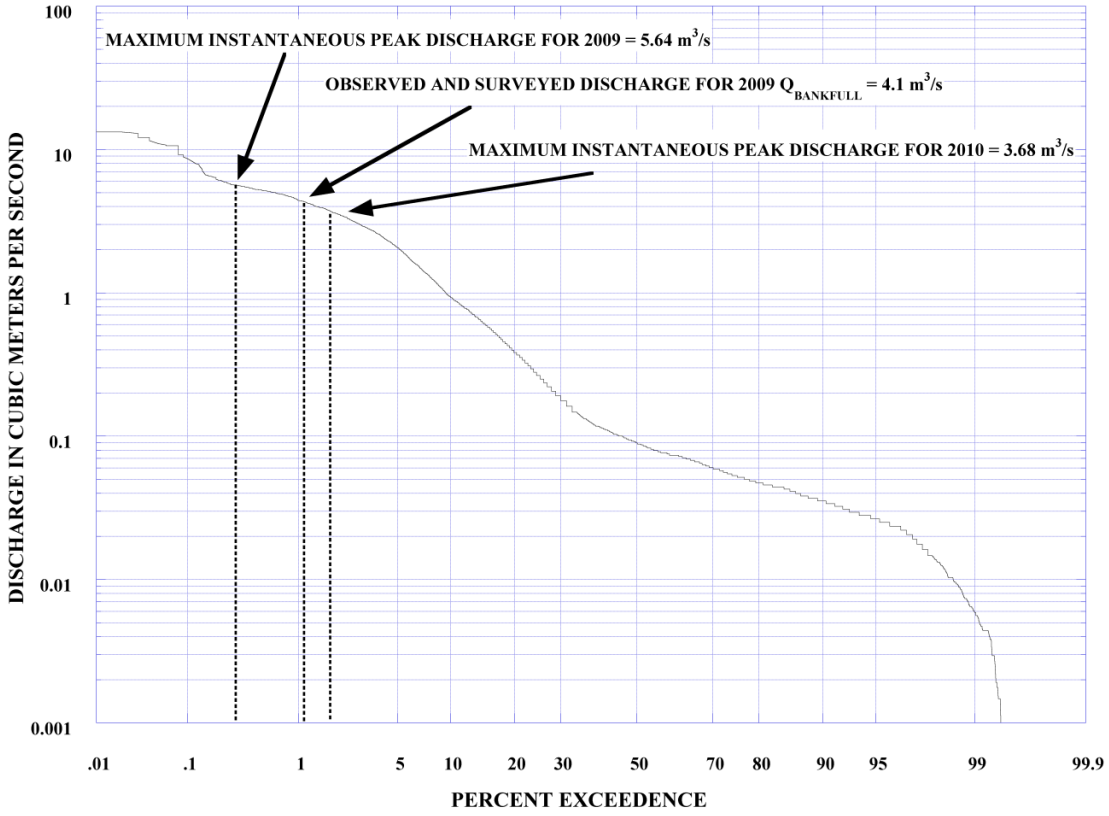


Figure 19: Flow Duration Curve created using 43 years of flow data from USGS gage # 09312600, White River below Tabbyune Creek, Utah in conjunction with 2 years of flow data from the upper Strawberry River at US Route 40. Shown are the percent exceedence values for three flows of interest; $Q_{max\text{-}2009}$, $Q_{max\text{-}2010}$ and $Q_{bankfull}$.

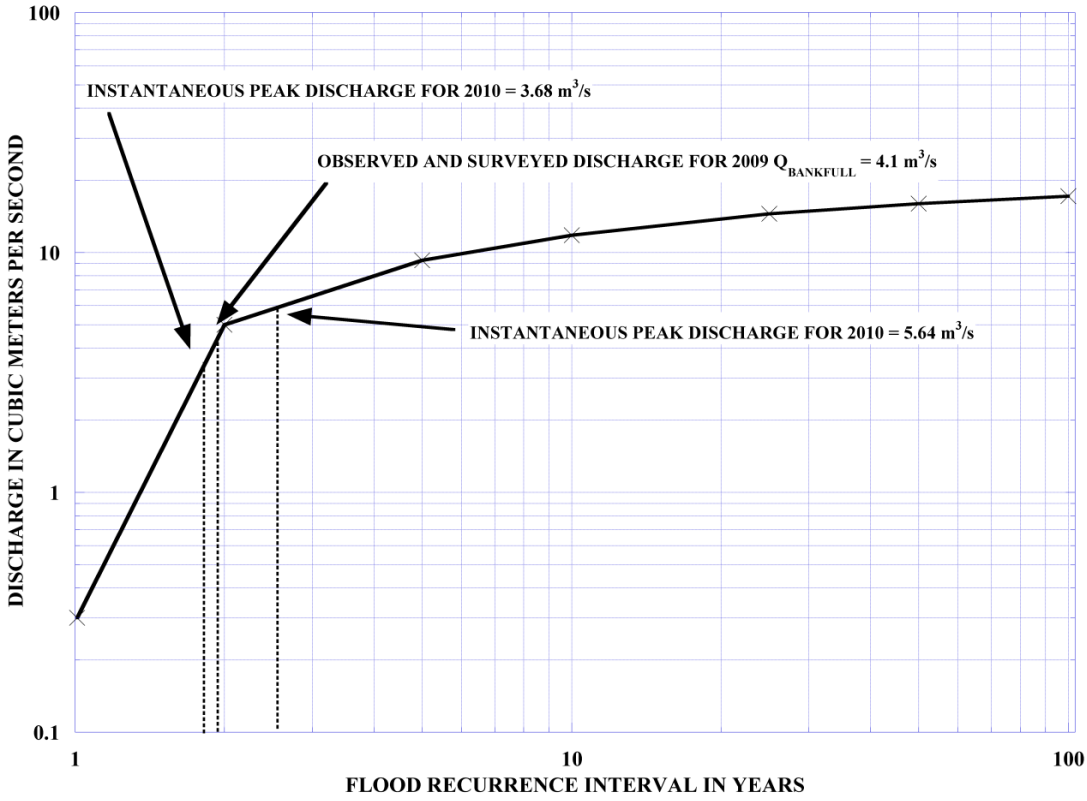


Figure 20: Flood frequency curve created with flow data from USGS gage # 09312600, White River below Tabbyune Creek. Shown are the flood recurrence intervals for three flows of interest; $Q_{max\text{-}2009}$, $Q_{max\text{-}2010}$ and $Q_{bankfull}$.

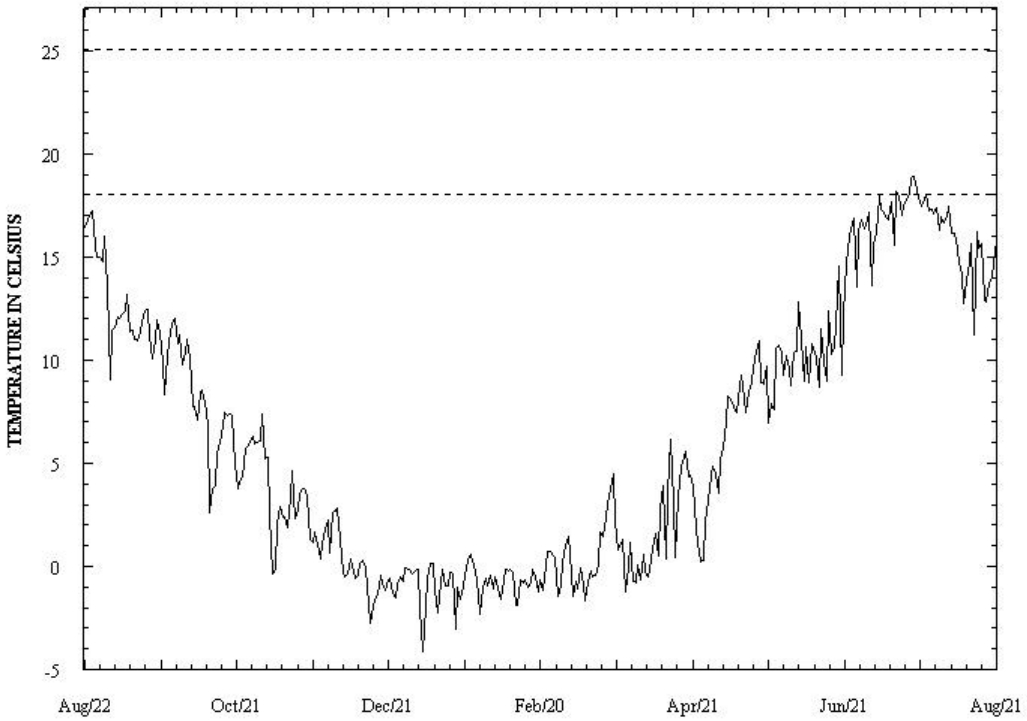


Figure 21: Temperature in Celsius recorded at U.S. Route 40 Bridge for 2009 and 2010 water years. The dashed line represents a zone of temperature where Bonneville cutthroat trout begin to show signs of stress and higher mortality rates (e.g., 18°C to 25°C) as a result of high summertime temperatures (Johnstone and Rahel, 2003).

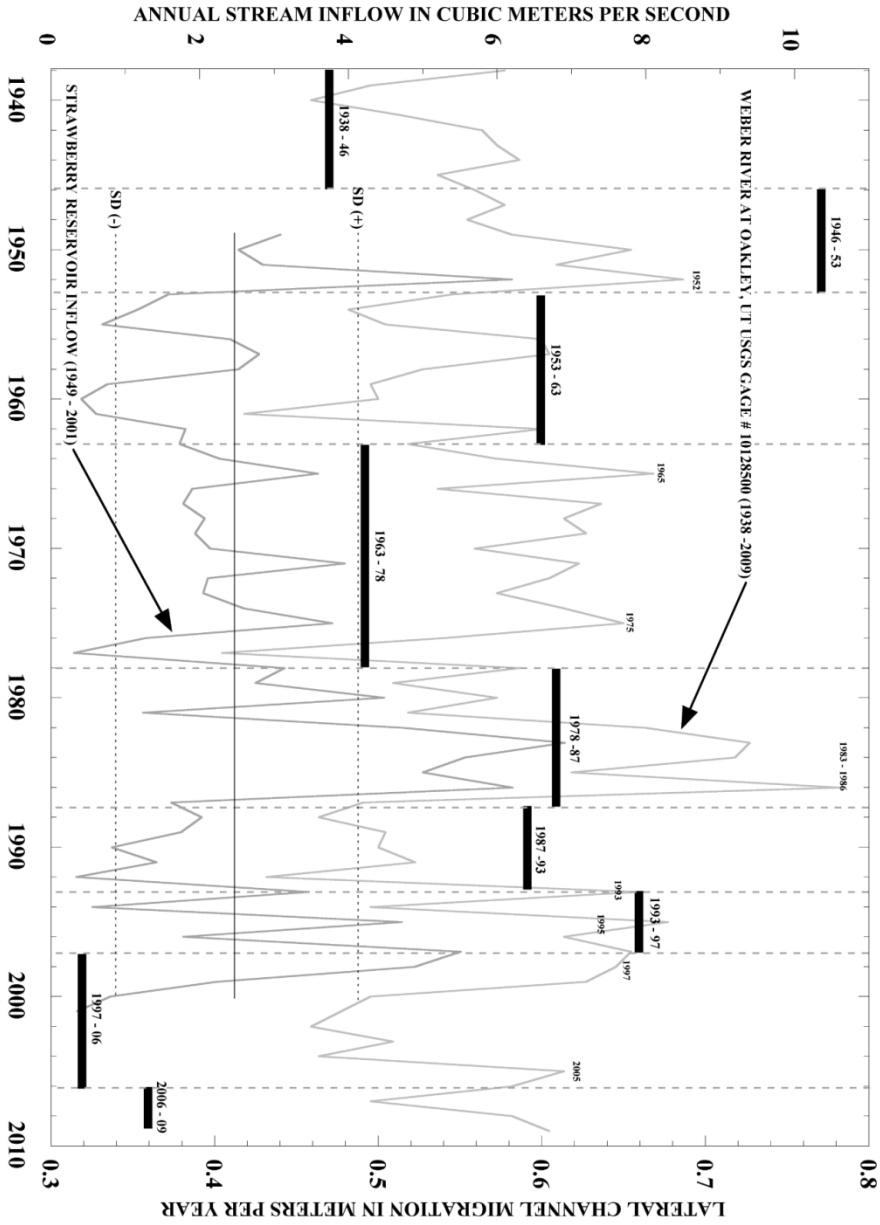


Figure 22: Total annual streamflow record of the Strawberry River from 1949-2001, reconstructed from records of Strawberry Reservoir water storage, inflows, and outflows, compared with the lateral channel migration rate for time periods from 1938-2009 and a long-term discharge record from USGS gaging station #10128500 on the Weber River at Oakley, Utah. High flow years (greater than one standard deviation above the mean) are labeled. Vertical dashed lines separate the periods for which lateral channel migration rate was calculated.

Appendix I-

Baillie, M.B., Salant, N.L., and Schmidt, J.C., 2011. Using a historical aerial photograph analysis to inform trout habitat restoration efforts. *Earth Surface Processes and Landforms*, DOI: 10.1002/esp.2196.

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Using a historical aerial photograph analysis to inform trout habitat restoration efforts

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ESPL
Earth Surface Processes and Landforms

ABSTRACT: Restoration of the upper Strawberry River included bank stabilization techniques because it was assumed that excessive bank erosion was degrading spawning habitat for Bonneville cutthroat trout (BCT). Using a long-term aerial photograph record, the historical range of variability in bank erosion rates and channel geometry was determined, and this information was used to assess present-day conditions and the rationale for restoration. Relative to historical variability, the channel planform was relatively stable and bank erosion rates were the lowest recorded in the post-disturbance era. Although a historical loss of riparian vegetation coincided with a shift to a wider and more sinuous channel, lateral migration rates declined and the channel narrowed as riparian cover increased in the decades before restoration, indicating a process of natural recovery. Furthermore, it was found that the percentage of fine sediment in the streambed before restoration was insufficient to affect BCT spawning success. Together these results suggest that bank erosion and fine sediment did not affect the quality of spawning habitat or the abundance of BCT on the upper Strawberry River. The results highlight how a historical analysis can be used to identify the sources of habitat degradation and inform the selection of restoration goals and strategies. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: aerial photographs; bank erosion; Bonneville cutthroat trout; fine sediment; lateral channel migration; restoration planning

Introduction

Although several researchers have emphasized the potential role of historical geomorphic and ecological data in the selection of restoration goals (Kondolf and Larson, 1995; Schmidt *et al.* 1998; Downs and Kondolf, 2002; Woolsey *et al.*, 2007), the application of such data to restoration project planning has not been widely adopted. In some cases, there is hesitance in using historical information, because it is assumed that comparing current with pre-disturbance conditions is inappropriate. Although restoring a stream to pre-disturbance conditions is typically infeasible where there has been a high degree of disturbance (Kondolf *et al.*, 2008), historical information nevertheless can inform the policy decision about the extent to which ecosystem rehabilitation might be attempted (Figure 1).

In this study, we illustrate another critical use of historical data: defining the problem and informing the choice of restoration strategy – the most basic of decisions about a restoration project. Historical context helps define temporal trends and the natural range of variability in geomorphic processes and ecosystem conditions. These data can be used to determine whether the system is degraded and the problem that needs to be fixed, which form the basis of effective restoration project planning.

As described below, bank stabilization, riparian planting, and in-channel habitat construction on the upper Strawberry River in central Utah was conducted with the primary goal of increasing resident and spawning populations of Bonneville cutthroat trout (BCT) (*Oncorhynchus clarki utah*). Based on field observations of bare, vertical banks and spatially and temporally limited measurements of bank retreat (USDA Forest Service, 2004), wildlife managers concluded that the modern channel was laterally unstable and exhibiting unacceptably large bank erosion rates (UDWR, 2007). Given low BCT reproductive success, it was further assumed that bank erosion had degraded BCT spawning habitat by increasing the proportion of fine sediment in spawning riffles. Unfortunately, no quantitative studies of long-term, historical bank erosion rates were conducted, nor was the fine sediment content of spawning habitat evaluated, before project implementation.

We analyzed the historical aerial photograph record of the upper Strawberry River to determine long-term trends and variability in lateral channel migration rates, channel dimensions, and riparian vegetation cover. In addition, we measured substrate characteristics of riffle areas to assess whether bank erosion was degrading spawning habitats. We sought to define the historical range and temporal trends of the critical geomorphic and habitat characteristics on which the project design was based. Comparing our analysis with the perceptions of the project planners, we demonstrate how historical quantitative data reveals an alternative view of ecosystem health at the time of project implementation that may have led to different project strategies. Our goal is to inspire rational development of project goals and strategies by highlighting how historical geomorphology can inform project planning.

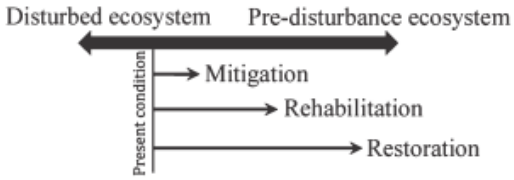


Figure 1. Three degrees of restoration to consider when selecting a restoration strategy.

Study Site

The upper Strawberry River is in the westernmost part of the Uinta Mountains (Figure 2(A)) and is tributary to the Duchesne River, which in turn is tributary to the Green River, the longest tributary of the Colorado River. The flow regime of the watershed is snow-melt dominated, with peak flows occurring in late April or early May and receding to base flow by mid- to late summer, as reflected in flow records from a pressure transducer installed in August 2008 at the US Route 40 bridge within the study area (Figure 2(B); Figure 3).

The Strawberry River was impounded by Strawberry Dam, completed in 1913 as part of the Strawberry Valley Project, one of the earliest water development projects of the US Reclamation Service. In 1974, Strawberry Reservoir was expanded by construction of Soldier Creek Dam, located 11 km downstream from the original dam.

Today, Strawberry Reservoir stores streamflow diverted into it from several streams draining the western Uinta Mountains. Water is exported from Strawberry Reservoir in a tunnel that transfers water to the Great Salt Lake watershed. The reservoir is one of Utah's most popular sport fishing areas and is managed as a premier trout fishery. In 1990, all aquatic life in the reservoir was poisoned in an effort to eradicate undesired non-game fish. Among the game fish species introduced thereafter was the Bonneville cutthroat trout (BCT), a native to the Great Salt Lake watershed and a state-listed Tier 1 sensitive species in its native range (Lentsch *et al.*, 1997; US Fish and Wildlife Service, 2001). Today, BCT are a highly prized part of the Strawberry Reservoir sport fishery.

We studied a 7-km section of river upstream from the reservoir, including several reaches that were the focus of restoration efforts from 2008 to 2010. Aerial photographs of the entire study section were used to assess historical changes in lateral channel migration rate, planform geometry, and riparian vegetation. We also sampled bed material in three 500-m reaches within the study area; these reaches were in various stages of project completion at the time of these measurements. We designate these study reaches as: 'Restored in 2008' (R08), 'Restored in 2009' (R09), and 'Unrestored' (Unrest) (Figure 2(B)).

The Strawberry Valley upstream from the reservoir has long been affected by livestock grazing, logging, road construction, and recreation. Upstream from US Route 40, five small diversions of the upper Strawberry River (Daniels Pass diversions; Figure 2 (C)) with a capacity to transfer between 0.93 and 1.6 m^3/s were operated between the late 1800s and 2001. Built between 1879 and 1893, these diversions also transferred water to the Great Salt Lake basin between May and October of each year. LaRue (1916) estimated that the total annual diversion was about $5 \times 10^6 m^3$.

Livestock grazing began in the valley in the early 1860s. From the 1940s to the 1960s, willows were mechanically removed to facilitate grazing of riparian areas. Furthermore, between 1965 and 1971, willows were chemically removed from riparian areas between Bull Springs and US Route 40. However, concerns over the impact of these activities on water quality, fisheries, and wildlife subsequently emerged (USDA Forest Service, 2004). Livestock grazing was retired in 1989 and 1990. Between 1989 and 1994, more than 48 km of roads in the watershed were closed and more than 30 km of stream banks were treated with revetments and willow plantings. In 2001, trans-basin diversions ended and the Daniels Pass diversions were retired.

Today, the upper Strawberry River between US Route 40 and Strawberry Reservoir is a low-gradient, meandering channel with riffle-pool sequences; riffles are dominated by gravel and cobbles, whereas pools are composed mainly of sand and silt. Upstream reaches contain beaver complexes, composed of long, wide, deep pools with silt and clay beds. Mean gradient is 0.0035 along the 7-km study section. The modern-day riparian vegetation community is dominated by willow, grasses, sedges, and sagebrush. Floodplain soils are composed of mostly silt- and clay-sized particles (>70%), suggesting that the sediment load of the river is dominated by fine-grained sediments (USDA Forest Service, 2004).

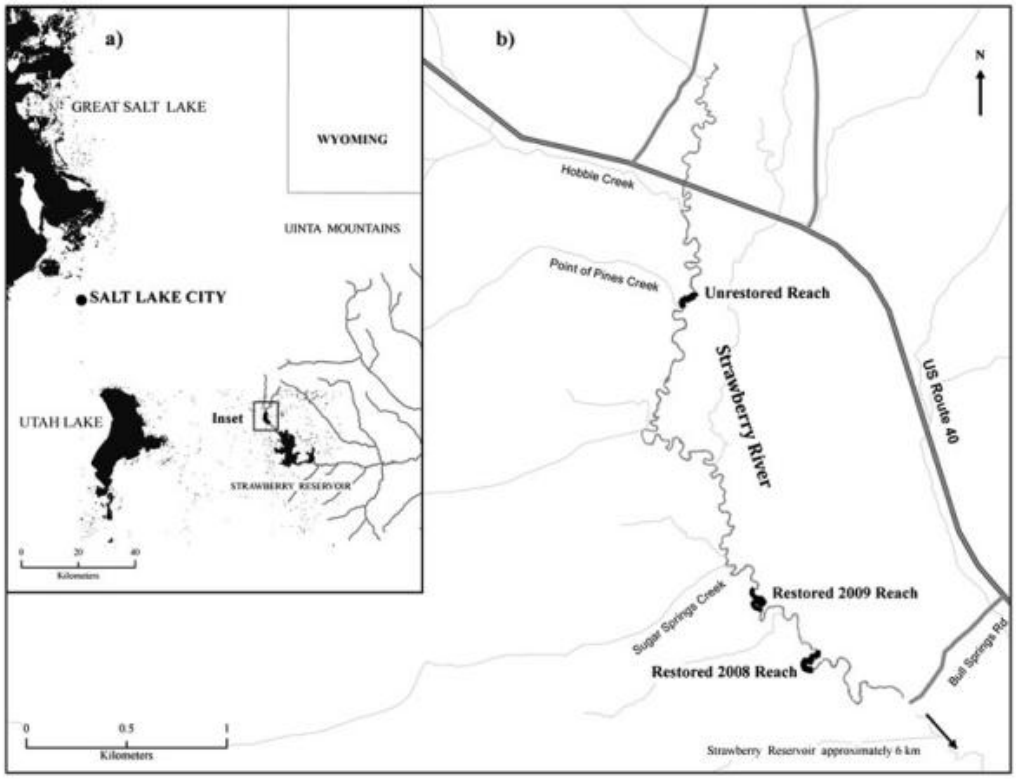
Bank stabilization and habitat improvement activities were completed on a 7-km section of river upstream from Bull Springs (Figure 2(B)) under the direction of the Utah Division of Wildlife Resources (UDWR), in collaboration with the US Forest Service (USFS). Restoration was primarily intended to address low resident populations and limited reproduction of BCT in the upper Strawberry River via improvements to physical habitat conditions. Although no studies have linked low BCT populations to physical attributes of the upper Strawberry River, summer stream temperatures have been recorded at sub-lethal levels for trout (22–23 °C). A major component of the project was the stabilization of vertical banks and re-establishment of native riparian plant communities (UDWR, 2007). Managers assumed that these efforts would decrease bank erosion rates and fine sediment production, thereby reducing the proportion of fine sediment in spawning gravels and improving the quality of spawning habitat. Additionally, it was assumed that re-vegetation would reduce channel width-to-depth ratio and stream temperatures.

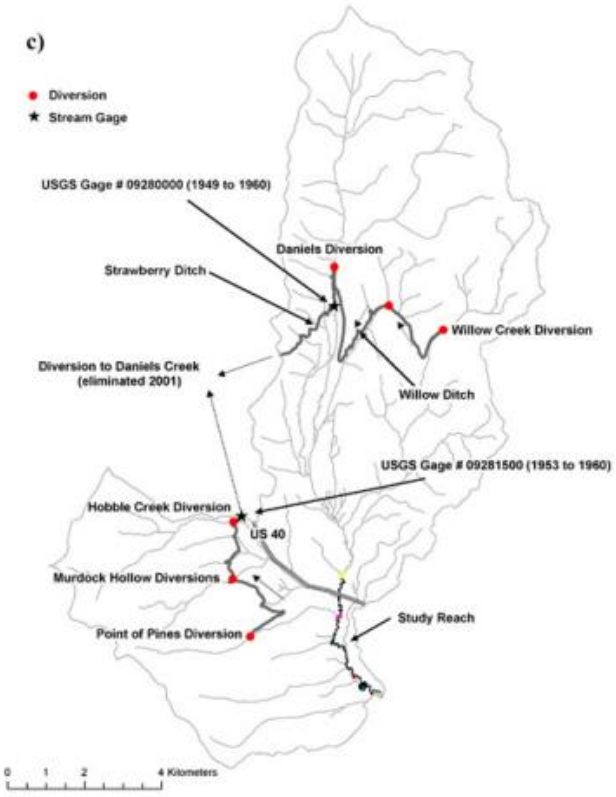
Bank stabilization and in-channel habitat changes were implemented according to standard 'Natural Channel Design' procedures (Rosgen, 1996), including the installation of rock and log vanes, root wads, and logs. Re-vegetation methods included the sloping of vertical banks, transplanting of willow clumps, planting of willow clippings, spreading of coconut fiber on the outside bends of meanders, and reseeding of disturbed areas with native riparian species. Additionally, UDWR stocked several hundred thousand young-of-year BCT every year between 2007 and 2010 throughout the study area and in upstream tributaries.

Methods

We used two sources of information to evaluate bank erosion rates and channel conditions of the Strawberry River: a long-term record of aerial photographs and present-day streambed samples. We developed a GIS database from photographs

Figure 2. (A) Location of upper Strawberry River study area in Utah, (B) study reaches, and (C) study site in relation to discontinued USGS gages and diversions within the upper Strawberry River watershed. This figure is available in colour online at wileyonlinelibrary.com/journal/espl


a)
GREAT SALT LAKE
WYOMING
UINTA MOUNTAINS
SALT LAKE CITY
UTAH LAKE
Inset
STRAWBERRY RESERVOIR
0 20 40
Kilometers
b)
N
Hobble Creek
Point of Pines Creek
Unrestored Reach
Strawberry River
US Route 40
Restored 2009 Reach
Sugar Springs Creek
Restored 2008 Reach
Bull Springs Rd
0 0.5 1
Kilometers
Strawberry Reservoir approximately 6 km


c)
Diversion
Stream Gage
USGS Gage # 09280000 (1949 to 1960)
Daniels Diversion
Strawberry Ditch
Willow Creek Diversion
Diversion to Daniels Creek
(eliminated 2001)
Willow Ditch
USGS Gage # 09281500 (1953 to 1960)
Hobble Creek Diversion
US 40
Murdock Hollow Diversions
Point of Pines Diversion
Study Reach
0 1 2 4 Kilometers

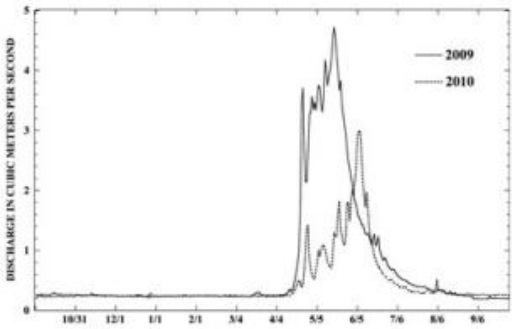


Figure 3. 2009 and 2010 hydrographs for the Strawberry River at US Route 40.

taken in 1938, 1946, 1953, 1963, 1978, 1987, 1993, 1997, 2006, and 2009 and used it to quantify changes in planform geometry, lateral channel migration rate, and riparian vegetation over time. In 2009 and 2010, we collected core samples from spawning habitats of restored and unrestored reaches to determine the percentage of fine sediment in the streambed.

Historical analysis

We obtained aerial photographs from the US Department of Agriculture Aerial Photography Field Office, the United States Geological Survey's Earth Resources and Science Center, and the Utah State Geographic Information Database (Table I). We used a 2006 digitally orthorectified quarter quadrangle (DOQQ) as a base layer for georeferencing unregistered images. Standard methods were used for rectification of the remaining unregistered aerial images, including the matching and transformation of ground-control points (GCPs) and pixel resampling (Leys *et al.*, 1999; Hughes *et al.*, 2006). We applied a second-order polynomial transformation to resample the image (Leica Geosystems, 2006) and computed the total root-mean-square error (RMSE) for each image based on the difference in position of GCPs on the transformed image and base layer (Hughes *et al.*, 2006).

Table I. Flight dates, issuing agency and associated office, scale, and photograph attribute for images of the upper Strawberry River, Utah. B/W=black and white; CI=color infrared; C=color

Acquisition date	Agency	Office	Scale(m)	Attribute
9/2/1938	USBR	US Bureau of Reclamation Salt Lake Aqueduct Project	1:11600	B/W
8/4/1946	USGS	EROS Data Center	1:11000	B/W
8/6/1953	USGS	EROS Data Center	1:19500	B/W
9/5/1963	USGS	EROS Data Center	1:11600	B/W
10/6/1978	USDA	Aerial Photography Field Office	1:19500	B/W
9/17/1987	USDA	Aerial Photography Field Office	1:7500	CI
8/24/1993	USGS	EROS Data Center	1:8500	B/W
9/30/1997	USGS	EROS Data Center	1:8501	B/W
6/1/2006	USDA	Utah Automated Geographic Reference Center	1:7500	C
8/13/2009	USDA	Utah Automated Geographic Reference Center	1:7500	C

We used the rectified images to compute rates of lateral channel migration (LCM) for each time period, as well as average channel width, channel sinuosity, and the percentage of riparian cover at each time step. To compute migration rates, we digitized the left and right active channel boundaries at each time step. We determined the active channel boundary to be the interface between vegetation and the non-vegetated channel bed. On the Strawberry River, the banks were covered with either willows or grasses up to the channel margin. Even in the absence of willows (i.e. during periods of no riparian cover), sedges and grasses were easily distinguishable from the channel bed and could be used to delineate the active channel margin. We acknowledge that overhanging riparian vegetation may obscure the channel margin in some locations, introducing a small degree of error into the location of the active channel boundary (O'Connor *et al.*, 2003; Micheli and Kirchner, 2002; Constantine *et al.*, 2009); given the relatively low density and small size of the vegetation along the channel, we expect this error to be minimal.

We then generated a channel centerline at the midpoint between the two boundaries, and intersected the centerlines from successive time steps to create polygons that represented areas of floodplain eroded in each time period. Following the method of Micheli and Kirchner (2002), we calculated the average migration rate for each polygon as the polygon area divided by one-half the polygon perimeter and the number of years between time steps. Mean annual LCM rate for the entire study area was calculated as the average of the rates computed for all the polygons in each time period; the number of polygons used in the calculation varied among years, ranging from 46 (1953–1963) to 230 (2006–2009). Following previously used methods (Micheli and Kirchner, 2002; Constantine *et al.*, 2009), we excluded from the analysis polygons formed where cutoffs occurred, because including meander cutoffs would artificially increase LCM rates. Although excluded from the calculation of LCM rates, we recognize that meander cutoffs could contribute a large amount of sediment to the channel, potentially affecting instream habitat. We therefore computed an estimated volume of sediment delivered to the channel via meander cutoffs in each time period for comparison with the volume of sediment generated by LCM, in order to assess whether cutoffs represented a significant supply of sediment to the channel relative to channel migration. We calculated meander cutoff sediment volumes by multiplying the total length of channel created via cutoffs by the average channel width from the photographs and previously estimated bank heights for each period (USDA Forest Service, 2004).

Errors associated with digitization and image rectification added error to our estimates of LCM for the polygons within each time period. Georectification error ranged from 0.16 m/yr to 0.58 m/yr for the different time periods due to differences in our ability to locate the same ground control points on matching photographs. We accommodated this error by excluding all polygons with a migration rate less than the period-specific error in the computation of mean annual LCM rate for each time period (Constantine *et al.*, 2009).

We also computed the channel width, channel sinuosity, and the percentage of woody riparian vegetation cover (i.e. willows) at each time step. We calculated the mean active channel width by dividing the area of a polygon defined by the left and right channel boundaries (of the entire reach) by the full length of the channel centerline. We generated the channel centerline at the midpoint between the two boundaries every 1–5 m, increasing the frequency of points along meander bends to incorporate the curvature of the channel. We calculated sinuosity (the ratio of channel length to valley length) from the digitized channel centerline and the distance between reach endpoints. We estimated the percentage of riparian cover within a 75-m buffer zone on either side of the channel centerline, representing the historical riparian zone (i.e. the area occupied by vegetation in the 1938 image, before the willow extirpation of the 1950s and 1960s). We visually identified woody vegetation (i.e. by shape, color, and location) and manually delineated vegetation polygons in each photograph, calculating the percentage of riparian cover as the polygon area divided by the total buffer area. In order to elucidate the relationship between stream hydrology and channel migration, we reconstructed a record of total annual stream flow of the upper Strawberry River using records of the Strawberry Reservoir water storage, inflows, and outflows from 1949–2001 (reservoir data provided by the US Bureau of Reclamation and Strawberry Valley Water Users; inflow/outflow data provided by Bob Gecy, USFS Hydrologist).

Streambed samples

We collected bulk sediment samples from riffle habitats to assess the fine sediment content of spawning gravels. Riffles were identified as the predominant locations of BCT spawning during redd surveys in June 2009. Samples were collected in October 2009 to assess substrate conditions following an extended period of low flow and in June 2010 to evaluate conditions during the period when BCT spawn. Because restoration was ongoing during this period, each sample date also represents different stages of restoration depending on the reach sampled. For the reach restored in July 2008 (R08), the 2009 and 2010 samples represented approximately 1 year and 2 years post-restoration, respectively. For the reach restored in July 2009 (R09), the two sample dates represented one month pre- and approximately 1 year post-restoration. The upstream reach was unrestored at both sampling dates.

We collected two evenly spaced samples from three riffles along each reach; the two samples per riffle were combined in order to amass a large enough sample to meet the criteria of Church *et al.* (1987). We used a McNeil sampler, because it allowed us to retain the very fine sediment suspended during collection (McNeil and Ahnell, 1964); we capped the base of the sampler to hold water and suspended material, which we then filtered through a $<4\,\mu m$ mesh. All particles >8 mm were sieved into standard size classes and wet-weighed in the field; all sediment <8 mm, including the filtered suspended material, was bagged and returned to the lab for particle size analysis. We calculated the percentage of fine particles <1 and <10 mm for each riffle and computed the mean ($\pm$SE) fine sediment content for each reach. Due to longitudinal connectivity among reaches, substrate conditions on different reaches cannot be considered independent, violating a necessary assumption of an analysis of variance. We therefore tested for significant differences in fine sediment content (<1 and 10 mm) among reaches or between sampling dates using a repeated measures model (Maindonald and Braun, 2003), treating reach or sampling date as a fixed factor ('treatment') and riffle (sample location within reach) as a random factor. We used a repeated measures model because samples were taken (repeated) at different streambed locations (riffles). We made comparisons among reaches on a single sample date and between sample dates on each reach, and considered a P-value <0.05 to be significant.

Results

Historical analysis

From 1938 to 2009, the average LCM rate was 0.54 m/yr (Figure 4(A)). LCM rate peaked between 1946 and 1953 at 0.77 m/yr and was lowest during the two most recent time periods, 1997–2006 (0.32 m/yr) and 2006–2009 (0.36 m/yr). Estimated sediment volumes contributed by meander cutoffs were relatively small compared with the volumes of sediment contributed by LCM in each period (e.g. sediment contributed from cutoffs ranged from 2–11% of sediment from LCM). LCM and meander cutoff sediment contributions follow the same historical trends, with sediment volumes greatest for 1946–1953 and lowest for the most recent time period (2006–2009). Eliminating meander cutoffs from the LCM calculations therefore did not affect our interpretation of the historical trends in bank erosion rate and potential sediment delivery. Variability in LCM rate can be assessed from the standard error (SE) of the mean, which was very low for the most recent decade (0.02) relative to the full period of record (0.05). Box plots for different time periods illustrate the historical range of variability in LCM, width, sinuosity (Figure 4). Sinuosity was relatively stable from 1938 until 1963 (mean$\pm$SE$=1.86\pm0.01$), but increased between 1963 and 1978 from 1.83 to 2.00 (Figure 4(B)), indicating bank erosion and bend growth. After sinuosity peaked in 1978, we observed a series of chutes and cutoffs in the non-vegetated floodplains of the later images that straightened sections of the channel. Sinuosity remained at approximately 1.9 ($\pm$0.03) from 1987 to 2009. Like sinuosity, mean channel width was relatively constant from 1938 until 1963, but steadily increased by ~86% between 1963 and 1987, peaking at 8.17 m (Figure 4 (C)). Mean channel width subsequently decreased by ~24% from 1987 to 1997, remaining roughly constant from 1997 to 2009, with a mean ($\pm$SE) of 6.2 ($\pm$0.04) m. Riparian cover steadily declined from 1946 until 1978 (Figure 4(D)), decreasing from 62 to 0%. Willow removal and livestock grazing during the 1950s and 1960s led to a complete loss of riparian cover from 1978–1997. Although no discernible riparian corridor was evident in the 1978, 1987, and 1997 photographs, cover increased slightly in 2006 and 2009, to 4 and 5.5%, respectively. Channel width and sinuosity were most variable during the period of declining or zero vegetation, but have remained relatively constant over the past couple of decades (Figure 4, box plots), suggesting a wider and more sinuous but equally stable channel to that of the early record (Figure 5). At the same time, channel migration rates dropped from 0.6 to 0.3 m/yr, the lowest rates in the post-disturbance era. From the

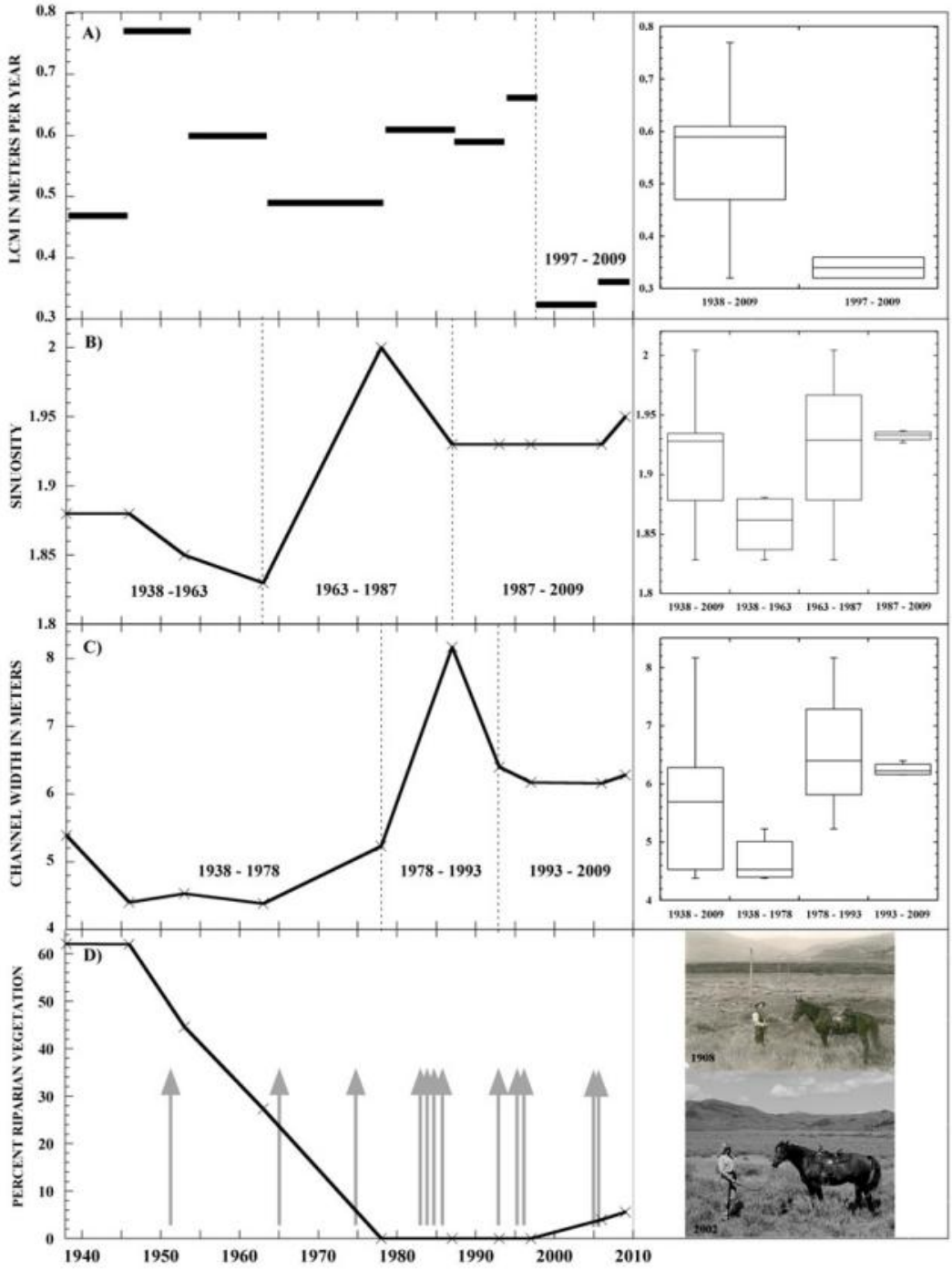


Figure 4. (A) Lateral channel migration, (B) sinuosity, (C) mean channel width, and (D) riparian vegetation cover of the upper Strawberry River, Utah, from 1938–2009. Box plots show the distribution of values for the full record (1938–2009) and periods of time within the record (demarcated by dashed vertical lines). Vertical arrows in (D) indicate high flow years. Photographs in (D) are from USDA Forest Service (2004), showing the change in vegetation cover between 1908 (top image) and 2002 (bottom image), looking up-valley.

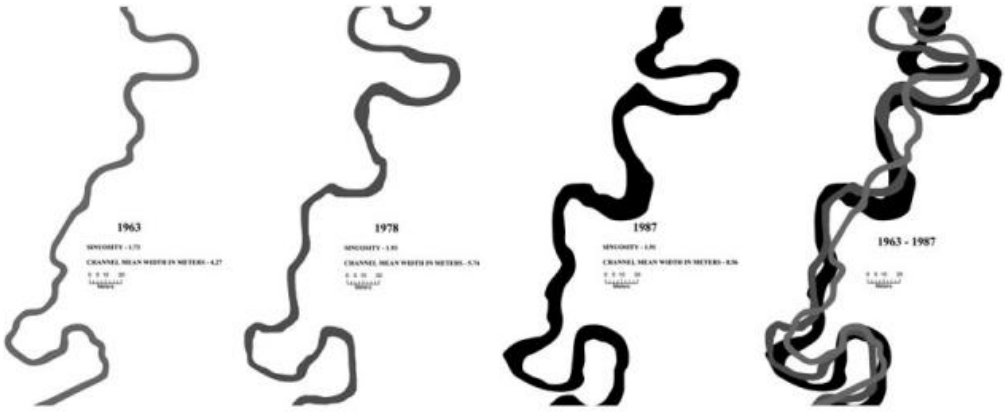


Figure 5. Polygons of the active channel from a section of the upper Strawberry River, from aerial photographs of 1963, 1978, and 1987, illustrating the increase in channel sinuosity and width in the 1970s and 1980s.

reconstructed total annual streamflow record (Figure 6), we determined that high flow years (greater than one standard deviation above the mean) occurred in 1952, 1965, 1975, 1983–1986, 1993, 1995, and 1997–1998, 2005–2006 (Figure 4(D) and Figure 6). A long-term flow record from USGS gaging station #10128500 on the Weber River, an adjacent watershed to the north of the upper Strawberry River, shows a very similar pattern of high and low flow periods over the past century, corroborating our reconstructed record. Periods of high flows are clearly linked to changes in channel stability;

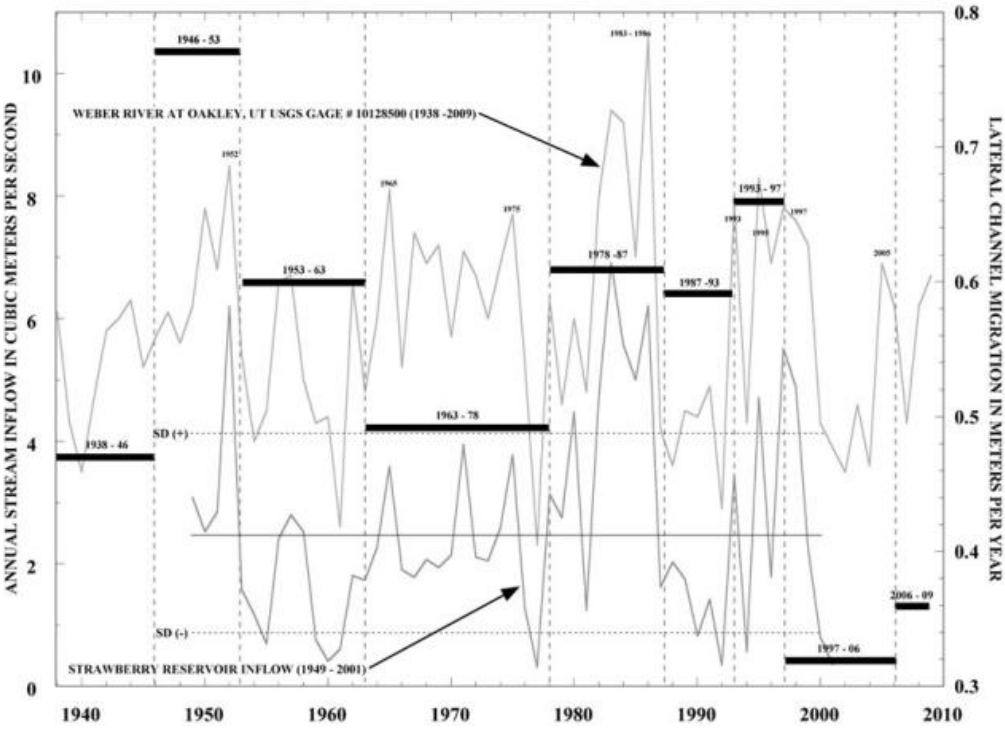


Figure 6. Total annual streamflow record of the upper Strawberry River from 1949–2001, reconstructed from records of Strawberry Reservoir water storage, inflows, and outflows, compared with the lateral channel migration rate for time periods from 1938–2009 and a long-term discharge record from USGS gaging station #10128500 on the Weber River, near Oakley, Utah. High flow years (greater than one standard deviation above the mean) are labeled. Vertical dashed lines separate the periods for which lateral channel migration rate was calculated.

in general, we observed higher LCM rates for periods experiencing greater than average flow and large changes in channel width and sinuosity following periods dominated by high flows (Figure 4(D) and Figure 6).

Streambed samples

On the upper Strawberry River in October 2009, the percentage of particles < 1 mm was < 10% and the percentage < 10 mm was <15% for all three reaches (restored and unrestored) (Table II), less than the emergence and the unsuitable thresholds (Hickman and Raleigh, 1982; Kondolf, 2000; see Discussion section) for spawning areas. In June 2010, particles < 1 mm occupied < 15% of the sample; only the percentage of particles 10 mm slightly exceeded the fry emergence threshold (Kondolf, 2000), with an average of 40% for the two restored and one unrestored reach.

The percentages of fine sediment < 1 and < 10 mm did not differ significantly among restored and unrestored reaches for either sampling date (Oct 09, < 1 mm: P=0.96; Oct 09, < 10 mm: P=0.21; Jun 10, < 1 mm: P=0.39; Jun 10, < 10 mm: P=0.46), indicating that neither restoration nor reach-scale differences had an effect on the fine sediment content of spawning gravels. Furthermore, the percentage of particles < 1 mm was not significantly different between sampling dates for any reach (R08: P=0.06; R09: P=0.75; Unrest: P=0.17), suggesting little seasonal or annual effects on streambed fine sediment. However, the percentage of particles < 10 mm was significantly greater in June 2010 than in October 2009 on all reaches (P<0.01). On average (±SE), the percentage of particles < 1 mm was 8.8 (±0.15)% in October 2009 and 12.6 (±0.44)% in June 2010; the percentage of particles < 10 mm was 10.7 (±0.07) % in October 2009 and 40.4 (±0.7)% in June 2010.

Discussion

Bare, vertical banks are commonly interpreted as indicative of high bank erosion rates and degraded habitat conditions. However, the simple observation of a bare bank does not reveal any information about rates of channel change, channel stability, or biologically relevant geomorphic characteristics. A historical analysis provides information about temporal variations in channel conditions and processes, which can be used to evaluate whether current attributes of the system are cause for concern or within the range of natural variability (Kondolf *et al.*, 2003; Wohl, 2008). On the upper Strawberry River, the assumption that bank erosion rates were high and contributing to degraded spawning habitat had no historical basis. Furthermore, there is no evidence to support the assumption that the quality of spawning habitat is contributing to low densities of Bonneville cutthroat trout (BCT). Nevertheless, restoration of the upper Strawberry River aimed to increase resident and spawning populations of BCT by, in part, stabilizing banks, reducing sediment loads, and improving spawning habitat (UDWR, 2007). Bank stabilization and revegetation techniques were intended to reduce bank erosion rates and in turn reduce fine sediment production and deposition.

Table II. Percentages of fine sediment <1 and <10 mm from riffle locations on three reaches of the upper Strawberry River, Utah, in October 2009 and June 2010. Values are the mean (SE) of three riffles.

Reach	October 2009		June 2010	
	< 1 mm	< 10 mm	< 1 mm	< 10 mm
Restored in 2008	8.93(1.4)	10.9(0.29)	9.92(2.6)	36.7(4.7)
Restored in 2009	8.46(1.5)	10.2(0.43)	14.6(1.8)	41.0(2.3)
Unrestored	9.00(1.9)	10.5(0.44)	13.2(2.5)	43.5(3.7)
Mean	8.79(0.17)	10.5(0.25)	12.6(1.4)	40.4(2.0)

However, our analysis shows that over the past decade, the channel planform was relatively stable, bank erosion rates were the lowest recorded in the post-disturbance era, and fine sediment was not degrading habitat conditions before restoration. Of course, we recognize that an aerial photograph record cannot extend far back enough in time to reveal pre-disturbance conditions, thus it is possible that recent LCM rates were still much higher than in the era before human activity, particularly considering that even the earliest aerial images available (1938) represent an altered ecosystem. For instance, oblique photographs from 1888 indicate that the riparian vegetation community was significantly wider and denser before human disturbance (USDA Forest Service, 2004). Furthermore, because of greater beaver activity and a higher water table, the riparian zone was probably dominated by hydric soils and wetland vegetation (i.e. grasses and sedges) in addition to willows. Since grass increases bank cohesiveness, these vegetative differences – combined with a lack of physical disturbance by livestock – probably helped maintain a narrower channel (Davies-Colley, 1997; Allmendinger *et al.*, 2005). Nevertheless, our analysis indicates a clear trajectory of recovery and channel stabilization in the post-disturbance era, suggesting a process of natural 'self-healing' by which the channel achieves a new quasi-equilibrium. Recovery is probably an outcome of the removal of livestock grazing in the early 1990s and the return of natural flows to the river in 2001. Our results suggest that channel stability and a trend of recovery have persisted for the past two decades, following a period of rapid channel change in the late 1970s and 1980s.

In the absence of bank stabilizing vegetation, the series of high flows in the early to mid-1980s probably triggered channel widening and increased sinuosity (cf. Thorne, 1990; Simon and Darby, 1999). Although vegetation loss and bank destabilization may have temporarily increased bend growth and curvature, it was possibly the lack of vegetation that caused sinuosity to subsequently decline in the late 1980s and early 1990s, due to the formation of chutes and cutoffs (Murray and Paola, 2003; Tal and Paola, 2007, 2010). Thus, the loss of riparian vegetation and high flow years did cause a short-term increase in bank erosion rates, by which the channel adjusted its width and sinuosity. However, the constant channel width and sinuosity of the past two decades suggests that the channel has achieved a new quasi-steady state. Observed changes in bank erosion rates and channel geometry are the exact response that would be expected following the removal and subsequent re-establishment of riparian vegetation. The apparent ability of the channel to heal naturally following the removal of grazing pressure suggests that a passive approach to restoration may be adequate for system recovery in the long term.

We also found that the percentage of fine sediment in spawning areas was insufficient to have the potential for a significant biological impact on BCT spawning success. Based on BCT habitat suitability criteria and studies of fry emergence, there is little evidence to suggest that excess fine sediment was degrading the quality of spawning habitat for BCT in the upper Strawberry River. Researchers have demonstrated that particles < 1 mm reduce gravel permeability and particles from 1 to 10 mm prevent emergence (Phillips *et al.*, 1975; McNeil and Ahnell, 1964). From a synthesis of available studies, Kondolf (2000) reported that fine sediment percentages corresponding to 50% emergence of salmonids occurs between 7 and 20% for particles <0.83 mm and ~30% for particles

<10mm. Similarly, the Habitat Suitability Index for cutthroat trout (Hickman and Raleigh, 1982) sets the 'unsuitable' threshold for fine sediment (< 3mm) at 25% for spawning areas and 45% for riffle-run areas. Historical bank erosion and channel widening does not appear to have affected present-day habitat conditions. Furthermore, we found that the amount of streambed fine sediment was similar among restored and unrestored reaches, indicating that bank erosion was not contributing to local or reach-scale differences in bed composition. Relative channel stability, low migration rates, and small quantities of streambed fine sediment indicate that bank erosion was not causing habitat degradation in this system, a finding that runs counter to the assumptions of project planners.

Given the apparent channel stability and low bank erosion rates of the recent decades, bank stabilization efforts on the upper Strawberry River may have been unnecessary. Furthermore, bank stabilization may have potentially detrimental effects on the function and structure of the riverine environment in the future. Immobile or permanent habitat structures can present problems for normally dynamic systems by limiting the growth of bank stabilizing vegetation, reducing small-scale channel adjustments, and increasing channel width; maintaining the structures over the long term can also be costly (Thompson, 2002). On the upper Strawberry River, the placement of boulders and log vanes in the stream banks was intended to constrain lateral migration and maintain a static channel condition. Lateral channel migration, however, has important effects on instream and floodplain habitat for fish and other organisms. In a meandering river, cut bank erosion leads to the deposition of point bars, which provides sediment suitable for the establishment of pioneer plant species such as willow and cottonwood (Read, 1958; Everitt, 1968; Wilson, 1970; Johnson *et al.*, 1976; Noble, 1979). Revegetation efforts on the upper Strawberry River may therefore be limited in the future if there is insufficient bank erosion and sediment deposition for willow establishment. Although lateral channel migration rates were relatively high in the 1940s and 1950s, vegetation cover declined during this period because of intense grazing pressure and mechanical willow removal (USDA Forest Service, 2004). Some vegetation growth has been possible in recent years due to the removal of livestock grazing in 1989, but may be constrained in the future without natural bank erosion and sediment deposition.

Furthermore, by disturbing late-stage plant communities and creating new surfaces for seedling growth, bank erosion helps maintain the diversity of floodplain plant communities (Stromberg, 2001). Channel migration also enhances the physical complexity of instream and floodplain habitats. Meander migration and cutoffs create valuable off-channel spawning and winter rearing habitat for salmonids, including overflow channels, sloughs, and wetlands (Beechie *et al.*, 1994). Although we recognize that accelerated bank erosion and channel widening can degrade instream habitat, cutbank erosion and lateral migration are essential components of a meandering river ecosystem. A historical comparison can help assess whether contemporary erosion rates are accelerated relative to past conditions; the record-low migration rates and stable channel form of the upper Strawberry River in recent decades indicate that bank erosion is an unlikely cause of habitat degradation in this system.

Revegetation efforts may still be of value, however, given that riparian cover in 2009 was much less than in the early part of the century. Furthermore, the channel widening that occurred in the 1970–1980s may also be a source of degradation; channel widening and a lack of riparian vegetation can reduce instream shading, which helps regulate water temperatures. Summer stream temperatures on the upper Strawberry River have been recorded at sub-lethal levels for trout (22–23°C) (Scott Miller, USU, unpublished data). Continued planting of willows could accelerate riparian recovery, but successful regrowth requires that the processes of bank erosion, point bar deposition, and overbank flooding occur naturally. If channel processes and ecosystem functions are constrained, physical habitat improvements (e.g. structure placement and riparian planting) will be ineffective in the long-term.

Furthermore, determining what life stages and factors (e.g. temperature, physical habitat, non-native species, or fish passage) limit BCT abundance would require a population study and limiting factors analysis. In addition, it is important to consider that BCT are not native to the upper Strawberry River and did not live in the river until the 1990s. As such, historical river characteristics (e.g. geography, habitat, or hydrology) may never have been suitable for BCT. Furthermore, the reservoir and UDWR fish trap and egg-collecting facility at the river outlet may pose unrecognized problems for BCT recruitment; for instance, BCT in the reservoir may be deterred from migrating upstream or simply unable to find the river mouth.

Conclusions

Restoration of the upper Strawberry River was justified and designed based on the assumptions that: (1) bank erosion rates were abnormally high; (2) excess fine sediment was degrading spawning habitat; and (3) these two conditions were linked. Unfortunately, no historical analysis was conducted before restoration to confirm these assumptions (i.e. determine whether present-day erosion rates could be considered excessive, or assess whether spawning gravels were actually degraded by fine sediment). Using a long-term aerial photograph record, we were able to establish the temporal sequence of change and the historical range of variability in channel migration rates and planform geometry and therefore place present-day conditions in a historical context. Relative to historical variability over the period of record, bank erosion rates were low and channel morphology was stable in the decade before restoration. Furthermore, we found that the percentage of fine sediment in the streambed before and during restoration was insufficient to affect BCT spawning success. Together these results suggest that bank erosion and fine sediment did not affect the quality of spawning habitat or the abundance of BCT on the upper Strawberry River. As such, bank stabilization efforts may have been unnecessary.

Given the many factors that could limit BCT abundance in the upper Strawberry River, effective management requires determination of realistic and desirable goals for restoration. Considering that BCT were not historically found in the upper Strawberry River, the creation of a viable, reproducing BCT population in this system is not equivalent to restoration of the pre-disturbance biological condition. Whether such a goal is realistic depends on potential limiting factors, such as migration barriers or water temperature, or life stages not assessed in this study. Re-establishing historical physical conditions also appears impractical and unnecessary, at least from a fish management perspective. Returning the system to its pre-disturbance condition would require reversing a century of human alterations, including the Strawberry Reservoir and associated diversions. Nevertheless, despite being altered from its pre-disturbance condition, the present-day channel is stable and bank erosion is not degrading spawning habitat. As such, the maintenance of suitable spawning habitat for BCT does appear to be a feasible management strategy. We recommend refocusing restoration efforts on other potential sources of degradation (e.g. riparian cover). We

suggest that restoration efforts on the upper Strawberry River not only inaccurately targeted bank erosion as a source of degradation, but may also inhibit riparian recovery and habitat improvement by constraining natural channel migration. Our results illustrate how a historical analysis can be used to identify sources of degradation and assist the development of a more effective restoration design plan.

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