THESIS

A CHANNEL STABILITY ASSESSMENT AND LOGISTIC REGRESSION MODEL FOR A REACH OF MUDDY CREEK BELOW WOLFORD MOUNTAIN RESERVOIR, IN NORTH-CENTRAL COLORADO

Submitted by

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ABSTRACT

A CHANNEL STABILITY ASSESSMENT AND LOGISTIC REGRESSION MODEL FOR A REACH OF MUDDY CREEK BELOW WOLFORD MOUNTAIN RESERVOIR, IN NORTH-CENTRAL COLORADO

Water resource managers face increasing pressure to meet community water needs while responsibly managing resource infrastructure and preserving aquatic and riparian ecosystems. Management of many western rivers involves multiple uses for multiple stakeholders, especially rivers downstream from dams impounding water-supply reservoirs. These resource management issues arise in a reach of Muddy Creek near Kremmling, Colorado, which serves multiple functions including: (1) wetland mitigation, (2) private, recreational fishing, (3) and agriculture. Alteration of streamflow from reservoir operations and loss of upstream sediment supply, in conjunction with legacy management effects, have resulted in channel instability and increased streambank erosion in Muddy Creek below Wolford Mountain Reservoir. A typical response to channel instability on managed rivers includes installation of erosion-control structures. However, installation of these structures to protect property and infrastructure is expensive and can have unintended consequences at adjacent locations, highlighting the need for resource managers to better understand the underlying geomorphic processes controlling channel adjustment within the reach.

To address these issues, field reconnaissance and channel surveying completed during base-flow conditions were used to (1) determine the dominant erosive and resistive processes within the reach that contribute to channel stability and response, and (2) assess the validity of using logistic regression techniques as an analytical framework and to estimate the probability or risk of localized streambank erosion. These findings can be used in conjunction with local management objectives to evaluate or gage acceptable risk to current infrastructure and to target and prioritize where monitoring or remediation should be conducted. Understanding the geomorphic processes and reach characteristics driving streambank erosion can be used to guide management and operational decisions within the reach to minimize impacts.

A map of probability of erosion, for each streambank, is presented which shows risk (as a probability of streambank erosion, ranging from < 3 to 80 percent) based on significant explanatory variables from the logistic regression model. The study found that stream-induced scour and undercutting have differing effects within the reach due to changes in the erosive power of the stream and relative difference in streambank and riparian characteristics. Areas most susceptible to streambank erosion occurred in wider cross sections where fluvial energy was oriented into the streambanks, not necessarily in areas with the greatest fluvial energy and potential erosive power (i.e., areas with the steepest bed slope). This suggests additional, localized conditions within the reach need to be considered.

Differences in streambank and riparian characteristics were shown to have varying levels of resistance to streambank erosion within the study reach. Larger streambank heights increased the probability of streambank erosion when these streambanks were not supported by bedrock outcrops of Pierre Shale or alluvial fans and talus slopes. Erosion-control structures decreased the probability of streambank erosion where structures retained original positions relative to flow. Where changes to flow orientation occurred, the probability of streambank erosion around these structures increased substantially. Riparian vegetation type also influenced streambank erosion as well as channel top-width. Streambanks covered in willows were found to decrease the risk of streambank erosion, whereas areas dominated by grasses increased streambank erosion potential as well as increased channel top-widths relative to areas dominated by willows.

Additional effects from reach-scale characteristics were evaluated. Areas of greater sinuosity and wider valley widths show increased probability of streambank erosion, as well as in areas located downstream of an irrigation diversion structure. This may be due to a combination of effects from further confinement of the reach as valley widths decrease, increased streamflow from tributaries, and/or the occurrence of increased seepage along areas near an irrigation ditch. Streambanks with observed saturated soils were also found to have between 20-44 percent increased odds of streambank erosion. A linkage between proximity of streambank seeps and unlined irrigation ditches and irrigation turn-outs was highly significant, with potential effects extending to distances up to 250 m from the irrigation water sources.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Water resource managers face increasing pressure to meet community water needs while responsibly managing water-resource infrastructure and preserving aquatic and riparian ecosystems. For example, management of many western rivers involves multiple uses for multiple stakeholders, especially rivers downstream from dams impounding water-supply reservoirs. In these systems, alteration of streamflow, sediment supply, and water temperature results in downstream conditions that can be vastly different from pre-dam (Andrews, 1986; Williams and Wolman, 1984). Changes downstream of dams may be localized or widespread and alter the physical and ecological conditions of the stream (Muth *et al.*, 2000). Morphological changes to channel form and process may occur, and are characterized by increases or decreases in channel stability, some with periods of widespread erosion and/or deposition (Andrews, 1986; Williams and Wolman, 1984).

A typical response to channel instability on managed rivers includes installation of erosion-control structures. However, installation of these structures to protect property and infrastructure is expensive and can have unintended consequences at adjacent locations (USDA, 1999; 2007). Implementation of revetments or other erosion-control structures along channel margins can be an effective way to limit site-specific streambank erosion (USDA, 1999; 2007). However, these erosion-control methods can promote streambank erosion or channel incision in adjacent areas or may fail to function as a channel adjusts towards a new dynamic equilibrium (Bormann and Julien, 1991; Elliott, 2011; USDA, 1999). In addition, reactive targeting and monitoring of areas that may be prone to streambank erosion is an expensive undertaking that does not guarantee successful resource management when the underlying geomorphic processes are not well understood. For example, placement of concrete blocks along the toe of a cut bank may limit streambank erosion at that location, but may increase the rate of streambank erosion in subsequent downstream river bends in a stream with an altered flow or sediment regime. Understanding the dominant geomorphic processes controlling channel change within the reach and understanding the relative importance of each can better inform management decisions. This understanding will allow resource managers to better predict and monitor for potential adverse changes while meeting the needs of the stakeholders. This in turn should minimize maintenance costs and allow for better stream-channel stabilization design based on an improved understanding of geomorphic processes instead of a reactive response to geomorphic symptoms of channel adjustment.

These resource management issues arise in a reach of Muddy Creek near Kremmling, Colorado, which has multiple functions for multiple stakeholders. This reach is located from 0.5 to 12.7 river kilometers downstream of Ritschard Dam, which forms Wolford Mountain Reservoir. Wolford Mountain Reservoir provides water storage and releases based on water rights and contract demands. The reach below the reservoir is an area used for (1) wetland mitigation, (2) private, recreational fishing (3) and agriculture. These multiple uses have implications for management strategies, and in this instance, maintenance of channel stability and water conveyance in Muddy Creek are increasingly important objectives for the resource managers and stakeholders.

1.1 DOWNSTREAM EFFECTS OF DAMS ON ALLUVIAL STREAMS

Dams built on main stem rivers result in various changes to the downstream river systems. These changes include direct alteration of streamflow timing, magnitude, and duration; as well as the physical and chemical properties of the released waters (McCully, 2001; Petts, 1979; 1984). Common changes include reduction in water temperatures and sediment concentrations, with various changes to water chemistry depending on geological and reservoir characteristics (Andrews, 1986; Muth *et al.*, 2000; McCully, 2001). These changes can have long-standing effects on aquatic species range and habitat, in addition to altering the form and function of downstream river systems. Although these changes are important, further discussion will focus on the morphological changes reported downstream of dams in alluvial streams as it may affect streambank erosional processes. The deformable nature of alluvial streams results in more rapid channel response to alterations, making them more prone to substantial changes to channel characteristics than in bedrock channels (Knighton, 1998).

Previous studies have demonstrated changes in streambed elevation and channel widths. Williams and Wolman (1984) studied 21 dams constructed on alluvial rivers, primarily located in the semiarid western United States. The findings of that study showed that flood peaks were generally decreased by the dams, with differing effects to other respects of the post-dam streamflow characteristics. Sediment concentrations and loads were often markedly decreased for hundreds of kilometers downstream. Streambed incision, when present, typically occurred within the first two decades following dam completion, and ranged from negligible amounts to 7.5 m in depth based on the 287 cross-sections studied. During this period of incision, Williams and Wolman also noted a coarsening of bed sediments that may or may not return to pre-dam conditions. Owing to the complicated relation of stream response to streamflow and sediment alterations, stream channel widths were reported to have increased, decreased, and remained constant following completion of the dams. Petts (1980) found that predictions of downstream effects in alluvial reaches were dependent on the relative changes in streamflow and sediment load pre- and post-dam as well as the specific locations and time periods evaluated. Different combinations of changes to flow regime and sediment load were found to result in narrowing, widening, incision, or aggradation of the stream channel for different examples. All of which may occur in response to these alterations for different locations at different times. Tributary sediment inputs, dam position within the drainage, vegetation type and extent, and streambed and streambank composition were all described as important factors influencing channel response.

Incision and narrowing of stream channels are also common responses reported in other studies (Andrews, 1986; Friedman *et al*., 1998; Ligon *et al*., 1995; Petts, 1979; Williams and Wolman, 1984). In some instances, rapid incision and potential entrenchment of the streambed were also reported as the river system adjusts towards a new equilibrium (Williams and Wolman, 1984). These conditions reduce the occurrence of out-of-bank flows, and may impact riparian vegetation patterns. Ligon *et al*. (1995) also reported channel simplification and increased stability of braided channel sections, leading to reduced out-of-bank flows and reduced channel avulsion. These findings were also reported by Friedman *et al*. (1998) for channels in the Great Plains. Based on findings from reaches located downstream of 35 dams, Friedman *et al*. (1998) concluded that braided streams typically narrowed, while meandering streams typically showed reductions in migration rates.

Channel evolution models (CEM) provide a useful framework to understand important changes in the dominant geomorphic processes controlling channel response to natural or human caused disturbances (Schumm *et al*., 1984). CEMs provide an indication of the direction or sequence of response along the longitudinal profile of a stream network, or at a fixed location through time. The progression follows a typical idealized sequence: (1) single-thread equilibrium condition, (2) incision and isolation of floodplain, (3) over-steepening of streambanks, increased streambank instability, channel widening with continued incision, (4) channel aggradation with continued widening, and (5) return to quasi-equilibrium at new, lower elevation (Schumm *et al.*, 1984; Simon, 1989; Simon and Downs, 1995). This highlights the inter-related nature of vertical and horizontal adjustments within a stream system in addition to outlining the large-scale changes to reach and cross-sectional geometry. Interpretation of the current CEM stage can guide appropriate mitigation efforts, but departure from this sequence is common and can result in planform change instead of return to pre-disturbance conditions depending on the magnitude of change and position relative to thresholds of equilibria (Hawley *et al.*, 2012; Knighton, 1998).

1.2 PREVIOUS WORK ON STREAMBANK STABILITY

Interest in streambank stability arises from multiple perspectives. Streambank erosion is an important fluvial process that can drive the evolution of river and riparian morphology (Knighton, 1998). It is considered in arenas related to stable channel design and protection of infrastructure and is also important to aquatic and riparian habitat (USDA, 2001; Rinaldi and Darby, 2008). Rinaldi and Darby (2008) describe the progression of research pertaining to streambank stability. They found that the primary focus of research from the 1950s into the 1990s was on measurement of streambank retreat (Hooke, 1980; Hanson, 1990; Lane *et al*., 1994; Lawler, 1993); determining the variables controlling streambank retreat (Grissinger, 1982; Kartha and Leutheusser, 1972; Knight *et al*., 1984; Lawler, 1992; Springer *et al*., 1985; Thorne, 1982; Thorne, 1990; Thorne and Abt, 1993); characterization of sediment delivery rates derived from streambank processes (Arulanandan *et al*., 1980; Walling *et al*., 1999); and determination of the effects of streambank processes on channel geometry (Lane, 1955; Lohnes and Handy, 1968; Millar and Quick, 1993; Simons *et al*., 1962; Thorne *et al*., 1981; Thorne and Tovey, 1981). Findings from these research efforts have related streambank composition, channel-geometry, and streamflow characteristics to streambank stability, while also highlighting parameters and mechanisms important to streambank erosional processes (streambank slope and height, soil cohesion, soil strength and erodibility factors, fluvial scour, and effects of riparian vegetation).

By the early 1990s, research emphases largely shifted to understanding vegetative effects on soil and streambank stability (Abernathy and Rutherfurd, 1998; Abernathy and Rutherfurd, 2000; Abernathy and Rutherfurd, 2001; Collison and Anderson, 1996; Dabney *et al*., 1997; Goodson *et al*., 2002; Gray, 1978; Gray and Barker, 2004; Griffin *et al*., 2005; Simon and Darby, 1999; Simon and Collison, 2002; Thorne, 1990); the importance of preparation processes such as desiccation, weathering, and freeze-thaw (Lawler *et al*., 1997; Simon *et al*., 2000; Dapporto, 2001); and the effects of pore-water pressure and confining pressure on streambank stability (Fredlund and Rahardjo, 1993; Simon *et al*., 2000; Simon and Collison, 2002; Simon and Curini, 1998). Riparian vegetation as well as characteristics of soil moisture contribute to the structural characteristics of streambanks (Knighton, 1995). Soil moisture can promote soil cohesion, but excess soil moisture can generate positive pore-water pressures, decrease matrix suction, and increase soil bulk unit weight, promoting streambank instability (Simon *et al*., 2000). Saturation of streambanks can also occur when water-surface elevations fluctuate rapidly during flood events or from flow management or releases from reservoirs (Chu-Agor *et al.*, 2008; Dapporto *et al.*, 2001; Karmaker and Dutta, 2013; Midgley *et al.*, 2012). Vegetation root structure can increase streambank integrity through enhanced tensile strengths with evidence that woody riparian vegetation (such as willows) may have produced greater critical average bank shear stress than that of non-woody covered streambanks (David *et al.*, 2009; Millar and Quick, 1998; Polvi *et al.*, 2014; Rosgen, 2006). A presentation of the functional differences of streambank stabilizing root characteristics was recently completed (Polvi *et al*., 2014). Polvi *et al.* (2014)

demonstrated that streambanks containing willow or other woody plants have greater stabilizing effects on streambanks than non-woody vegetation because of advantages in rooting structure strength, the reduced soil moisture through consumptive use, and added roughness, which decreases flow velocity and promotes deposition of sediment. However, this is not universally accepted because non-woody vegetation has been shown to contribute more strength per unit root area with less added weight than woody vegetation, emphasizing the need to consider the total effects of vegetation on streambank erosional processes (Simon and Collison, 2002).

Additional advances from implementation of computer modeling of width adjustment and channel migration based on interactions between fluvial scour and mass wasting processes along streambanks provide scientific rigor to streambank stabilization assessment techniques. Assessments of streambank erosion range from generalizations regarding occurrence to more sophisticated computer models predicting streambank erosion quantity allowing for planar, cantilever, and rotational failures of the streambank in models such as BSTEM (Bank-Stability and Toe-Erosion Model; Simon *et al*., 2000) (Darby and Thorne, 1996b; Dapporto *et al*., 2001, 2003; Rinaldi *et al*., 2004; Rinaldi and Casagli, 1999; Casagli *et al*., 1999; Simon *et al*., 1991; Simon *et al*., 2000; Simon and Collison, 2002; Thorne and Abt, 1993). Characterization of vegetation effects for streambank stabilization has been the focus of research to determine best practices or guides for channel restoration (Evette *et al*., 2012; Norris *et al*., 2008; Merritt *et al*., 2010; Winward, 2000).

More recent efforts have aimed to combine modeling effects of fluvial and mass wasting into channel stability assessments that also account for changing conditions of soil moisture to better represent the progression of conditions as they change during a specified streamflow or precipitation sequence (Dapporto and Rinaldi, 2003; Simon and Collison, 2002). These advances leverage enhanced computational power available in personal computers today and more accurate representation of scour and shear forces used to assess Limit Equilibrium Method (LEM) solutions (Dapporto and Rinaldi, 2003; Simon and Collison, 2002). These methods are also more data intensive, and are often used to characterize more detailed streambank erosion over limited areas for specified flow intervals, producing refined predictions that are often limited to studies of smaller spatial and temporal conditions.

Other efforts focus on identifying areas most susceptible to impacts from alteration of the stream system. Bledsoe *et al.* (2012) provide an example where a management tool and template is presented and used to assess stream segment susceptibility to erosion and degradation to address urbanization. This effort highlights a resource management need to apply the collective knowledge of geomorphic processes and channel response into an understandable tool. Bledsoe *et al.* (2012) created a series of decision trees and checklists that resource managers can use to identify and prioritize areas of concern and better understand next steps to assess or address the problem.

1.3 LOGISTIC REGRESSION USE IN GEOSCIENCES

Use of logistic regression is common in social and medical sciences but is limited in applications in the geosciences. Some examples of the use of logistic regression within the geosciences include determination of the probability of detecting chemicals associated with sediment, surface water, and groundwater resources (Battaglin, 1996; Gurdak and Qi, 2006; Rupert and Plummer, 2009; Field *et al.,* 1999); prediction of the likelihood of debris flows, landslides, or levee failures (Ayalew and Yamagishi, 2005; Ohlmacher and Davis, 2003; Flor *et al.*, 2010; Griffiths *et al.*, 1996; Rupert *et al.*, 2003, 2008); and assessment of the likelihood of changes to fluvial system planform or stability (Bledsoe and Watson, 2001; Bledsoe *et al.*, 2012).

Logistic regression analysis provides probability of occurrence for response variables that can be characterized within the binomial distributions (i.e., failure *vs.* success; or occurrence *vs.* non-occurrence) over a continuous range of probability from 0 to 1 (Helsel and Hirsch, 2002; Ott and Longnecker, 2001). Logistic regression provides output that is framed in a more intuitive concept of risk assessment. The regression predictions can be constructed to quantify the probability or 'risk' of occurrence of a specific outcome (within medical sciences two examples include: the probability of patient mortality, or survival probability beyond a given timeframe), an output useful to decision makers and resource managers because it inherently conveys the measure of certainty of the occurrence. This measure of certainty can be translated through the decision process, where an evaluation can include changing levels of acceptable risk depending on the specific conditions that relate to loss of property, resource, or life.

1.4 STUDY OBJECTIVES AND HYPOTHESES

This thesis evaluates a reach of Muddy Creek below Wolford Mountain Reservoir in order to (1) determine the dominant erosive and resistive processes within the reach that contribute to channel stability and response, and (2) assess the validity of using logistic regression techniques as an analytical framework for geomorphic assessments. Logistic regression is used in this paper to estimate the probability of localized streambank erosion and provide insight into the processes controlling channel stability in the study reach.

Logistic regression is used to test the following hypotheses, with the type-I error threshold set at 5 percent ($\alpha = 0.05$). An evaluation of the statistical relations between regression parameters and the occurrence of streambank erosion within the reach will be used to evaluate whether a relation exists between an explanatory variable and streambank erosion within the reach (e.g., positive regression coefficients indicate processes or characteristics that promote or ‘increase’ streambank erosion; negative regression coefficients indicate processes or characteristics that reduce or ‘decrease’ streambank erosion).

Hypothesis 1 tests whether stream-induced scour and undercutting have differing effects on streambank erosion due to changes in the erosive power of the stream. This includes an evaluation of regression parameters related to channel geometry, energy grade line indicated by bed slope, and direction of flow relative to streambank positions (hereafter flow angle-of-attack).

H_{o1}: Areas with greater erosive power do NOT significantly increase the probability of streambank erosion in the study reach.

H_{a1}: Areas with greater erosive power significantly increase the probability of streambank erosion in the study reach.

Hypothesis 2 tests how differences in the streambank structure and vegetation influence resistance to streambank erosion, or whether management strategies for the reconfigured reach or mitigation wetlands have significantly affected streambank erosion in the study reach. This includes an evaluation of conditions related to streambank height, riparian vegetation, presence and function of erosion-control structures, and proximity to irrigation infrastructure.

H_{o2}: Streambank and riparian characteristics do NOT significantly affect the probability of streambank erosion in the study reach.

H_{a2}: Streambank and riparian characteristics significantly affect the probability of streambank erosion in the study reach.

Hypothesis 3 tests whether reach-scale characteristics have any effect on streambank erosion. This includes an evaluation of the effects of valley width, channel sinuosity, and proximity to terraces and alluvial fans.

H_{o3}: Reach-scale characteristics do NOT significantly affect streambank erosion in the study reach.

H_{a3}: Reach-scale characteristics do significantly affect streambank erosion in the study reach.

An additional priority of this work is to present logistic regression methods as an analysis framework that can be applied to other reaches or watersheds to address other geomorphic issues. In this application, logistic regression analysis will aim to strike a balance between the level of cost associated with deriving data used to assess streambank erosion and the accuracy of the predictions to inform management and assess risk.

Hypothesis 4 tests how well logistic regression techniques can be used to identify areas susceptible to streambank erosion.

H_{o4}: Logistic regression techniques can NOT be used to successfully predict the risk of streambank erosion in the study reach.

H_{a4}: Logistic regression techniques can be used to successfully predict the risk of streambank erosion in the study reach.

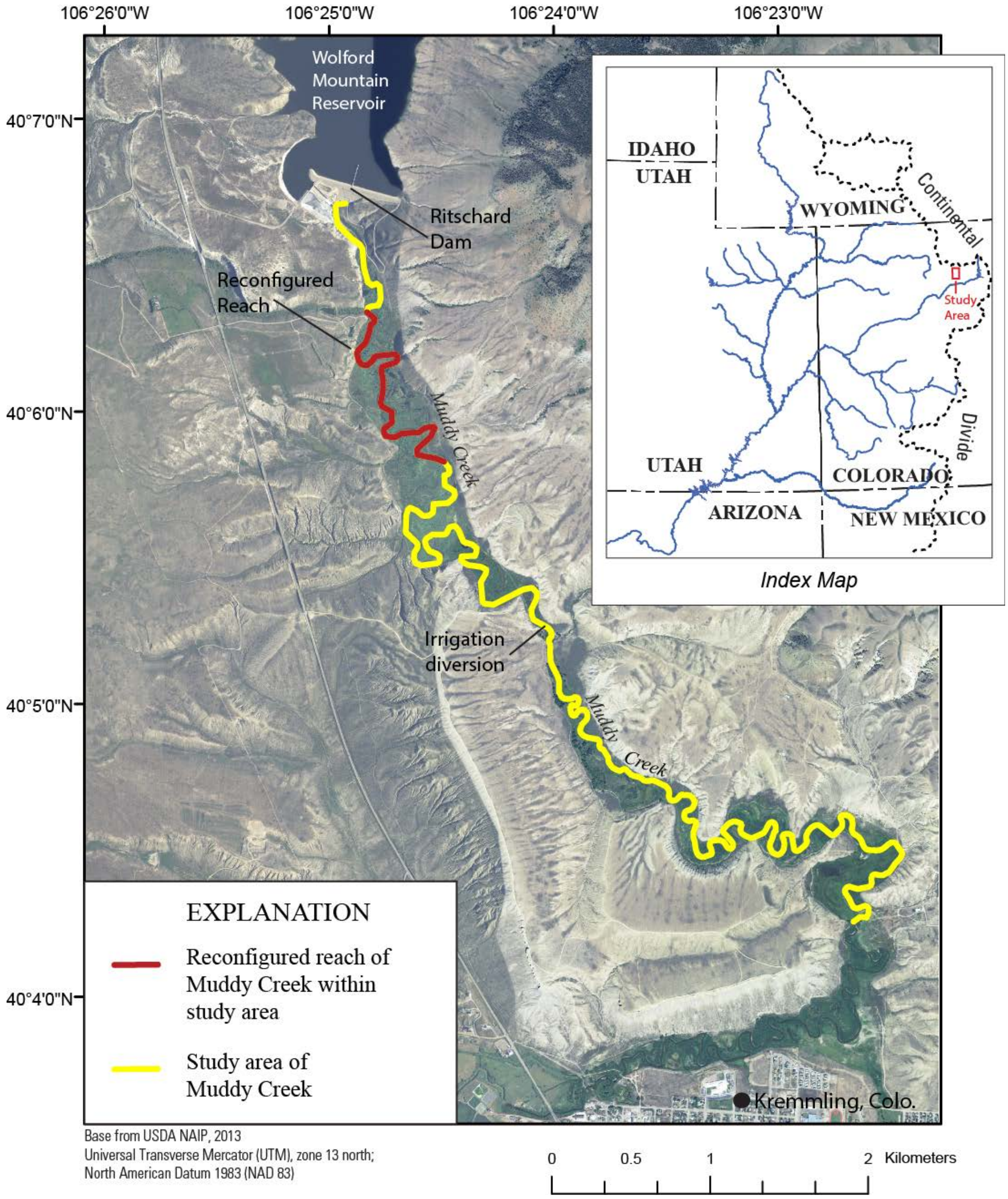
Successful calibration of a significant logistic regression model will provide the analytical framework to determine the processes important to streambank stability within the reach. Analysis of correlation between reach characteristics (hydraulic, streambanks and riparian, and reach-scale) to locations of streambank erosion is used to inform and validate a conceptual model of channel adjustment for the study reach. Logistic regression also provides predictions of risk to infrastructure and property, which can inform resource managers and aid targeting and mitigation strategies within threatened areas. Additional factors associated with channel stability that were not included in the logistic model, as well as general channel monitoring techniques, are also discussed.

2 STUDY AREA

Muddy Creek below Wolford Mountain Reservoir is a meandering, gravel-bed stream near Kremmling, Colorado (Figure 1). Muddy Creek and its major tributaries originate in the Gore Range and Rabbit Ears Range of north-central Colorado. Mean annual precipitation ranges from 305 to 635 mm in the lower watershed near the study reach (Stevens and Sprague, 2003). Agriculture has been centered along the valley bottoms, with numerous diversions in place since the late 1800s. The agriculture is primarily used to support livestock grazing in pastures and hay production (CDSS, 2013; Butler, 1990). Higher elevation areas within the basin along the northern and western boundaries are used for recreation and timber harvesting (Butler, 1990). Upper Cretaceous Pierre Shale dominates the landscape, producing badlands composed of shale and sandstone that readily supply abundant fine sediments to the fluvial system (Izett and Barclay, 1973; Butler, 1990). The transition of geologic members within the Pierre Shale Formation produces notable differences in downstream valley width, particularly near the irrigation diversion indicated in Figure 1. Areas of larger valley widths are accompanied by more sinuous sections of stream. Wolford Mountain is a fault block remnant of Precambrian Age composed of quartz monzonite and Boulder Creek Granodiorite. The east abutment of Ritschard Dam is an exposure of the fault block remnant (Izett and Barclay, 1973; Butler, 1990).

Streamflow within Muddy Creek is derived primarily from snowmelt, but in the study reach streamflow is regulated entirely by releases and spills from Ritschard Dam and Wolford Mountain Reservoir. The study reach begins approximately 460 m downstream from the Ritschard Dam at the USGS streamflow gage 09041400 and ends 12.7 river km downstream

(Figure 1). Streamflow data have been collected since July 1995 at USGS streamflow gaging station 09041400 Muddy Creek below Wolford Mountain Reservoir near Kremmling, Colorado.



Base from USDA NAIP, 2013
Universal Transverse Mercator (UTM), zone 13 north;
North American Datum 1983 (NAD 83)

Figure 1. Map showing study reach of Muddy Creek below Wolford Mountain Reservoir near Kremmling, Colorado.

The gage is located downstream from Ritschard Dam and 6.5 km northwest of Kremmling, Colorado. The drainage area of the watershed upstream from the gage is 700 km^2. The maximum instantaneous peak discharge recorded at the gage was 36 m^3/s (1,270 ft^3/s) on June 8, 2011 (USGS, 2014).

2.1 BACKGROUND

Ritschard Dam was constructed from 1992–94, and Wolford Mountain Reservoir has an 80 cubic hectometers storage capacity (66,000 acre-foot), and covers approximately 627 hectares (1,550 acres) at full storage (Stevens and Sprague, 2003). When filled to capacity, usually in April through June, additional inflow passes through the reservoir and, since 1995 when filling began, creates the annual discharge peak in the study reach. These releases, in conjunction with applied irrigation water, support mitigation wetlands (created to offset losses of wetland habitat due to inundation from the reservoir) located along Muddy Creek. Irrigation pipelines and ditches are used to supplement water to support riparian habitat. Meander migration and streambed scour may expose irrigation infrastructure and can threaten the quality or abundance of these wetlands.

Regulation by the reservoir has also had an attenuating effect on annual variation in streamflow and water temperature, and turbidity was substantially reduced as a result of reservoir sedimentation (Stevens and Sprague, 2003). Peak discharges downstream from the reservoir were the same or slightly less than peak discharges upstream from the reservoir, but the duration of the largest streamflows (greater than the upper 15th percentile) downstream from the reservoir decreased, whereas the duration of moderate and low streamflows increased as a result of reservoir operations (Stevens and Sprague, 2003). Additional alteration of the flow regime has occurred that resulted in reductions of the magnitude of rainfall runoff peaks downstream of the reservoir and reductions in the rate of water-surface elevation change (Stevens and Sprague, 2003). However, late summer and early fall flow variations have increased below Wolford Mountain Reservoir from reservoir releases to meet water needs (Stevens and Sprague, 2003).

Additional changes to an upper portion of the study reach include reconfiguration with channel stabilization and flow-directing boulder structures (the natural-channel design approach, Rosgen, 2006) to stabilize streambanks and improve trout habitat. The reconfigured portion of the study reach begins approximately 1 km downstream from the Ritschard Dam (Figure 1). The reach was modified in Fall 2003 to enhance and improve trout habitat, but the channel pattern (meander dimensions, channel alignment, sinuosity, and bed slope) in the reach was not changed (Elliott *et al.*, 2011). Revetments (riprap and log cribs) were added to some streambanks to mitigate erosion and meander migration, and the angle of some cut-bank scarps was reduced from near vertical to a lesser slope (Elliott *et al*., 2011). Additional alteration through boulder grade-control and flow-directing structures called "cross vanes" and "J hooks" (Rosgen, 1996) was completed in late 2003. Other individual boulders or boulder clusters were placed randomly in the channel to create velocity breaks to enhance fish habitat. Many willow seedlings and cottonwood saplings were planted along the streambanks and riparian zone. The reconfigured reach is approximately 2.5 river km in length with dozens of boulder structures throughout.

2.2 PREVIOUS STUDIES

Previous studies assessed potential reservoir effects on Muddy Creek. Following completion of the reservoir project, one estimated downstream effect of Wolford Mountain Reservoir included channel incision of about 0.12 m in the 210 m immediately downstream from Ritschard Dam (Butler, 1990). The presence of larger bed sediments (gravel to small boulders) in stream riffles within the reach was thought to reduce the potential for incision of the stream following construction of Wolford Mountain Reservoir (U.S. Forest Service, 1988).

Ruddy (1987) estimated that at least 97 percent of the total-sediment discharge in Muddy Creek was transported in the suspended phase. A review of the particle size analysis from Elliott *et al*. (2011), in conjunction with field observation, shows that bed-load transport occurs only during extreme flow conditions, and in limited locations within the reach. A two-dimensional hydrodynamic model was used to assess median grain-size transport within two reaches of Muddy Creek (Elliott *et al.*, 2011). The results show that only isolated areas of the gravel bed are mobilized, even at flows that are out-of-bank (greater than 20 m^3/s or 697 ft^3/s) (Elliott *et al.*, 2011). These flow conditions occur less than 2 percent of the time based on available streamflow data at USGS streamflow gage 09041400 (Figure 2).

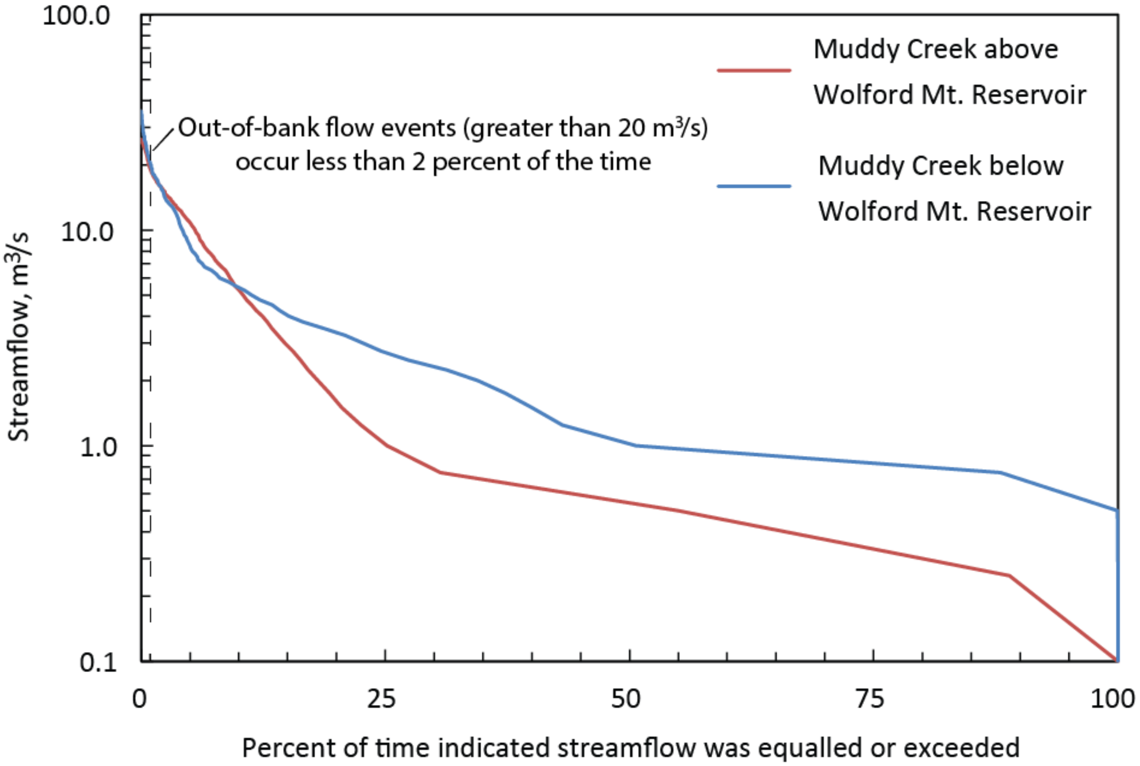


Figure 2. Streamflow duration curves above and below Wolford Mountain Reservoir. Data for Muddy Creek below Wolford Mt. Reservoir includes the post-reservoir time period only.

3 DATA COLLECTION AND ANALYSIS METHODS

Field reconnaissance and channel surveying were completed during base-flow conditions September 16-27, 2013. This effort included measurement of channel characteristics (streambank heights, channel top-width, and channel bed slope), while also georeferencing geomorphic-stability indicators (observations of streambank erosion, subsurface flow, stream channel modification and function, vegetation type and condition, and animal disturbance).

3.1 STREAMFLOW GAGE DATA

Specific gage analysis, an analysis that compares water-surface elevations through time for a fixed streamflow, at the Muddy Creek gages was used to assess the effects of the altered flow regime on channel form above and below Wolford Mountain Reservoir. Consistent reductions in elevation can be indicative of general incision of the streambed, or may be the result of widening of the cross-sectional flow area. Trends that describe a general increase in water-surface elevation tend to be more indicative of aggradation of the streambed, or narrowing of the cross-sectional flow area. These relations are observed in many instances within vertically or laterally unstable systems (Carpenter et al., 2012; Czuba et al., 2010; Jones et al., 2012A, 2012B; Risley et al., 2010; Wallick et al., 2010, 2013), but can also be related to changes in other channel characteristics like hydraulic roughness.

3.2 CHANNEL SURVEYING

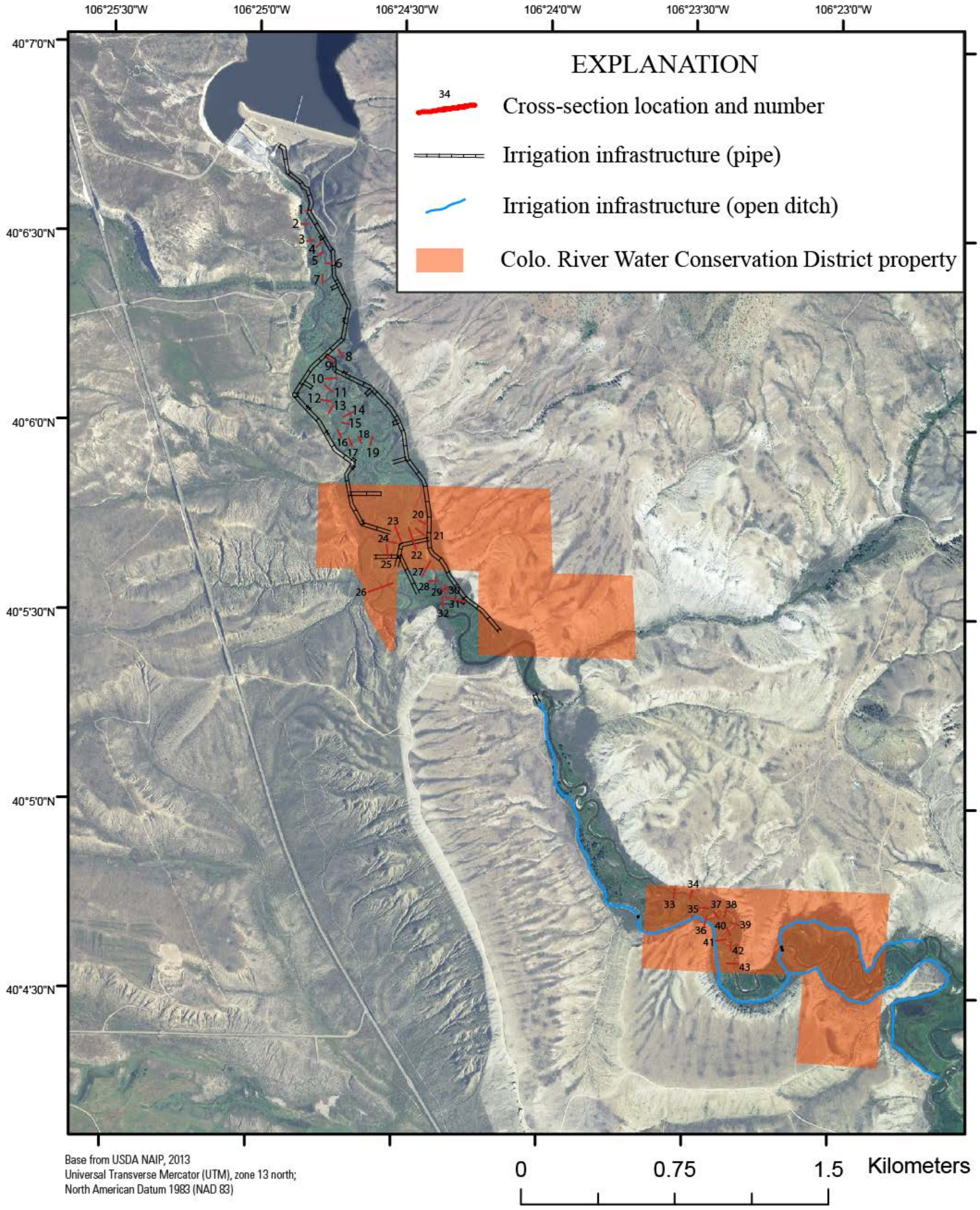
Surveying efforts require differing levels of precision and reach extent depending on study objectives. For geomorphic assessments, vertical accuracy of 0.030 m is acceptable for survey points of geomorphic features (Elliott and Parker, 1999). On-site measurements of channel characteristics are tailored to a specific stream reach and to the monitoring objective. The aerial extent of monitoring is dependent on the size of the reconfiguration project, geomorphic and ecological variability within the reconfigured reach, the project budget, and other site-specific considerations. At a minimum, monitoring data are collected over a representative stream reach of at least several channel widths in length (Elliott and Parker, 1999). For this study, assessment of the entire reach was deemed necessary to evaluate adverse-channel change potential and implications for existing mitigation wetlands and irrigation infrastructure.

Channel surveys typically focus on the river bed, low-lying gravel and cobble bars, islands, side channels, streambanks, levees, and nearby terraces that would contain up to about the 5- or 10-year flood (Elliott and Parker, 1999). Vertically, the survey should include the deepest portion of the channel to the top of the flood-confining terrace, streambank, or levee (Elliott and Parker, 1999). Additionally, surveys of the thalweg at riffles and crossings in meanderings streams are important to determine bed slope controls. Identification of these surfaces in conjunction with distinction between streambanks (left or right) facilitates calculations of streambank height and channel widths. In this study, channel characteristics (streambank height, channel top-width, and bed slope) and geomorphic-stability indicators (observations of streambank erosion, subsurface flow, stream channel modification and function, vegetation type and condition, and animal disturbance) were quantified using field reconnaissance and real-time kinematic (RTK) global positioning system (GPS) surveying. Incorporation of RTK-GPS was done to increase the efficiency of the survey over the larger reach length. Standard GPS surveying techniques are described in Rydlund and Densmore (2012). Additional information can be found in USDA Forest Service General Technical Report

RM-245 (Harrelson *et al*., 1994) for guidelines regarding basic surveying techniques, identification of bankfull indicators, and measuring other important stream characteristics.

The survey was completed during base-flow conditions September 16-27, 2013, following methods described in Elliott and Parker (1999) and Rydlund and Densmore (2012). Cross-section surveying was paired with previous USGS channel monitoring surveys (http://co.water.usgs.gov/projects/rcmap/publications.html 2001, 2003, 2006, 2008, and 2012) to further assess changes in reach conditions through time (Figure 3). The vertical and horizontal precision of the RTK-GPS, as rated by the manufacturer, are ±0.020 m and ±0.010 m, respectively (Trimble Navigation Limited, 2009). In the field, observations agree with these levels of precision. Control points were surveyed to a greater level of precision by increasing the measurement period from 3 to 300 epochs.

The RTK-GPS setup consisted of a base station, which included a receiver and radio (Trimble R8 GNSS RTK-GPS receiver and a Trimble HPB450 radio modem), and four rover setups, each of which included a receiver and controller pair (Trimble R8 GNSS RTK-GPS receiver and Trimble TSC2 controller). The base station was first located at a fixed position at the west end of the reach along a ridge line to maximize radio transmission coverage in the study reach. To improve communication between the rovers and base, a second location was selected for the base station deployment along a ridge in the eastern end of the reach. The second position was used to supplement survey points along the southern most section of the study reach that had poor radio reception from the base during surveying efforts at base location one. Positional information from base location one was used to set the location of the second base position to preserve relative position and improve accuracy.



Base from USDA NAIP, 2013
Universal Transverse Mercator (UTM), zone 13 north;
North American Datum 1983 (NAD 83)

Figure 3. Location of resurveyed cross-sections below Wolford Mountain Reservoir.

All survey data were collected with a common coordinate system, geoid, ellipsoid, and datum. The coordinate system used was Universal Transverse Mercator (UTM), zone 13 north; the horizontal datum was North American Datum 1983 (NAD 83), and the vertical datum was North American Vertical Datum 1988 (NAVD 88), Geoid 2012A, ellipsoid World Geodetic System 1984 (WGS 84). Data from the base station, collected throughout the study, were submitted to the National Geodetic Survey's Online Positioning User Service (OPUS) Web site for processing (http://www.ngs.noaa.gov/OPUS/, accessed September 18, 2013). All survey data were recomputed to reflect the OPUS solution correction, and were referenced to RTK-GPS positions using Trimble Business Center (version 2.07) and OPUS solutions.

Elliott and Parker (1999) suggest that monitoring cross sections are most beneficial if located along the channel in areas most sensitive to alteration by streamflow; for example, in areas that might scour or aggrade as bed material is transported, or in meander bends where lateral channel migration or streambank erosion could occur. Cross sections should be oriented perpendicular to the bankfull flow and should be spaced up- and downstream along the channel at an average of about 3 to 6 times the mean bankfull channel width. In longer reaches, the monitoring cross sections can be clustered in shorter sub reaches that are representative of the whole reach. Further consideration of cross section spacing is determined by site-specific considerations. Cross sections can be spaced wider apart where the channel is uniform (has little curvature, similar cross-section shape, same grade, same roughness) and should be spaced more closely where the channel is irregular (width or slope vary abruptly, islands or bends are present, roughness varies), near bridge abutments and piers, and near flow-directing structures commonly used for erosion control.

Measurements along previously established cross sections were used to evaluate channel change in the reach, in addition to longitudinal survey efforts using standardized methods (Elliott and Parker, 1999). Replicate channel surveys with a common datum and coordinate system enable detection of geomorphic change that might occur as a result of flood scour, bed-material aggradation, or lateral channel migration (Emmett and Hadley, 1968). This promotes detection of channel changes by removing the natural variation in cross-section characteristics that occur along a stream reach.

Survey shots along the cross section were completed in a straight line (under a stretched tag line or along a navigated course between two GPS-located endpoints), and numbered about 30-40 locations between the streambanks. Closer spacing was required when there was greater streambed irregularity, wider spacing was acceptable when the streambed was more uniform and on the flood plain (Elliott and Parker, 1999).

3.3 PROCESSING GEOGRAPHIC INFORMATION

To facilitate statistical assessments of channel characteristics and geomorphic-stability indicators, the survey data and field reconnaissance data were related to other features in the reach using a Geographic Information System (GIS). This facilitated analysis of features by distance and relative streambank position (left or right) to provide insight into the processes controlling channel stability in the Muddy Creek study reach and to investigate changes in stream reach characteristics through time.

3.3.1 AERIAL IMAGES

Acquisition and georeferencing of aerial imagery was completed from available U.S. Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP) data sets.

Recent NAIP images are available as georeferenced digital data sets (2004, 2009, 2011, and 2013). Hard copy aerial images were also available for the study reach for earlier time periods (1962, 1969, 1970, 1983, 1989, 1994, and 1999). Georeferencing of two of the available time periods (1962 and 1994) was completed using the georeferencing extension in ArcGIS so that comparisons in channel characteristics could be evaluated. Georeferencing of the scanned imagery was completed through selection of a minimum of 10 spatially-distributed control points identifiable in both the 2013 NAIP digital data set and the image being rectified. Intersections of roadways, buildings, and prominent, discrete land marks were used as control points between images. Georeferencing was completed using 1st or 2nd order polynomial fit of control points within the images. Additional control points were added, as necessary, until the images visually converged and the root mean square (RMS) error of the control points was less than 1.1 m between time periods, for each georeferenced image.

A random selection of points along the study reach resulted in 54 locations used to characterize the channel widths at each location for each time period of the imagery. Comparisons of channel widths between 1962 and 1994 are used to evaluate the stability of the channel width prior to completion of Wolford Mountain Reservoir in 1995. Comparisons of channel widths between 1994 and 2013 are used to evaluate changes in channel form following completion of Wolford Mountain Reservoir. Due to differences in image resolution and quality, this analysis compares mean channel widths for each time period to reduce the effects of errors from individual channel width measurements. Parametric group comparison techniques (paired t-test) were used to assess statistical significance of differences between means for each time period (Helsel and Hirsh, 2002).

3.3.2 CHANNEL CHARACTERISTICS AND GEOMORPHIC-STABILITY INDICATORS

Data collected during field reconnaissance and surveying were incorporated into a GIS to assess channel change. The Spatial Analyst tool in ESRI Arc Map (ArcGIS version 10.0) was used to post-process and spatially relate channel characteristics to the observed geomorphic stability indicators along both streambanks of the reach. This processing resulted in a continuous, downstream spatial index of channel characteristics at 1-meter increments, as well as a georeference structure for additional data analysis. Care was taken to reference this information for both the left-bank and right-bank spatial index, when applicable.

Identification of channel characteristics (channel top-width, streambank height, and bed slope) was determined from the elevation and position information obtained during the field surveying effort. Differences in elevations between survey points at the top and bottom of each streambank were used to determine streambank height along the reach. Differences between left and right top-of-bank positions are used to determine channel top-width. Bed slope was determined by plotting streambed elevations as a function of downstream distance. A best-fit line was used to approximate the slope between vertical control features (tops of riffles, boulder cross-vanes, irrigation diversion, and bedrock outcrops) along the longitudinal profile of the stream. Bed slope is used to assess differences in the energy grade line though the reach, a parameter important in the calculation of boundary shear stress, as demonstrated in the Duboys' equation (Chow, 1959):

$$\tau = \gamma h S \tag{1}$$

Where:

τ is the mean boundary shear stress, in Pascal;

γ is the specific weight of water (9,810 Newtons per cubic meter);

h is the hydraulic radius or mean flow depth, in meters; and

S is the energy grade line for a specific streamflow, in meters per meter.

Bed slope is used as a measure of the energy grade line and indicator of the erosive power of the stream, although metrics such as boundary shear stress or stream power were not calculated directly. Areas with steeper bed slope are used to indicate areas of greater fluvial energy and greater potential erosive power within the reach.

Additional characteristics were also calculated and referenced to the spatial index based on valley and channel measurements (sinuosity, flow angle-of-attack, inside or outside of meander bend, and valley width). Sinuosity, a measure of how straight or winding a stream path is, was determined as the ratio of downstream distance to down valley distance for a given section of a stream using standard techniques (Knighton, 1998). Sinuosity was determined for each point in the study reach using a moving calculation window, with the calculated value attributed to the point at the center of the calculation window. Variations in the length of the calculation window were explored and a distance of 1.77 river km was selected because this interval resulted in a mound shaped frequency distribution and produced sinuosity values that matched the range of sinuosity within the reach.

Flow angle-of-attack, the degree to which the primary flow direction was oriented toward a streambank, was also determined throughout the reach using methods modified from Knighton (1998). This provided a means to address difference in the hydraulic forces acting on the toe of the streambanks along straighter sections and throughout meander bends where flow angle-of-attack can range from +90 degrees, defined for flows oriented directly towards a downstream streambank along the outside of a meander bend; to -90 degrees, defined for flows oriented directly away from a streambank along the inside of a meander bend. These two cases represent extremes along a continuum of potential flow-angle-of-attack values. Flow angle-of-attack describes the extent to which higher velocities are directed towards a streambank. The calculated values represent flow conditions ranging from base flow to bankfull. During flood conditions, the orientation of the flow relative to the streambanks may change, but was not accounted for in this study because no observations of flow direction during flood stage conditions were available. Identification of streambank position relative to the inside or outside of a meander bend was also included in the spatial index.

Valley width was measured for each location of streambank based on interpretation of valley margins using USDA NAIP 2013 aerial imagery. This was accomplished using the distance function in Spatial Analyst tool (Arc Map 10.0) by discerning the boundary between valley floor vegetation and the abrupt change to sparsely-vegetated, sharp rising shale residuum bluffs or alluvial fan deposits.

Streambank and riparian characteristics (streambank and vegetation composition) and geomorphic indicators of streambank erosion were joined to the downstream spatial index using the spatial join function in Spatial Analyst tool (Arc Map 10.0). Identification of erosion control features and functional status, animal disturbance, bedrock outcrop, talus slope, and outside of meander bend, are based on presence, absence (1 or 0, respectively). Riparian condition was evaluated through field observation and aerial extent using USDA NAIP imagery from 2013. Vegetation was consistent over large reaches of the stream and was classified as polygon features attributed as 6 general categories: (1) grasses and sedges, (2) willows, (3) sagebrush, (4) mixed grasses and willows, (5) cottonwood grass mix, (6) or barren talus slopes/shale residuum; each identified as either sparse, moderate, or thick. Streambank material was observed in 3 general categories (bedrock shale and silt/sandstone, fine grained over-bank deposits, and alluvial fans with inter-bedded layers consisting of particles sizes from boulders to clay). Geomorphic indications of erosion were used to identify the spatial occurrence and extent of recent streambank erosion within the reach. Some examples of streambank and riparian characteristics and streambank erosion are shown in Figures 4 and 5.

Figure 4. Photographs showing (A) willow and boulder erosion-control structures, (B) streambank sediment profile (fine-grained overbank deposits), and (C) vegetation distribution in Muddy Creek below Wolford Mountain Reservoir, September 16-27, 2013.

Figure 5. Photographs showing (A) mass wasting or block failure, (B) flanked j-hook, and (C) exposed roots idicative of recent streambank erosion in Muddy Creek below Wolford Mountain Reservoir, September 16-27, 2013.

Undercutting of these streambanks produced cantilevered blocks of intact alluvium, often heavily vegetated, with numerous observed blocks of vegetation and soil that have mass wasted into the channel and remained intact. Orientation of these blocks and the relative depth of flow within the channel determine how long these blocks remain in place on the streambed. In some locations these blocks have retained their original orientation and appear to have reestablished along the streambank toe, reducing the observed streambank height and further armoring the streambank slope.

The spatial index is used to evaluate the statistical significance of erosional processes within the reach and to estimate the probability of localized streambank erosion based on logistic-regression techniques. Separation of areas in- and downstream-of the reconfigured reach is explored to determine whether there are detectable differences. Comparisons are made based on regression coefficients and statistical significance, as well as through comparisons of streambank erosion between reaches using paired t-tests for differences in the mean values between groups (Helsel and Hirsch, 2002).

3.4 LOGISTIC REGRESSION ANALYSIS

Using standard logistic-regression techniques (Helsel and Hirsch, 2002), this analysis estimates the probability of localized streambank erosion, and provides insights into the processes controlling channel adjustment in the reach. Streambank erosion is the dependent categorical variable (coded as 1 for eroding, and 0 for stable), while channel characteristics and the remaining geomorphic stability indicators (subsurface flow, stream channel modification and function, riparian characteristics, and animal disturbance) are the explanatory variables.

Streambank erosion occurs at varying scales and timeframes within river systems. Selection of the spatial and temporal extent for this analysis required obvious indications of erosion that occurred within the last high-flow season. A combination of color, compaction, and the presence of less-resistant soil structures was used to assess if streambanks were eroding or stable. Often this was visually apparent through an examination of root exposure and the soil profiles, as well as observation of the corresponding sediments deposited along the bank toe or channel margins.

A step-wise approach was used to select an appropriate regression model based on a subset of the field observations (~12,000 observations), selected at random, for calibration of the logistic-regression model. Selection of an appropriate regression model included comparisons of models where all explanatory-variable combinations were significant (p-values less than 0.05) and where the adjusted coefficient of determination (adjusted R^2) was maximized and the Akaike Information Criterion (AIC) was minimized (Helsel and Hirsch, 2002). Care was taken to avoid inclusion of explanatory pairs with more than moderate colinearity, to prevent errors in regression coefficient determination. This was gaged through an assessment of the standard error for each parameter and variance inflation factors.

The odds ratio is defined as the ratio of the probability of obtaining a 1 (streambank erosion) divided by the probability of obtaining a 0 (stable streambank), where p is the probability (or risk, in percent) of a response of 1 (Helsel and Hirsch, 2002). The logistic-regression equation is presented in the form:

$$p = \frac{\exp\left(\beta_0 + \beta_1 X_1 + \beta_2 X_2 ... + \beta_n X_n\right)}{\left(1 + \exp\left(\beta_0 + \beta_1 X_1 + \beta_2 X_2 ... + \beta_n X_n\right)\right)} \tag{2}$$

Where:

p is the probability (or risk) of streambank erosion, in percent from 0 to 1;

exp is the natural logarithm base, approximately 2.718;

β_0 is the regression intercept;

β_n is the nth regression coefficient; and

X_n is the nth explanatory variable.

Logistic regression is later used with a conceptual model that describes the processes controlling channel form and function within the study reach so resource managers can better predict and monitor streambank erosion. This conceptual model is derived from observations in the field as well as the theoretical response of channel characteristics to alterations in flow regime and basin characteristics over time.

4 CHANNEL STABILITY ASSESSMENT

Stream channels respond to disturbances in a series of ways, each typical of a different response time period. As indicated by Knighton (1998), a typical response progression for an intermediate sized, gravel-bed stream, such as Muddy Creek, could include the following adjustments to channel form components: channel width and or channel depth (10^0–10^1 years); bedform changes in pebble clusters (10^0–10^2 years); meander wavelength (10^1–10^3 years); reach gradient (10^1–10^3 years); longitudinal profile gradient and concavity (10^2–10^4 years). Consideration of this progression of channel response can be useful to evaluate channel stability in Muddy Creek. Recall that development of water and land use change began along Muddy Creek and its tributaries upstream of the study reach 100-130 years ago. Based on the time constraint of the response, changes in channel width and depth, changes to boulder clusters, meander wavelength, and reach gradient have potentially occurred in response to this initial disturbance. In contrast, the channel response to completion and operation of Wolford Mountain Reservoir has had less time to occur, and is likely still occurring today.

Existing data sets available to evaluate channel response in Muddy Creek are limited. Available field data include repeat cross-section and study-reach surveys, along with stream-gaging information. Specifically, this information measures channel width and depth adjustment as well as evidence of changes in reach gradient. Available remotely sensed data include multiple years of repeat aerial imagery. This imagery provides a means to assess channel adjustment and includes measures of channel width, meander wavelength, and evidence of reach gradient. The channel adjustment data sets are used in various applications in the following sections to assess channel stability. Results of the field and remotely sensed data analyses, a conceptual model of channel adjustment, and a channel stability or risk assessment map (derived using logistic regression) are provided.

4.1 RESULTS FROM FIELD AND REMOTELY SENSED DATA ANALYSIS

Available streamflow data from the Muddy Creek streamflow gages were used to evaluate trends in water-surface elevation relative to a reference datum (specific gage analysis) for specific streamflows within the study reach. Recall, consistent reductions in water-surface elevation can be indicative of incision of the channel bed, or may be the result of lateral widening of the cross-sectional flow area whereas trends that describe an increase in water-surface elevation tend to be more indicative of aggradation of the streambed, or narrowing of the cross-sectional flow area (Carpenter et al., 2012; Czuba et al., 2010; Jones et al., 2012A, 2012B; Risley et al., 2010; Wallick et al., 2010, 2013).

Evaluation of the specific gage analysis at the Muddy Creek gage shows little evidence of recent channel incision or widening downstream of Wolford Mountain Reservoir, with an average observed highly significant increase of approximately 1.9 cm in water surface elevations per year over the past 10 years (95% confidence interval 1.8 – 2.0 cm/year) and 0.41 cm per year over the last 18 years below the dam (95% confidence interval 0.39 – 0.43 cm/year) (Figures 6A and 6B). This increase in water-surface elevation may indicate channel aggradation at these locations, or result from channel narrowing. Additionally, there is an indication of incision or widening in the streamflow record above the dam prior to 2003, with a highly significant average observed decrease of approximately 1.2 cm in water surface elevations per year over the previous 13 years (95% confidence interval 1.3 – 1.2 cm/year).

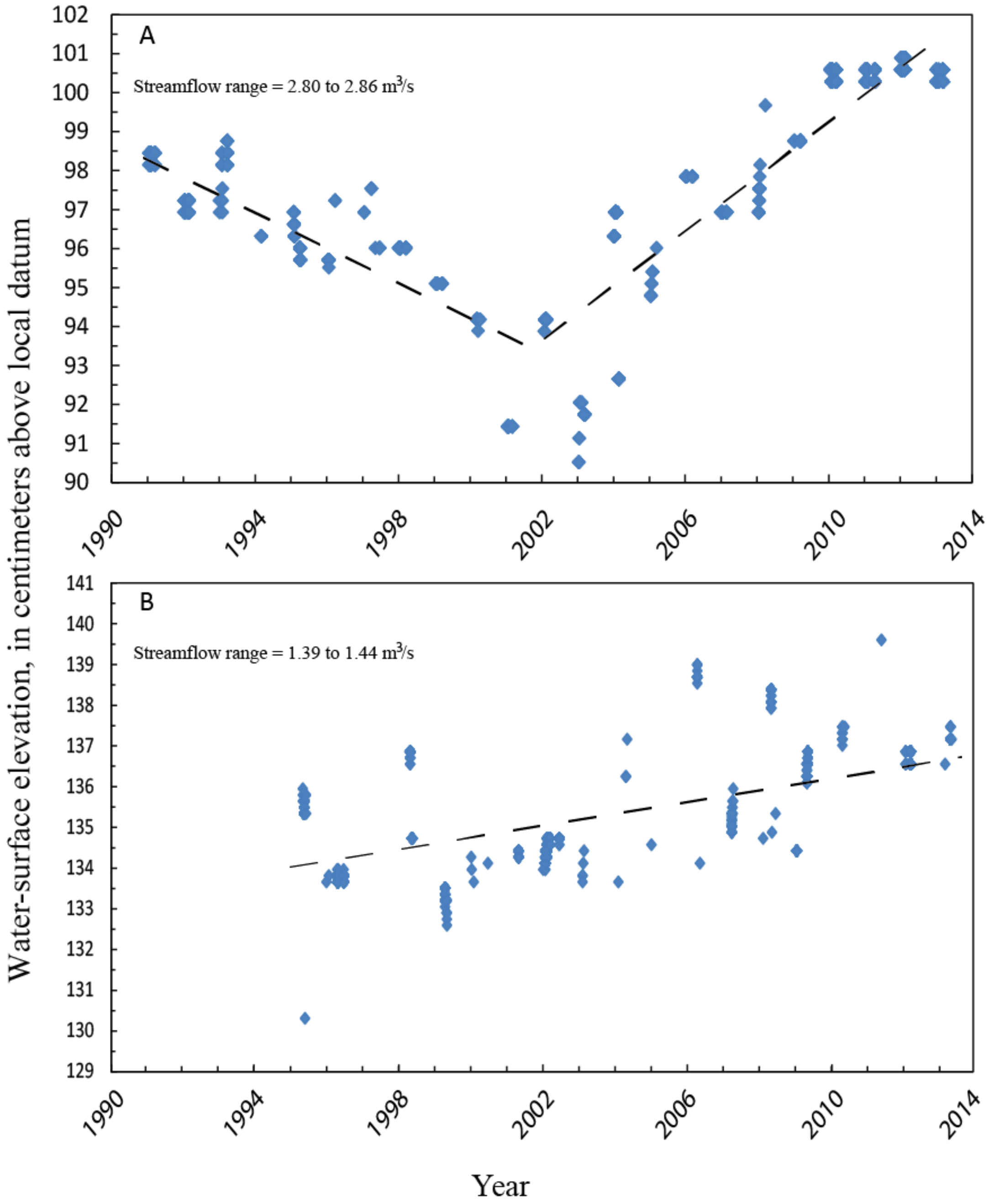


Figure 6. Specific gage analysis showing changes in reference water-surface elevation for streamflow gages (A) 09041090, Muddy Creek above Antelope Creek near Kremmling, Colo.; and (B) 09041400, Muddy Creek below Wolford Mountain Reservoir, near Kremmling, Colo.

Bed slope throughout the reach is shown as the best-fit line in Figure 7. Bed slope is steepest in the first 1.7 km of the reach and also for the first 0.5 km downstream of the irrigation diversion dam. The reconfigured reach contains both steep and flatter reaches that alternate in pattern and were often controlled by manmade boulder structures, bedrock outcrop, and coarser riffle deposits. The downstream-most 5 km of the reach show a more consistent and less steep bed slope profile.

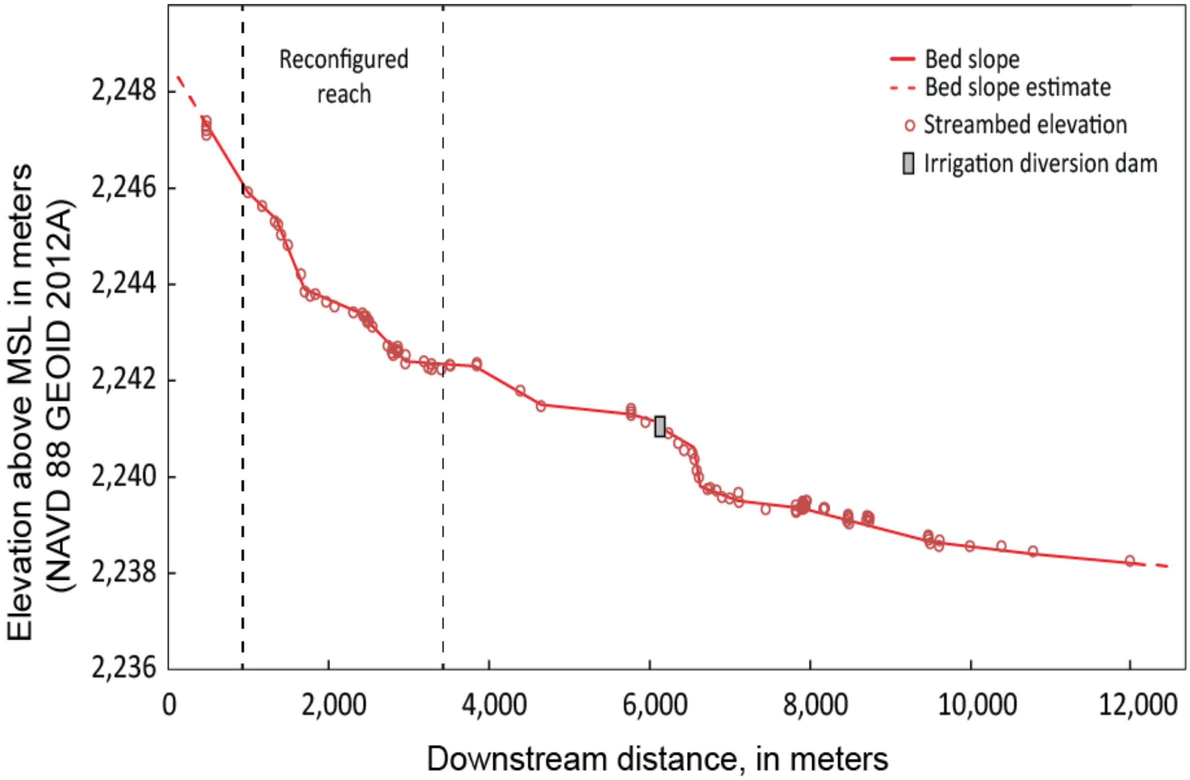


Figure 7. Graph showing bed slope determined from surveyed points and best-fit line.

Cross-section surveys along Muddy Creek were used to evaluate channel geometry. A positive correlation between channel top-width and width-to-depth ratio was found (Figure 8). Width-to-depth ratios ranged between 6 and 11 for the surveyed cross sections along Muddy Creek, with top-widths ranging between 11 and 23 m. Additional analysis showed an association between channel top-width and vegetation occurrence in riparian areas. The mean channel top-widths in areas dominated by grasses are wider than those in areas dominated by willows (p-value less than 0.001) (Figure 9).

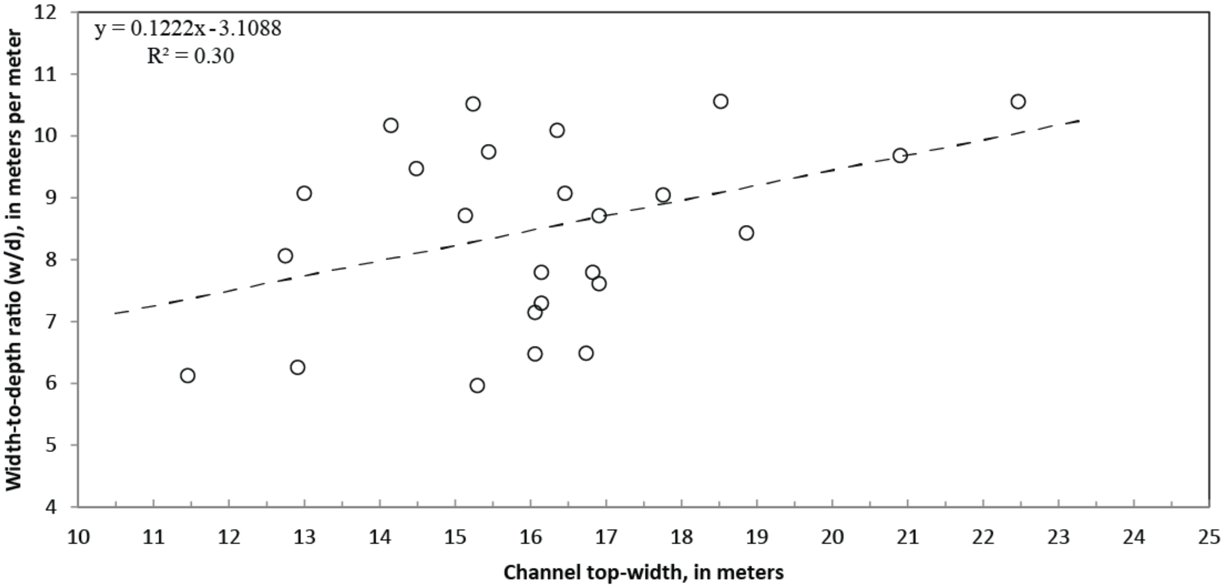


Figure 8. Scatter plot showing the relation between width-to-depth ratio (w/d) and channel top-width based on cross-section surveys of Muddy Creek below Wolford Mountain Reservoir.

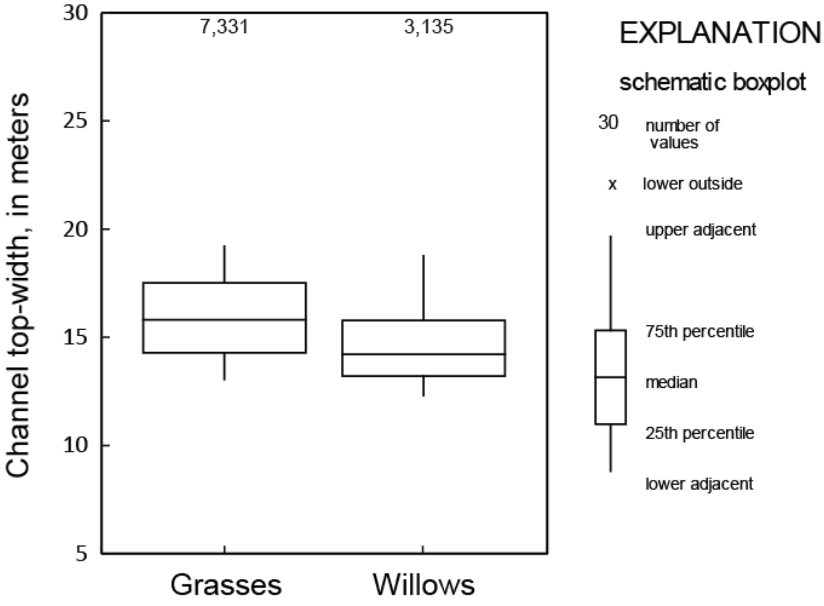


Figure 9. Comparison of channel top-width based on riparian vegetation in Muddy Creek below Wolford Mountain Reservoir.

Evaluation of channel width through time was done for the study reach through the comparisons of observed channel widths in USDA NAIP imagery from 1962, 1994, and 2013. This analysis shows that for 54 randomly selected locations within the study reach, mean channel width is decreasing through time (Figure 10). Reductions in channel width are statistically significant (p-values less than 0.05) using paired t-test where the mean channel width in 2013 is narrower than mean channel widths for both 1962 and 1994, and the mean channel width in 1962 is not statistically different from 1994.Taken in combination with the specific gage analysis for the area, the data indicate narrowing as the driver of the observed trend at 09041400 post-reservoir.

A comparison of mean meander-wavelengths in USDA NAIP imagery from 1962, 1994, and 2013 was completed (Table 1). This analysis shows similar results to the channel width assessment. Comparisons of meander wavelength show statistically significant (p-values less than 0.05) reductions in the mean using paired t-test with 2013 being shorter than both 1962 and 1994, and the mean of 1962 not statistically different from 1994. An increase in the sinuosity of the reach was observed prior to 1995 in the NAIP imagery, with an additional increase occurring by 2013 (Table 1).

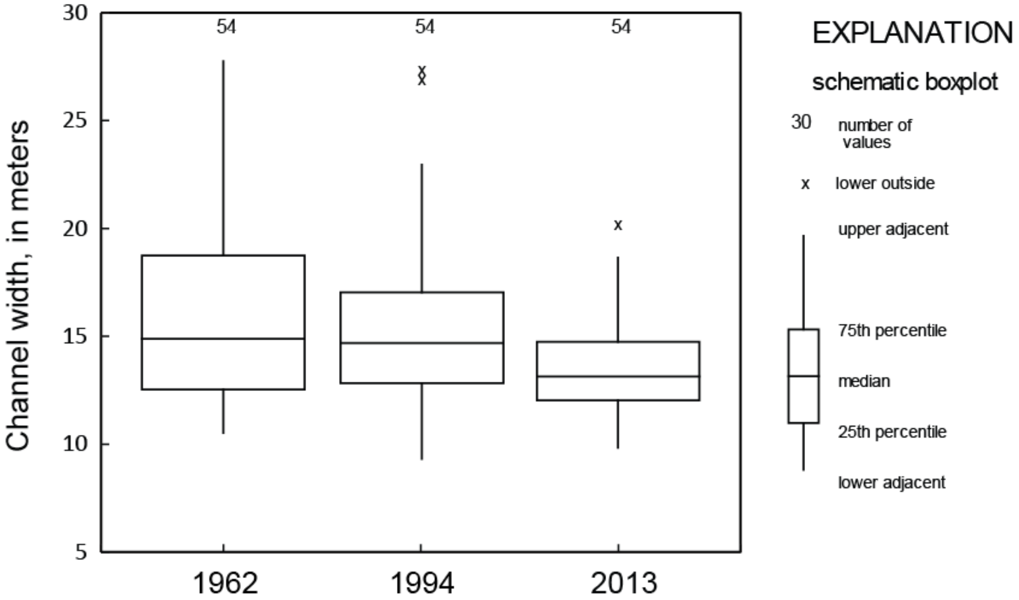


Figure 10. Channel width determined from USDA NAIP imagery at 54 randomly selected locations along the study reach of Muddy Creek below Wolford Mountain Reservoir in 1962, 1994, and 2013.

Table 1. Descriptive statistics results on meander wavelength based on USDA NAIP imagery along Muddy Creek below Wolford Mountain Reservoir, 1962, 1994, and 2013.

	Meander wavelength, m		
Year of aerial image	1962	1994	2013
Mean	156.7	160.3	133.3
Standard error	8.30	8.60	5.80
Median	144.0	152.0	127.0
Standard deviation	55.6	55.1	41.2
Skewness	1.10	1.10	1.40
Maximum	318	348	287
Minimum	77.0	79.0	60.0
Count	45	41	50
Sinuosity	1.33	1.74	1.78

Repeat cross-section surveys can be used to evaluate changes to vertical and horizontal positions within the channel. This is illustrated in Figure 11, where observation of channel cross-section change is shown for two time periods. When the lowest point of the streambed has decreased in elevation between time periods, the rate of vertical adjustment is represented as a negative (-), indicating incision; likewise, increases in elevation are represented as positive (+), indicating aggradation. Where the channel boundary/streambanks have shifted away from the former channel center, it is described as a negative (-) rate of lateral adjustment, indicating erosion of a streambank. When the channel boundary shifted towards the former channel center, it is shown as a positive (+) rate of lateral adjustment, indicating deposition along a streambank.

An analysis of repeat cross-section surveys shows inconsistent measures of incision and aggradation within the reach (Figure 12). Incision rates range from -5.9 cm per year to depositional rates of 5.5 cm per year. The reach was separated into groupings based on stream position relative to in-channel features and sediment sources, to evaluate trends between groupings (Figure 3). Group 1 includes the areas immediately downstream of the dam, an area most sediment-deprived due to reservoir sediment trapping (cross sections 1-7, Figure 3). Group 2 includes an area altered by channel reconfiguration (channel stabilization and flow-directing boulder structures), and an area of imposed channel form and grade control (cross sections 8-19, Figure 3). Group 3 is an area downstream of the reconfigured reach, a location where alteration upstream may have significant effects on the channel downstream through response to changes in bed slope and sediment inputs from upstream source areas (cross sections 20-32, Figure 3). Group 4 is located downstream of an irrigation diversion dam and a large tributary confluence thought to be an important sediment input (USFS, 1988). This area may also have greater constraints on fluvial channel form due to reduced valley widths (cross sections 33-43, Figure 3).

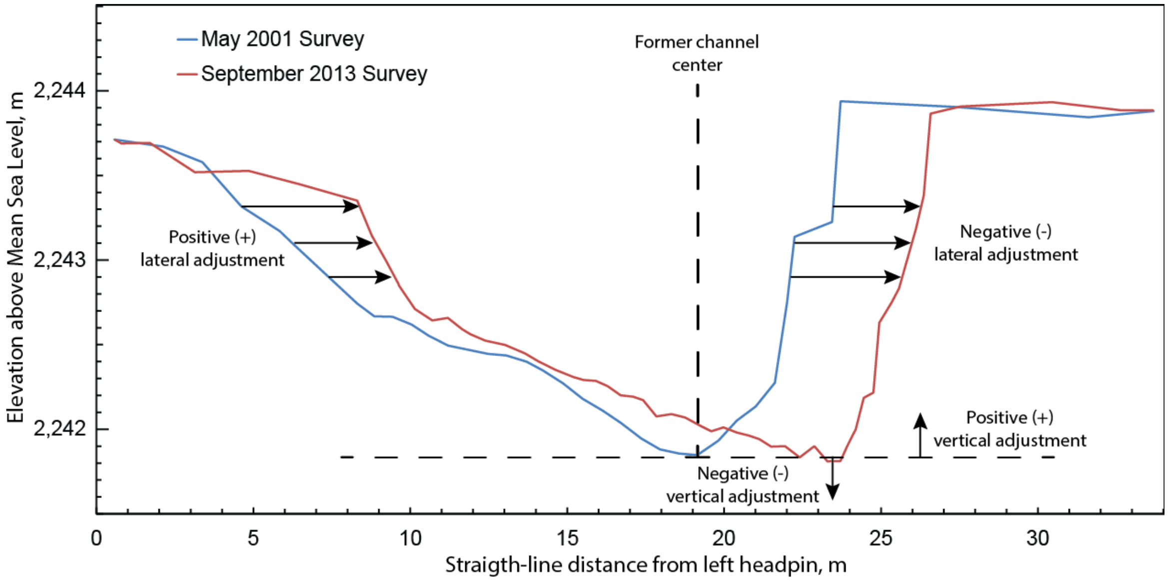


Figure 11. Explanation of vertical and lateral adjustment definitions in cross sections.

Table 2 shows that the mean and median incision rates of Group 1 and Group 4 are less than zero (incising); Group 2 are greater than zero (aggrading), and Group 3 are less than and greater than zero, respectively (incising and aggrading, respectively). Statistical testing of the mean shows that, at a 95-percent confidence level, only Group 1 has a mean incision rate statistically different from zero. This appears to contradict the specific gage analysis at 09041400, but the rate of water-surface elevation rise (cm/year), is near zero, and would plot near the range of incision rates observed in Group 1 (Figure 12). Greater variability in the remaining groups increases the uncertainty of a unidirectional response of either incising or aggrading within Groups 2–4 and may indicate more localized conditions are important to streambank erosion processes.

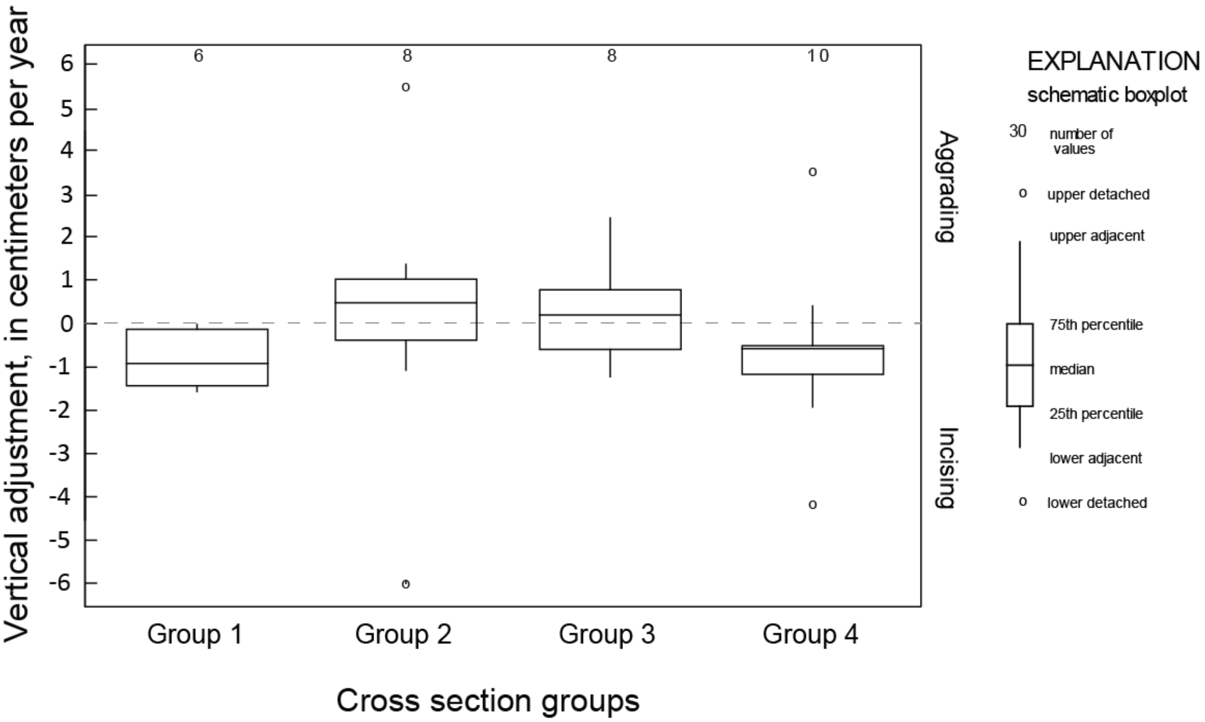


Figure 12. Calculated rates of vertical adjustment based on repeat cross-section surveys of Muddy Creek below Wolford Mountain Reservoir, 2001-2012, 2003-2012, or 2001-2013.

Table 2. Descriptive statistics on vertical adjustment rates based on repeat cross-section surveys of Muddy Creek below Wolford Mountain Reservoir, 2001-2012, 2003-2012 or 2001-2013.

Vertical incision rates, cm/year				
Classification in study reach	Group 1	Group 2	Group 3	Group 4
Mean	-0.84	1.10	-0.45	-0.63
Standard error	0.28	0.79	0.77	0.60
Median	-0.93	0.61	0.05	-0.58
Standard deviation	0.69	2.08	2.32	1.91
Skewness	0.16	1.93	-1.78	0.62
Maximum	-0.02	5.52	2.42	3.57
Minimum	-1.58	-1.08	-5.94	-4.10
Count	6	7	9	10

Additional assessment from repeat cross-sectional surveying shows lateral adjustment rates within the study reach (Table 3). In Figures 13, the rates of change are grouped as point bar, occurring on the inside of a meander bend, or cut bank, occurring on the outside of a meander bend. Note that the rate of change for lateral adjustment of cross sections is an order of magnitude greater than the vertical adjustment rates (Table 2, ~1 m; Table 3, ~10 m). Also, the reconfigured reach (Group 2) shows the largest positive changes between groups, meaning that point bars are depositing at a greater rate in the reconfigured reach than the other groups. This may be an effect of boulder structures placed in the stream that are designed to alter flow direction and redistribute sediment within the channel, resulting in increased deposition along point bars. Group 1 has the lowest variability, which may arise from the combination of the stream's inability to further incise (due to streambed armoring and lateral confinement) and the reduction in sediment available for deposition.

Table 3. Descriptive statistics on lateral adjustment rates based on repeat cross-section surveys of Muddy Creek below Wolford Mountain Reservoir, 2001-2012, 2003-2012, or 2001-2013.

Lateral adjustment rate, cm/year		
	Inside bend	Outside bend
Mean	13.3	8.9
Standard error	1.4	2.6
Median	-11.3	6.6
Standard deviation	8.1	15.4
Skewness	-1.1	1.0
Maximum	-2.4	56.4
Minimum	-38.0	-16.7
Count	34	34

Comparisons of the locations of observed seepage along streambanks and irrigation infrastructure show the effects of water augmentation within the valley bottom. An assessment of seepage proximity to irrigation infrastructure and mitigation wetlands shows that the distance from streambank seeps to unlined irrigation ditches and irrigation turn-outs was highly significant (p-value less than 0.0002) within the study reach (Figure 14). Interpretation of Figure

14 shows that the distance from which irrigation source appears to affect streambank seep occurrence extends outwards to a distance of 250 m.

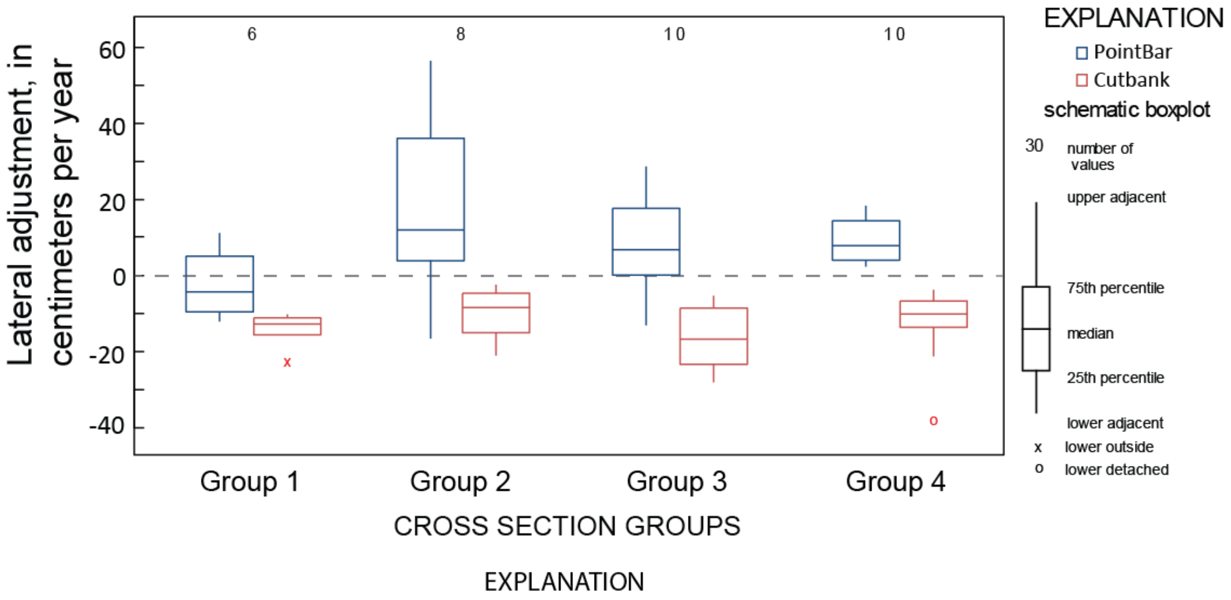


Figure 13. Calculated rates of lateral adjustment based on repeat cross-section surveys of Muddy Creek below Wolford Mountain Reservoir, 2001-2012, 2003-2012, or 2001-2013. Group 2 is the reconfigured reach.

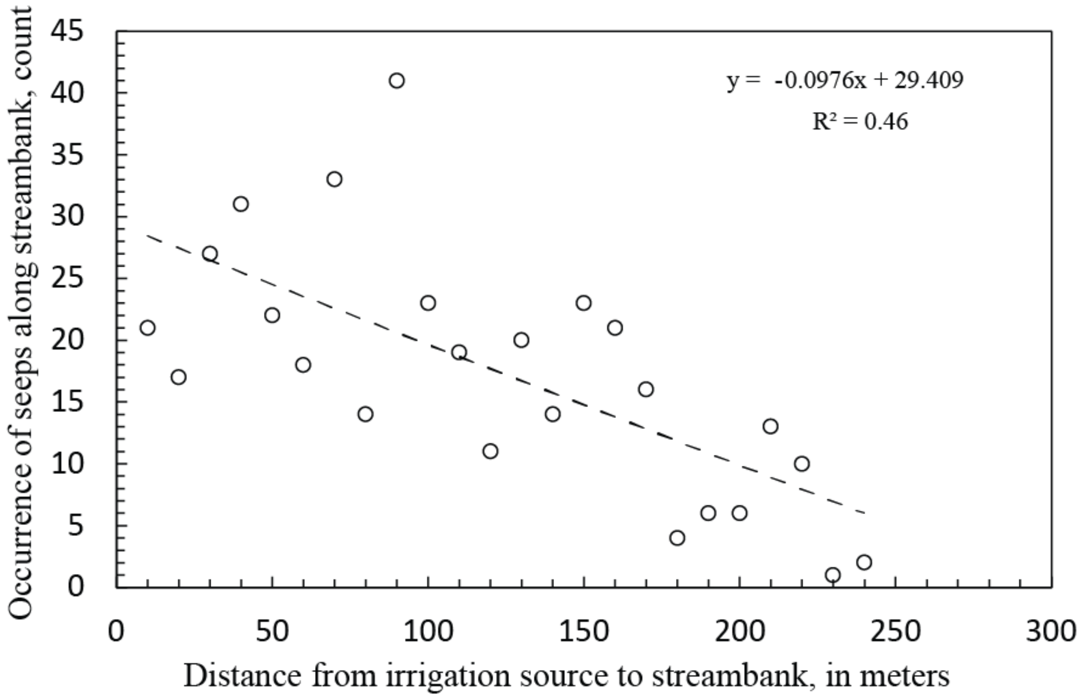


Figure 14. The relation between irrigation ditch/irrigation turnout and streambank seeps.

4.2 LOGISTIC REGRESSION MODEL OF STREAMBANK EROSION

Channel stability is evaluated using logistic regression to assess the risk of lateral instability with the study reach and to identify explanatory variables that affect streambank erosional risk. Grouping the explanatory variables from the logistic regression model by coefficient slope direction, positive (+) or negative (-) coefficients separate variables that increase probability of streambank erosion (positive coefficients) from variables that decrease the probability of streambank erosion (negative coefficients) (Table 4).

The magnitude of effect each parameter has on the combined risk of streambank erosion is shown in Figure 15. From the explanatory variables that increase the risk of streambank erosion, streambank heights approaching 1.5 meters show the greatest risk. Wider channel top-widths and nonfunctioning boulder structures also substantially add to the risk of streambank erosion. Conversely, hillslope deposits, bedrock outcrops, and beaver dams show the largest decreases to streambank erosion risk with magnitudes of effect twice as large as the median values for many parameters shown to increase risk.

Table 4. A summary of the logistic-regression model and statistical diagnostics.

Explanatory variables	Description of parameter	Standard error	T value	p-value
Intercept	Y-axis intercept	0.168	-26.02	<0.001
Explanatory variables with positive (+) regression coefficients, which result in increased probability of streambank erosion				
Flow angle-of-attack	Difference between primary flow direction and streambank alignment, between -90 – +90 degrees.	0.00148	8.44	<0.001
Outside bank along meander bend	Bank on outside of meander bends, 1 or 0.	0.0901	4.09	<0.001
Channel top-width	Distance between the tops of each streambank, in meters.	0.00837	6.84	<0.001
Streambank height	Streambank height less than 1.5 meters based from survey, in meters.	0.0657	17.11	<0.001
Nonfunctioning boulder structures	Boulder structures that were flanked or undercut and are no longer functioning for erosion control, 1 or 0.	0.159	6.45	<0.001
Grasses	Vegetative cover along channel margins with greater than 40 percent grasses, 1 or 0.	0.0544	11.38	<0.001
Sinuosity	The ratio of river length and valley distance, dimensionless.	0.0595	5.34	<0.001
Valley width	Distance between the bases of each valley slope, in meters.	0.000380	7.03	<0.001
Downstream reach	Group 4, reach downstream of irrigation diversion dam and large tributary, 1 or 0.	0.0742	10.02	<0.001
Explanatory variables with negative (-) regression coefficients, which result in decreased probability of streambank erosion				
Beaver dam	Channel margins within 25 meters of beaver dams, binary variable.	0.314	-2.96	<0.01
Bedrock	Outcropping of Pierre Shale/shale residuum, 1 or 0.	0.335	-4.14	<0.001
Hillslope deposit	Exposed talus or alluvial fan deposits along channel margins, 1 or 0.	0.283	-6.38	<0.001
Erosion-control structures	Rocks or logs revetments used in erosion control, 1 or 0.	0.128	-3.55	<0.001
Willows	Vegetative cover along channel margins with greater than 40 percent willows, 1 or 0.	0.0893	-8.51	<0.001

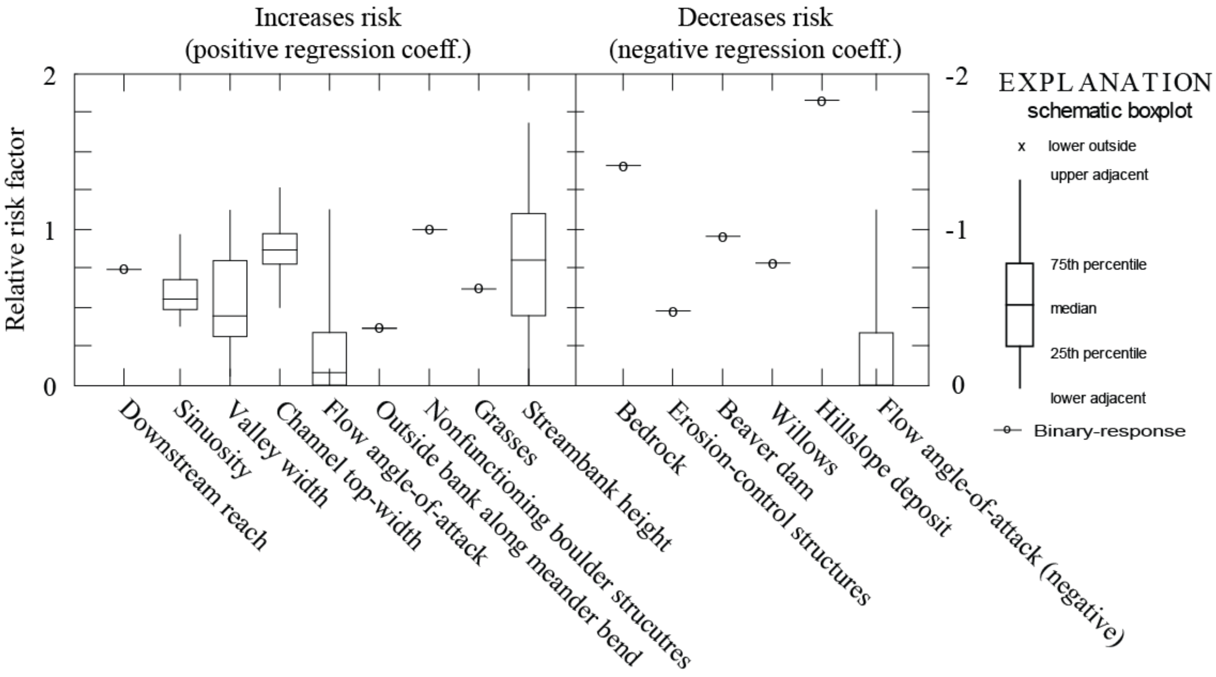


Figure 15. The relative risk factor magnitude for each logistic regression parameter.

4.2.1 MODEL VALIDATION

A validation of the logistic regression model is presented through the assessment of the error related to the predictions of streambank erosion risk (ranging from 0 to 100 percent). The mean standard error of prediction for the logistic regression model is 1.2 percent, with a maximum error of 7.3 percent within the validation data set. A second assessment of error is shown in Figure 16 where a random, independent subset of observation (~12,000 observations) was used to validate the logistic-regression model predictions. Simple linear regression (SLR) analysis was used to quantify the goodness-of-fit of the observed streambank erosion and predicted values. A perfect SLR model (1:1-line) would have an R^2 value of 1.0, a slope of 1.0, and a y-axis intercept of zero. Points plotting above the 1:1-line indicate that the logistic regression is over-predicting streambank erosion (a margin of safety); points plotting below the 1:1-line indicate under-predictions of streambank erosion. In general, the logistic regression validation approximates the 1:1-line for predicted and observed streambank erosion, and the y-axis intercept is approximately zero, indicating a good linear fit. The coefficient of determination (R^2) of the SLR is 0.90, indicating 90 percent of the variability is explained. This verification indicates that the risk for streambank erosion in the validation data set is well characterized for the independent validation data set.

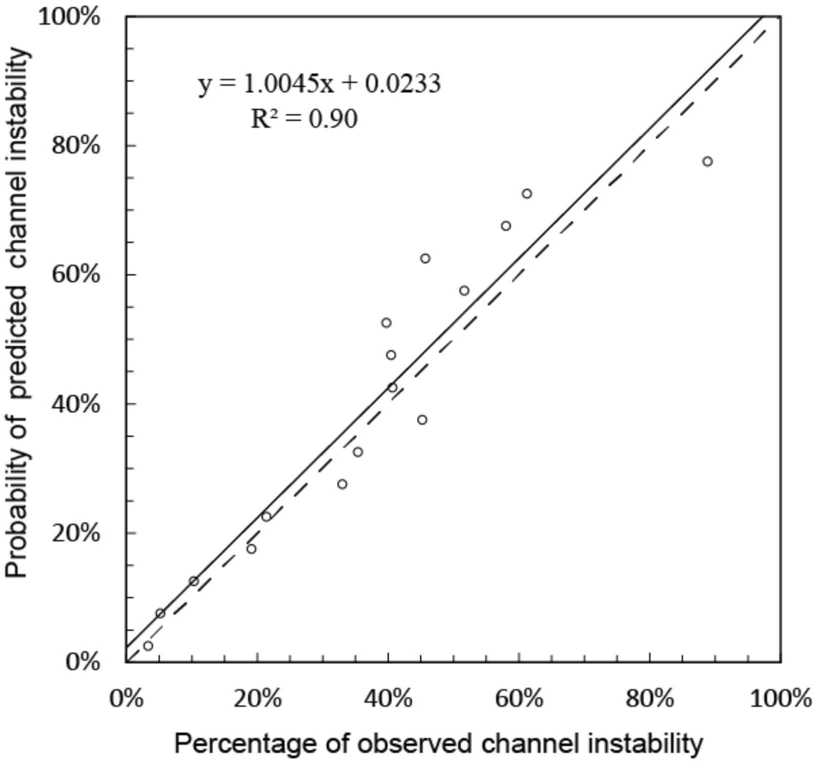
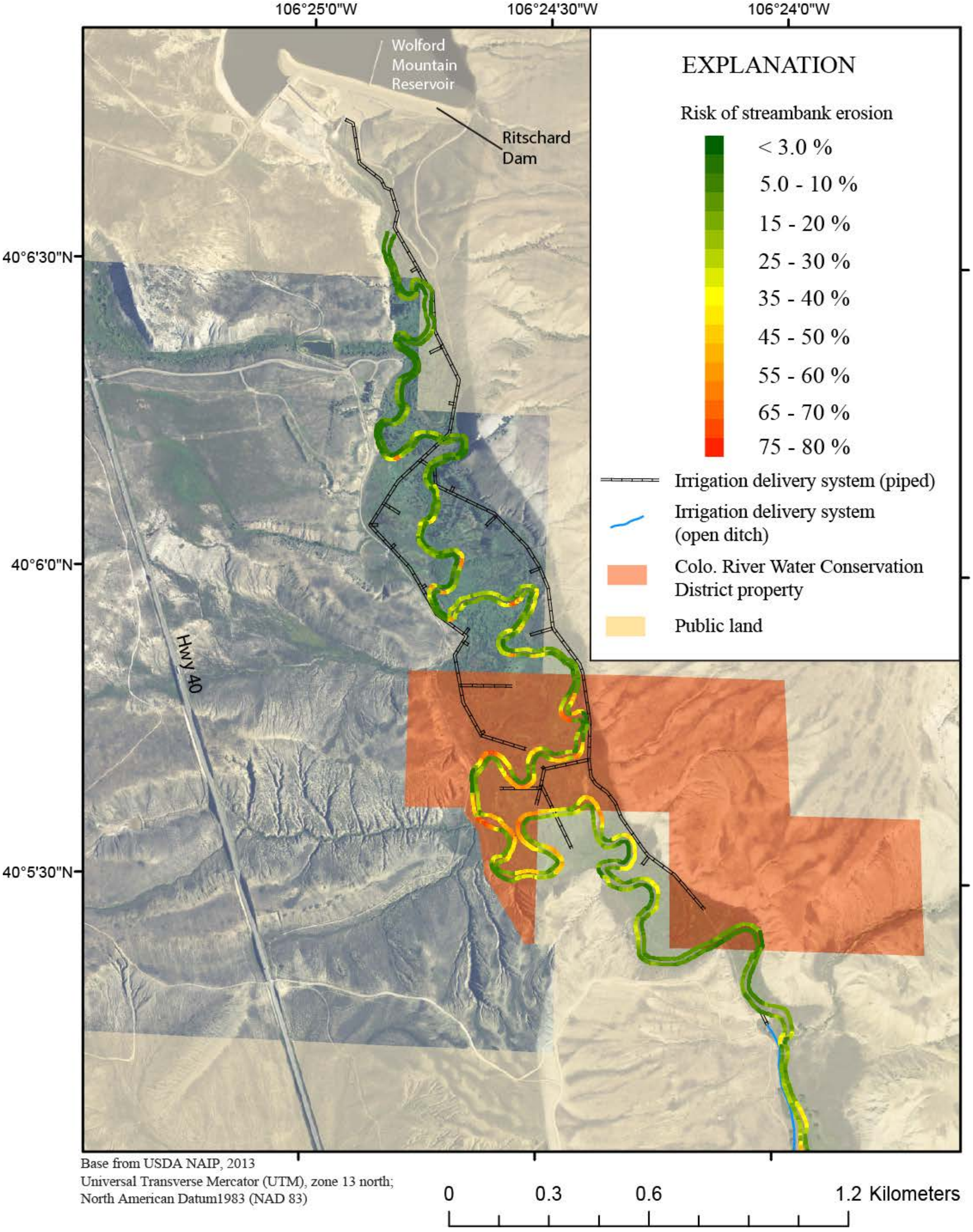


Figure 16. Goodness-of-fit of logistic regression predictions and streambank erosion.

4.2.2 STREAMBANK EROSION RISK ASSESSMENT

A map of probability of erosion, for each streambank, is presented which shows risk (as a probability of streambank erosion, ranging from <3 to 80 percent) based on the combination of all significant (p-value less than 0.05) explanatory variables. This map illustrates the combined risk for streambank erosion when all variables are considered together. These findings can be used in conjunction with local management objectives to evaluate or gage acceptable risk to current infrastructure and property. The risk of streambank erosion occurrence along left- and right-banks in the Muddy Creek study reach is shown in Figures 17 and 18. Red margins indicate greater probability of streambank erosion and green shading indicates areas with a lesser probability. This risk map can be used to target and prioritize where monitoring or remediation should be conducted and can be used to determine the current and future vulnerability of infrastructure and resources. Identification of geomorphic processes and reach characteristics driving streambank erosion is presented in the following sections and can be used to guide management and operational decisions within the reach to minimize impacts.



Base from USDA NAIP, 2013
Universal Transverse Mercator (UTM), zone 13 north;
North American Datum1983 (NAD 83)

Figure 17. Map showing predicted risk of streambank erosion within the upstream portion of the study reach of Muddy Creek below Wolford Mountain Reservoir.

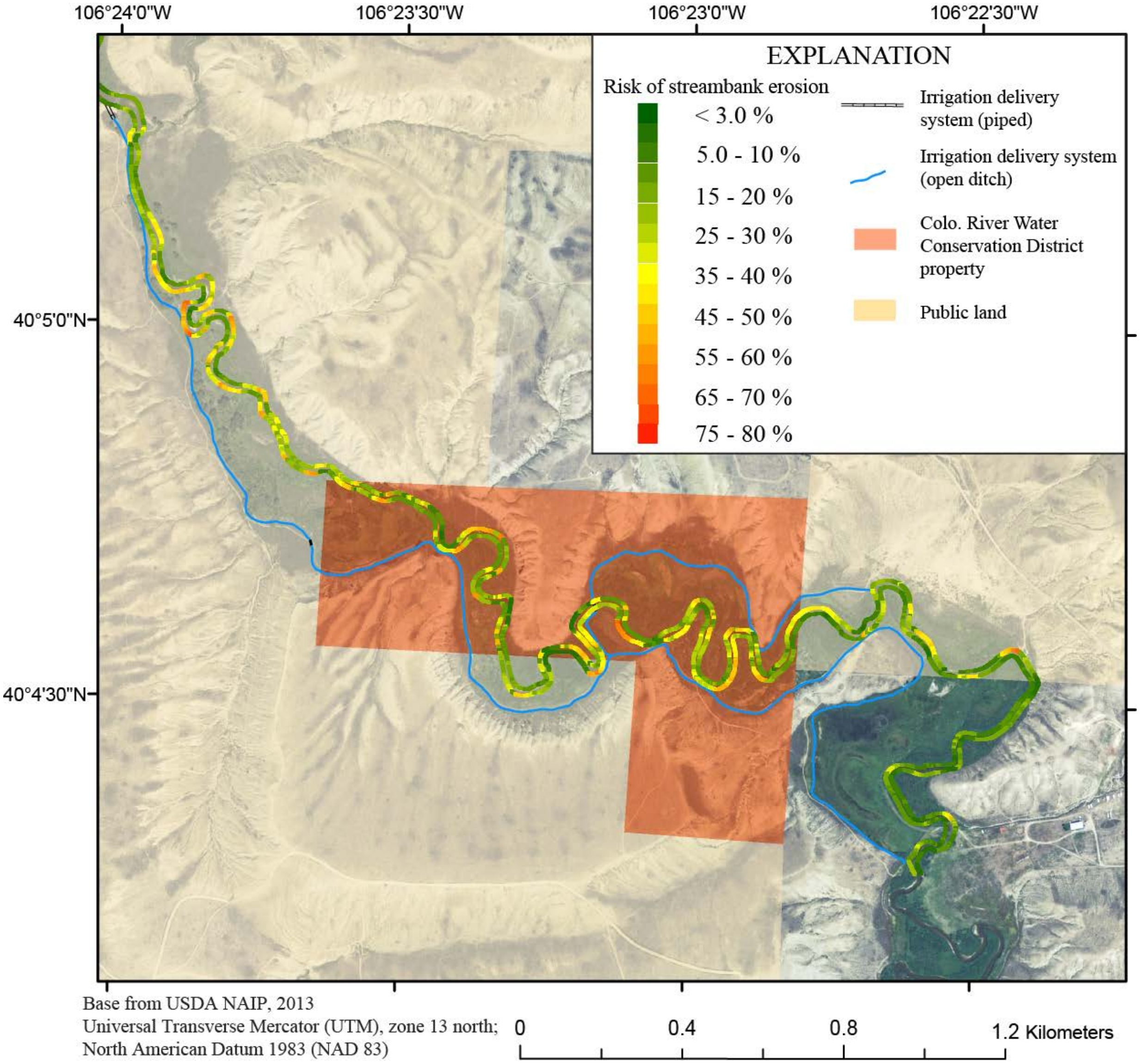


Figure 18. Map showing predicted risk of streambank erosion within the downstream portion of the study reach of Muddy Creek below Wolford Mountain Reservoir.

5 DISCUSSION

A combination of factors influences channel stability in the study reach. To consider the processes and conditions that control these interactions in Muddy Creek, it is helpful to apply a conceptual model to the fluvial system (Figure 19). This conceptual model helps track geomorphic processes and reach characteristics that affect streambank erosion based on anthropogenic activities. An overview of this conceptual model is presented below.

Effects from legacy management (land use and stream management) and current management (land use and reservoir management) have altered the flow regime and incoming sediment to the study reach. Additionally, direct effects on the channel and riparian conditions exist from operation and maintenance activities (related to channel reconfigurations; i.e., erosion control structure placement and maintenance; and mitigation wetlands operations; i.e., irrigation water diversion and application methods). In this system, the flow regime dictates the fluvial energy (hydraulic characteristics), and in conjunction with channel and riparian characteristics (channel geometry, vegetation, etc.), facilitates adjustment of the stream system through sediment transport and erosion processes. Sediment transport within the reach changes local and reach-scale channel characteristics, represented as vertical response (aggrading, incising, or equilibrium conditions) and horizontal response (narrowing, widening, and migration) in the conceptual model. Vertical response influences the rate and occurrence of horizontal response within the reach, which in turn affects streambank and riparian characteristics and reach-scale characteristics as the process continues through the cycle.

Using the conceptual model to evaluate legacy management from the 1880s–1920s (land use and stream management), there has likely been an increase in incoming sediment from

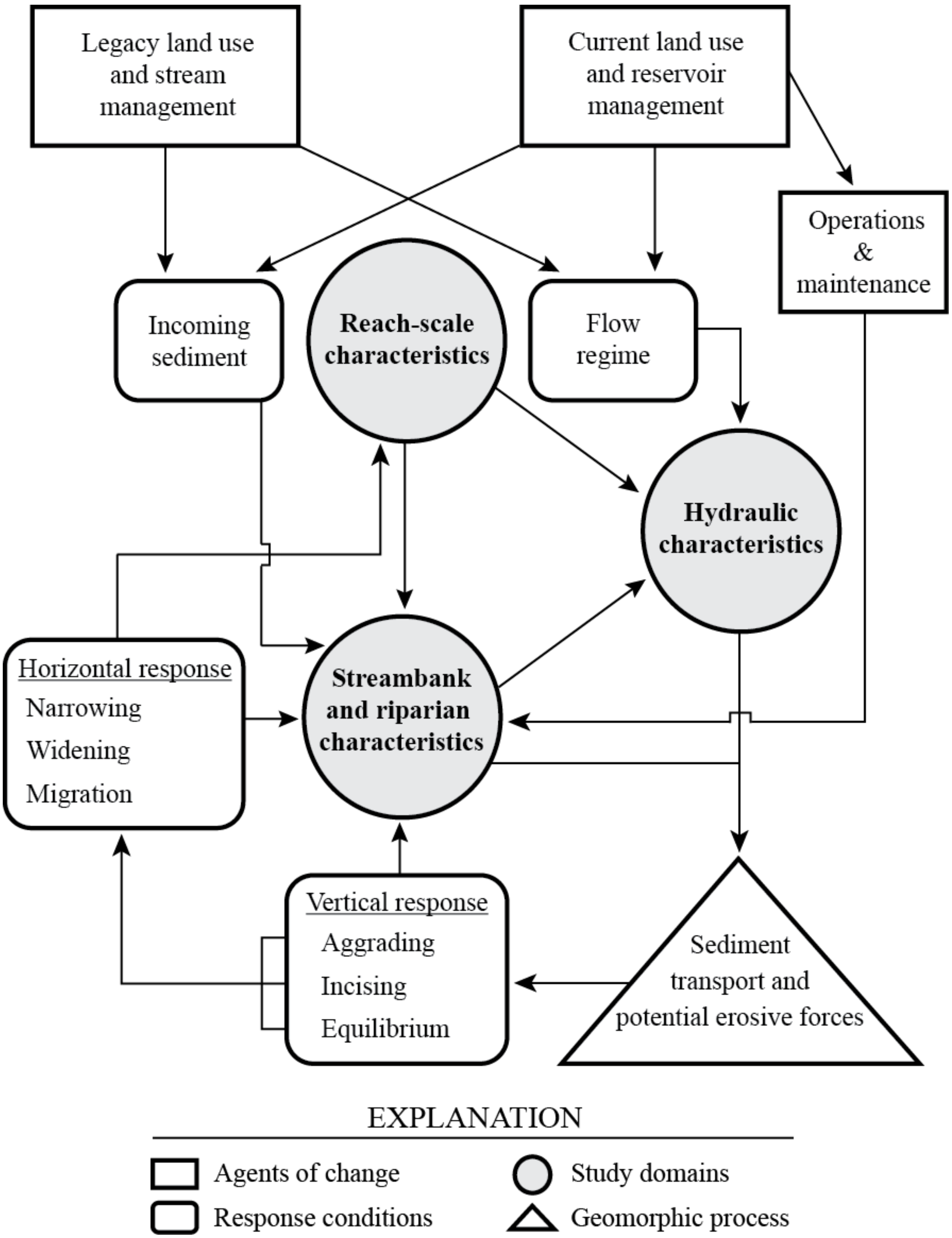


Figure 19. Conceptual model of anthropogenic influence and geomorphic processes within Muddy Creek below Wolford Mountain Reservoir.

timber harvesting and grazing, coupled with reductions in streamflow from diversion and storage structures. The vertical and horizontal response in the study reach was affected, as indicated through the specific gage analysis upstream of the reservoir, with incision or channel widening likely occurring in response to these earlier disturbances. These changes are likely over-shadowed in comparison to recent responses below the reservoir. Due to data limitations for Muddy Creek prior to construction of Ritschard Dam, a more thorough and direct comparison of pre- and post-dam disturbance rates is not made in this analysis.

Using the conceptual model to evaluate current land use and reservoir management (post-dam conditions), results of this analysis show that the changes in streamflow and incoming sediment have led to reductions in channel top-width, incision directly downstream of the dam (Group 1), increases in sinuosity, and reductions in meander wavelength. These post-dam data sets provide an indication that channel adjustment is currently occurring in Muddy Creek below Wolford Mountain Reservoir. To determine the persistence of these changes, and to better define future change sequences, additional discussion of the geomorphic processes driving channel response is presented.

5.1 GEOMORPHIC PROCESSES AND CHANNEL RESPONSE

Drawing from geomorphic concepts presented in the ‘graded stream’ from Mackin (1948), and described in ‘regime theory’, introduced by Leopold and Maddock (1953), observed channel response in the study reach suggests that changes (reach-scale and cross-section scale characteristics) will continue in Muddy Creek until continuity between basin sediment supply and fluvial sediment transport is restored. Schumm’s (1969) work on direction of response for streams adjusting to a new dynamic equilibrium has been widely used to predict the direction of change based on changes to streamflow and incoming sediment load combinations; but, this may not apply directly to the study reach because Schumm's assessment was based on responses in streams with sand-bed channels. Schumm's equations suggest that the reductions in streamflow and incoming sediment load will result in reductions in channel width, w/d ratio, and meander wavelength; increases in sinuosity; and increases or decreases in channel depth and channel slope (Knighton, 1998). For Muddy Creek, these predictions may still be indicative of the direction of change, but the changes may occur more slowly, only occurring during and following much larger streamflow events than those needed in sand-bed channels, in order to provide conditions where sediment transport of the gravel-bed is widespread.

Further consideration of the response of gravel-bed streams, such as Muddy Creek, will require inclusion of additional theories derived from more representative data sets. When reductions in streamflow and sediment are considered separately, regime theory suggests that the response of a gravel-bed channel to reductions in the channel forming streamflows, often deemed effective discharge or bankfull streamflow, will be reductions in cross sectional width and depth, in conjunction with an increase in channel slope (Knighton, 1998). Further analysis of Muddy Creek is warranted because large uncertainties exist for specific predictions of channel adjustment owing to complicated interactions between reach and cross section conditions, non-linearity and threshold response direction, and lagged and legacy response (Schumm, 1991; Richards and Lane, 1997; and Trimble, 1997). In the study reach, results from field and remotely sensed data analysis are in agreement with reductions in channel width (channel narrowing determined from remotely sensed aerial imagery analysis, Figure 10), but there was a mixed response to channel depth (observed aggradation in some locations based on repeat cross-section analysis, Figure 12).

In a meandering, gravel-bedded stream, like the study reach of Muddy Creek, potential adjustments to channel slope include changes in meander form (Knighton, 1998). Interpretation of changes to meander form are further complicated by the well-established (but varying) relation between meander wavelength (spacing of meander bend sequences), radius of curvature (a measure of how tightly a meander bends curves), and channel width and dominant discharge (Williams, 1986; Dury, 1964; Calrton, 1965; Ackers and Charlton, 1970; Ferguson, 1975; and Dury, 1977). Reductions in meander wavelength were observed in the study reach and can indicate reductions in channel slope as sinuosity increases (Table 1), but increases in reach sinuosity also predate the completion of Ritschard Dam (1994) for the study reach, suggesting changes to reach characteristics may have already been underway. These changes may be the result of legacy land use change or water developments (predating Wolford Mountain Reservoir) or may relate to large-scale adjustments that are part of the natural dynamic equilibrium of the stream.

Recall from previous discussions, Williams and Wolman (1984) found that typical responses of alluvial channels downstream of dams included incision during the first one or two decades following dam completion along with channel widths that increased, decreased, and remained constant. Incision and narrowing are common responses to upstream dams due to flow alteration with loss of sediment transport through the reservoir (Andrew, 1986; Petts, 1979; Williams and Wohlman, 1984). Findings from Butler (1990) and evaluation from the repeat cross-section surveys indicate an incision response is likely occurring in the upper portion of the study reach (Group 1) with mixed vertical adjustments occurring further downstream (Groups 2-4) (Figure 12).

Based on an evaluation completed before construction of Ritschard Dam, the study reach may have limited incision capabilities due to gravel and cobble riffle sequences that act to armor the streambed and control incision rates and bed slope within the reach (USFS, 1988). Additional hard-point structures placed or observed in the reach will also limit this incision (irrigation diversion structure, 1995; boulder cross vanes, fall 2003; and bedrock outcrops). Additional inputs of coarse material at tributary mouths/deltas and sediment inputs along channel margins cutting through alluvial fans also limit the incision potential of the stream by providing a source for coarse bed sediments as well as the bed material needed for additional channel adjustments such as narrowing.

The response of a stream to reductions in incoming-sediment loads is often characterized by reduction in channel slope, as indicated by Lane's balance (Lane, 1955):

$$QS \propto Q_s D_{50} \qquad (3)$$

Where:

Q is the volumetric streamflow rate,

S is the slope of the energy grade line,

Q_s is the incoming bed material transport rate, and

D_{50} is the median particle size of the incoming bed material load.

However, in meandering streams, increases in sinuosity can overcome local constraints on incision, such as those mentioned previously in Muddy Creek (Knighton, 1998). Dust and Wohl (2012) expanded Lane's relation to include elements of cross-sectional, planform, and bedfrom geometry with: (1) slope proportional to total change in elevation along the channel and inversely proportional to sinuosity and bedform amplitude; and (2) incoming bed material transport rate inversely proportional to the width to depth ratio of the cross-sectional geometry. This allows for a more complete portrayal of complex channel response, which often includes changes to the cross section or planform of the stream. In Muddy Creek, adjustment of slope is contributing to streambank erosion through undercutting or over-steepening of the streambanks (a height of the streambanks exceeding a maximum, stable height termed "critical bank height") as determined by sediment particle size, sorting, root structure, and soil moisture (Rosgen, 2006; Knighton, 1998; and Simmons *et al*., 2000). In this reach, the streambanks are composed primarily of fine materials, dominated by silt- and clay-sized particles deposited in varying thicknesses, but generally homogenous and very cohesive. The cohesion of these particle increases the erosive forces needed to entrain streambank materials. This material promotes large critical bank heights and near-vertical streambank slopes. When critical bank heights are exceeded, mass wasting dominates the erosive processes in this system, enhanced by fluvial undercutting and removal of the streambank toe. This promotes lateral adjustment of the channel towards a new dynamic equilibrium as channel slope and energy grade line are reduced.

CEMs outline the typical, idealized progression of channel adjustment beginning with vertical response of incision until critical bank heights are exceeded and mass wasting promotes widening (Schumm *et al.*, 1984). Differences in the erodiblity between the streambed and streambanks, produce a departure from this progression in Muddy Creek. Due to coarse riffle deposits, bed rock outcrops, and erosion control structures channel down-cutting is limited, making the study reach highly susceptible to continued streambank erosion and lateral migration as streambanks are undercut or over steepened and the system continues to decrease channel slope through increased sinuosity. This likely will limit the CEM sequence and changes in Muddy Creek channel characteristics to adjustment of cross-section shape (w/d and channel top-width) and reach sinuosity through meander migration. This process of lateral advancement is likely to continue until the combination of changes in channel geometry (w/d, bed slope, and sinuosity) reduces the erosive energy within the stream system and reaches a new balance with the altered flow regime and reduced incoming sediment loads (Schumm *et al.*, 1984). This can pose substantial risk to irrigation infrastructure within the mitigation wetlands where eroding streambanks are in close proximity to existing irrigation ditches and pipelines.

The occurrence of mass wasting of streambank material seems to be controlled in part by the streambank height, and also by riparian vegetation. The reach was comprised of primarily (1) grasses and sedges, (2) willows, (3) sagebrush, (4) mixed grasses and willows, (5) cottonwood grass mix, (6) or barren talus slopes/shale residuum. Where there was vegetation, sage brush occurred exclusively on drier, higher-elevation terraces or alluvial fans. Willows, grasses and sedges, mixed, and cottonwoods occurred at a range of elevations nearer base flow water elevations. Blocks of mass-wasted streambank showed varying thicknesses of sediment and roots, but the woodier vegetation appeared more resistant to undercutting, resulting in more stable streambanks.

To better relate conditions in the reach to geomorphic process, reaches are further separated into study domains that define streamflow and channel characteristics that are important in streambank erosion processes: (1) hydraulic characteristics, to test whether stream-induced scour and undercutting have differing effects within the reach due to changes in the erosive power of the stream; (2) streambank and riparian characteristics, to test whether differences in the relative cohesion or streambank soil structure and vegetation have differing levels of resistance to streambank erosion within the reach, or if management strategies for the private fishing area or the mitigation wetlands have significantly affected streambank erosion in the study reach; and (3) reach-scale characteristics, to test for any effect on streambank erosion.

5.1.1 HYDRAULIC CHARACTERISTICS

The hydraulic characteristics are represented by a combination of regression parameters related to channel geometry, energy grade line (indicated by bed slope), and direction of flow relative to streambank positions (hereafter flow angle-of-attack). The evaluation of variations in fluvial energy acting on the streambanks and channel margins helps to determine whether localized potential erosive forces explain the observed streambank erosion within the study reach.

To identify areas within the reach where localized hydraulic characteristics explain streambank erosion, bed slope is used as an indicator of the energy grade line. Areas with greater bed slope have greater potential fluvial energy and erosive power. Bed slope was evaluated within the reach, but was not as strongly associated with streambank erosion within the study reach as other variables. This is likely due to a combination of colinearity with other explanatory variables and observations that areas with the steepest bed slopes were not associated with the highest rates of streambank erosion. Differences in the size of streambank-toe materials within the reach also contribute to this observation. In areas with greater bed slope, the size of streambank-toe material is largest, and is likely limiting the erosive potential and correlation strength of bed slope to streambank erosion within the reach. As such, bed slope was not significant (p-value less than 0.05) or included in the final logistic model.

Results from the logistic regression show that flow angle-of-attack, outside of meander bend, and channel top-width, increase the probability of streambank erosion (Figure 15). This is explained through a discussion of hydraulic characteristics in the channel. Flow angle-of-attack describes the extent to which flow is directed towards a streambank. As water moves downstream within the channel, alterations in the flow direction result in differing velocities along the channel margins and differing potential erosive forces. One common example of this can be described by the helical flow pattern within a meander bend, which produces a zone of maximum boundary shear stress along the outside bend of a meander, beyond the bend apex (Knighton, 1998).

Within the study reach, as channel top-widths increase so does the width-to-depth ratio (w/d) (Figure 8). The w/d ratio is a commonly used metric to describe cross-sectional channel geometry (Knighton, 1998). There can also be an association between larger w/d ratio and enhanced streambank erosion or channel instability (Rosgen, 2006). Vegetative influences are correlated to observed differences in mean channel top-width with wider channel-top-widths associated with areas dominated by grasses (Figure 9). In combination, flow angle-of-attack, outside of meander bend, and channel top-width can describe areas that are more susceptible to streambank erosion, especially in areas where fluvial energy is directed at the streambank, such as the outside of tight meander bends (Knighton, 1998). Areas of wider top-width may also occur in areas that are at a different stage of the CEM where changes in dominant geomorphic process are occurring and aggradation of the streambed may occur in conjunction with future increased streambank stability (Schumm *et al.*, 1984). Further monitoring would be needed for confirmation.

Further support arises from the logistic regression, where backwater areas upstream of two beaver dams were found to decrease the risk of streambank erosion (Figure 15). Both beaver dams were located within Group 2, and were built on top of boulder weirs within the reconfigured reach. These structures, in conjunction with the beaver dams, produced areas upstream with substantially reduced velocities and vastly increased flow depths. The increased flow depths inundated additional boulder structures located within 25 m upstream, with instances of inundation extending out-of-bank. These reductions in bed slope reduce the energy grade line as well as reducing gravitational forces acting on undercut streambanks, which may explain some of the observed reduction in streambank loss in these areas. However, additional risk of meander cut-off may exist due to these structures, warranting future monitoring.

5.1.2 STREAMBANK AND RIPARIAN CHARACTERISTICS

The streambank and riparian characteristics are represented by a combination of regression parameters related to streambank height, presence and functional status of erosion-control structures (riprap and nonfunctioning boulder structures), and riparian vegetation (grasses or willows). The evaluation of variations in conditions along the streambank help determine whether differing streambank conditions explain resistance to streambank erosion from fluvial scour or mass wasting.

Results from the logistic regression show that, within the study reach, larger streambank heights increase the probability of streambank erosion to a point (Figure 15). As streambank heights within the reach increase, the streambanks become more prone to erosion through fluvial scour and undercutting. This is consistent with streambank geotechnical assessments: for a given streamflow condition, taller streambanks are geotechnically less stable than shorter streambanks and are more prone to mass wasting through over-steepening and undercutting. This process of over-steepening and undercutting of streambanks was commonly observed in the study reach. The strongest relations were found between streambank erosion and streambanks less than 1.5 m in height because of interactions between taller streambanks and bedrock outcrops.

Many streambanks within the reach that were taller than 1.5 m contained evidence of bedrock outcrops of Pierre Shale or weathered shale residuum. This type of streambank composition resists mass wasting and streambank erosion through structural support of the streambanks provided from shale bedding structures and inter-bedded siltstone ledges. Some additional areas of taller streambanks included areas along alluvial fans and talus slopes which consisted of inter-bedded gravels and sand/fines and larger blocky material. Some of these areas were prone to mass wasting, but the larger sized materials within these deposits reduce erosion potential of the streambanks and form reduced angles of repose. Incorporation of variables for bedrock and hillslope deposits provided a means to characterize more resistant streambank areas within the reach that showed decreased probability of streambank erosion (Figure 15).

Rock or log revetments are often used to reduce the potential of streambank erosion (Blodgett and McConaughy, 1986; Rosgen, 2006; and USDA, 2007). Within the study area, erosion-control structures decreased the probability of streambank erosion where structures retained original positions relative to flow (Figure 15). However, where changes to flow orientation occurred that resulted in loss of original function, a situation termed ‘nonfunctioning boulder structures,’ the probability of streambank erosion increased when the nonfunctioning structure directed flow into adjacent or downstream streambanks. Observations within the reach of nonfunctioning boulder structures included flanked j-hooks and cross vanes, and toppled rock and log revetments.

Differences in vegetation type were observed within the study reach and were found to have significant differences in relation to occurrence of streambank erosion within the logistic regression. Areas containing willow or other woody plants were associated with areas less prone to streambank erosion, while areas dominated by grasses increased the probability of streambank erosion (Figure 15). These findings are specific to the study reach, and may be a product of rooting depth or water consumptive use of the species present. Additionally, there is an association between the differences in the stable channel widths of alluvial streams and the presence and abundance of woody vegetation, with decreased widths associated with wooded areas (David *et al.*, 2009; Knighton, 1998, Simon and Collison, 2002). This was consistent with the findings in this analysis with highly significant (p-value less than 0.001) differences in mean channel top-width between areas vegetated with grasses and willows (Figure 9).

Riparian vegetation as well as characteristics of soil moisture contributes to the structural characteristics of streambanks. Vegetation root structure can increase streambank integrity, with woody riparian vegetation (such as willows) having far greater critical average bank shear stress than that of grass covered streambanks (Millar and Quick, 1998; Polvi *et al.*, 2014; Rosgen, 2006). Soil moisture can also promote greater soil cohesion, but excess soil moisture can generate positive pore-water pressures, decrease matrix suction, and increase soil bulk unit weight, promoting mass wasting (Simon *et al.*, 2000). Additional interpretation is found when considering modifications to regime theory (additions for vegetative effects based on vegetation type) that are included in later empirical relations by Hey and Thorne (1986), which predict wider stable channel widths for areas dominated by grasses instead of woody vegetation such as willows. This may have implications relating back to hydraulic conditions within the reach, such that larger w/d ratios (i.e., wider top-widths) are also associated with enhance streambank erosion or channel instability because of vegetative effects.

5.1.3 REACH-SCALE CHARACTERISTICS

The reach-scale characteristics are represented by a combination of regression parameters related to larger-scale features beyond the local, hydraulic boundary condition that influence channel form or response. The evaluation of variations in channel form and response help to determine whether reach-scale characteristics explain the observed streambank erosion in the study reach. Reach-scale characteristics include the effects of valley width and channel sinuosity. Proximity of the active channel to alluvial fan deposits and valley walls can control and confine the position of the channel as well as limit lateral adjustment. Within the logistic regression, areas of greater sinuosity and wider valley widths show increased probability of streambank erosion (Figure 15). These two parameters are interrelated because valley geometry imposes a maximum channel slope and meander-belt width on a channel reach, limiting channel sinuosity (Knighton, 1998).

As previously mentioned in the Hydraulic Characteristics section, increased fluvial energy and potential erosive power were used to interpret the importance of fluvial forces acting on the streambanks (bed slope as an indicator of energy grade line, flow angle-of-attack, outside of meander bend, and channel top-width). Assuming this interpretation is correct, then as sinuosity increases, the reach-averaged fluvial energy and potential erosive energy will decrease and the probability of streambank erosion in the study reach should also decrease. For a given valley slope, increased sinuosity decreases bed slope through the addition of channel length. However, it appears that even though reach-averaged fluvial energy is reduced in areas with greater sinuosity, localized conditions promote streambank erosion where flow is directed into the streambanks. This may also explain why areas within the study reach that have the steepest bed slopes (and straightest flow paths) do not have the greatest occurrence of streambank erosion.

The study reach was separated into groupings based on stream position relative to in-channel features and sediment sources, to evaluate trends between the 4 previously defined groupings. This was done to identify whether any group combination had increased risk of streambank erosion within the study reach. Group 4 (located downstream of an irrigation diversion dam and a large tributary confluence, Figure 3) showed increased risk of streambank erosion (Figure 15). Previous investigators (USFS, 1988) believed that channel adjustment in Muddy Creek would be lessened below larger tributaries because of the introduction of additional coarser sediments from these sources. This is not supported based on findings from the logistic regression analysis. Specific causes of the increased risk of erosion in Group 4 are unclear, but may reflect a combination of effects from further confinement of the reach as valley widths decrease, increased streamflow from tributaries, and the occurrence of increased seepage along areas near the irrigation ditch.

5.2 ADDITIONAL RISK FACTORS

Additional observed risk factors within the reach included observed processes that were either localized to specific areas or were not significant (p-values less than 0.05) in the final logistic-regression model.

5.2.1 TRIBUTARY DELTAS

Tributaries are important sediment inputs for the reach. The U.S. Forest Service (1988) identified potential effects for the reduced sediment supplied due to Wolford Mountain Reservoir. They identified Cow and Horse Gulches as important sediment inputs into the reach below the reservoir. These sediment inputs include larger materials such as gravels, cobbles, and small boulders which are important for maintaining vertical control of the reach through armoring of riffle sections along these tributary deltas (USFS, 1988). Additionally, large streamflow events on these and other tributaries create sediment deposits that can increase boundary shear stress on opposing streambanks through localized channel narrowing. This increase in boundary shear stress can be a driving force for localized streambank erosion and may need to be monitored in areas near infrastructure or other sensitive areas in the reach.

5.2.2 SATURATED SOILS

Excess soil moisture or raised water-tables near channel margins can contribute to processes that promote mass wasting of the streambanks and are identified as the leading cause of streambank failures in incised channels (Simon *et al.*, 2000). The combination of increased weight and pressure within streambanks supporting the blocks can exceed the resistive forces, resulting in increased risk of mass wasting of the block into the stream channel (Simons and Collison, 2002; Simon *et al*., 2000; Knighton, 1998). Thus, areas under the added weight of saturated soils, in conjunction with the loss of matrix-suction, in areas that are over-steepened or undercut, are at increased risk of streambank erosion (Simons and Collison, 2000). This is supported by observations within the study reach and calculation of the odds ratio (Ott and Longnecker, 2001). Streambanks with observed saturated soils and the presence of groundwater seeps, through-flow, and subsurface erosion (soil piping and dissolution) were found to have between 20-44 percent increased odds of streambank erosion (95% confidence interval).

Determination of the underlying causes of increased groundwater levels and raised soil moisture were evaluated. An assessment of seepage proximity to irrigation infrastructure and mitigation wetlands shows that distance from streambank seeps to unlined irrigation ditches and irrigation turn-outs was highly significant (p-value less than 0.0002) within the study reach (Figure 14). Locations that may be at a higher risk for these types of accelerated streambank erosion include: areas within 250 m of irrigation turnouts and unlined ditches, and areas where tributaries focus shallow groundwater near the surface of streambanks. In the study reach this may occur throughout areas of the mitigation wetlands. Observations made during field investigations highlight additional indicators such as active seeps and areas demonstrating erosional soil piping. Erosional soil piping occurs through removal by dissolution or transport of sediments along preferential flow pathways of groundwater in the shallow subsurface (Knighton, 1998). Additional risk of streambank erosion may occur when water-surface elevations rapidly decrease such as following rainfall runoff peaks or large changes to reservoir releases. This can promote conditions where pore-water pressure and increased unit weight promote streambank erosion through mass wasting.

5.2.3 ANIMAL DISTURBANCES

Observed animal disturbances within the reach included stream crossings/slides, burrows/dens, and beaver dams. All contribute to localized disturbances in vegetation and channel geometry, often with increases in localized erosion. Beaver dams also change the streamflow properties such as bed slope in and upstream of backwater areas. This produces greater inundation of streambanks and vegetation as well as reductions in bed material load transport through the affected areas. This reduces the velocity of flows in the affected areas and increases the flow depth.

Within the logistic regression analysis, beaver dams correlated with a reduction in streambank erosion. This is likely because of the reduced bed slope that results in reduced scour and undercutting, but may also be due to additional support provided by the hydrostatic pressure from the backwater conditions in the stream on the saturated streambanks. Elevated water levels within the backwater area may also enhance riparian vegetation growth, adding to streambank integrity and overbank roughness.

One drawback, not observed, is the added potential of channel avulsion. In highly sinuous reaches, out-of-bank flows can trigger meander cutoffs through channel avulsion processes. Such changes in channel sinuosity could have far-reaching consequences. If large sections of channel are bypassed by meander-cutoffs, a substantial increase in channel slope can occur. These increases in channel slope would likely increase fluvial energy and potential erosive force, promoting further incision or enhanced lateral migration through cutbank propagation; however meander-cutoff formation is a natural geomorphic process that can also provide useful wetlands habitats that are self-maintaining and provide additional mitigation credits.

Incorporation of beaver dams into mitigation strategies for streambank erosion can also provide additional advantages. These benefits are coupled with promotion of floodplain reconnection and increased streambank stability (Pollock *et al.*, 2014). Backwater habitat created from beaver dams provides beneficial changes to both the stream hydrology and ecosystem. Beaver dams promote increased storage of sediment, carbon, and nutrients as well as increases in the abundance and biodiversity of riparian and aquatic species (Polvi and Wohl, 2013). Placement of wooden stake lines at strategic locations in the reach can encourage occupancy and construction of beaver dams (providing additional structural support to aid permanent establishment) and mitigate potential impacts of increased fluvial energy from meander-cutoffs (Pollock *et al.*, 2014).

5.2.4 HILLSLOPE-COUPLING

In areas of the reach where channel migration has resulted in the outside of a meander bend occurring in contact with an erosion-resistant boundary, alteration of typical meander migration direction can occur. Erosion-resistant boundaries include: alluvial fan deposits, bedrock outcrops, and valley walls. Lateral migration of meander bends in uniform floodplain materials precede along a ‘typical’ path that is both downstream and towards the outside of the meander bend along a diagonal. In some instances within the study reach, this ‘typical’ path is altered where an erosion-resistant boundary increases lateral migration along the upstream half of the meander bend, forming an elliptical bulge in the channel (as viewed from above). Divergence in the flow path along the erosion-resistive boundary creates a re-circulation eddy which concentrates flow along the streambank at the point of intersection, in the upstream direction. During base-flow conditions, this area is characterized as shallower than the surrounding channel, with relatively slower velocities. In contrast, during snow-melt runoff, velocities are likely much faster and generate localized areas of enhanced scour with lateral channel migration moving in the up-valley direction. This may be important to resource managers when assessing the risk to infrastructure because this process results in an atypical direction of lateral migration of the meander bend.

6 CONCLUSIONS

The objective of this study was to evaluate a reach of Muddy Creek below Wolford Mountain Reservoir in order to (1) determine the dominant erosive and resistive processes within the reach that contribute to channel stability and response, and (2) assess the validity of using logistic regression techniques as an analytical framework for geomorphic assessments to aid stakeholders in management of this reach. Field reconnaissance and channel surveying were completed during base-flow conditions September 16-27, 2013. Measurement of channel characteristics (streambank heights, channel width, and bed slope) and georeferencing geomorphic-stability indicators (observations of streambank erosion, subsurface flow, stream channel modification and function, vegetation type and condition, and animal disturbance) were used to assess streambank erosion. From this data set, logistic regression was used to estimate the probability of localized streambank erosion and provide insight into the processes controlling channel stability in the study reach in order to test four hypotheses.

Hypothesis 1 tested whether stream-induced scour and undercutting have differing effects on streambank erosion within the reach due to changes in the erosive power of the stream. An evaluation of the regression parameters related to channel geometry, energy grade line indicated by bed slope, and direction of flow relative to streambank positions (flow-angle-of-attack) showed a significant increase in the probability of streambank erosion in the study reach for areas where the flow angle-of-attack was oriented towards the streambanks. Results from the logistic regression show that flow angle-of-attack, outside of meander bend, and channel top-width increase the probability of streambank erosion. Thus, H_{o1} is rejected in favor of H_{a1}; but this result is not necessarily universally true for the study reach because the areas with the greatest fluvial energy and potential erosive power (i.e., areas with the steepest bed slope) were not the areas with greatest abundance of streambank erosion, suggesting additional, localized conditions within the reach need to be considered.

Hypothesis 2 tests how differences in the streambank structure and vegetation influence resistance to streambank erosion, or if management strategies for the reconfigured reach or mitigation wetlands have significantly affected streambank erosion in the study reach. An evaluation of characteristics related to streambank height, riparian vegetation, presence and function of erosion-control structures, and proximity to irrigation infrastructure relative to streambank erosion were evaluated. Results from the logistic regression show that, within the study reach, larger streambank heights increase the probability of streambank erosion to a point because they became more prone to erosion through fluvial scour and undercutting. Many streambanks taller than 1.5 m were less prone to erosion because they gained additional structural support from bedrock outcrops of Pierre Shale or alluvial fans and talus slopes. Incorporating variables for bedrock and hillslope deposits provided a means to characterize more resistant streambank areas within the reach that showed decreased probability of streambank erosion. Similarly, erosion-control structures decreased the probability of streambank erosion where structures retained original positions relative to flow. However, where changes to flow orientation occurred and directed flow into adjacent or downstream streambanks, streambank erosion increased. Differences in vegetation type were observed within the study reach and areas containing willow or other woody plants were associated with areas less prone to streambank erosion, while areas dominated by grasses (local species present in the study reach) increased the probability of streambank erosion. The increased risk of streambank erosion from grasses in the study reach may not reflect the bank stabilizing characteristics of different grass species in other settings. Previous investigations have shown that grasses can promote greater streambank stability than woody vegetation (Simon and Collison, 2002). Streambanks with observed saturated soils and the presence of streambank seeps were also found to have between 20-44 percent increased odds of streambank erosion (95% confidence interval). Determination of the underlying causes of increased groundwater levels and raised soil moisture were evaluated. A linkage between proximity of streambank seeps and unlined irrigation ditches and irrigation turn-outs was highly significant (p-value less than 0.0002), with potential effects extending to distances up to 250 m from the irrigation water sources within the study reach. Thus, H_{o2} is rejected in favor of H_{a2}.

Hypothesis 3 tests whether reach-scale characteristics have any effect on streambank erosion. This included an evaluation of the effects of valley width, channel sinuosity, and proximity of terrace and alluvial fans relative to streambank erosion in the study reach of Muddy Creek downstream of Wolford Mountain Reservoir. Within the logistic regression, it was observed that areas of greater sinuosity and wider valley widths show increased probability of streambank erosion. Areas most susceptible to streambank erosion occurred where the flow angle-of-attack was oriented towards the streambank materials in areas susceptible to erosion through scour, under-cutting, and/or mass wasting. Coarser bed sediments amour the streambed, limiting incision potential within the reach and increasing streambank erosion within areas that are more sinuous. Group 4 (located downstream of an irrigation diversion dam and a large tributary confluence) showed increased risk of streambank erosion. Specific causes of the increased risk of erosion in Group 4 are unclear, but may be due to a combination of effects from further confinement of the reach as valley widths decrease, increased streamflow from tributaries, and the occurrence of increased seepage along areas near the irrigation ditch. Thus, H_{o3} is rejected in favor of H_{a3}.

Hypothesis 4 tests how well logistic regression techniques can be used to identify areas susceptible to streambank erosion. The successful calibration and validation of the logistic regression model demonstrate the utility of this analytical framework as a tool for geomorphic assessment. The logistic regression shows that the greatest risk of streambank erosion occurs in areas with wide channel cross sections along the outside of tight meander bends with steep, tall (up to 1.5 m), and grassy streambanks. In this analysis, H_{o4} is rejected in favor of H_{a4}. Logistic regression has many benefits and can be applied to a range of geomorphic issues. It also provides interpretable predictions of risk that can be directly applied by resource managers and stakeholders to the targeting and mitigation strategies of areas that threaten infrastructure and property.

7 RECOMMENDATIONS FOR CHANNEL STABILITY MONITORING

On-site measurements of channel stability are tailored to a specific stream reach and to the monitoring objective. For Muddy Creek, the risk maps (Figure 17 and 18) can be used to prioritize locations where survey or photographic monitoring should be conducted. Selection of the logistic regression provides a framework that can be used to target areas for future channel monitoring based on a risk assessment of streambank erosion potential. In general, interpretation of Figures 17 and 18 supports continued lateral channel migration in areas where there are large differences in the probability of streambank erosion when comparing left and right channel margins, with the direction of migration towards the channel margin that shows greater risk. For example, along the inside and outside channel margins within meander bends, it is widely known that lateral channel migration typically occurs along the outside of the meander bend where erosive forces are greatest. When considering overall reach stability, lateral stability is indicated in areas where both channel margins indicate less risk along the reach. An example of this is the upstream-most section of the study reach, where both streambanks are shaded green.

A vulnerability assessment can be implemented to rank or target areas where streambank erosion may threaten the infrastructure, by using the combination of risk along a stream reach and proximity of this reach to irrigation infrastructure. This vulnerability assessment should include a comprehensive evaluation of the reach, or selective areas, with varying levels of acceptable risk based on resource management objectives and strategies. Areas found to be at greatest risk of streambank erosion include areas with wide channel cross sections along the outside of tight meander bends with steep, tall, grassy streambanks. Monitoring of boulder structures, beaver dams, and areas downstream of the irrigation diversion dam, as well as areas prone to meander cutoffs, is also advised. Monitoring locations near irrigation infrastructure, and areas within 250 m of irrigation turnouts and irrigation ditches, may also be more susceptible to streambank erosional processes.

Recommendations for monitoring methods include repeated surveys of the channel cross section and longitudinal profile, measurement of sediment-size characteristics of the streambed and streambanks, and oblique photography from monumented locations throughout the reach. Because these surveys, measurements, and photographs are to be replicated, it is essential that they be referenced to permanent monuments where standardized methods are employed. Descriptions of these techniques are presented in Elliott and Parker (1999) and the U.S. Geological Survey Reconfigured Channel Monitoring and Assessment Program (RCMAP) web page (http://co.water.usgs.gov/projects/rcmap/monitormethods.html).

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