THESIS

SURFACE WATER AND GROUNDWATER EXCHANGE ALONG THE CACHE LA POUDRE RIVER: CONSIDERATIONS FOR CONSERVATION PLANNING

Submitted by

Claudia A. Browne

Graduate Degree Program in Ecology

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2014

Master's Committee:

Advisor: Richard Knight
Co-Advisor: Reagan Waskom

David Merritt
Michael Ronayne

ABSTRACT

SURFACE WATER AND GROUNDWATER EXCHANGE ALONG THE CACHE LA POUDRE RIVER: CONSIDERATIONS FOR CONSERVATION PLANNING

This study offers a method for estimating riparian water budgets from river point flow data to demonstrate how a water budget framework can guide strategic conservation planning. Groundwater and surface water exchange patterns along the Cache la Poudre River were evaluated in the period of 1980 to 2009 to describe variations between river reaches, relationships to flow, and to develop water budgets in three riparian study areas. In the absence of sufficient groundwater data along the river, this approach is intended to contribute a pragmatic way to begin to evaluate riparian water availability, to guide targeted field data collection, and to develop strategic riparian conservation and restoration plans. Major study questions explored the magnitude, timing, and frequency of alluvial exchange, and the potential relationship between alluvial exchange and a specific flow threshold. Results showed that river loss (associated with alluvial recharge) occurred during a wide array of flows, and that the direct relationships of alluvial exchange to flow were often only weakly correlated. The study also found that inter-annual variations in riparian water supplies – specifically the aquifer storage deficit from the previous year – influenced potential water availability in the rooting zones of riparian plant communities. In high risk priority conservation areas, installation of piezometers is needed to collect targeted field data and validate water budgets to assess impacts of pending land and water use scenarios such as lined irrigation ditches, reduced return flows, and/or lined gravel pits.

ACKNOWLEDGMENTS

My deepest gratitude goes to my advisors at Colorado State University (CSU) -- Drs. Richard Knight and Reagan Waskom -- who offered unflagging inspiration and wisdom throughout this study. I am also grateful to committee members Drs. Michael Ronayne (CSU) and David Merritt (US Forest Service) who were invaluable in helping to clarify several technical aspects of the analysis. I would also like to acknowledge Professors N. LeRoy Poff, Brian Bledsoe, and Kurt Fausch for their inspirational teaching and dedication to sustaining riparian and aquatic ecosystems. Heartfelt appreciation also goes to: Steve Malers of Colorado Open Water Foundation for his patient assistance with TSTool; Andy Pineda and Lucas Shawcross of Northern Colorado Water Conservancy District who generously provided point flow data and background documentation; Water Commissioner, Mark Simpson for helping navigate the tangled web of diversions and return flows on the Poudre; Kingsbury Browne III and Dr. Alan Carpenter for editorial assistance, and; finally, Dr. Ayman Alzraiee who was exceptionally generous in the early efforts to decipher the South Platte Decision Support alluvial groundwater model and assess its potential use for a local analysis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Water resources that support native ecosystems in the southwestern United States and in other semi-arid regions are under increasing pressures from population growth and the demands of multiple users. Climate change models suggest that increased frequency and severity of droughts are likely to add to these pressures in the next 100 years (McDonald, 2010). Throughout the world, interest in providing water for ecosystems is gaining momentum. Australia's "*National Principles for the Provision of Water for Ecosystems*" was introduced in the late 1990s to attempt to define the water requirements of various ecosystems (Eamus *et al*., 2006). Numerous countries have established similar policies, including the European Union's "*Water Framework Directive*" (EU, 2000), which establishes the importance of integrating ecosystem needs into water management (Acreman *et al.,* 2013).

Colorado's existing water management framework was not established to take into account ecosystem needs. The beneficial use tenet of state water rights means that water is allocated for human uses that are first in time. Rights are primarily defined in terms of agricultural, potable, and industrial uses. In the 1970s, the State's Instream Flow Program was established to provide a mechanism for protecting aquatic habitat and preventing cessation of flow in some river reaches. More recently, Colorado's Statewide Water Supply Initiative recommended protecting environmental values and pursuing water management strategies that include benefits to riparian and aquatic environments (CWCB, 2011). The application of the instream flow program is limited, however, and strategies for assessing environmental benefits are still focused on aquatic ecosystems. There is, therefore, a pressing need to identify water management strategies that provide water for ecosystems along rivers in the context of increasing and competing demands. Ensuring water for riparian and wetland areas is particularly important in Colorado, because these areas cover less than 3% of the land area but provide critical habitats for 80% of wildlife species (McKinstry *et al.*, 2004, NRCS, 1996). In addition to habitat values, these wetlands and riparian areas offer other ecosystem services such as improved water quality and flood attenuation.

Studies have shown that man-made river flow alterations are almost always linked to negative effects on the extent and functions of native aquatic and terrestrial biota (Poff and Zimmerman, 2010; Bunn and Arthington. 2002). In the late 1990s, the natural flow regime was introduced as an important framework for describing riverine ecological processes (Poff *et al.*, 1997; Richter *et al*., 1996). Several authors (Arthington *et al.*, 2006; Naiman *et al*., 2002; Newman, *et al.* 2006) emphasize the need to better determine the relationships between flow and ecological responses. More recently, the proposed "Environmental Limits of Hydrologic Alteration" (ELOHA) approach outlined a method to establish basic environmental flow standards using information on flow frequency, timing, duration, magnitude, and rate of change (Poff *et al.*, 2010). Specifically, the ELOHA approach is based on understanding 1) the hydrologic framework, 2) the regional classification of the river system, 3) the degree of alteration, and 4) flow-ecology relationships. A range of flow regimes have been evaluated for various ecological functions including effective discharge for sediment transport and channel maintenance, minimal baseflows to support aquatic species, and flood flows and inundation periods for native species recruitment and riparian vegetation distribution (Richter and Richter, 2000; Auble *et al*., 2013). Concurrent with the increased awareness of the role of environmental flows, there has been an increased awareness of the need to consider groundwater and surface water as one resource (Winter *et al.*, 1998; Brunke and Gonser, 1997). There has also been growing recognition that the surface – ground water continuum needs to extend beyond a stream channel to include adjacent, groundwater-dependent ecosystems such as floodplain wetlands, riparian forests and shrublands (Hughes and Rood, 2003; Eamus *et al.*, 2006; TNC, 2007; Acreman *et al.,* 2005). The awareness that "streams and riparian zones are coupled in their vulnerability to habitat degradation" (Baxter *et al*, 2005) emphasizes the need for improved integrated land and water management efforts including conservation and restoration (Arthington *et al*., 2006).

Groundwater and surface water exchange processes along rivers in arid and semiarid climates are important for maintaining water for groundwater dependent ecosystems (Winter et al., 1998) (Figure 1). This exchange process also plays an important role in biochemical cycling such as nitrogen processing, for example, when temporary anaerobic conditions trigger microbial denitrification (Brunke and Gonser, 1997). Riparian ecosystems can experience biological stress when the water table declines below rooting depths or beneath the discharge zone (Stromberg *et al*., 2007; Naumberg *et al.,* 2005; Rood *et al.,* 2003). The responses of riparian plants to changes in water availability vary by species and rooting depth patterns along a gradient that can be characterized in hydrologic guilds, i.e., groups of species that share adaptations to water balance conditions *(*Merritt *et al.,* 2010*).* Stresses ultimately result in mortality when the water table falls below the maximum rooting depth during extended or critical periods or the rate of decline is too rapid (Scott et al. *1999;* Shafroth *et al., 2000*; Stromberg et al., 2007). The sensitivity of many riparian species means that changes in water availability can result in loss of native diversity and habitat from competition by non-riparian plant species, invasive species, and channel encroachment.

Linkages between the alluvial exchange process and water availability in riparian areas are not well understood due to their complexity. Factors that complicate understanding ecosystem responses to hydrologic conditions include variations in topography and landscape context, soil moisture and texture, inter-annual variation, precipitation, duration of saturation, and timing and rate of water table decline (Stromberg *et al*., 2007; Naumberg *et al.*2005; Rood *et al*., 2003, Merritt *et al*., 2010). For example, short-term fluctuations in groundwater levels can occur within a period of several days that are not evident at annual or even monthly time scales (Brownbill *et al.*, 2011, Jolly *et al*., 2008). Additionally, the lag time between water fluctuations and observable responses limits the ability of riparian research to inform water management in a timely manner.

Many numerical models, field experiments, mapping and other tools have been developed to attempt to evaluate the dynamics of river hydrology in relation to ecological conditions such as vegetation distribution patterns (USGS, 1998; Chen *et al*., 2014; Tharme, 2003; Rood *et al*., 2003; Baird *et al*., 2005; Naumberg *et al.*, 2005; Webb and Leake, 2006; Orellana *et al*., 2012; Pahl-Wostl *et al.*, 2013; Rains *et al*., 2004; Springer *et al*., 1999; Toner and Keddy, 1997). Many of the modeling efforts do not capture alluvial exchange patterns or are extremely complex and data intensive and, therefore, have limited practical use for resource managers. To assist management efforts, a conceptual framework and practical method for evaluating water availability for riparian ecosystems is needed to guide focused data collection and conservation planning. Water budget accounting offers a possible approach for evaluating the vulnerability of specific locations and the tradeoffs of water availability for ecosystems under changing land and water use scenarios. The need for this type of research has been identified in the new science plan recently launched by the U.S. Geological Survey (USGS, 2007) and in the National Water Census. The plan highlights the importance of water for ecosystems and the need to better understand “how water budgets affect ecosystems” (USGS, 2014).

This study examines groundwater-surface water exchange patterns along the Cache la Poudre River in northern Colorado in relation to flows and describes components of the water budgets. Information on groundwater and geologic conditions beneath riparian areas along this river is scarce to nonexistent. Only recently have stakeholders in the watershed begun to explore coordinated management opportunities (PHA, 2013), but a detailed plan on priorities for conservation, restoration, data collection or adaptive management is still lacking. The absence of groundwater data and coordinated riparian conservation planning is particularly striking given pending land and water use changes (e.g., new storage facilities, water extraction, and irrigated land dry-ups) and the fact that the Cache la Poudre is recognized as a river of local significance and national heritage (Bartholow, 2010).

The overarching purpose of this study is to create a method for developing riparian water budgets from river point flow data, in the absence of groundwater data, and to demonstrate how a water budget framework can guide focused field investigations and strategic conservation planning. Major study questions were: 1) Do alluvial exchange patterns vary by reach? 2) When does alluvial groundwater recharge occur? 3) What is the relationship between alluvial recharge and flow, and is there a specific flow threshold? 4) Are riparian water budgets similar in different reaches? And finally and perhaps most importantly, 5) How can water budget analyses be used to evaluate inter-annual variations in riparian water supplies and provide a framework for assessing potential implications of water management scenarios? One contribution of the study is to fill a gap when sufficient groundwater data are missing to help managers begin to characterize riparian water availability, with the understanding that targeted field investigations are also needed to improve strategic riparian conservation and restoration planning.

STUDY AREA

The Cache la Poudre River is located in the Colorado Piedmont section of the Great Plains where over one hundred years of water and land use changes have extensively altered riverine processes (Figure 2). The study covers 83 km (52 miles) from where the river emerges from the Rocky Mountains near the “Mouth of the Canyon” USGS stream gage to just upstream of its confluence with the South Platte River. The river is characteristic of a snow-melt driven system through a transitional zone between mountains and plains. Human land and water use patterns, including gravel ponds, agriculture and urban development, have heavily altered the river flow patterns and the surrounding landscape.

The Western Regional Climate Center (WRCC) reports that average annual precipitation from 1893-2012 was 40 cm (15.9 inches) in the City of Fort Collins. Mean monthly temperatures for the same period of record ranged from -1.7^{o} C (29^{o}F) in December to 21^{o}C (70^{o}F) in July.

Existing geologic and hydrogeologic information reveals that bedrock beneath the study area consists of Pierre Shale, which is typically encountered at depths of 6 to 12 m (20-40 ft.) below ground surface (Robson *et al*., 2000; SPDSS, 2013). Near-surface bedrock and rock outcrops also occur in several places within the study area. Post-Piney Creek Alluvium overlies the shale and is characterized as poorly-sorted, dark gray, sandy to gravelly alluvium with organic material. Groundwater is present in an unconfined water table aquifer in the alluvium. The underlying shale bedrock is characterized by very low permeability and thus provides an impermeable boundary for the alluvial aquifer. The alluvium width is generally 1.4 km (0.9 mi)

*(*PHA*, 2013).* The alluvium is sometimes unevenly distributed on either side of the river, e.g., where bedrock outcrops reduce the width on one side. Regional groundwater contour mapping shows the direction of groundwater flow parallels the river flow in the upper reaches of the study area, while in the lower reaches, regional groundwater flow is directed toward the river (Robson *et al.*, 2000).

At the outset of this study, a network of stream gages, diversions, and return flow points was identified for the portion of the study area within the alluvium (Table 1). As shown on Figure 2, the network includes three main reaches with over 40 subreaches between water structure nodes.

Because of their high biodiversity and importance to wildlife, riparian vegetation communities, including herbaceous wetlands, forested/shrub wetlands, and forested/shrub riparian, are priority ecosystems for the study area. Existing wetland and riparian mapping (based on 2009 aerial photographs used by CNHP, 2011) was screened to identify riparian areas most likely to be directly affected by the groundwater-surface water exchange along the river. The screening process found that within the alluvium, 94 and 98% of the mapped riparian and wetland areas, respectively, are located within 500 meters (1640 feet) of the river's edge; therefore, this distance is used to define an active alluvial riparian zone. Within this 500-meter zone, approximately 700 hectares (1,735 acres) of riparian plant communities have been mapped. The majority of the mapped areas are fairly small, i.e., less than 5 ha (12.4 acres) (Table 1). Review of 2011 aerial photographs indicates that some of the mapped areas have already disappeared e.g., from recent development and gravel mining (or were incorrectly mapped initially). Because conservation values of natural communities generally increase with size, three of the largest riparian areas with similar dimensions were selected from the active alluvial zone as sample locations for the water budget analysis (Figure 2). One riparian study area was selected within each of the main reaches based on the presence of an existing forest area of at least 10 ha with similar river frontage length and relatively natural streambanks. Key features of each of the areas are described below.

- Study Area 1 is on the north side of the river in Reach 1, near La Porte, CO, within a 3.7 km (2.29 mi) segment (or subreach) that extends between the Little Cache Ditch and Arthur Ditch. On the upgradient (west edge), Study area 1 is bounded by the Little Cache and Taylor Gill diversion ditch, and the downgradient edge is bounded by an unnamed surface water drainage feature. Based on the available literature and mapping, the water budget assumed bedrock elevation is 1536 meters (5040 feet); mean ground surface elevation is 1546 meters (based on range of 1545-1547 meters, 5070-5076 feet on USGS topographic map), and; an initial depth to groundwater of 1542 meters (5060 feet) (Robson *et al*., 2000; CDWR,2014).
- Study Area 2, in Reach 2, is also on the north side of the river, in the Colorado State University Environmental Learning Center property. It is located within a 1.3 km subreach (0.8 mi) that extends between the Ft. Collins Wastewater Treatment Plant (WWTP#2) and the Boxelder Gage. Based on the available literature and mapping the water budget assumed bedrock elevation is 1481 m (4860 feet); mean ground surface elevation is 1486.5 meters (based on range of 1485.5-1487 m, 4874-4880 feet), and; an initial depth to groundwater of 1485 m (4873 feet) (Robson *et al*., 2000; CDWR, 2014).

- Study Area 3 is in the Frank State Wildlife Area, within Reach 3. The channel is mapped along the southern boundary of the riparian forest, but aerial mapping and groundtruthing show the main channel now bisects the site. A bedrock outcrop is present south of the area, and shallow bedrock is present near the surface. The water budget applied the following assumptions: bedrock elevation is 1455 meters (4775 feet); ground surface elevation is 1458.5 m (4785 feet) (ACE, 2008), and; initial depth to groundwater was 1457.3 meters (4781 feet).

METHODS

A Mass-Balance method, also called a Point-Flow Analysis, was used to calculate river gain and loss values that were then used in a water budget analysis. The combination of point flow and water budget approaches provides a practical way to link river and riparian water relationships and facilitates comparison of potential water availability along a river corridor in the absence of sufficient groundwater data. The Mass-Balance method calculates daily river gains and losses (alluvial exchange) based on available time-series data for known inflows and outflows. The difference between two river gages, after all known diversions and return flows are accounted for, is distributed evenly along the reach. If the difference is positive, then the reach is gaining water during that period; and conversely, if the change in flow is negative, then the river is losing water. The results of the Mass-Balance calculations between nodes (i.e., at the subreach scale) provide groundwater recharge (river loss) and groundwater discharge (river gain) inputs as volumetric flow (m^3/d) for the water budgets in three riparian study areas. Because total alluvial exchange values include unmeasured stream inflows and overbank surface outflows, some constraints are applied to the exchange values when applied to the water budget. This study does not attempt to calibrate the water budget, rather the estimates provide a means for analyzing potential relationships and scenarios.

Point Flow Analysis Method

The Point-Flow Analysis or mass-balance method is based on the equation, data sources and assumptions presented below.

$$\text{Gain}_{\text{RIVER}} = \Sigma_{\text{ OUTFLOWS}} - \Sigma_{\text{ INFLOWS}} \qquad (1)$$

$Gain_{RIVER}$ is the daily rate in cubic meters per second (cms), which is calculated as the difference between known river inflows and outflows for a given reach. A negative “gain” indicates the reach is a losing river for that day or period. The river gain or loss is divided by the length of the reach to obtain a unit change (cms per km) that is uniformly distributed across a reach. The river gain or loss is also used to calculate the flow upstream and downstream of points or nodes. Daily river gain or loss values also provide inputs to the riparian water budget (described in next subsection).

$\Sigma_{INFLOWS}$ is the sum of the river flow at the gage at the upstream boundary of a reach and return flows from reservoir releases and wastewater treatment plant discharge.

$\Sigma_{OUTFLOWS}$ is the sum of the river flow at the downstream gage and diversion flows.

The primary source of flow data for the gages, diversions, and returns is the Colorado Division of Water Resources and Colorado Water Conservation Board’s joint “hydrodatabase” for the Colorado Decision Support System (CDSS). Other information on the status and locations of diversions points and return flows were provided by the District Water Commissioner, the City of Fort Collins Utilities Department, and Northern Colorado Water Conservancy District (NCWCD).

Data coverage was reviewed to confirm completeness of the State’s historical records, and based on this evaluation, the 30-year analysis period from 1980-2009 was selected. Data gaps and quality control issues in the State’s historical dataset made it difficult to create an independent point flow analysis for this study period; therefore, an existing daily point flow analysis dataset was obtained from NCWCD for the use of the current study. The data were high quality having undergone extensive quality assurance and control review (through 2005), and analysis methods were well documented (NCWCD, 2010; MWH, 2010). NCWCD's methods also include an added level of analysis whereby dry river bed days serve as temporary "gages" and gains and losses are redistributed accordingly (resulting in improved accuracy of the results). The State's Time Series Tool (TSTool) (CDWR, 2014) was used to automate data extraction from the Point Flow Analysis data sets for the period of record and for the portion of the network included in the study. Outputs of interest at the subreach scale are the daily flow below the node at the upstream end and the daily gain or loss used to estimate alluvial recharge and discharge. TSTool also offered an analysis command to output the gain and loss for each reach on a monthly basis.

Methods to integrate river gain and loss data into an alluvial groundwater study were modified from the South Platte Decision Support (CDM Smith, 2013), which applied constraints to the gain and loss values based on subsurface conditions to reduce the effects of "extreme" events. The SPDSS documentation notes, however, that constraints of gain or loss calculated for an entire river are not necessarily appropriate for a local scale. Therefore, this study applied a modified approach to refine the constraint assumptions as described in the water budget method below.

Water Budget Method

A water budget approach was used to estimate daily and monthly changes in aquifer storage (as volumetric rates) beneath the three study riparian areas. A preliminary conceptual model was used to help select parameters for the water budgets. The study areas are intended to represent prototypes whose water budgets can be compared to view a variety of relationships and considerations. Therefore, inputs were based on uniform, relatively large patch sizes of 10-ha with standard dimensions of 0.6 km of river frontage by 0.17 km width. Other assumptions included a uniform depth to bedrock beneath a study area and relatively flat surface topography. While these assumptions are simplifications, the intent of this approach is to describe and compare how interactions immediately adjacent to the river channel can influence potential riparian water availability and to guide future field verification efforts.

The water budget accounting is calculated on a daily time-step interval and is based on the equations, data sources and assumptions presented below.

$\Delta \text{Storage}_{GW} = (Q_{ARchg\ in} + Q_{IRRin} + Q_{GWRECHG\ in} + Q_{GWinflow)} - (Q_{GWDSCHGout} + Q_{ETout} + Q_{GWoutflow)}$

(2)

$\Delta Storage_{GW}$ is the daily volume of water gained or lost to the alluvial aquifer in the riparian area.

Aerial Recharge ($Q_{ARchg\ in}$) is the amount of precipitation *that reaches the water table*. It is based on daily precipitation records from the Fort Collins climate station ((053005; WRCC, 2014) and a conservative recharge percentage of 3% for "native land" (per SPDSS, Appendix B, 2013). The remainder of precipitation is not a factor in the riparian water budget as it is presumed to disperse via surface runoff and/or infiltrate into the unsaturated zone where it is evaporated or transpired.

Irrigation conveyance leakage (Q_{IRRin}) is estimated using a conservative canal seepage loss rate of 14%, based on conveyance efficiencies for nearest ditch (Larimer County Canal) presented in SPDSS (Task 56 Memorandum, 2008) uniformly allocated across ditch length. Note that only the most upstream riparian area near La Porte includes a ditch conveyance input.

GWinflow and *GWoutflow* are the regional groundwater inflows at the upgradient boundary and the groundwater outflows at the downgradient boundary of a study area. For the purposes of this analysis, it was assumed that these values change slowly, and therefore, are insignificant at a daily interval. Field verifications are needed to refine and improve this assumption for individual reaches in the future (see further discussion of implications in Limitations).

Alluvial recharge and *alluvial discharge* ($Q_{GWRECHG\ in}$ and $Q_{GWDSCHGout}$) are inflows and outflows from the river that are derived from the mass-balance analysis, where rates (cm/s per km) are converted to volumes based on 0.6 km of river frontage. In Study areas 1 and 2, where the forests are on one side of the river, half of the total exchange is allocated to the water budget. Study area 3 is bisected by the channel, so all of the water flows into and out of the forest. (Note that for the riparian water budget, the signs change so that alluvial groundwater recharge into the riparian area from the river is positive or inverse of river loss, and groundwater discharge from the riparian area to the river is negative or inverse of river gain.)

Because it has been suggested in the pilot point method (USGS, 2012) that fundamental hydrogeologic properties restrict groundwater movement through the subsurface, a maximum loss of 0.17 cms per km (6 cfs per mi) and maximum gain of 0.25 cms per km (9 cfs per mi) were applied based on constraints already established for the Poudre (CDM Smith, 2013). Unlike the pilot-point flow method, the current water budget approach also accounts for the surplus or balance of the unconstrained water – a portion of which may flow overbank and infiltrate into the floodplain to recharge the riparian area. The difference between the total reach exchange and the constrained exchange is the unmeasured surplus attributable to surface water pathways (which includes overbank). An infiltration rate of 10% of this surface water loss (based on the South Platte Decision Support ditch leakage recharge rates) was applied to the water budget to account for water reaching the saturated zone (during periods when storage is available). In other words:

$$Q_{GWRECHG\ in} = Q_{GWRECHGinviaGW} + Q_{GWRECHGinviaSW} \tag{3}$$

Where, $Q_{GWRECHGinviaSW} =$ - (Reach loss $_{total}$ - $Q_{GWRECHGinviaGW}$)* 10% infiltration to saturated zone

Evapotranspiration (Q_{ETout}) is based on monthly values documented in the SPDSS alluvial groundwater model, adjusted by month (per CDM Smith, 2013, Appendix B), and then equally distributed by day. A conservative, estimated rate for phreatophytes (i.e., plants that rely on groundwater) is based on 0.5 m (1.7 ft) per year assuming an average 0.6 m (2 ft) depth to water table. None of the sample areas have open pond features nor is open water in the river channel included in the riparian water budget, so no evaporative loss was included.

Data Analysis

Exploratory data analysis was conducted in Excel to view graphs and calculate descriptive statistics to characterize river gain and loss patterns. Groundwater-surface water exchange patterns were characterized through the indicators listed below.

1) Magnitude—daily rates (cms) of river gain or loss for each reach and subreach.
2) Frequency—numbers of days in which alluvial recharge occurred per year over the 30-year study period. Spatial distribution of most frequent occurrences is also included.
3) Timing—distribution of average days of river loss by month.

Linear correlation coefficients were also generated to evaluate the relationships between river flow and alluvial exchange for each reach and for the subreaches that contained study riparian areas.

The results of the water budget calculations allowed for exploration of overall patterns of aquifer inflows and outflows for each component as well as daily changes in water storage beneath the riparian areas. Potential impacts on plants were characterized by evaluating when water would be present within the rooting zones of various species in the hydroriparian moisture class. Three general rooting zones were established: a shallow zone <0.3 m below ground surface (bgs) used by herbaceous wetland plants; a middle zone <2 m bgs available to willow shrubs (and tree saplings), and <3 m bgs used by cottonwood trees (Stromberg, 2013). To calculate the water storage capacity in each zone, a factor of 0.17 for specific yield (S_y) was applied to the total volume of each zone (CDM Smith 2013). Specific yield is a function of porosity and represents the water that will drain from an aquifer due to gravity. The estimates assume relatively flat land surface and bedrock depths of greater than 3 meters for all three study area.

To test the implications of storage in terms of water table fluctuations, a sensitivity analyses was run for riparian Study area 1 without ditch leakage. The change in hydraulic head was estimated from the following relationship for specific yield, S_y (Freeze and Cherry, 1979):

$$S_y = \frac{\text{Volume of water}}{(\text{unit area})^* (\Delta h)} \tag{4}$$

Daily change in hydraulic head (Δh) was solved by multiplying specific yield and volume of storage change for the riparian area. Inherent in the simplified solution are the following assumptions: the river loss is distributed laterally without vertical diffusion; the streambank is pervious, and; storage capacity is uniform.

Limitations

In the absence of available groundwater elevation and site-specific data, many assumptions are embedded in the water budget analysis. For example, total gain and loss values are equally distributed along a reach when, in reality, streambed heterogeneity and variations in streambank material and channel geometry could alter gain and loss rates. Similarly, estimated evapotranspiration values are evenly distributed across the study areas, when in fact rates fluctuate depending on depth to water, soil moisture, weather, and plant type. Local topographic variations are not captured, although they can affect infiltration and thus storage.

The water budget model does not capture regional groundwater inputs beneath the study area, and instead examines the contribution of focused recharge from the river on riparian storage capacity. Regional groundwater components are acknowledged in Equation 2, but insufficient data exists at this time to include them in the calculations. The implications of the role of regional groundwater is that it could cause a rise in the aquifer during the growing season that would increase the estimated number of days when water is in the rooting zone, and the converse would also be true.

Another assumption is that the change in storage is distributed evenly across the 10-hectare area, but the lateral extent of influence is unknown. Flows into the aquifer are a function of the gradient (i.e., the difference in hydraulic head between the river and surrounding aquifer per Darcy's Law), and lateral extent of influence for the same rate of recharge will vary depending on the head difference between the river and the aquifer. This assumption of a uniform width has two possible implications: 1) if the lateral extent is wider, then the estimate of days in the rooting zones would decrease (because the water spreads out more), or 2) if the lateral extent is narrower, then the estimate of days in the rooting zone would increase (i.e., the water is less spread out). In the future, site-specific data is needed to calibrate the water budget and validate the accuracy of the conceptual framework.

The applicability of the findings in the Cache la Poudre River to other river systems is also unknown. The project area is possibly similar to other Colorado Front Range tributaries of the South Platte River with similar diversion and return structures; however, additional research would be needed to confirm if findings are applicable on other tributary rivers.

RESULTS

The Mass-Balance method generated daily gain and loss values as well as estimates of river discharge at nodes for the 30-year period from 1980-2009. These data were used for the water budget calculations that estimated daily changes in storage in the alluvial aquifer beneath three riparian study areas. Note that the first part of the Results section is focused on exchange in river Reaches 1-3: and the water budget discussion is focused on the riparian Study areas 1-3, which make up a small percentage of the area along their associated Reaches.

Magnitude

As shown in Figure 3, the magnitude of daily gains and losses per kilometer was not uniform from the mouth of the canyon to Greeley. During the 30-year period, Reach 2 exhibited the widest range of daily gain and loss from -5.7 to 5.4 cms (-202 to 191 cfs), and Reach 3 had the smallest range of -3 to 1.4 cms (-107 to 49.3 cfs). The water that leaves the river (negative values in Figure 3) is potential water gained into the terrestrial ecosystems. Therefore, river loss data are of particular significance for the riparian water budget and is the focus of the following data summaries.

Frequency of loss

The point flow analysis indicates river loss occurred in at least one of the three reaches on 3,072 days during the 30-year study period (out of 10,958 days total). The mean number of days per year with losses was 103, or, 28% of the days per year may experience river loss in at least one reach (with median of 97 and standard deviation of 45.2). The number of loss days estimated from the mass balance may be higher than actual days due to lag times in streamflow in a reach: however, because proximate gages are relatively close together (within less than one day flow) this is not believed to be as significant a factor as in other rivers. (To test a method used in the South Platte, results were also averaged for 2 days to observe effects of smoothing the data. The averages were not used here, however, because the approach increased the number of days in one reach by 40 days, while only decreasing the total number by 6 loss days overall.)

As shown on Figure 4, the maximum number of days occurred in 1983 (228 days), and 1998 had the minimum number of days of river loss (49 days). A slightly higher percentage of the days with loss occurred in the 1980s (43%) compared to roughly 29% occurring in each of the latter two decades. The years in which the most days of river loss occurred were also years with the highest river flows (Figure 6). But the number of days of river loss is significantly higher than the number of days when average daily flows were reported above flood stage at the upstream and downstream gages (11 days at the Mouth of Canyon gage and 93 days at Greeley) during the 30-year period.

Reach 2, between the Lincoln to Boxelder gages, experienced the most frequent number of days of river loss (accounting for 49% of the number of occurrences), followed by Reach 1 with 45% of the loss occurrences. Reach 3 had the least number of days with river loss, accounting for only 6% of the occurrences.

Timing

Days with river loss occurred in every month of the year (Figure 5). Over 50% of the losing stream days occurred in April-July in keeping with what would be expected in a snowmelt-driven system. June had the most days of loss (17% of all loss days), and November had the smallest percentage of days with loss (4%).

Timing of exchange patterns varied between reaches, and there were only 7 times in the study period when all 3 reaches showed losses on the same day. On the days when river loss occurred, most of the time it was recorded in only one reach. On 432 days (12% of loss days), however, river loss occurred in two or more reaches on the same day.

River flow and alluvial exchange relationships

Figures 6 presents alluvial gain and loss per mile (cms) for each reach plotted against river discharge at the upstream gage of each reach (7-day moving average, cms). As shown, a strong linear correlation between flow and alluvial exchange was not found, although one was initially anticipated based on information from the nearby South Platte River (Sjodin *et al.*, 2001, CDM Smith, 2013). Exploratory analyses of data for each reach on a monthly basis by decade (i.e., alluvial exchange to discharge for all dates in January 1980-1989, etc.) found varying correlations that were negative, positive, or nonlinear. Above 100 cms 7-day moving average (3500 cfs), only losses were reported in Reach 2: but it cannot be considered a true threshold given that both gains and losses occur below that rate.

Because of the number of diversions and return flows along this "working" river, it was suspected that river flow measured at the gages (i.e., at the upstream end of each reach) varied from flow at the subreach scale (i.e., as estimated below the upstream node of a subreach). Comparison of river flow at the gages used for reach scale and at the upstream nodes found that in Reach 1 and Reach 2, the median and mean flows through the riparian subreaches were lower (e.g., as much as 20%). However, comparisons of river flow at the upstream nodes and gains and losses at the subreach scale (in those subreaches with riparian study areas) also did not identify any consistent relationships. The strongest negative correlation was found for June 1980-1989, which had a Pearson's r value of -0.36 (with p value of <0.0001).

Riparian water budgets

The 30-year mean monthly inputs and outputs (Figure 7) illustrate the differences in the overall water budget patterns of each riparian area. Riparian Study area 1 had the highest mean inflows and outflows during most months, and Study area 3 had the lowest mean inflows and outflows in all months. The reduced amount of exchange in riparian Study area 3 reflects its location in the lower part of the watershed where the water table is expected to be higher from agricultural return flows.

Review of the relationships of individual watershed components revealed variations in the timing and magnitude of inputs and outputs in the same reach between years. An example of this inter-annual variation is provided for riparian Study area 1 (in Figure 8) to compare the maximum inflow year in 1980 to minimum inflows in 2002.

A sensitivity analysis of the water budget estimated the change in storage without ditch water (in Riparian area 1). Change in storage in terms of estimated groundwater elevation is shown in Figure 9. The simulated hydrograph demonstrates how the riparian Study area 1 water budget is heavily subsidized by the leakage from the irrigation ditch.

To assess the effectiveness of the change in storage to maintain water availability for the riparian plant communities, daily change in storage was compared to the percent of available storage capacity filled in the riparian rooting zones. As shown in Figure 10, riparian Study area 3 had water available in the rooting zone (storage capacity filled above 0%) more often than the other two riparian areas despite the relatively low exchange rate in this reach. Figure 9 also shows how inter-annual factors may affect riparian water availability. For example, change in storage in Riparian area 1 was higher in 1995 than in 2005; but based on the assumptions in the water budget, there would have been insufficient water in 1995 to fill the rooting depth, possibly related to the storage deficit from the preceding year (Figure 10).

To understand the possible stress of low water storage on the riparian plant communities, Figure 11 shows the number of days in each growing season when water storage was estimated to be within the root zone for each riparian plant group. Riparian water storage was present within the rooting depth for trees during 9 years in riparian Study area 1, 15 years in Study area 2, and 21 years in Study area 3. Years when water was not present in any of the rooting zones *and* annual precipitation was below normal are highlighted in Figure 11 as possible stress or mortality periods.

The study results suggest: Study area 1 has marginal riparian water availability and benefits from supplemental irrigation water; Study area 2 has the most dynamic exchange patterns and related changes in storage; and Study area 3 has relatively low alluvial exchange and the highest number of years with available water in rooting zones. These observations highlight the potential vulnerability of riparian water supplies in specific locations along the Poudre River and the importance of assessing inter-annual variation when planning for conservation and restoration.

DISCUSSION

Aquatic and riparian ecosystems are intertwined physically, biologically, and hydrologically. Functional floodplains, and especially overbank flooding, have been identified as critical for riparian and riverine ecosystems because of their role providing fish habitat, food-chain support, nutrient cycling, and scouring areas for regeneration of cottonwoods and other disturbance-adapted species. Groundwater-surface water exchange in the alluvial aquifer is another key indicator of hydrologic interaction. The intent of this study is to describe and compare how interactions immediately adjacent to the river channel can influence potential riparian water availability and to guide future evaluations and field verification efforts. The following observations were made in response to study questions: 1) river alluvial exchange patterns are reach specific; 2) alluvial groundwater recharge occurs relatively frequently and in every month; 3) the direct relationship of river loss to flow was not strongly correlated nor clearly related to a flow threshold; 4) riparian water budgets are location-specific; and 5) water budget analysis demonstrates potential implications of water management scenarios. The findings are important because they suggest water planners cannot assume that high flows will successfully replenish the riparian water supply the same way in different reaches. The study also highlights the importance of considering inter-annual influences, and specifically how a water deficit from a preceding year can affect riparian water supply.

Along the Cache la Poudre River, the magnitude and timing of alluvial exchange varies significantly between reaches and within the same reach between years. The difference in exchange patterns between reaches is not surprising given the differences in landform, geology, and land use. The broader, deeper alluvium in the lowest reach (Reach 3) and the high irrigation return flows likely moderate the influence of the river (because the aquifer is fuller, the gradient is toward the river more often) near Greeley, as opposed to the upper-most reach (Reach 1), which has a steeper gradient and narrower channel. The variation of alluvial exchange patterns emphasizes that strategies for water management for ecosystem conservation purposes will be most effective when planned at the individual reach scale.

The frequency of alluvial recharge also varies between reaches, with Reach 2 having the most frequent river loss. River loss also appeared to occur more frequently than would be expected based on then number of days of flood stage at the stream gages. The frequency of river loss is important, because it demonstrates that the alluvial exchange process may depend on a range of flows not just overbank flood events as is often cited as a key process for alluvial recharge (Doble et al., 2012). Local topography, soil heterogeneity, compaction and other factors make it difficult to estimate timing and contribution of overbank recharge along a river reach. Therefore, one benefit of this study method is to remove these obstacles by combining overbank recharge, hyporreheic recharge beneath the channel, and bank storage to estimate the total influx to the aquifer system. The results contradict, to some extent, prior observations that the tributaries of the South Platte River, such as the Poudre, primarily exhibit river loss during peak flows “when stream stage is significantly higher than the average” (CDM Smith, 2008).

Water budget analyses and conceptual models of the aquifer beneath riparian areas provide further insights into the complexity of the surface water-groundwater exchange relationships and the potential implications for conservation of these ecosystems. The results of the current study suggest that the direct relationship of river loss to flow were often only weakly correlated. This finding differs from the results of a groundwater exchange study nearby along the South Platte River (Sjodin, 2001) that suggested a clear flow threshold value: in that study, alluvial recharge increased linearly when moderate to high flows occurred (above 40 m^3/s or 1,400 cfs). Although both rivers share regional characteristics of snowmelt-driven systems, the South Platte is a large plains river system compared to the Poudre study, and it is possible that lag time between gages was a more significant factor in the South Platte study.

The study highlights the importance of considering the change in storage in relation to the storage *deficit* from the preceding year and rooting depths. For example, comparisons of changes in storage in Riparian area 1 suggest that the riparian water availability was influenced by the storage deficits from the preceding years (Figure 10). The ability of alluvial exchange to replenish the riparian water can be considered in terms of its ability to maintain groundwater within the rooting depths of target plant communities during critical periods in the growing season. This maintenance of elevated water relates not only to the incoming rate of alluvial recharge a factor, but also to the residence time and rate of groundwater discharge from the aquifer to the river.

The results show how the effectiveness of aquifer recharge is also influenced by the configuration of the channel. The high number of years (21) of available water in the riparian Study area 3 rooting zones demonstrates how an area with more river frontage (both sides instead of only one side) is beneficial to the riparian water supply. While this may seem obvious for Study area 3, the implications also relate to the negative effects of channel straightening where the length per area is reduced.

Finally, the sensitivity analysis of riparian Study area 1 without ditch water demonstrates how marginal locations may depend on supplemental water to maintain existing forest productivity. Therefore, should irrigation conveyance practices change, e.g., if the ditch were lined or abandonned, the riparian plant communities in this area would likely be stressed.

As water managers grapple with the provision of water for ecosystems, flow is the "master variable". Flood inundation in particular is known to play an important role in nutrient cycling, controlling invasive and non-riparian species, and encouraging cottonwood recruitment. A subtle refinement of the environmental flow paradigm is suggested here: the need to integrate inter-annual effects and site-specific alluvial exchange considerations. This refined understanding is important because similar pulse or episodic flow events may not result in the same effective recharge of the aquifer in the riparian rooting zone. Variations in exchange patterns result in each riparian area exhibiting its own unique water budget signature. Fluctuations in storage capacity in the aquifer varied due to subreach influences, including different exchange rates, supplemental water sources, and channel alignment, despite the similar sizes and river frontages of the three riparian areas. Ideally, environmental flow planning needs to be flexible enough to respond to aquifer storage deficits from preceding years, and it is best considered on a reach scale.

The dynamic nature of river systems and their large scale make it cost prohibitive to install measuring devices at a fine enough scale or for a long enough period to be meaningful along an entire river. Results of water budgets for the three study areas suggest a possible framework for assessing riparian water management scenarios using a phased approach. Water budgets offer an initial tool for screening potential conservation and restoration areas to assess their vulnerability to riparian water shortage. Categories of risk, such as low, moderate, or high, could be assigned based on number of years rooting zones have insufficient water. Alternative scenarios could then be modeled to test changes to inflows and storage using various management actions including regraded floodplains, realigned channels, lined irrigation ditches, and/or added irrigation. In high-risk, priority riparian areas, groundwater monitoring wells (or piezometers) are needed to collect targeted field data to calibrate the water budget and establish adaptive management criteria. Once site data are available, groundwater modelling could then be completed to validate the water budgets and test additional scenarios of altered river flows, addition of new structures (such as lined water storage pits) as well as changes to diversion and irrigation patterns.

To apply this approach on the Poudre, for example, water managers could complete water budget analyses on additional study areas where sizeable native riparian vegetation patches exist (e.g.,> 2 hectares) and in locations where restoration could create linkages between patches. Installation of piezometers equipped with automatic data loggers are needed in strategic locations – such as where pending land and water use changes may include lined irrigation ditches, reduced return flows, and/or lined gravel pits – to collect targeted field data, validate water budgets, and assess potential impacts. In locations where water budgets suggest a moderately vulnerable water supply, management objectives could be developed to plan for supplemental water during critical years. Given the Poudre’s place in water rights history, it could even be fitting to explore using a pilot effort that extends the instream water rights program to cover such provisions of water for riparian ecosystems. Locations where riparian water is relatively stable may become priorities for conservation acquisition. In locations where water supplies are at marginal and native plant communities are struggling could be priorities for restoration planning that improves water availability through for example channel realignment or floodplain lowering. Using this stepwise, strategic approach along with adaptive management feedback along the Poudre will enable improved resource protection along a working river system and will inform the long-term dialogue with surrounding land and water managers.

TABLES

Table 1. Summary of Project Reaches and Structures.

Reach No.	Reach length km (mi)	% of Study Reach	Gage Station Names	Diversion No.	Return No.	Total structures
1	18 (11.2)	22%	Canyon Mouth to Lincoln	14	2	16
2	9.4 (5.85)	11%	Lincoln to Above Boxelder/near Tinmouth	4	3	7
3	55.9 (34.74)	67%	Boxelder/Near Tinmouth to Greeley	8	12	20
Totals	83.4 (51.8)			26	17	43

Table 2. Distribution of riparian and wetland areas within 500 m alluvial riparian zone along Cache la Poudre River (CNHP, 2011).

Sizes of Polygons [1] (ha)	Hectares (acres)	% of total ~700 ha/1735 ac
0-5	492 (1210)	70%
5-10	140 (345)	20%
>10	72 (178)	10%

1. The identification of patch sizes and distribution were for screening of discrete polygons only, and aggregating adjacent similar wetland types would result in mosaic patches that are larger than the discrete polygons.

FIGURES

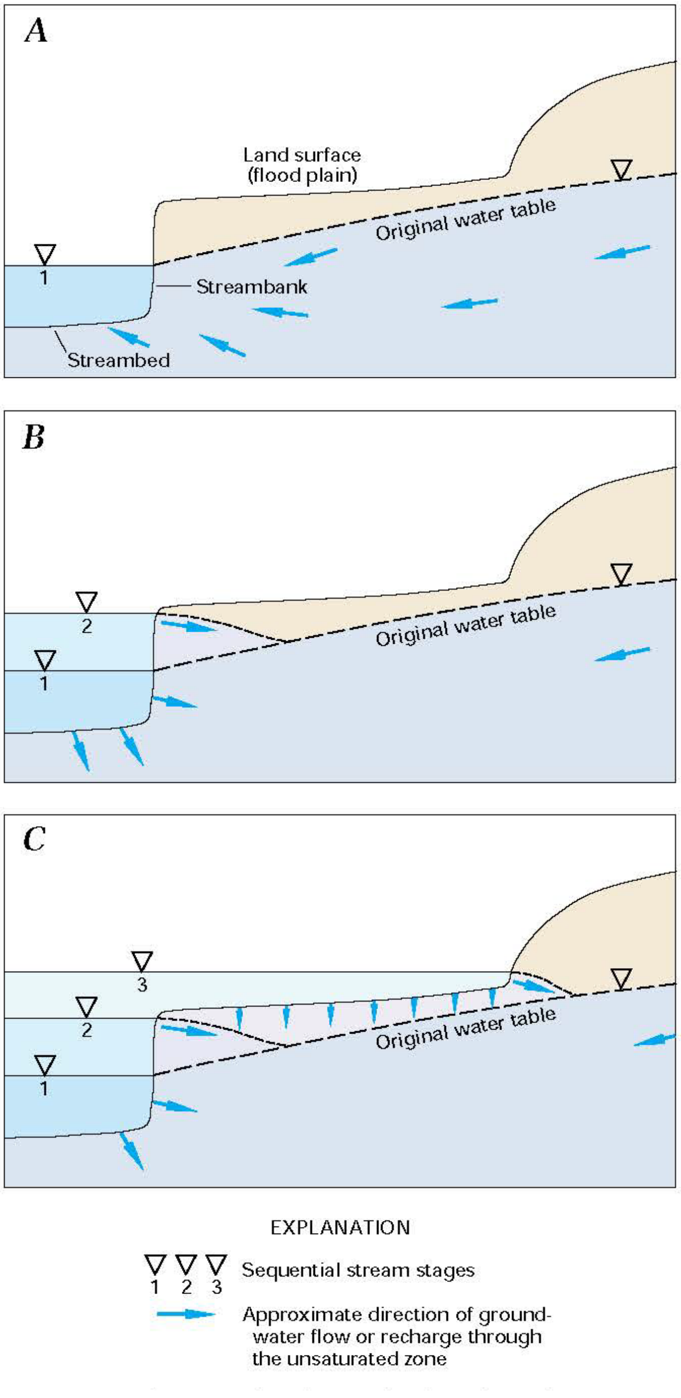


Figure 1. Examples of groundwater and surface water exchange patterns. (Winter et al., 1998)

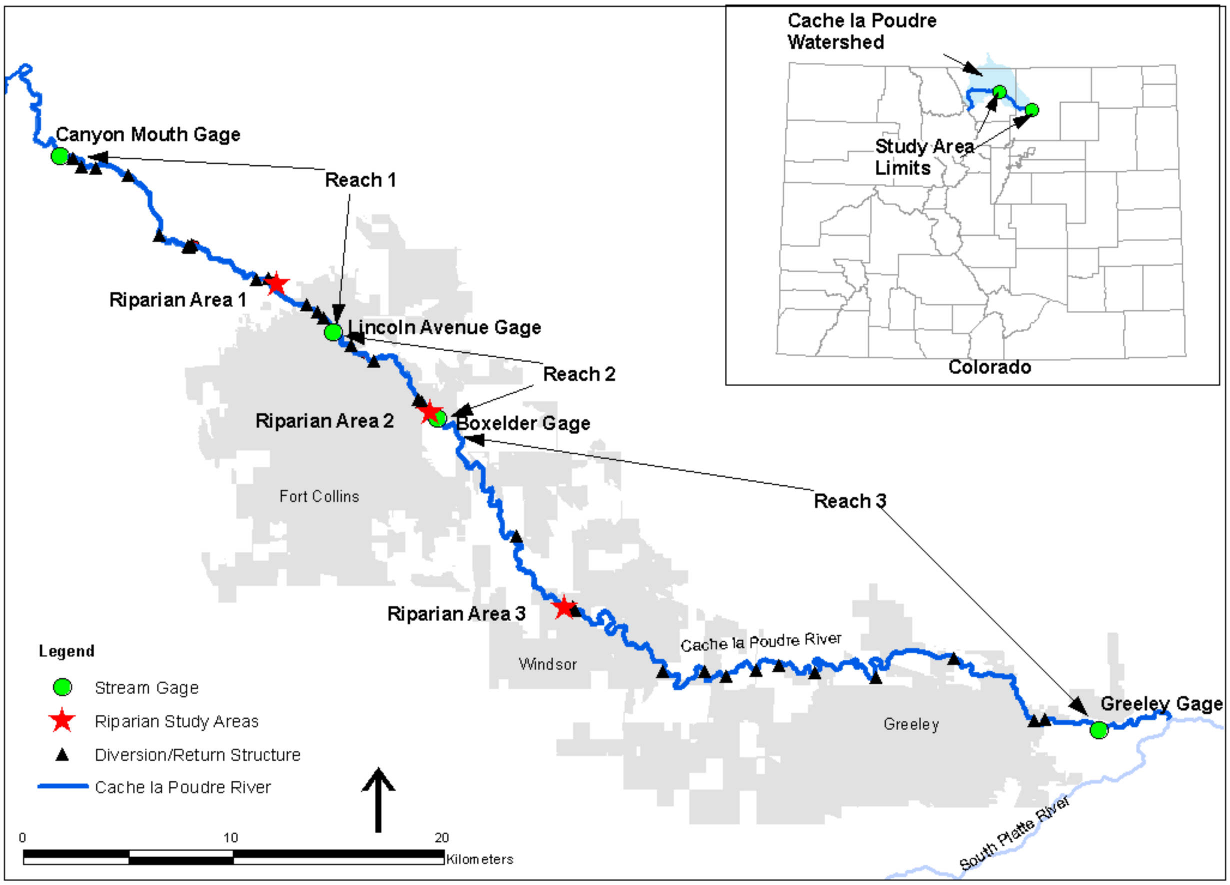


Figure 2. Location of Study Area and inset of Cache la Poudre River basin in Colorado .

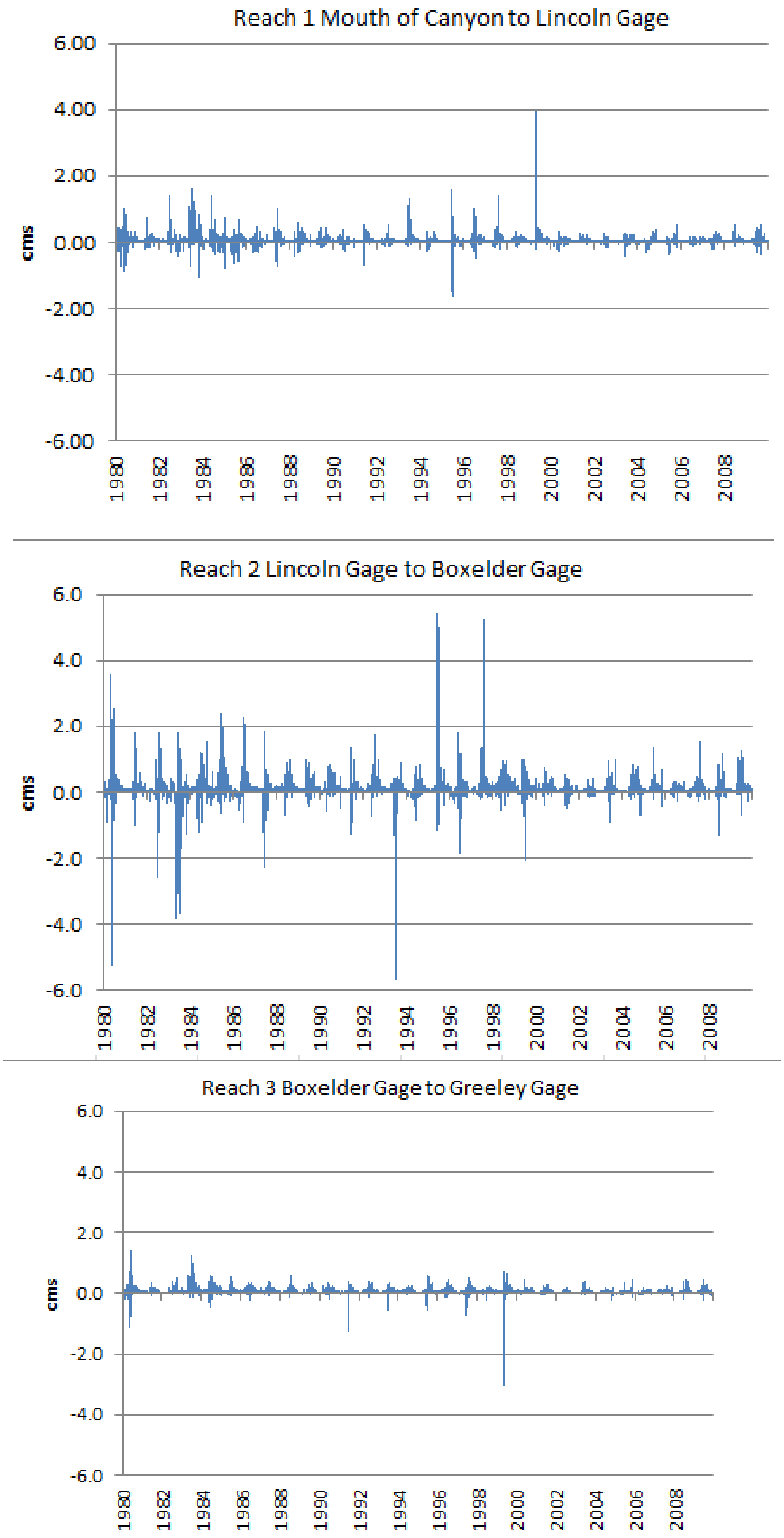


Figure 3. Daily alluvial exchange per river mile for Reaches 1-3, 1980-2009

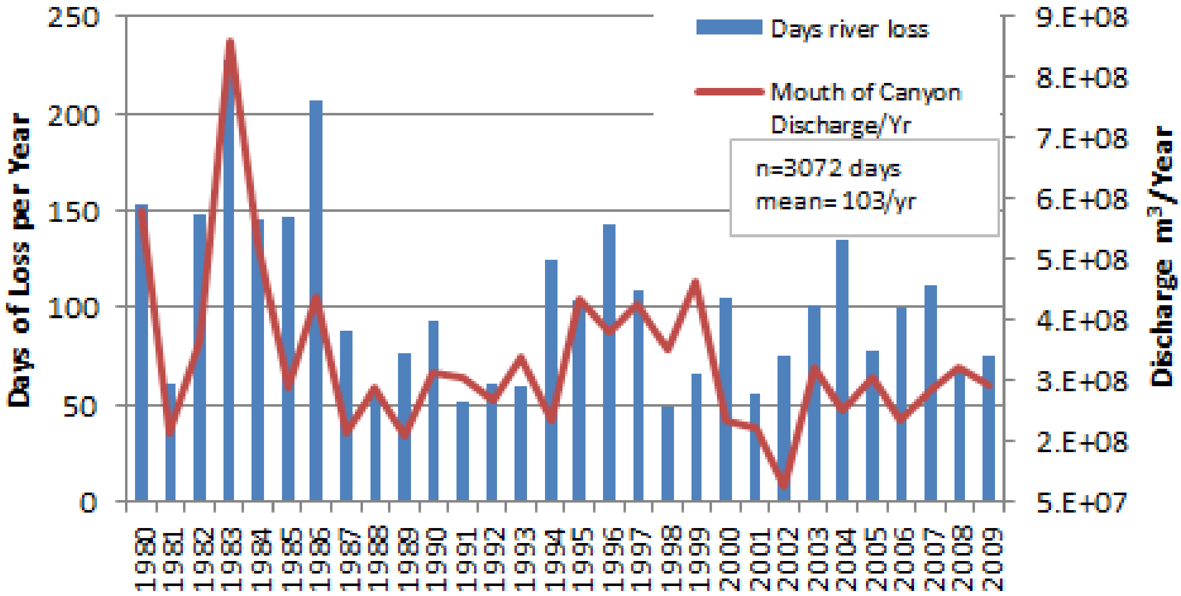


Figure 4. Days of river loss per year (in at least one reach) 1980-2009.

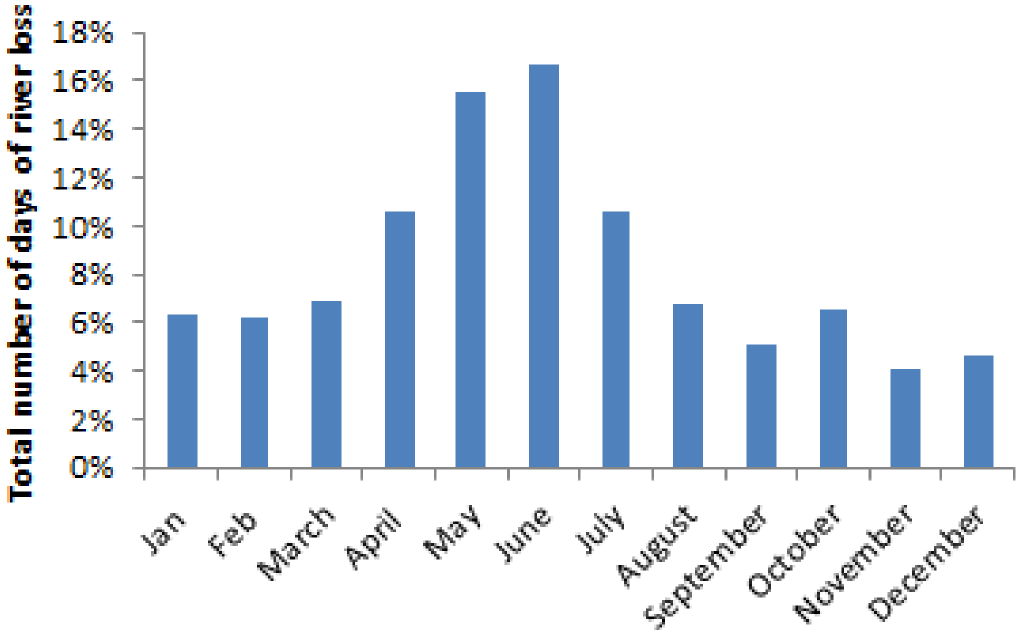


Figure 5. Timing of days of Cache la Poudre river loss by month for all reaches 1980-2009.

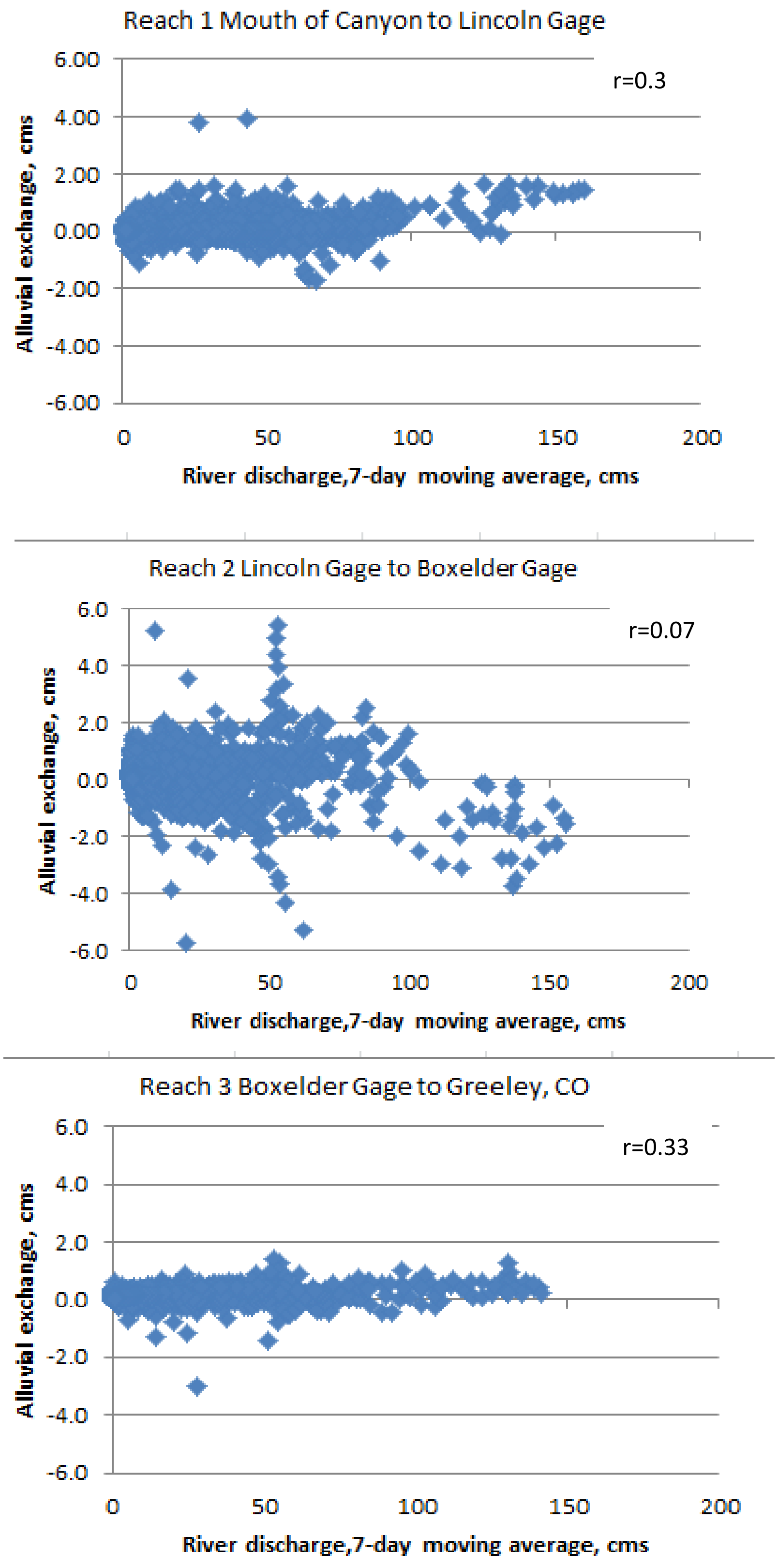


Figure 6. Relationship between alluvial exchange and upstream discharges Reaches 1-3, 1980-2009. All p values=<0.0001.

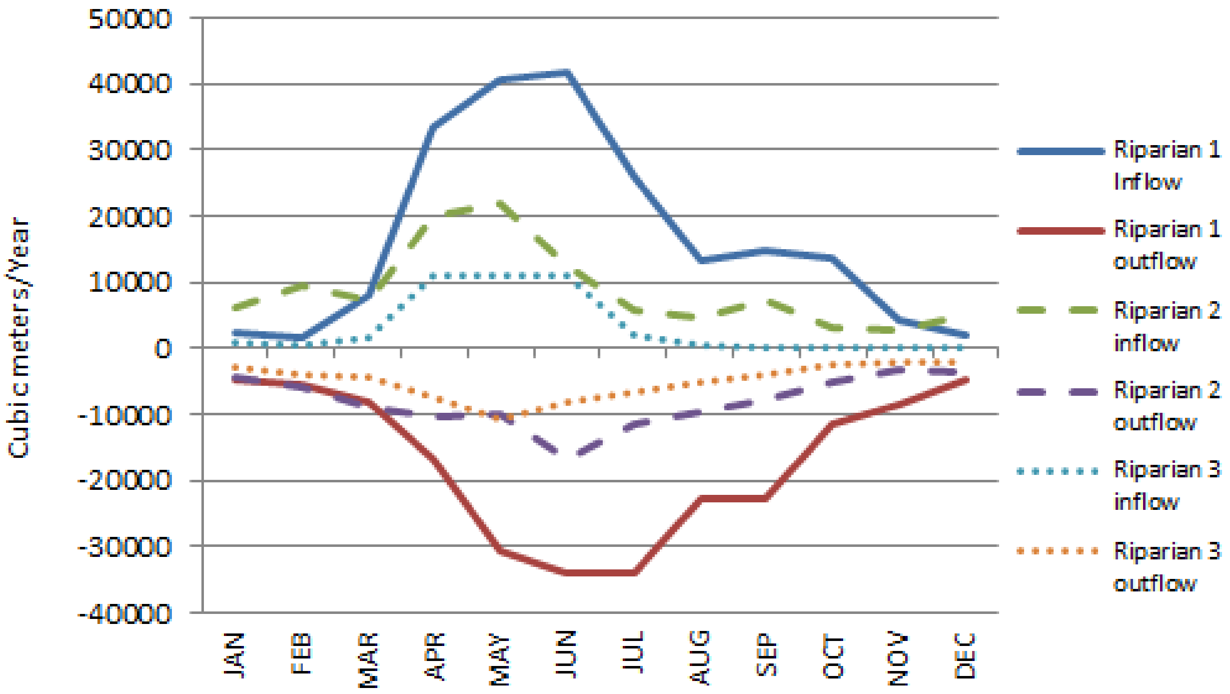
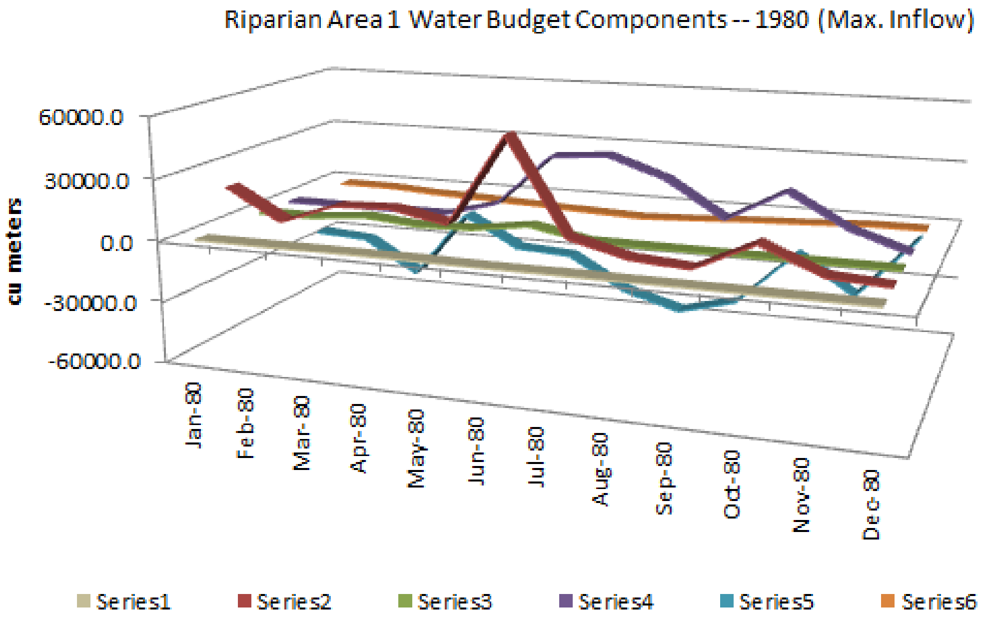


Figure 7 Mean annual groundwater inflows and outflows for riparian study areas 1980-2009.



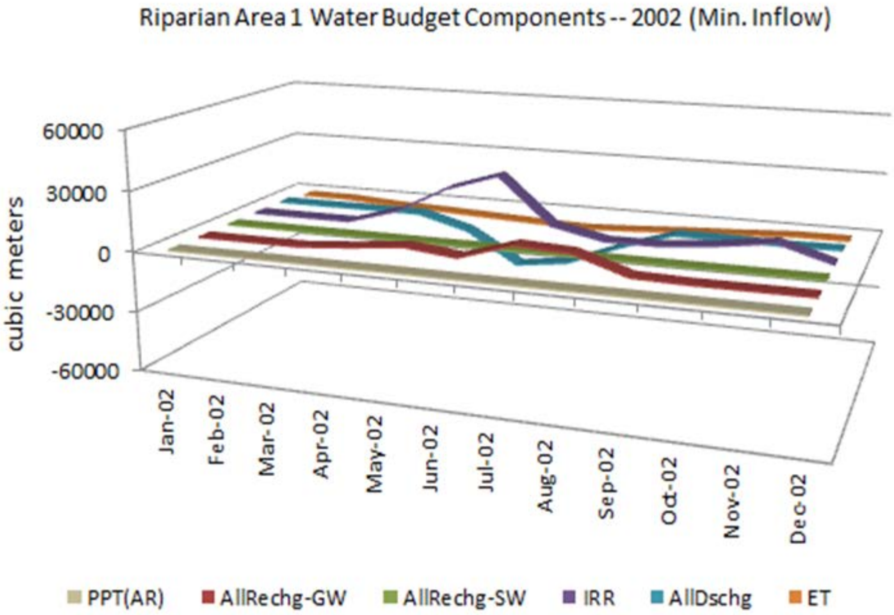


Figure 8. Examples of water budget components for Riparian Study area 1 for 1980 (maximum inflow year) and 2002 (minimum inflow year).

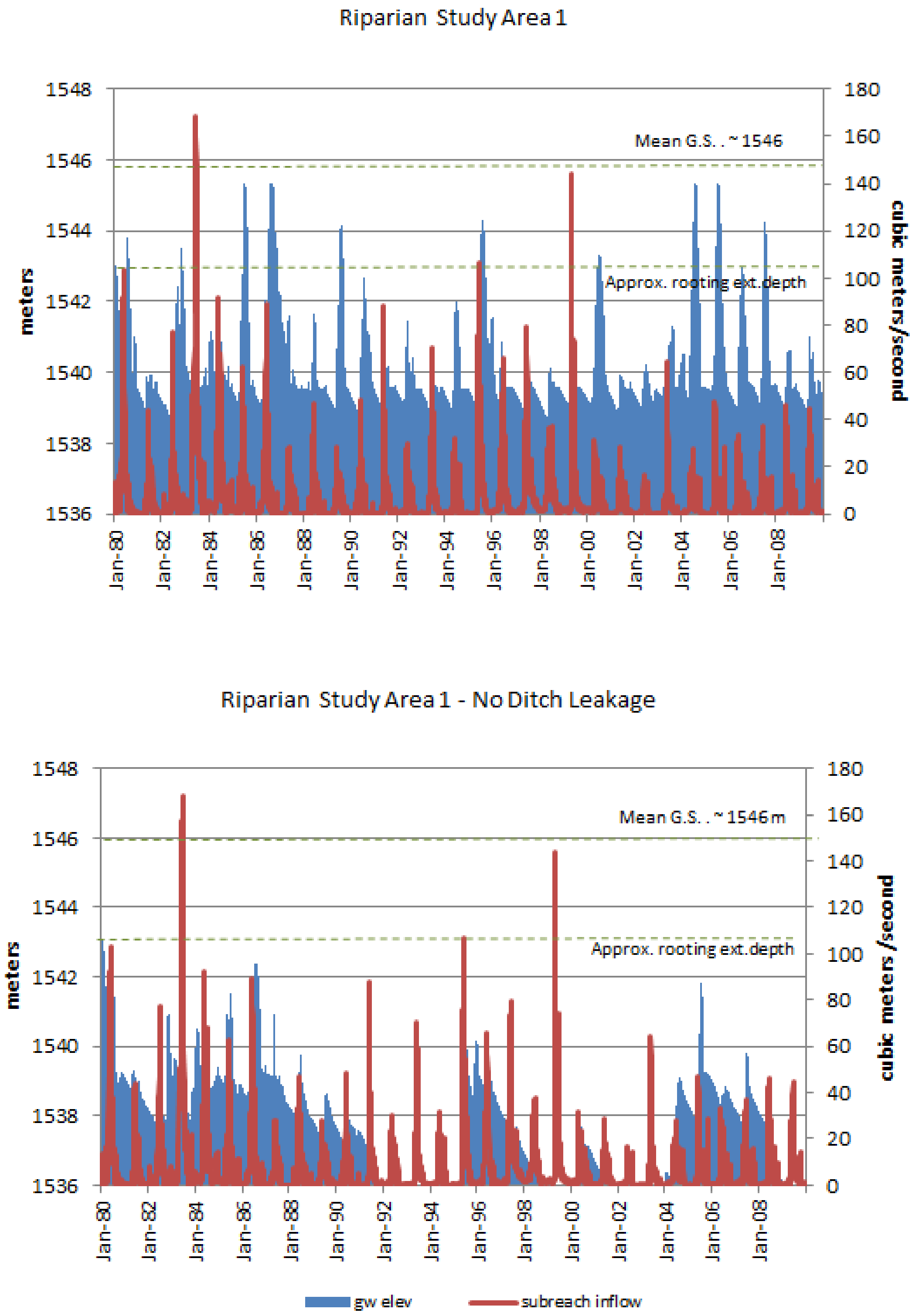


Figure 9. Change in estimated groundwater elevation with and without ditch leakage in Riparian Study area 1. River discharge at upstream node also provided on secondary axis.

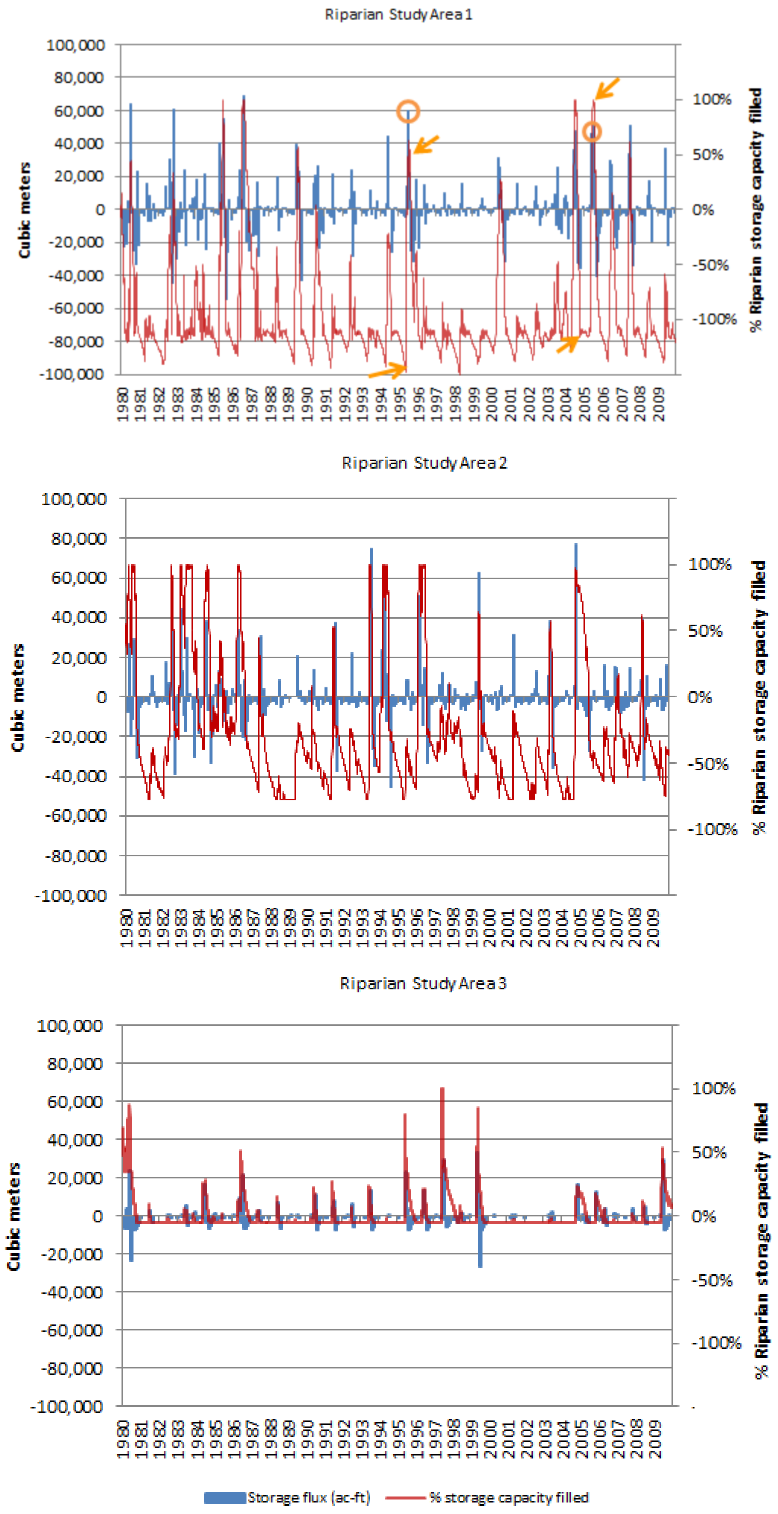


Figure 10. Daily change in storage (m^3) compared to % of riparian storage capacity filled. When % filled is above 0%, groundwater is available within the maximum rooting zone (based on riparian tree species). See text in Results for explanation of orange highlights comparing 1995 and 2005 in riparian Study area 1.

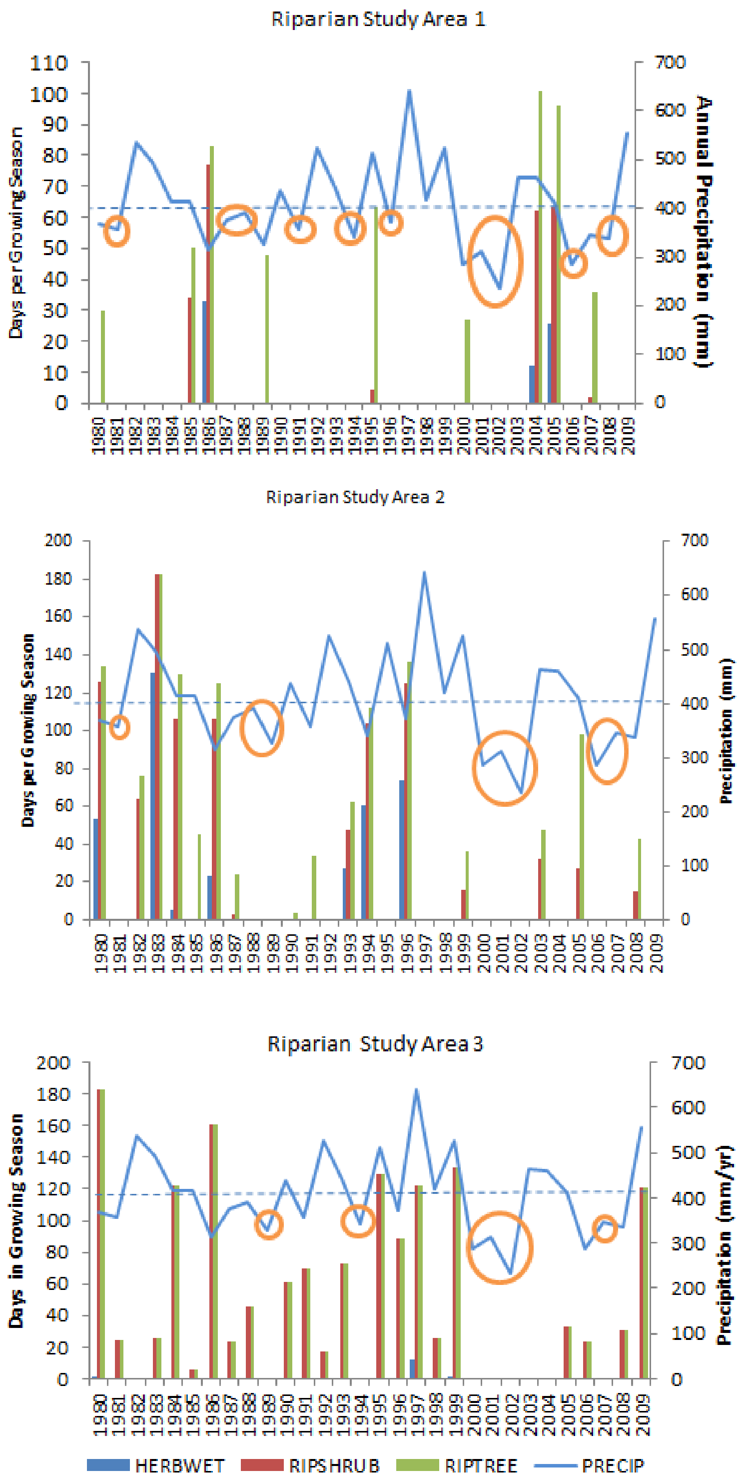


Figure 10. Number of days per annual growing season within rooting zones for herbaceous wetland plants (HERBWET), riparian shrubs (RIPSHRUB), and riparian trees (RIPTREE). Blue dashed line is average precipitation. Orange circles indicate years when storage is low (<14 days of the season) within riparian tree rooting zone and precipitation is below average. See Results section for further detail.

REFERENCES

Acreman M C, Overton I, King J, Wood P, Cowx IG, Dunbar M J, Kendy E, Young W. 2013. The changing role of eco-hydrological science in guiding environmental flows. *Hydrological Sciences Journal*, Special Issue on environmental flows, *manuscript in review***.**

Anderson Consulting Engineers (ACE) 2008. Northern Integrated Supply Project Environmental Impact Statement River Morphology and Sediment Transport Technical Report Cache la Poudre River. Prepared for the U.S. Army Corps of Engineers.

Arthington AH, Bunn SE, Poff NL, Naiman RJ. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* **16**: 1311-1318.

Auble, GT, Friedman JM, Scott ML. 2013. Relating Riparian Vegetation to Present and Future Streamflows, *Ecological Applications*, **4**: 3 (Aug., 1994), 544-554.

Baird KJ, Stromberg JC, Maddock III, T. 2005. Linking riparian dynamics and groundwater and ecohydrologic approach to modeling groundwater and riparian vegetation. *Environmental Management*, **36**:4, pp 551-564.

Bartholow JM. 2010. Constructing an interdisciplinary flow regime recommendation. *Journal of American Water Resources Association* (JAWRA) 1-15. DOI:10.1111/j.1752-1688.2010.00461.x.

Baxter CV, Fausch KD, Saunders WC. 2005. Tangled webs: reciprocal flows of invertebrate prey link streams and riparian zones *Freshwater Biology* **50**, 201–220

Brownbill RJ, Lamontagne S, Williams RM, Cook PG, Simmons CT, Merrick N. 2011 Interconnection of surface and groundwater systems – river losses from losing-disconnected streams. Technical final report, June 2011, Figure 6. New South Wales Office of Water, Sydney.

Brunke M and Gosner, T. 1997. The ecological significance of exchange processes between rivers and groundwater. *Freshwater Biology*, **37**:1-33.

Bunn SE and Arthington, AH. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* **30**: 492-507.

Camp, Dresser, and Mckee Smith (CDM Smith), 2013. South Platte Decision Support System Alluvial Groundwater Model Report, April 2013. Prepared for the Colorado Water Conservation Board and the Colorado Division of Water Resources.
— Phase 4 Task 46.2 Stream Gain/Loss Estimates Technical Memorandum, April 10, 2008
— Task 56 Memorandum, Conveyance and Application Efficiencies March 2008, Appendix A.

Chen, Y, Wang B, Pollino CA, Cuddy SM, Merrin LE, Huang C. 2014. Estimate of flood inundation and retention on wetlands using remote sensing and GIS. *Ecohydrology,* Article first published online: 17 JAN 2014, DOI:10.1002/eco.1467.

Colorado Division of Water Resources (CDWR), 2014. Colorado Decision Support System (CDSS), 1997-2014. TSTool Time Series Tool (10.31.00beta) and Hydrobase datasets.

Colorado Natural Heritage Program (CNHP), 2011. National Wetland Inventory (NWI) mapping of the Cache la Poudre and South Platte Rivers.

Colorado Water Conservation Board (CWCB). 2011. Colorado Water Conservation Board Statewide Water Supply Initiative 2010. January 2011.

Doble RC, Crosbie RS, Smerdon BD, Peters L, Cook FJ. 2012. Groundwater recharge from overbank floods. *Water Resources Research*, **48**, WO9522.

Eamus D, Froend R, Loomes R, Hose G, Murray B. 2006. A functional methodology for determining the groundwater regime needed to maintain the health of ground-water dependent vegetation. *Australian Journal of Botany*, **54**, 97-114.

ESRI, 2014. World aerial imagery, last updated October 2, 12014. Source date 2011. http://www.arcgis.com/home/item.html?id=10df2279f9684e4a9f6a7f08febac2a9

European Union (EU). 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy OJ L 327, 22.12.2000.

Freeze RA and Cherry JA. 1979. Groundwater. Englewood Cliffs, NJ, Prentice-Hall.

Hughes FMR and SB Rood. 2003. Allocation of river flows for restoration of floodplain forest ecosystems: a review of approaches and their applicability in Europe. Environmental Management **32** (1) 12-33.

Jolly ID, McEwan KL and KL Holland.2008. A review of groundwater–surface water interactions in arid/semi-arid wetlands and the consequences of salinity for wetland ecology, *Ecohydrology* **1**, 43–58. DOI: 10.1002/eco.6

MWH, 2010. Technical Memorandum, C-BT Return Flow Study, Cache la Poudre River Point-flow Model QA/QC. Reference 1009524.021802

MacDonald, GM. 2010. Water, climate change, and sustainability in the southwest. PNAS December 14, 2010, **107** (50), 21256–21262. www.pnas.org/cgi/doi/10.1073/pnas.0909651107.

McKinstry MC, Hubert WA, Anderson SH. 2004. Wetland and Riparian Areas of the Intermountain West: Ecology and Management. University of Texas Press.

Merritt DM, Scott M L, Poff N L, Auble G, Lytle D. 2010. Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds. *Freshwater Biology* **55**: 206-225.

Naiman RJ, Bunn SE, Nilsson C, Petts GE, Pinay G, Thompson LC. 2002. Legitimizing fluvial ecosystems as users of water: an overview. *Environmental Management* **30**:455-467.

Natural Resource Conservation Service (NRCS) 1996. Riparian Areas: Reservoirs of Diversity. NRCS, USDA, Working Paper No. 13 by Gerald L Montgomery, Northern Plains Regional Office, Lincoln, Nebraska February 1996.
http://www.nrcs.usda.gov/TECHNICAL/land/pubs/wp13text.html#functions

Naumburg E, Gonzales RM, Hunter RG, McLendon T, and DW Martin. 2005. Phraetophytic vegetation and groundwater fluctuations: a review of the current research and application of ecosystem response modeling with an emphasis on the Great Basin vegetation. Environmental Management **35** (6), 726-740. DOI:10.10076/s00267-004-0194-7.

Newman BD, Wilcox BP, Archer SR, Breshears DD, Dahm CN, Duffy CJ, McDowell NG, Phillips FM, Scanlon BR, and ER Vivoni. Ecohydrology of water-limited environments: a scientific vision. *Water Resources Research*, **42**:WO6302: doi:10.1029/2005WR0044141, 2006.

Northern Colorado Water Conservancy District (NCWCD) 2010. Point Flow Analysis Software Users Guide. Berthoud, Colorado.

Orellana F, Verma P, Loheide SP, Daly E. 2012. Monitoring and modeling water-vegetation interactions in groundwater-dependent ecosystems. *Review of Geophysics*, **50**, Issue 3, Article first published online : 24 JUL 2012, DOI: 10.1029/2011RG000383.

Pahl-Wostl, C, Arthington AH, Bogardi J, Bunn S.E, Hoff H, Lebel L, Nikitina E, Palmer M,. Poff NL, Richards K, Schluter M, Schulze R, St. Hilaire A, Tharme RE, Tockner K, and D Tsegai. 2013. Environmental flows and water governance: managing sustainable water uses. Current Opinion in Environmental Sustainability 5: 1-11.

Poudre Heritage Alliance (PHA), 2013. Cache la Poudre National Heritage Area Management Plan.

Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman R J, Kendy E, Acreman MC, Apse C, Bledsoe BP, Freeman MC, Henriksen J, Jacobson RB, Kennen JG, Merritt DM, O'Keeffe JH, Olden JD, Rogers K, Tharme RE, Warner A. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology* **55**: 147-170.

Poff NL, and JKH Zimmerman. 2010. Ecological response to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology* **55**: 194-205.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime: a paradigm for river conservation and restoration. *BioScience* **47**: 769-784.

Rains MC, Mount JF and EW Larsen. 2004. Simulated changes in shallow groundwater and vegetation distributions under different reservoir operation scenarios. *Ecological Applications* **14** (1)192–207.

Richter BD, Baumgartner JV, Powell J, Braun DP. 1996. A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* **10**:1163-1174.

Richter BD and HE Richter. 2000. Prescribing flood regimes to sustain riparian ecosystems along meandering rivers. *Conservation Biology* **14**:1467-1478.

Robson SG, Arnold LR, Heiny JS. 2000. Geohydrology of the Shallow Aquifers in the Fort Collins-Loveland Area, Colorado, Plates 1-5, Hydrologic Atlas HA 746B.

Rood, SB, Braatne JH, Hughes, FMR. 2003. Ecophysiology of riparian cottonwoods: streamflow dependency, water relations and restoration. *Tree Physiology* **23**, 1113-1124.

Scott, ML, Shafroth, PB, Auble GT. 1999. Responses of riparian cottonwoods to alluvial water table declines. *Environmental Management* **23** (3) 347-358.

Shafroth1 PB, Stromberg JC, and DT Patten. 2000. Woody riparian vegetation response to different alluvial water table regimes. *Western North American Naturalist* **60** (1) pp. 66–76.

Sjodin A, Lewis WM Jr., Saunders JF III. 2001. Analysis of groundwater exchange for a large plains river in Colorado (USA). *Hydrological Processes* **15**, 609-620.

South Platte Decision Support System (SPDSS), 2013. Division 1 South Platte Decision Support GIS Datasets. 2013 Structures.

Springer AE, Wright JM, Shafroth PB, Stromberg JC and DT Patten. 1999. Coupling groundwater and riparian vegetation models to assess effects of reservoir releases. *Water resources research* **35 (**12) 3621-3630.

Stromberg, JC. 2013. Root patterns and hydrogeomorphic niches of riparian plants in the American Southwest. *Journal of Arid Environments* **94**, 1-9.

Stromberg JC, Beauchamp VB, Dixon MD, Lite SJ, Paradzick C. 2007. Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in the arid south-western United States. *Freshwater Biology* **52**, 651-679.

Tharme RE. 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies of rivers. *River Research and Applications* **19**: 397-441.

The Nature Conservancy (TNC), 2007. Groundwater and biodiversity conservation: a methods guide for integrating groundwater needs of ecosystems and species into conservation plans in the Pacific Northwest. Prepared by J Brown, A Wyers, A Aldous, and L Bach. December 2007.

M Toner and P Keddy, 1997. River hydrology and riparian wetlands: a predictive model for ecological assembly. *Ecological Applications* **7,** (1) 236-246.

U.S. Geological Survey, 1998. Analytical Solutions and Computer Programs for Hydraulic Interaction of Stream-Aquifer Systems, By PM Barlow and AF Moench. Open-File Report 98-415A

U.S. Geological Survey, 2007. Facing tomorrow's challenges—U.S. Geological Survey science in the decade 2007–2017: U.S. Geological Survey Circular 1309.

U.S. Geological Survey. 2012. Comparison of two methods for estimating base flow in selected reaches of the South Platte River, Colorado. Prepared by JP Capesius and LR Arnold. Scientific Investigations Report 2012-5034.

U.S. Geological Survey, 2014. National water census-water budgets. The emerging science of ecological water: Accessed 8/19/2014 http://water.usgs.gov/watercensus/water-budgets.html Last Modified, 24-Feb-2014.

Webb RH, and SA Leake. 2005. Ground-water surface-water interactions and long-term change in riverine riparian vegetation in the southwestern United States. *Journal of Hydrology* **320,** 302–323.

Western Regional Climate Center (WRCC), 2014. Fort Collins climate data. www.wrcc.dri.edu, accessed 8/26/2014.

Winter T, Harvey JW, Franke OL, Alley WM. 1998. Ground Water and Surface Water A Single Resource, USGS Circular 1139. Usgs.gov/circ/circ1139/pdf/