Reestablishing Hydrologic and Ecological Integrity:

The Use of Reference Sites to Determine Environmental Characteristics Necessary for Restoration at the Headwaters of the Colorado River in Rocky Mountain National Park, CO

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1. INTRODUCTION

Riparian habitats are among the most diverse, dynamic, and complex ecosystems on earth (Naiman *et al*. 1993) providing important ecosystem services and functions (Wilen and Bates 1995, Mitsch and Gosselink 2000, Postel and Richter 2003). Riparian areas in the southwestern US have been significantly impacted by anthropogenic hydrologic, ecological, and geomorphic modifications in the 20th century (Birken and Cooper 2006). More than 50 percent of wetlands in Colorado have been lost and productive wetlands have disappeared at a staggering rate (Noss *et al*. 1995 and Yuhas 1996). From its headwaters in Rocky Mountain National Park (RMNP) to the Gulf of California, the Colorado River flows 2,330 km encountering diversions, impoundments, and a plethora of human uses and inputs (Meyers 1966, Glenn *et al.* 1996, Gleick 2003). The integrity and functionality of the Colorado River and its adjacent wetlands are of great social, economic, and ecological importance; providing water resources, fishery stocks, wildlife habitat, and intrinsic socio-ecological value (Meyers 1966, Rowell *et al.* 2005).

Riparian plant species require specific environmental conditions for establishment and persistence (Baker 1989, Rot *et al.* 2000, Shaw and Cooper 2008). Water table depth and dynamics, soil structure, geomorphological processes, and climatic conditions determine the composition and vigor of the vegetation (Scott *et al.* 1996, Shafroth 2002 a, Gage and Cooper 2004, Woods and Cooper 2005). Riparian vegetation provides essential ecosystem functions including stream shading and cooling, bank stabilization, nutrient exchange, flow regulation and attenuation of flood peaks, increased groundwater recharge, and inputs of terrestrial subsidies (Beschta 1997, Xiong and Nilsson 1997, Fausch *et al.* 2002, Langendoen *et al.* 2009) as well as creating critical habitat for beaver, birds, invertebrates, browsing ungulates, and other wildlife (Beier 1987, Naiman and Decamps 1997, Wolf *et al.* 2007).

Anthropogenic reductions in stream flow rates and increased depth to water table have altered riparian vegetation, causing a shift in community structure and the environmental benefits associated with intact vegetation composition (Shafroth *et al.* 2002 b, Woods and Cooper 2005, Cooper *et al.* 2006, Leeds *et al.* 2009). Historically, riparian restoration efforts have exclusively addressed revegetation often overlooking the importance of restoring the hydrologic regime (Stromberg 2001). More research is needed to analyze the specific ecosystem characteristics driving riparian vegetation establishment and persistence.

1.1 HISTORY

The headwaters of the Colorado River in RMNP (Figure 1) has been impacted by the Grand Ditch for more than 100 years (Woods 2001). Operated by the Water Storage and Supply Company, the Grand Ditch runs 24 km along the east face of the Never Summer Mountain Range at approximately 3,200 m elevation above sea level. Constructed in stages from 1890-1936 using hand tools, black powder, and eventually machinery, the 6 m wide 1-2 m deep hand-constructed earthen channel diverts nearly 50 percent of the water that is tributary to the Colorado River headwaters within RMNP. Flowing north along a gentle gradient, the transbasin diversion canal intercepts Colorado River tributary runoff from the Never Summer Mountain Range redirecting an average of 20 million m^3 of water per year from the Colorado River watershed over the continental divide to Long Draw reservoir, and into the Cache La Poudre River where it descends to the Front Range for agricultural and municipality water uses (Woods 2000).

Water diversion has modified the hydrologic regime of the Colorado River headwaters reducing total annual flow and altering the magnitude and timing of peak flows. Prior to the installation of the Grand Ditch, the Colorado River headwaters flow would have had a rapidly rising peak flow from melting snow pack runoff followed by a slowly receding limb as the melt decreased and infiltration ensued. Currently the Grand Ditch captures the snowmelt peak diverting it to Long Draw Reservoir. When Long Draw is full, the head gates to Colorado River tributaries along the ditch are opened yielding significantly delayed and diminished peak flows. The receding limb is also shortened by this procedure due to lack of melt water and the growing season demand for irrigation water from the Cache La Poudre (Figure (hydrograph)). Grand Ditch flow reductions limit downstream flooding and sediment transport capacity and lowers the water table deleteriously altering conditions conducive to riparian vegetation establishment (Woods and Cooper 2005).

The most obvious visual impact of the Grand Ditch is the hillside scaring caused by repeated breaches, failures, and debris events (Figure (Photo)). More than 70 years of debris flows and sedimentation have resulted in an increased input of large and fine grained sediments in the Colorado River headwaters and extensive aggradation in the Lulu City Wetland (Rubin 2010).

In 2003 a section of the Grand Ditch breached above Lulu Creek, inundating the creek, several km of the Colorado River and its floodplains, and the Lulu City wetland with more than 36,000 m^3 of sediment and debris (RMNP Fact Sheet 2010). Historical air photo analysis and soil pit excavation stratigraphic interpretations revealed several previous debris flow event occurrences prior to the 2003 breach (Figure (cooper sed outlines)). Sediment from these debris flows has increased the elevation of the Lulu City wetland, altered the channel and course of the Colorado River, and resulted in a lowered water table in some areas. Riparian vegetation is sensitive to alterations in groundwater depth, because it limits the establishment of critical plant species, shifts species composition, affects ecosystem functions, and causes a die back and mortality of individuals in dewatered areas (Rood and Mahoney 1990, Smith *et al.* 1991, Dixon and Johnson 1999, Rood *et al*. 2002). Vegetation composition is determined in part by available groundwater (Brinson *et al.* 1985, van Coller *et al.* 2000) and other environmental variables such as climate, elevation, aspect, and soil structure (Perona *et al*. 2009). Riparian vegetation is dependent on shallow groundwater which may be linked to stream water (Rood *et al*. 2003, Cooper 2006) and without groundwater the vegetation composition would shift from obligate riparian to upland species (Smith *et al.* 1991, Stromberg 1996 .

1.2 PURPOSE

RMNP receives nearly 3 million visitors annually with a great deal of foot traffic along the Colorado River trail. The social integrity of a restored riparian corridor, stream channel, and wetland will provide significant benefits. With so many of Colorado's rivers and wetlands negatively impacted by water manipulation, impoundment, and diversion, it is critical to better understand the management and restoration of this resource and its riparian vegetation (Brinson and Malvarez 2002).

A greater understanding of the environmental characteristics that sustains riparian vegetation is important for designing a restoration protocol (Naiman *et al*. 1993, Stromberg 2001). Successful restoration requires a clear understanding of natural riparian processes and the disturbance type and extent of degradation within an ecosystem (Goodwin *et al*. 1997), as well as geomorphological processes, ecological functions, and vegetation composition (Kondolf 1998, Naiman *et al*. 2000). A restoration plan needs *a priori* standards of physical and ecological conditions that are naturally sustainable (Goodwin *et al.* 1997); however, restoration should never be considered in lieu of conserving high quality environments (Boon 1998). Restoration improves ecological quality, enhances ecosystem functions and biological integrity (Schmidt *et al.* 1998, Bendor *et al*. 2009), and in riparian areas has been found to increase aquatic and terrestrial wildlife habitat and water quality (Harris 1999). It is critical to include extensive pre-restoration assessments and post-restoration monitoring and management in designing a restoration protocol (Kondolf 1998, Zavaleta *et al.* 2001, Palmer *et al.* 2005, Follstad *et al*. 2007).

Restoration efforts often lack appropriate reference sites (Lane and Texler 2007, Brewer and Menzel 2008). I surveyed a range of reference reaches analogous to the Colorado River headwaters and adjacent wetlands to determine the groundwater and soil structure characteristics that support riparian vegetation and communities. Reference sites were in the Rocky Mountains of Colorado at comparable elevation, valley and stream gradient, stream channel width, and stream flow to the impacted areas at the headwaters of the Colorado River.

According to the National Research Council (NRC 1992) restoration is the process of returning "an ecosystem to a close approximation of its condition prior to disturbance." Recently, however, this concept has been replaced by the current Society for Ecological Restoration definition of restoration as "The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed." (SER International Science & Policy Working Group 2004). This distinction is important for the restoration of the Colorado River headwaters in RMNP as it is difficult to determine what exactly the condition of the Colorado River, its floodplains, and riparian vegetation was prior to disturbance. Furthermore, it may not be feasible to restore the Colorado River to its pre-ditch disturbance condition in a time of changing climate and stream flows that are depleted by Grand Ditch diversions (Stanford *et al.* 1996, Hobbs 2007, Katz *et al.* 2009). Norris and Hawkins (2000) simply define restored river health as the degree to which a site supports the biota that would be expected to occur in the absence of alterations by humans. However, this is not feasible in a location with so many current and persisting alterations. Restoration of the Colorado River headwaters will require a great deal of planning, applied physical manipulation, and continued post restoration monitoring, management, and evaluation.

Restoring intact zones of riparian connectivity is one of the most important and greatest challenges facing natural resource managers (Naiman *et al*. 2000, Norris and Hawkins 2000). Review of the primary ecological drivers determining riparian vegetation composition is key to understanding and naturalizing ecological processes for restoration (Stromberg 2001). Investigation of the groundwater and soil characteristics necessary for establishment and persistence of riparian vegetation has provided important insight for the restoration design and management of the headwaters of the Colorado River in RMNP.

1.3 OBJECTIVES

We investigated the environmental conditions in riparian ecosystems at reference sites in the northern Rocky Mountains of Colorado. Through three seasons of data collection, were explored current impacted conditions at the headwaters of the Colorado River including seasonal groundwater fluctuations, flow rates, and introduced sediment thickness; and offsite reference conditions including riparian vegetation occurrence, cover, and community type, and their environmental persistence drivers. Our objectives were to (1) Determine current conditions at the impacted reaches of the Colorado River headwaters, (2) Provide insight into the environmental drivers of riparian vegetation persistence using analogous on and offsite reference conditions, and (3) synthesize the required environmental characteristics conducive to riparian vegetation persistence necessary for restoration implementation.

The research goal is to provide context for future restoration planning at the headwaters of the Colorado River. Preliminary research, discovery, and collection of reference condition data are critical to better understanding and execution of lasting and sustainable restoration outcomes (Harris 1999).

2. STUDY AREA

The restoration study site is in western Rocky Mountain National Park at the head of the Kawuneeche valley along the headwaters of the Colorado River, its tributaries, and adjacent wetlands. The Kawuneeche valley ranges from 2,700 – 3,100 m above sea level and is flanked by two mountain ranges that rise 1,200 m above the valley floor. The Never Summer Mountains to the west were formed by a now-extinct volcanic chain consisting primarily of Oligocene granitic magmas and metamorphic formations covered by an extensive lateral moraine from Pleistocene glaciations and unstable hydrologically welded tuff. The highly erosive volcanic formations of Specimen Mountain stand to the east consisting mostly of Proterozoic biotite schist with some Oligocene rhyolitic lava flows and tuff

(Braddock and Cole 1990). Silt loam and loamy sand textured mineral soils in the valley naturally vary in thickness (Braddock and Cole 1990); however multiple debris events over the past 100 years have artificially thickened this substrate and introduced larger grained material into the system. The valley bottom vegetation along the Colorado River Headwaters is a mix of riparian shrubland dominated by the willows *Salix monticola, S. geyeriana,* and *S. drummondiana*, dry meadows with the grasses *Calamagrostis canadensis* and *Deschampsia cespitosa*, and peat accumulating fens that include *Salix planifolia* and *Carex aquatilis*. Upland slopes are dominated by the conifers *Abies bifolia*, *Picea englemannii*, and *Pinus contorta* (Woods 2000 and Westbrook *et al.* 2006). The Kawuneeche Valley typically has a blanket of snow from October to June with air temperatures below 0° C from November to April. Early summer is typically dry and warm with air temperatures in the teens C, while late summer brings monsoonal rains and slightly decreased temperatures. Air temperature ranged from -7 to +12 C and -10 to +13 C in 2009 and 2010 respectively. Precipitation was 60 cm in the 2009 water year and 23.3 inches in the 2010 water year (current and historic weather data found at NRCS website). The study area is a mixture of high and low gradient stream channels and riparian zones, wetlands, and wet meadows. Colorado River stage and discharge data has been collected at the Baker Gulch USGS gage 5 km downstream from the study site since 1954. Average Colorado River flows are 1.8 m^3/s with a minimum recorded flow of 0.7 m^3/s (1954) and a maximum recorded flow of 5.1 m^3/s (2011) (USGS Baker Gulch Gage Data). Stream flows are altered by water diversion into the Grand Ditch, resulting in a delayed peak and as much as a 60 percent reduction of snowmelt peak flows and summer receding flows (Woods 2001).

The sites slated for restoration have been greatly impacted by altered stream flow, aberrant sedimentation, and the resulting shift in riparian vegetation. Reference sites in and out of RMNP provide insight into soil characteristics, groundwater depths, and vegetation composition that can be used to plan restoration.

Four reference reaches within the Colorado River valley in RMNP (Figure (ref map)) and 10 reference reaches outside of the Colorado River valley were analyzed during the course of my work (Figure ref map)). The offsite reaches were along Saint Vrain Creek and Big Thompson River on the East side of RMNP, Willow Creek in the Routt National Forest north of the town of Clark, two reaches of Willow Creek in the Arapaho National Forest north of the town of Granby, Elk River in the Routt National Forest northeast of Clark, Homestake Creek and Eagle River in the White River National Forest south of Redcliff, Cataract Creek in the Dillon Ranger District south of Heeney, and Ranch Creek in the Arapaho National Forest east of Tabernash.

3. METHODS

3.1 Reference Sites

I selected four reference reaches comparable in discharge and gradient to Lulu Creek (Reach 1), the Colorado River (Reach 2), and Lulu City Wetland (Reach 3) (Figure (reach map)) reaches affected by the 2003 Grand Ditch breach in June of 2009 using physical site attributes (e.g. elevation, aspect, slope, channel size, valley size, and flow rates) in conjunction with a visual reconnaissance survey (Cooper, Rathburn, and Potter 2009). Reference reaches are along Sawmill Creek, the Colorado River at Shipler Park, Lost Creek, and just below the confluence with Beaver Creek (Figure). Reference surveys were conducted onsite at the headwaters of the Colorado River and tributaries in the Kawuneeche Valley in RMNP and offsite at selected watersheds elsewhere in the northern Rocky Mountains of Colorado.

3.1.1 Onsite Reference

Groundwater Monitoring: In June of 2009 I installed 35 groundwater monitoring wells at the onsite reference reaches (Figure photo), including 13 at Lost Creek, 8 at Shipler Park, 6 at Sawmill Creek, and 8 below Beaver Creek. Wells were constructed of 1 ½ inch slotted PVC pipe with a perforated bottom cap and solid top cap. Wells were installed along transects perpendicular to the river to monitor water table cross sections across the flood plain gradient. Wells were installed by hand using a spade, rock bar, post-hole-digger, and bare hands. Floodplain pits were excavated below the groundwater to the point where the sides of the pit could no longer hold shape. PVC wells were inserted and the hole backfilled. Completed wells varied from 0.5 – 1.5 m deep. Staff gauges were installed at each reference reach to measure stream height. 50 wells had been previously installed in the reaches impacted by the breach (Gage 2004). Groundwater levels were monitored using the 85 total wells. Manual depth to water (DTW) measurements were taken biweekly during June through October using an electronic tape (Figure photo). Water table depth was logged as the distance from the top of the well casing to the water table and stickup (PVC height above ground surface) was subtracted to give DTW to the nearest mm. To corroborate the manual DTW measurements, eight In-situ Level Troll 100 digital data loggers were installed, with 2 at each reference site. The data loggers were suspended by 24-gauge steel galvanized wire attached to a horizontal steel bolt threaded through the top of the well. The stickup to bolt and cable length were measured and recorded for later calibration. The data loggers recorded total pressure of the water column and temperature every 15 minutes from in July – October 2009 and June – October 2010. The data was downloaded and corrected using In-situ Baro-merge software and In-situ Barrologger data from the Kawuneeche visitor center in RMNP.

Vegetation Analysis: In August 2009 I analyzed the vegetation in 25 m^2 plots centered around each reference site groundwater monitoring well. All species present were noted and percent canopy cover by species was visually estimated for each plot. Plant species nomenclature follows Weber and Whitman (2001).

Soil Stratigraphy: In September of 2009 using a small Bobcat with an excavator attachment 51 pits were dug in zones 3 and 4 (Figure (photos)) and 7 PVC groundwater monitoring wells were installed. Pits were less than 2 meters deep due to the length of the excavator arm and varied in width depending on the collapse of the hole. The pits filled with ground water and required continuous bailing by a diesel-powered pump. Soil stratigraphy interpretations revealed thickness of post breach sediment layers and uncovered buried vegetation.

Tree Ring Analysis: 3 woody plants were extracted from 3 different pit locations in Zones 3 and 4. An unknown willow species (*Salix spp*.), narrowleaf Cottonwood (*Populus angustifolia*), and Lodgepole Pine (*Pinus contorta*) were taken to the CSU lab where I found the point-of-germination pith, counted annual growth rings, and developed an approximate germination year for each specimen (Figure (photo)).

Stream Flow: Daily flows from June – September long term stream discharge data were compiled for the Colorado River using the USGS Baker Gulch gage in RMNP. A daily flow hydrograph was created for each site for the 2009-2010 and the 2010-2011 water years (Figure (hydrograph)).

3.1.2 Offsite Reference

In the spring of 2010 I selected 10 offsite reference reaches in 6 watersheds in northern Colorado. Reference sites were selected on National Forest lands using the United States Forest Service Valley Bottom Classification (VBC) (Carlson 2010). The VBC organizes river reaches by basin, valley width, channel width, stream volume, gradient, and elevation in ArcMap. Utilizing the physical site attributes of the RMNP reaches affected by the breach, the VBC selected several hundred random sites comparable to the Colorado River headwaters and tributaries. I further rectified the VBC selection using United States Geological Survey (USGS) seamless server orthophotos in ArcMap to analyze standardized elevation, aspect, and gradient conditions. I used Google Earth to determine land ownership and proximity of potential sites to roads. Finally, I used on-the-ground field observations to identify the least disturbed sites. I selected an exemplary 1 km reach within each of the 10 reference sites, and randomly selected 10, 25 m^2 homogenous riparian vegetation survey plots per reach for a total of 100 survey plots. Ten reference surveys per reference condition are desirable to provide adequate comparison within each watershed (Barbour *et al.* 1999).

Offsite reference site surveys were conducted over a two-week period in July 2010. For each reference survey I measured stream gradient, depth to groundwater, soil characteristics, and vegetation composition. I used USGS stream gage data to determine current and historic stream stage at each survey location.

Groundwater Monitoring: Pits were excavated at the center of each 25 m^2 survey plot to measure DTW. Each pit was excavated using a 10 cm diameter bucket auger. Pits remained open for approximately 24 hours to allow groundwater levels to stabilize before DTW was measured (Figure (photo)).

Soil samples: A 10 x 30 cm^2 soil core was collected from each groundwater pit and placed into a 1 gallon zipper-lock bag. Immediately upon return from the field I measured soil water content by weighing approximately 10 grams of wet soil from each survey plot, placing samples in the drying oven at 105^0 c for 72 hours, and reweighing. I sieved the samples to 25.4 mm, 12.7 mm, 5.6mm, and 2 mm and weighed each size class to determine percent weight per sample of materials larger than sand. I then conducted a soil particle size analysis using the hydrometer method (Carter 1993) to determine soil type and percentage of sand, silt, and clay smaller than 2 mm (Figure (photo)).

Vegetation Analysis: Homogenous stands of riparian vegetation were identified using orthophotos and onsite inspections. Survey plots were 25 m^2 and ranged from adjacent to the stream channel to higher on the floodplain. Only riparian communities were surveyed. All species present were noted and percent canopy cover by species was visually estimated for each plot. Plant species nomenclature follows Weber and Whitman (2001) (Figure (photo)).

Stream Flow: Long-term stream discharge data were compiled from the closest USGS stream gaging stations to each reference site (Table (gage # and distance downstream of ref site)). A daily flow hydrograph was created for each site for the 2009-2010 and the 2010-2011 water years.

3.2 STATISTICAL ANALYSIS

I used repeated measures analysis of variance (ANOVA) to analyze environmental characteristic driven riparian vegetation persistence. In SAS 9.2, I fit a generalized linear model (GLM) to my data to analyze environmental characteristic predictors for individual species. A stepwise selection summary with optimal value of criterion was utilized to determine best predictors of environmental characteristics for individual species persistence and community classification. A Proc Mixed procedure of least squares was fit with each reach to determine presence likelihood and significance of each species in reaches 1-3. The Proc Means procedure using the difference of least square means generated mean estimates of environmental variables across community types and reaches to better understand what environmental variables drive each community and reach. The Proc Frequency procedure was used to determine the likelihood of a community fitting within a reach or a reach fitting within a community. Random model effects required a fit with both random and fixed effects. Random effects were elevation, depth to water, soil texture, soil gravel percentage, bank width, reach gradient, valley width, valley to bottom ratio, slope class, and valley class. Fixed effects were elevation, slope class, and valley class.

3.2.1 Multivariate analysis

Plant communities were identified using hierarchical agglomerative cluster analysis (McCune and Grace 2002) utilizing the Sorenson (Bray Curtis) distance measure and flexible beta group linkage method with beta = -0.25 in the ordination software program PC-ORD 5.0 (McCune and Grace 2002). An indicator species analysis was used to determine the optimum number of clusters produced by the dendrogram. Plant communities were determined by species type and environmental variables. Species and community distribution patterns were related to environmental variables using nonmetric multidimensional scaling (NMS) in PC-ORD 5.0 based on the Sorenson (Bray Curtis) distance measure, followed by correlation analysis of the stand scores and environmental variables.

4. RESULTS

4.1 ENVIRONMENTAL CHARACTERISTICS/VARIABLES

Vegetation composition is strongly driven by environmental characteristics (Harris 1999 and Norden *et al.* 2007) including surface water, groundwater, soil texture, soil grain size, river magnitude, and valley width. Tall willow and riparian community establishment and persistence are especially sensitive to alterations in hydrology and sedimentation (Todd *et al.* 2010). For more than 100 years the headwaters of the Colorado River has experienced significantly altered hydrology, reduced flow rates, and an aberrant input of sediment due to tributary diversion and failure of the Grand Ditch. On and offsite reference reach surveys provided a look into the conditions expected for the Colorado River without the historic modifications of the Grand Ditch and concepts for restoration after ditch related impacts.

4.1.1 GROUNDWATER/RIVER STAGE

Colorado River flows varied depending on snowpack, Grand Ditch flow releases, and late season monsoonal precipitation. Peak runoff differed between survey years due to total snowpack water content. 2009 was dry with an early snowmelt while 2010 had heavy snowpack, a cold spring, and delayed peak runoff. River stage varied between 2009 and 2010 (Figure (hydrographs of 2009 and

2010)). Total water year precipitation was comparable between 2009 and 2010 (23.8 inches and 23.3 inches respectively) (NRCS snotel 688); however, the greatest difference came in timing of rainfall. 2009 witnessed a typical snowmelt as temperatures warmed through may, while 2010 experienced rain on snow events and continued precipitation after the melt through June. This above average flow pulse quickly filled Long Draw Reservoir and, due to unusual precipitation events in the Front Range, the stored water was not required until later in the season. Thus, Grand Ditch allowed flow down tributary streams and into the Colorado River. The June flows of 2010 were rated at a 30—40 year return interval (Rathburn 2010) and served to rework much of the impacted reaches, move large quantities of sediments, and effectively saturate or disconnect many areas that had been somewhat stable for the preceding 7 years.

DTW was seasonally affected by the diversion and release of water by the Grand Ditch. DTW fluctuations corresponded conversely to the ditch release gage at Long Draw Reservoir with a mirror image symmetry (Figure (well and ditch hydrograph)). DTW was also affected by precipitation events in both 2009 and 2010 (Figure (DTW hydrograph over precip bars)). DTW increased below the ground surface during the summer in both study years with an increase of -27 to -45 cm in 2009, and -28 to -56 cm in 2010 (Figure (DTW charts)). DTW varied by community and reach though not significantly. DTW was greatest in community E (mean DTW = -76 cm) followed by community A (Mean DTW = -55 cm). B,C, and D were comparable (mean DTW = -46, -47, and -46 cm). Greatest DTW was found in Reach 1 (Mean -76 cm). Reaches 2 and 3 DTW were comparable at Mean -50 cm.

The 14 most common species surveyed at reference sites occupied distinct hydrologic zones (Figure). *Salix wolfii* occurred in locations with the deepest average water table (Mean DTW = -63 cm). *Salix ligulifolia* and *Carex aquatilis* occurred in locations with the shallowest average groundwater (Mean DTW – 37 cm and 39 cm respectively).

4.1.2 Soils

Soil texture analysis revealed 7 distinctive classes of soil present at the on and offsite reference sites. Clay, clay loam, silty clay, sandy clay loam, loam, silt loam, and sandy loam. Soil properties varied some between sample plots, but were generally strongly correlated with one soil type. While soil texture class was not significant for community composition, soil texture larger than 2 mm significantly influenced community composition. These gravels had greater strength in determining community and individual species presence. Soil texture larger than 2 mm was significantly different between communities A and D ($p < 0.0179$), C and E ($p < 0.0356$) and D and E ($p < 0.0113$). Soil texture larger than 2mm was significantly different between reaches 1 and 3, with a mean percent frequency of 28% at Reach 1, 13% at Reach 2, and 8% and Reach 3. The greatest percentage of gravels larger than 2mm was found in descending order in community E, A> B> C> D

While soil texture was not a significant determinant of species composition, soil texture larger than 2 mm did significantly influence vegetation persistence. The 14 most common species surveyed at reference sites occupied distinct textural zones (Figure).

Stratigraphic analysis illustrated the complex matrix of sediment deposition in reaches 2 and 3 (Figure (stratigraphy charts)). Soil stratigraphy interpretations of the excavated pits exposed variable sediment thickness deposited by the 2003 flood across Lulu City wetland (Reach 3). Sediment thickness varied according to least resistant flow path and the magnitude and intensity of the event. I developed sediment thickness representational maps for both the solitary 2003 debris event deposition (Figure) and total sedimentation (Figure).

Aerial photo analysis (Cooper 2007) corroborated stratigraphic illustrations of sediment thickness from events prior to 2003. Historic photos from 1937, 1953, 1969, 1987, 2001, and 2003 show evidence of ditch caused debris events extending down through Lulu City Wetland (Figure (cooper photo sediment lobes)). The 1937 photo revealed a seemingly intact historic wetland bisected by a meandering Colorado River channel and a landscape dotted with defunct and intact beaver ponds. The 1953 photo introduced 2 large areas of bare sediment, one plugging the mouth of the wetland with a dike of material, the other spread across the upper west side of the wetland. The 1953 photo also revealed a shift in Colorado River channel configuration from the center of the wetland to the upper west side that sporadically disappeared before returning to the historic channel. The 1969 photo exposed thin but long drifts of sediment along the entire west side as well as a pronounced new Colorado River channel on the upper west side connecting to the historic channel half way down the wetland. What was once the historic Colorado River channel, by 1969 looked like a collection of intact beaver ponds with standing water – evidence of surface and subsurface flows gravitating to the lowest spot in the wetland from the new elevated west side river channel. The 1987 photo yielded new lobes of sediment extending midway down the western and central portions of the wetland and the emergence of two distinct river channels half way down the wetland. By 1987 the lower historic Colorado River channel was disconnected from the new channel (though still flowing) and a new lower channel had connected to the west. In 2001 some evidence of the 1980's event is visible and the new river channel is fully connected and has straightened. The 2001 photo also revealed a significant drying of the ponds along the historic channel. The 2003 photo offered an impressive new lobe of sediment extending from the mouth almost half way down the wetland and inundating both new and historic Colorado River channels. These historic aerial photos suggest Grand Ditch related disturbance and sedimentation regime that has been in place for more than 70 years. The exact initiation of these historic debris events is unknown, but the results have been significant for the alteration of hydrology, soil texture, and riparian vegetation community structure.

4.1.3 Bankfull channel width

Bankfull channel width (BCW) is the measure of river magnitude potential. BCW is significantly different between communities (except for a and c and b and d) and is significantly different between all reaches.

4.1.4 Mean Gradient of Reach

Mean Reach Gradient (MGR) is the percent slope of each reach gradient. MGR is significantly different between all reaches. MGR is steepest to gentlest from reach 1 to 3. Mean 0.03, 0.02, 0.01 and by community from E, A, D, B, and C.

4.1.5 Hydrogeomorphic Valley width

Hydrogeomorphic Valley Width (HVW) is the distance of the valley bottom between the toe slopes. HVW is significantly different between reaches 2 and 3.

4.1.6 Slope Class

Slope Class (SC) signifies 3 categories of potential stream energies ranging from <0.1% to >4% slope. SC is not significantly different between reaches.

4.1.7 Valley to Bankfull Channel Width Ratio

Valley to bankfull channel width ratio (VBCWR) determines confinement through the ratio of valley width and stream width. VBCWR is significantly different between reaches 1 and 2 and 2 and 3.

4.1.9 Elevation

Elevation is significantly different between reaches 1 and 2 and 1 and 3.

4.1.10 Valley Class

Valley Class (VC) is a matrix of all of the above variables that determine the heterogeneity of analogous sites. VC is significantly different between all reaches.

4.2 VEGETATION COMMUNITIES

A total of 49 vascular plants commonly occurred in the on and offsite reference reaches (Table (species list)). Only frequently occurring species were included for this study. *Carex* (n=121) was the most observed monocot genus while *Salix* was the most prevalent woody dicot (n=254).

Vegetation persistence was driven by different environmental variables. Each of the commonly occurring species had a significant environmental driver (Table (driver table)).

Five communities were identified and distinguished by characteristic indicator species (Table (community table)). Communities were named by the top 2 indicator species. Indicator species were not necessarily the dominants, but had the greatest indicator value per PC-ORD 5.0 (McCune and Grace 2002). Mean percent cover of each species was expressed for the community that species fell into. Constancy class expressed frequency of occurrence of each species per community.

Community A: SALBOO-ALNTEN (*n=38*)

- Community A occurred at an average elevation of approximately 2533 m beside moderate grade streams (mean gradient 0.015) with a mean water table depth of -55 cm during mid-growing season and a sandy clay loam soil texture with 15% by weight gravels larger than 2mm. The best environmental predictor for Community A was DTW. SALBOO was most likely to occur at Reach 2 though not significant (P = 0.0897) at a 13% likelihood. ALNTEN was significantly likely to occur in Reach 2 (P = 0.0006) at a 15% likelihood.

Community B: CARUTR-SALWOL (*n=10*)

- Community B occurred at an average elevation of approximately 2617 m beside moderate gradient streams (mean gradient 0.013) with a mean depth to water table of -46 cm during mid-growing season and sandy clay loam and clay loam soil texture with 14% by weight gravels larger than 2mm. The best environmental predictor for Community B was Reach Gradient. CARUTR was most likely to occur in Reach 2 (P = 0.1913) at a 11% likelihood. SALWOL was most likely to occur at Reach 2 though not significant (P = 0.198) at a 7% likelihood.

Community C: CARAQU-SALGEY (*n=25*)

- Community C occurred on average at an elevation of approximately 2616 m beside moderate grade streams (mean gradient 0.011) with a mean depth to water table of -47 cm during mid-growing season and a sandy clay loam soil texture with 17% by weight gravels larger than 2mm. The best environmental predictor for Community C was DTW. CARAQU was significantly likely to occur in Reach 2 (P = 0.008) at a 30% likelihood. SALGEY was significantly likely to occur at Reach 3 (P = 0.0006) at a 27% likelihood.

Community D: SALMON-CALCAN (*n=30*)

- Community D occurred on average at an elevation of approximately 2628 m beside moderate grade streams (mean gradient 0.013) with a mean depth to water table of -47 cm during mid-growing season and a sandy clay loam soil texture with 6% by weight gravels larger than 2mm. The best environmental predictor for Community D was Soil Percentage. SALMON was most likely to occur in Reach 3 though not significant (P = 0.391) at a 5% likelihood. CALCAN was significantly likely to occur at Reach 3 (P = 0.00029) at a 49% likelihood.

Community E: VACSCO-ABIBIF *(n=3)*

- Community E occurred on average at an elevation of approximately 2909 m beside high grade streams (mean gradient 0.034) with a mean depth to water table of -76 cm during mid-growing season and a sandy clay loam soil texture with 28% by weight gravels larger than 2mm. The best environmental predictor for Community E was the Valley to Bankfull Ratio. VACSCO was significantly likely to occur in Reach 1 (P = 0.0001) at a 34% likelihood. ABIBIF was significantly likely to occur at Reach 1 (P = 0.0001) at a 54% likelihood.

THIS IS WHERE THE NMS RESULTS WILL GO! Species and community distribution patterns were correlated with environmental variables using nonmetric multidimensional scaling (NMS) in PC-ORD 5.0. A slow and thorough analysis yielded a three axis solution to the relationship between species, communities, and environmental variables (Figures (Ordination graphs)). *Talk about axis relationships.*

4.3 IMPACTED REACHES

Each community varied by reference condition and was related to one or more impacted reach. Analysis of analogous reference reach surveys found Reach 1 to be entirely determined by community E with 100% of E species found in Reach 1. Reach 2 was determined by both community C (64%) and A (60%). Reach 3 was primarily determined by community B with 100% of B species found in Reach 3 followed by community D (53%) (Table (community/reach table).

Reaches varied in environmental variables. Analysis of analogous reference reach surveys found Reach 1 to consist exclusively of Community E with an average elevation of 2909 m, an approximate DTW of -76 cm during the mid growing season, a sandy clay loam soil texture with 28% by weight gravels larger than 2 mm, a bankfull channel width of 5, a mean gradient of 0.034, a hydrogeomorphic valley width of 245, a valley to bankfull channel width ratio of 53, and a valley class of 4. Reach 2 was at an average elevation of 2575, with an approximate DTW of -51 cm during the mid growing season, a sandy clay loam soil texture with 16% by weight gravels larger than 2 mm, a bankfull channel width of 7, a mean gradient of 0.013, a hydrogeomorphic valley width of 147, a valley to bankfull channel width ratio of 19, and a valley class of 3. Reach 3 was at an average elevation of 2623, with an approximate DTW of -46 cm during the mid growing season, a sandy clay loam soil texture with 10% by weight gravels larger than 2 mm, a bankfull channel width of 10, a mean gradient of 0.013, a hydrogeomorphic valley width of 189, a valley to bankfull channel width ratio of 34, and a valley class of 8 and 4.

Each impacted reach had a best predictor for determining persistence of expected vegetation communities. The best predictor for Reach 1 was the Valley to Bankfull Width Ratio, a definition of river confinement determined by valley floor and river width. Best predictor for Reach 2 was Reach Gradient, the gradient percentage of the entire reach. Best predictor for Reach 3 was DTW, a measurement of depth to groundwater below the ground surface. Each reach had a best predictor for vegetation communities, though all characteristics provided some sort of influence on persisting composition.

4.4 TREE SAMPLES

Annual growth ring counts of the 3 extracted trees yielded a span of germination dates (Table (Tree dates) photos). All three trees germinated on bare streamside sediments deposited by historic debris events and were subsequently partially buried by later sediment influx. The *Pinus contorta* sample germinated in approximately 1971, the *Populus angustifolia* sample germinated in approximately 1966, and the *Salix spp*. sample germinated in approximately 1953.

4.5 GROUND SURFACE AND WATER TABLE MODELS

Ground surface models developed from sediment pit excavations reveal a desired ground surface in Lulu City Wetland significantly below the current ground surface (Figure (Cross sections)). Reference site depth to water table measurements offer insight into necessary groundwater depths for persistence of riparian vegetation. Current and desired water table cross sections reveal ideal restoration parameters (Figure (DTW cross sections)).

4.6 CLIMATE TRENDS

Phantom Valley SNOTEL station #688 2.5 km downstream from the impacted reaches of the Colorado River recorded the most proximate historic climate data for the region. Precipitation varied little between 2009 (total water year precipitation = 23.8 in) and 2010 (total water year precipitation = 23.3 in), and was negligibly less than the 20 year average (total water year precipitation average for 1991-2010 = 25.5 in). Precipitation was greater from April through June in both years (Mean April-June 2009 precipitation = 6.3 in. Mean April-June 2010 precipitation = 7.8 in) than from July through September (Mean July-September 2009 precipitation = 3.9 in. Mean July-September 2010 precipitation = 4.9 in). April through June exceeded the 20 year average (Mean April-June 20 year average = 5.4 in) while July through September fell short of the 20 year average (Mean July-September 20 year average = 5.3 in) (Table (Mean precip and SWE 09/10/20yr)).

Snow water equivalent (SWE) readings taken on April 1 varied between 2009 (2009 April 1 SWE = 9.9 in) and 2010 (2010 April 1 SWE = 6.8 in) with the 20 year average falling somewhat in between (20 year average April 1 SWE = 8.9 in) (Table (Mean precip and SWE 09/10/20yr)).

Mean daily temperatures ranged from 2.3 °C (2009) to 1.8 °C (2010) with a 20 year average mean of 0.8 °C (1991-2010) (Table (Mean daily temp from snotel. 09/10/20yr)). Monthly average highs occurred in July (2009 = 12°C, 2010 = 13°C, 20 year average = 12.4°C) followed closely by August (2009 = 12°C, 2010 = 11°C, 20 year average = 11°C). Monthly average lows occurred in December (2009 = -7°C, 2010 = -10°C, 20 year average = -9.8°C).

5. DISCUSSION

The use of analogous reference conditions is a crucial component for the design of restoration goals (Harris 1999, Stromberg *et al.* 2007). Reference conditions are useful for modeling what conditions and systems would have occurred pre-degradation (White and Walker 1997). While the intention is not to restore ecosystems to a predetermined condition along a timeline, it is important to understand what processes occur at analogous sites. Alterations in river flows greatly affect sedimentation, soil texture, nutrient cycling and propagule distribution and, in turn, alter the establishment and persistence of willows and riparian vegetation (Nilsson and Svedmark 2002).

This study found that riparian vegetation has specific environmental drivers for persistence. These findings support the assertion that riparian species require a shallow water table, course textured growing medium, and vary in presence based on channel size, valley width, gradient, and elevation (Harris 1999, Merritt and Cooper 2000, and Norden *et al.* 2007).

The 49 species frequently observed at the reference sites broke out nicely into 5 community types. Each community, characterized by 2 dominant species and containing other less common species, was determined by environmental characteristics particular to the community. While many species and communities were significantly related to one environmental characteristic it is likely that establishment and persistence of riparian vegetation is a collection of favorable characteristics. In addition, species and communities do not have exact lines of delineation and form under various conditions while tending to cluster under optimal circumstances.

Woody species such as willow and alder were found in sites with a wide range of water table depth likely due to variance in site conditions once established. Another factor potentially driving the outliers along a water table gradient is that beaver dams had recently breached in some areas, while others were recently constructed inundating previously dryer reaches.

Groundwater monitoring wells were read less often during the 2010 season than in previous years due to the 30-40 year flood event and offsite reference site data collection. The deep snowpack, rain on snow events, and the resulting swift flood waters prohibited safe Colorado River crossing limiting groundwater well monitoring. In addition, until the peak stage had subsided, most stream side groundwater monitoring wells were flooded. Offsite data collection commenced between July 20 and August 6, 2010 limiting onsite DTW collection along the Colorado River. DTW varied greatly between reference sites while many of the species present were ubiquitous. This variability is likely telling of the difference between establishment and persistence, where establishment requires different environmental characteristics than persistence.

The impacted reaches degradation and requirements for restoration vary widely. In all cases restoration will be required to transition from an onset of an upland alternative stable state establishment to that of a hydrological and ecologically intact riparian corridor. Reach 1 is the most degraded due to the tremendous impact received by the 2003 debris event, the thickness and size of sedimentation, the instability of the substrate, the limited natural recovery seen to date, and the age at which the reference vegetation reaches maturity. Restoration is not only most important in reach 1, but may also be the most difficult. Reach 2 is significantly degraded in sections while maintaining several intact segments of vegetation, topography, and hydrology. Reach 2 will require streamside sediment removal to safeguard against the already establishing upland vegetation, however, quantity removed and effort exerted will be less than in reaches 1 and 3. Reach 3 contains the greatest collection of sediments as a result of multiple debris events. The elevated current channel and porous substrate pose a significant impediment in natural recovery. In order to establish reference determined vegetation and restore topographic, hydrologic, and soil type integrity a great deal of sediments must be removed.

Tree ring analyses indicate that all three ßtrees germinated on bare streamside sediment deposited by historic debris events thus asserting that at the time of recruitment, 1953, 1966, and 1971, there were recent debris flow bare sediments along the Colorado River. Historic aerial photos reveal a similar story in the Lulu City Wetland with recent bare sediments visible in 1953, 1969, and 1987. These results give us a better perspective into the dates and impacts of historic ditch-related sedimentation and explain the various even aged stands of trees along the elevated floodplain of the Colorado River.

Ground surface and water table models reveal an uneven distribution of sediments and a variable DTW throughout reaches 1, 2, and 3. While ground surface and water table elevations are approximate across the landscape, they provide a cross sectional view integral to restoration. Offsite DTW measurements captured only a snapshot of mid-growing season depth; however, persistence of large woody riparian species tolerates seasonal and episodic fluctuations in DTW.

Onsite climate trends during the study period express a variable annual modulation in temperature and precipitation hovering near the 20 year average. Long term climate models, however, predict warmer direr winters with decreased snowpack and warmer possibly wetter summers. This shift poses a great concern for the sustainability of riparian vegetation along an already altered and dewatered river. With decreased snow pack, earlier and lowered spring flows, and a greater demand for

Grand Ditch diverted irrigation water; DTW may continue to drop further exacerbating riparian vegetation persistence even after restoration.

6. IMPLICATIONS FOR RESTORATION

Restoration of riparian corridors is known to be of significant importance for ecosystem services such as wildlife habitat, fresh water, nutrient cycles and fluxes, and flow regulation (Benayas *et al.* 2009 and Palmer and Filoso 2009). In a large meta-analysis, Benayas (2009) found ecosystem services to increase up to 25% after restoration. Carbon stabilization and sequestration are current topics of interest with ongoing global temperature increase. Riparian restoration practices may yield the potential for a carbon sink and climate change mitigation through development of peat forming wetlands and riparian vegetation (Cowunberg 2011) (Drainage of peatlands leads to the decomposition of peat… causing significant losses of carbon and nitrogen to the atmosphere). (Restoration of peatlands provides a major contribution to the mitigation of climate change). Cost benefit analysis for restoration… and the intrinsic value of restoration (tourism, ecosystem services, wildlife, clean water/air, headwaters – very important!, flood control, sedimentation of reservoirs downstream, water retention and aquifer recharge,)

As the hydrologic engineers of the rivers of the west, beaver play an integral role in riparian manipulation and modification (Wright *et al.* 2002) and are a key geomorphic engineer that has driven the formation of floodplains, fluvial landforms, and wetland and riparian habitat in the Kawuneeche Valley (Westbrook *et al.*2006). Beaver dams serve to slow flood peaks, increase overbank flooding, stimulate groundwater recharge (Westbrook *et al.* 2006), and catch and retain sediment (Butler and Malanson 2005 and Westbrook *et al.* 2010). Beaver populations plummeted during the mining rush of the 19th century as fur trappers and prospectors moved through the area (Buchholtz 1983). A recovering beaver population soared to an estimated 600 individuals along the Colorado River by 1940, only to drop to approximately 30 (none present in the study area) by the turn of the century (Packard 1947 and Mitchell *et al.* 1999). The recent decline is likely correlated with the elevated browsing pressure of a booming elk and moose population and the subsequent reduction of large woody riparian vegetation (Hess 1993). Up stream, at the headwaters of the Colorado River, beaver absence is likely the result of habitat loss caused by ditch related hydrologic modifications and large sediment inputs that have flipped the impacted reaches from a typical riparian regime, with shallow groundwater and woody riparian vegetation, to a virtual upland environment of elevated gravel terraces, increased depth to groundwater, and recruitment of conifers and xeric vegetation. The absence of beaver along the upper Colorado River is of significant deleterious impact with increased sediment transport, establishment (and potential persistence) of anomalous streamside vegetation, fast and detrimental peak flows, decreased overbank flows, lowered water table, and limited groundwater recharge. The ultimate return of beavers to the Kawuneeche Valley is of significant importance for hydrologic engineering and the National Park visitor experience. The restoration of a tall willow community with a shallow groundwater table will help encourage beaver recolonization resulting in a beneficial hydrologic influence and perpetuation of intact riparian and wetland ecosystems.

The Mountain Pine Beetle (*Dendroctonus ponderosae*) has greatly impacted the Westside of RMNP, with the largest outbreak of its kind on Lodgepole pines (*Pinus contorta)* in park history (NPS website http://www.nps.gov/romo/naturescience/mtn_pine_beetle_background.htm). While the native beetle attacking a native tree is a natural historic process, research has found the large and continued infestation to be potentially exacerbated by the warmer drier winters resulting from climate change, summer drought, and dense forest stands due to fire suppression (Sims *et al.* 2011). One potentially beneficial impact of beetle kill that could assist restoration at the headwaters of the Colorado River is an introduction of large woody debris that may slow flows and trap sediment and negate the deleterious effects of increased surface runoff, swift peak flows, and increased sediment input (Kegley and Safranyik 2001).

Local climate models expect a shift in annual temperature and precipitation patterns for the northern Rocky Mountains due to climate change (Rangwala and Barsugli 2010). Snow pack and the snow water equivalent have decreased significantly throughout the mountains of the west over the past 50 years (Barnett et al. 2008, McCabe & Wolock 2009). While the northern Rocky Mountains have seen less impact than other ranges (Hamlet et al. 2005, CWCB 2008), the predicted rise in ambient air temperatures will likely reduce snowpack and runoff (Mote et al. 2005, CWCB 2008). The effects of reduced snowpack and runoff and altered timing at the headwaters of the Colorado River could be significant. In a landscape already affected by lessened peak flows and lowered water table, a small decrease in hydrologic input could promote a further shift into an alternative stable state of upland species establishment.

Reservoirs are notorious sediment traps with a limited life due to natural sediment transport (Mahmood 1987). The first large man made impoundment the Colorado River encounters is Shadow Mountain Dam just 27 km downstream as the crow flies from the impacted areas at the headwaters in RMNP. The town of Grand Lake and the reservoir managers and concerned by increased sedimentation partially due to Grand Ditch related debris events and the impact it would have on water quality, recreation, algal blooms. Restoration would serve as a potential safeguard against increased sedimentation from the Colorado River.

Restoration is a key factor in preserving natural habitat, ecological systems, and human resource needs. Though applied restoration may yield functional results, continued tributary interception and diversion by the Grand Ditch and the impacts of the resident browsers must be considered when designing, implementing, and monitoring a large scale restoration effort at the headwaters of the Colorado River.

7. RESTORATION CONCEPTS

The purpose of this research was to explore the environmental characteristics necessary for persistence of appropriate riparian vegetation at the headwaters of the Colorado River in order to provide context for restoration. I do not intend to present restoration recommendations, rather an outline of current and desired conditions within which to frame possible restoration concepts. Large scale restoration along the headwaters of the Colorado River in RMNP will require extensive preliminary research, baseline data collection, on and off site reference site analysis, applied physical and ecological restoration methods, and detailed post restoration monitoring. Restoration will need to follow a balanced and weighted program targeting cost, RMNP guidelines, public opinion, and efficacy. The goal of restoration would be to reestablish the hydrologic and ecological integrity of the impacted reaches of the Colorado River, while creating a self sustaining system that functions within the variable confines of climate change and Grand Ditch altered flows.

Restoration must be self perpetuating – initiating natural hydrologic and geomorphic processes and jump starting successional dynamics. Revegetation will serve to stabilize banks and land surface, catch sediments, provide shade and nutrient inputs, and perpetuate recovery through propagule dispersal. Restoration efforts may include recreating appropriate ground surfaces and landforms, reconnecting surface water and ground water interactions, and riparian/wetland revegetation. Extensive grading and sediment removal could be followed by revegetation. A post restoration monitoring plan must be in place prior to breaking ground. Monitoring will follow the progress of ground surface and landform stability, suitable groundwater depth, vegetation establishment and persistence, as well as continued observations of sediment movement and deposition.

The following are the current and desired post-restoration geomorphic settings and land surface elevations, hydrologic regimes and groundwater depths, and vegetation composition for the degraded portions of Lulu Creek (Reach 1), the Colorado River (Reach 2), and Lulu City Wetland (Reach 3).

LULU CREEK (Reach 1)

Current condition: The soil substrate consists of large gravels, cobbles, and boulders and high unstable sediment banks of unconsolidated materials. This material has proven to be highly unstable and transient in peak flows, continuously rearranging and transporting material into reaches 2 and 3. Irregular piles, jams, and scatters of large woody debris are strewn in the creek and adjacent floodplain. The DTW ranges from -52 to -102 cm below the current ground surface in the areas connected to the stream. Much of the exposed ground surface is greatly disconnected from stream and groundwater inputs due to towering sediment deposition. The high terraced flood plain is virtually desertified with little or no vegetation establishment likely due to substrate size and type, extreme DTW, and a lack of connectivity to the groundwater and stream. Current vegetation establishment is limited to xeric upland species such as *Picea englemanii*, *Pinus contorta*, and scattered herbaceous vegetation. Lulu Creek receives unpredictable and variable flows. The Lulu Creek headgate is the closest to the ditch operator's quarters allowing for convenient manual release. In addition, Lulu Creek is the last regulated tributary before the Grand Ditch empties into Long Draw Reservoir allowing for maximum water to be collected from tributaries along the ditch and then quickly dumped down Lulu Creek if not needed in the reservoir. During the midsummer months it is not uncommon for Lulu Creek to be running near peak flows while the other tributaries are at drought conditions. These releases are not only seasonally inappropriate, but also provide significant flow volume to an area of unstable loosely consolidated materials prone to sloughing, sliding, and eroding. This poses a major concern for restoration success as any work downstream will be compromised by a large discrete event or continuous sediment transport. Stabilization, channel armoring, unstable bank removal, reconnecting ground surface and groundwater table interactions, and revegetation along Lulu Creek are the first critical steps in restoration.

Desired post-restoration condition: Based on the adjacent Sawmill Creek reference condition, the desired post-restoration condition of Lulu Creek (Reach 1 would include an average DTW of- 53 cm, a soil texture of coarse sandy loam with a 28 percent by weight of gravels larger than 2 mm, and establishment and persistence of an overstory of *Picea englemanii* and *Abies bifolia* and an understory of *Vaccinium angustifolium*, *Mertensia ciliata*, *Senecio triangularus*, and *Arnica cordifolia*. The requisite water table depth will vary as recovery progresses and succession ensues. An average DTW < 50 cm will allow herbaceous perennial and riparian willow establishment while sustenance of late seral conifers could tolerate 1 -1.5 m DTW. Stabilization is the first priority for restoration, without it debris events will continue to emanate from reach 1 negating all efforts downstream.

COLORADO RIVER (Reach 2)

Current condition: The soil substrate is a collection of large sands, gravels, and cobbles along elevated terraced floodplains composed of unconsolidated sediments. DTW varies along transects perpendicular to the Colorado River depending on extent of impact and deposition of sediments. DTW ranges from -12 to -65 cm below the ground surface. Floodplains along the reach vary from virtually connected to greatly disconnected from the stream channel. This, of course, correlates with the effects of historic debris events to the reach from slightly impacted to severely impacted. Current vegetation is a mix of *Salix drummondiana*, *Salix monticola*, *Carex aquatilis*, and *Pentaphylloides floribunda* among others in the less impacted areas. The severely impacted areas are an uneven aged mix *of Picea* *englemanii*, *Abies bifolia*, and *Pinus contorta*, due to multiple debris events and historic sedimentation. One survey found *Senecio atratus* a species typically limited to dry alpine talus slopes and placer mine tailings.

Historical air photo analysis conducted by Cooper 2007 revealed a meandering channel with pools and riffles, a floodplain composed of coarse- to fine-grained mineral material, and landforms including point bars, floodplains, high terraces, and abandoned channels and ox bows. Topography and the corresponding vegetation should be mixed with higher surfaces maintaining scattered stands of conifers, floodplains and point bars sustaining willows, and abandoned channel and oxbow bottoms supporting grasses and sedges.

Desired post-restoration condition: Based on 10 analogous reference conditions surveyed around Colorado, the desired post-restoration condition of the Colorado River (Reach 2) would include an average DTW of -46 cm, a soil texture of clay loam and sandy clay loam with a 16 percent by weight gravels larger than 2 mm, and establishment and persistence of *Salix geyeriana*, *Salix drummondiana*, *Alnus tenuifolia*, *Populus angustifolia*, *Carex utriculata,* and *Carex aquatilis*

LULU CITY WETLAND (Reach 3)

Current condition: The soil substrate is a variable collection of fine sands and coarse gravels and cobbles. Multiple debris events of the past 80 years have frequently inundated Lulu City Wetland with sediment plugs, terraces, islands, and irregular ground surface topography. With the historic Colorado River channel blocked by a sediment dike, the current river channel is elevated above the rest of the ground surface perched atop a sediment plume on the west side of the valley. Stream flows are lost through the porosity of the sediments, gravity fed as surface and subsurface flows to the lower points of the valley. DTW ranges from -5 to -160 cm below the current ground surface due to sedimentation. The ground is wetted, saturated, and flooded in many parts of the valley limiting tall willow recruitment while encouraging short willow and sedge proliferation. Elevated sediment deposits have become dry havens for upland species. Because of the highly variable DTW and soil texture, the vegetation in the wetland is an incongruous mixture of wetland and upland species. The gravel terraces and fans are dominated by *Pinus contorta*, *Picea englemanii*, and *Abies bifolia*, while the lower wetted areas are a sea of *Carex aquatilis* and *Salix planifolia.*

Desired conditions: Based on 4 analogous reference conditions surveyed around Colorado, the desired post-restoration condition of Lulu City Wetland (Reach 3) would include an average DTW of -61 cm, a soil texture of sandy loam and sandy clay loam with a 10 percent by weight gravels larger than 2 mm, and establishment and persistence of *Salix monticola*, *Calamagrostis Canadensis*, and in low lying abandoned channels and oxbows *Carex utriculata*. It is important to note excavation of coarse sediments from zone 4 may change base levels destabilizing the channel upstream demanding grade control channel stabilization.

Record peak flows of 2011, reconfigured the channels of Lulu Creek and the Colorado River and redistributed a great deal of large and small sediments. Restoration will need to take in to account the unstable and unpredictable nature of sediment transport within the affected reaches and must target sediment stabilization first. It will also be necessary to conduct a basic DTW and stratigraphic survey before breaking ground, as site conditions vary annually.

Elk and moose browsing pressure are of sincere concern for restoration success. Lacking a natural predator, large ungulate populations have exploded in RMNP. Willows within the Kawuneeche Valley have succumbed to die-back and/or closely cropped stems due extreme browsing pressure. The entire restoration area will need to be exclosed to large ungulates.

Post-restoration monitoring will be of specific importance due to the perpetual impacts and water diversion of the Grand Ditch.

8. CONCLUSION

Riparian areas and wetlands are important ecological components of the landscape providing essential ecosystem functions including habitat, stream temperature stabilization, sediment filtration and water purification, and stream bank stabilization (Richardson *et al.* 2007). Headwater regions are specifically important for providing clean water (water quality maintenance) to downstream users. The Colorado River passes through 7 states and serves more than 30 million users as it faces extensive diversion, withdrawal, and inputs before eventually running dry before entering the Gulf of California. With so many stakeholders in the river's fate, the restoration and management of the Colorado River headwaters is of significant importance. The riparian areas and wetlands of the Colorado River headwaters are threatened by recreational use, an overabundance and year round stock of browsing wildlife, increased sedimentation, and altered hydrology as a result of tributary interception and diversion by the Grand Ditch. This region is also susceptible to changes in climate that may alter temperature, precipitation, snowpack, and groundwater (Ababneh and Woolfenden 2010). As much as 50 percent of Colorado's riparian areas and wetlands have been lost in the last 2 centuries (Noss *et al.* 1995 and Yuhas 1996), making it very important to understand these systems and the best restoration and management practices for their continuance (Dahl and Johnson 1991, Brinson and Malvarez 2002).

Historically, restoration of streamside vegetation has been of the cookbook variety, formulaic with certain species planted in certain conditions. In many cases simply removing an unwanted species or planting a desired individual misses the point, targeting the symptom not the cause. Vegetation is the indicator of the underlying conditions in the physical environment (Stromberg et al. 2007). This study targets more specifically a current approach of modeling applied restoration efforts on analogous reference sites. In a region significantly impacted by perpetually altered hydrology, aberrant sedimentation, and the early stages of an ecological alternative stable state; it is impossible to piecemeal restoration, historic data, or exclusively onsite predictors for restoration. While the results of this study are not applicable for most other riparian restoration efforts due to the specificity of the site, species, and local environmental characteristics; the methods, however, will be useful for developing future restoration along a myriad of sites.

This study identified the key environmental drivers for riparian vegetation persistence at three distinct reaches along the Colorado River Headwaters and the specific vegetation conducive to those growing conditions. Also demonstrated were the specific environmental requirements for persistence of individual species and plant communities. Only environmental characteristics driving established vegetation were explored, further research is necessary to determine appropriate conditions for riparian vegetation establishment at the headwaters of the Colorado River in RMNP.

As our thirst for water continues to grow in the arid west, we are faced with a pronounced dilemma. How do we balance our need for water with that of functional ecological integrity? Reference site guided restoration and management are critical pieces to designing and implementing large scale restoration that will help to create that balance.

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