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Downstream effects of stream flow diversion on channel characteristics and riparian vegetation in the Colorado Rocky Mountains, USA

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ABSTRACT: Flow diversions are widespread and numerous throughout the semi-arid mountains of the western United States. Diversions vary greatly in their structure and ability to divert water, but can alter the magnitude and duration of base and peak flows, depending upon their size and management. Channel geometry and riparian plant communities have adapted to unique hydrologic and geomorphic conditions existing in the areas subject to fluvial processes. We use geomorphic and vegetation data from low-gradient (≤3%) streams in the Rocky Mountains of north-central Colorado to assess potential effects of diversion. Data were collected at 37 reaches, including 16 paired upstream and downstream reaches and five unpaired reaches. Channel geometry data were derived from surveys of bankfull channel dimensions and substrate. Vegetation was sampled using a line-point intercept method along transects oriented perpendicular to the channel, with a total of 100 sampling points per reach. Elevation above and distance from the channel were measured at each vegetation sampling point to analyze differences in lateral and vertical zonation of plant communities between upstream and downstream reaches.

Geomorphic data were analyzed using mixed effects models. Bankfull width, depth, and cross-sectional area decreased downstream from diversions. Vegetation data were analyzed using biological diversity metrics, richness, evenness and diversity, as well as multivariate community analysis. Evenness increased downstream from diversions, through reduced frequency of wetland indicator species and increased frequency of upland indicator species. Probability of occurrence for upland species downstream of a diversion increases at a greater rate beginning around 0·5 m above active channel. The results suggest that channel morphology and riparian plant communities along low-gradient reaches in montane environments in the Colorado Rocky Mountains are impacted by diversion-induced flow alteration, with the net effect of simplifying and narrowing the channel and homogenizing and terrestrializing riparian plant communities. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS: diversion; riparian vegetation; channel geometry; Colorado; flow regulation

Introduction

Diversion involves removing water from a stream for consumptive use such as agricultural irrigation. Although some flow may be returned to the stream downstream from the point of diversion, some length of the stream typically has less flow as a result of the diversion. Diversions are common in streams flowing through arid and semi-arid environments, but are becoming more widespread even in wetter climates as human population density and intensive, off-channel consumptive uses of water continue to grow. Relative to flow regulation associated with dams, however, remarkably few studies have examined the effects of diversion on river ecosystems.

To date, studies examining the impacts of diversions have focused primarily on the effects on in-channel geometry and aquatic biota. These studies have demonstrated that diversions: reduce the cross-sectional area of flow (McKay and King, 2006); reduce channel width by allowing encroachment of riparian vegetation (Ryan, 1997); result in morphological simplification of the channel (Stamp and Schmidt, 2006); increase the abundance of patches of fine sediment and low-velocity habitats (Baker *et al.*, 2011); alter water chemistry (Kagawa, 1992); and reduce the richness, abundance and diversity of macroinvertebrate functional feeding groups (Englund and Malmqvist, 1996; Rader and Belish, 1999; McIntosh *et al.*, 2002; McCarthy, 2008). Among the studies that have examined the effects of diversions on riparian vegetation, results have been mixed. Some studies have found effects in the form of reduced tree growth rates (Stromberg and Patten, 1990), reduced stomatal conductance and water potential (Smith *et al.*, 1991),

or reduced stem diameters (Bohn and King, 2000) downstream from diversions, whereas others have not observed effects from diversions (Harris *et al*., 1987).

Part of the difficulty in quantifying the effects of diversions is that, unlike many dams, detailed hydrologic records of diversion operation are typically not kept, particularly in small channels. The legal right to divert water from a stream typically specifies the maximum quantity that can be diverted each year between specified start and end dates. The structures used to divert water are quite diverse, however, with respect to the proportion of total flow that the structure is capable of diverting and the design of the structure. Some structures completely block flow downstream from the structure, whereas others allow some flow to bypass the diversion. Some structures divert water at all times; others divert water only during peak flows. The variability in what is permitted and the quantity of water actually diverted is a function of the availability of water and the actions of the diverter. In many cases, structures designed to block all downstream flow can be opened to allow bypass flows. Consequently, studies investigating the downstream effects of diversions using data from numerous streams are typically constrained in the ability to detect and quantify changes to the natural or historic flow regime.

Several of the studies examining the effects of diversions have been conducted in the arid and semi-arid portions of the western United States, a region with more than a century-long history of diversion. Many of these diversions occur relatively high in the drainage basin of snowmelt-fed river networks, with water diverted at high elevations being sent via ditch and tunnel to lower elevation agricultural and municipal areas. A primary finding of previous work on diverted streams in the western United States is that, within mountainous river networks, low-gradient channel segments are more likely to exhibit statistically significant geomorphic changes in response to diversions than are higher gradient channels (Wesche *et al*., 1988; Ryan, 1997; Baker *et al*., 2011). Low-gradient channels typically have cobble to sand substrate and pool-riffle bedforms that respond more readily to changes in water and sediment supply than do the coarser substrate and step-pool bedforms of nearby higher gradient channel segments (Montgomery and Buffington, 1997; Ryan, 1997).

This study focuses on these lower gradient segments of mountainous river networks on the Routt National Forest (NF) of Colorado, USA. There are currently 921 flow diversions within the boundaries of this national forest (CDSS, 2012), which encompasses an area of 5200 km^2. This high spatial density of diversions exemplifies water use across the National Forest lands of the western United States. Also exemplary for the region is the desire of resource managers to better understand whether there are thresholds beyond which diversions cause significant alterations to stream morphology and/or riparian communities. The ability to identify stream segments sensitive to diversions could be used to prioritize protection and restoration of these segments, particularly in the context of ongoing requests to permit additional diversions on National Forest lands. Consequently, we focused on the low-gradient stream segments most likely to respond to diversions. We examined characteristics of channel geometry and riparian vegetation to identify which components of the river ecosystem respond to flow diversion, and how these components varied as a result of diversion. The structures that create diversions on these streams are typically some type of head gate (<2 m tall) that can be lowered or raised to control water movement into the diversion ditch.

The primary objectives of this research are to: (1) investigate the extent to which existing flow diversions have altered channel characteristics and riparian plant communities on streams in the Routt NF, and (2) identify environmental variables that are most sensitive to flow diversions. We address these objectives by testing three hypotheses. (Hypothesis 1, H1) Channels with flow diversions exhibit significantly different channel geometry than channels without diversions. The assumption underlying this hypothesis is that reduced flow magnitudes alter sediment transport capacity, resulting in changes to cross-sectional geometry, channel gradient, planform geometry, or channel substrate. (Hypothesis 2, H2) Riparian vegetation community composition (richness, abundance, heterogeneity, evenness) differs significantly upstream and downstream from diversion sites. The rationale underlying this hypothesis is that riparian plant communities are controlled by hydrogeomorphic processes (Naiman and Décamps, 1997; Bendix and Hupp, 2000; Amoros and Bornette, 2002). Diversions typically reduce peak and base flows, potentially causing streams to lose water to groundwater, as well as decreasing overbank flows, associated infiltration, and riparian water tables. Therefore, riparian species requiring greater soil moisture than upland species will be particularly affected by diversions. A secondary hypothesis related to riparian vegetation is: (Hypothesis 3, H3) Significant differences exist in riparian species composition upstream and downstream from diversions with respect to lateral and vertical zonation of species relative to the active channel.

The methods we used to characterize channel morphology are similar to those used in previous studies and in most studies of channel form. The methods used to characterize riparian vegetation community composition are original to this study, but could be applied to any riparian community. Similarly, the methods and results of this study are applicable to any relatively small (third-order or smaller) river subject to flow diversion. Our finding that riparian vegetation communities are significantly affected by diversions will likely apply to many other arid and semi-arid regions where streamflow, floodplain inundation, and riparian water tables strongly influence riparian vegetation community structure.

Study Area

Data were collected in the Routt NF in northern Colorado (Fig. 1). The Routt NF includes more than 5200 km^2 spread across three mountain ranges and spanning elevations of 1900 to 3950 m on both sides of the continental divide. Lithology is spatially variable and includes Precambrian-age metamorphic and granitic basement rocks in the Park and Gore Ranges. In the Rabbit Ears Range and Elkhead and Flattop Mountains, volcanic basalts create the high points and are underlain by Jurassic to Cretaceous-age sandstone, shale, and conglomerate (Hail, 1968). Pleistocene valley glaciers extended down to 2300 m on the western slope of the continental divide and 2600 m on the eastern slope (Atwood, 1937), leaving locally well-developed glacial troughs. Valley geometry varies longitudinally from high-gradient (>9%), laterally confined valleys to lower gradient (<3%), relatively unconfined valley segments.

Mean annual precipitation varies from 64 to 125 cm, but averages 93 cm across the study areas. Hydrographs are relatively consistent between individual study basins, with a snowmelt peak between mid-May and mid-June and secondary peaks from summer convective storms. Drainage area at the study reaches averaged 23 km^2 (Table I). None of the creeks are gaged.

Upland conifer forests throughout the study area consist primarily of pine (*Pinus contorta*), spruce (*Picea engelmannii*), fir (*Abies lasiocarpa*), Douglas-fir (*Pseudotsuga menziesii*), and aspen (*Populus tremuloides*). Riparian vegetation communities include five groups: coniferous-dominated forests and woodlands;

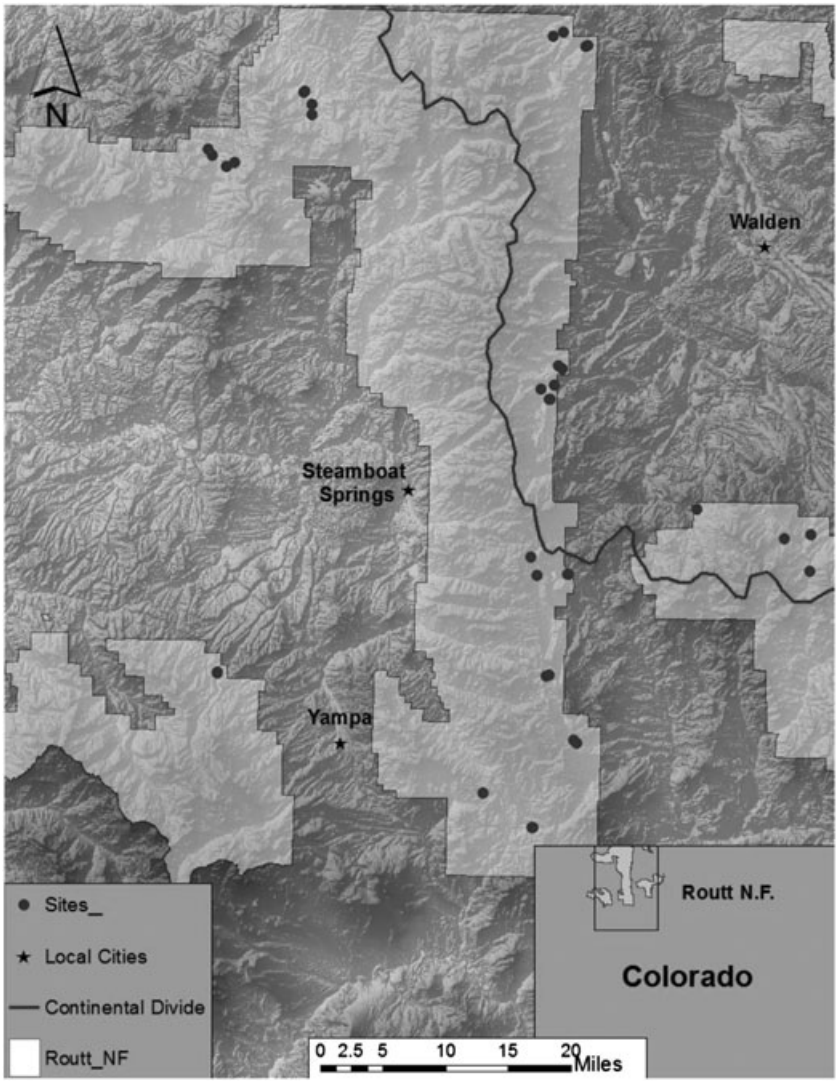

Figure 1. Location map showing the extent of the Routt National Forest (NF) (lighter gray shading) within Colorado (inset at lower right). Study reaches indicated by black dots.

deciduous-dominated woodlands; willow (*Salix* spp.)-dominated deciduous shrublands; non-willow-dominated deciduous shrublands; and herbaceous wetlands (Kettler and McMullen, 1996). Willow-dominated deciduous shrublands are most common at our study reaches because this group prefers the low-gradient alluvial stream reaches that we selected for analysis. Many of the alluvial valley segments in the study area have indications of past or present beaver (*Castor canadensis*) activity in the form of beaver dams and anastomosing channel networks formed in association with beaver dams.

The structure type, maintenance, and details of diversion operations vary widely among the study sites and may influence the effects of the structure on stream channels and biota. Some structures include concrete head gates able to divert all flow. At other sites, peripheral structures built of wood or concrete utilize rock weirs and tarps to direct flow, occupy the channel margins, and only have the capacity to divert a moderate portion of any flow on the stream. Observations during the field seasons suggest that some structures are maintained multiple times each season, whereas others appear to be unrepaired for years at a time. Many of the structures are associated with a water right more than a century old, and associated records of maintenance and timing or magnitude of water withdrawal are infrequent or completely absent. All of the structures are relatively small (<2 m tall) and used for local irrigation purposes during the summer growing season. Because interannual variability in precipitation is relatively high, the absolute volume of water and the proportion of total flow diverted each year vary substantially. The inability to quantify the effects of diversions on flow regime at the study reaches constitutes a major limitation of this study.

Methods

Selection of study reaches

Because this study focused on lower gradient, response reaches, we targeted single-thread, straight and meandering, alluvial channels on low to moderate gradient (<3%) valley segments. These study reaches had pool-riffle or plane-bed morphology, were underlain by sedimentary bedrock or glacial deposits, and were typically at middle elevations (2325–2825 m). Channel substrate varied from coarse sand (1 mm) to small cobble (64–90 mm), with a median size of coarse gravel (32–45 mm). Reaches were chosen based on (i) stream gradient (<3%), (ii) lateral valley confinement (partly confined, with valley-bottom width 2–10 times channel width; unconfined, with valley-bottom width > 10 times channel width) and (iii) diversion characteristics (amount of flow diverted, date of diversion construction, timing of water extraction, currently operational), as recorded on Colorado's Decision Support System (CDSS) website. Reaches

Table I. Morphologic characteristics of study reaches

Reach	Drainage area (km^2)	Gradient (m/m)	Width (m)	Depth (m)	Sinuosity (m/m)	D_{50} (mm)	Entrenchment (m/m)
Control							
Beaver	28·2	0·018	14·2	0·32	1·2	95	1·2
Chedsey	17·8	0·005	10·2	0·38	1·5	54	2·6
Jolley	2·0	0·021	1·0	0·2	1·1	7	9·5
Little Muddy	8·0	0·019	5·2	0·2	1·3	62	5·0
Muddy	12·2	0·002	4·4	0·25	1·3	45	2·3
Service	3·9	0·031	1·3	0·18	1·3	23	3·5
Slater	6·0	0·027	2·8	0·28	1·5	81	1·8
Slater #2	3·4	0·020	1·6	0·32	1·4	40	3·5
South Fork Big	17·0	0·005	9·1	0·6	1·7	21	1·8
Red Dirt	47·9	0·017	4·6	0·50	1·1	61	2·6
West Fork	35·9	0·025	7·1	0·34	1·0	—	—
Summit	9·6	0·008	2·5	0·29	1·3	37	1·8
Rock Willow	16·5	0·009	5·6	0·35	1·9	61	2·4
Newcomb	27·4	0·004	9·2	0·55	1·1	58	1·4
Grizzly	27·4	0·010	5·3	0·28	1·3	45	—
Trout	57·2	0·046	8·0	0·43	1·1	58	1·3
Porcupine[a]	0·6	0·009	1·0	0·1	2·7	0·2	6·7
Willow[a]	12·0	0·009	5·6	0·35	1·9	61	2·4
Diverted							
Beaver	30·6	0·012	9·2	0·4	1·1	66	2·6
Chedsey	20·8	0·016	5·9	0·32	1·2	90	1·7
Jolley	4·8	0·015	1·6	0·15	1·1	0·2	5·9
Little Muddy	8·8	0·020	2·8	0·28	1·2	58	2·9
Muddy	19·6	0·014	3·4	0·30	1·3	58	3·0
Service	4·4	0·005	2·1	0·15	1·2	8	6·1
Slater	32·1	0·006	5·8	0·42	1·2	42	2·8
Slater #2	3·5	0·028	2·1	0·25	1·3	44	2·5
South Fork Big	51·3	0·013	7·2	0·45	1·5	100	1·8
Red Dirt	47·9	0·007	5·2	0·31	1·7	71	1·5
West Fork	35·9	0·025	5·8	0·26	1·0	—	1·0
Summit	11·6	0·022	2·3	0·16	1·1	50	1·9
Rock Willow	16·5	0·010	2·7	0·35	1·0	67	2·3
Newcomb	40·7	0·004	10·6	0·71	1·0	100	—
Grizzly	27·5	0·016	4·8	0·26	1·2	51	—
Trout	57·2	0·027	6·4	0·22	1·1	79	1·6
Ninegar[a]	1·1	0·036	1·0	0·1	1·1	47	3·2
Rock #1[a]	12·1	0·010	2·7	0·35	1·0	67	2·3
Rock #2[a]	22·9	0·003	4·8	0·25	1·1	45	2·7

Note: Gradient is channel-bed gradient; width and depth are for bankfull
[a]Superscript indicates an unpaired reach.

were selected to: minimize variations in geomorphic and hydroclimatic setting between reaches; avoid other human impacts, including log floating from historic timber harvest, recent timber harvest, fire, or grazing by cattle or sheep; and avoid active beaver dams. The majority of diversions on the Routt NF are located at changes in stream gradient or at property boundaries. Where possible, we chose reaches with similar gradients upstream and downstream from the diversion.

Because the study reaches are not gaged, we estimated flow parameters using the US Geological Survey's online program StreamStats (Capesius and Stephens, 2009). This program calculates basin parameters using 10 m digital elevation models (DEMs). The program estimates peak stream flow characteristics for different recurrence intervals based on the distribution of drainage area with respect to elevation, mean annual precipitation, and mean watershed slope.

We sampled 37 reaches: 19 downstream from diversions and 18 upstream from diversions. Reaches upstream from diversions are assumed to be minimally affected by flow regulation and are designated control reaches. Reaches downstream from diversion are assumed to be potentially affected by flow regulation and are designated diverted reaches. Of the 37 reaches sampled, 16 were paired reaches with data collected upstream and downstream from a single diversion. Most of the paired reaches differ little in elevation and drainage area, limiting potential confounding effects of longitudinal patterns in stream characteristics. Not all reaches were paired because diversions are commonly located at changes in gradient and valley geometry, making the upstream reach too steep for comparison to the downstream reach.

Field methods

Fieldwork was conducted during the summers of 2011 and 2012. Data collection for channel morphology centered on stream reaches with a length approximately 20 times the bankfull channel width. We used a laser theodolite to measure a longitudinal profile and to survey five bankfull cross-sections at locations chosen to proportionally represent channel units such as pools and riffles. Bankfull stage was identified based on the combined presence of slope breaks, changes in particle size, undercuts, changes in vegetation, debris from high water, and depositional features such as tops of point bars (Harrelson *et al.*, 1994). Cross-section surveys extended to the edge of vegetation transects (described later). We used a gravelometer and a random walk method (Wolman, 1954) to measure 100 bed clasts per reach in riffles. Field data were used to derive

bankfull width, average depth, width/depth, cross-sectional area, bed D_{50}, channel gradient, sinuosity, and entrenchment, defined as the ratio of flood-prone width to bankfull width, where flood-prone width is derived from an elevation twice the bankfull depth (Rosgen, 1994).

We characterized riparian vegetation starting at the active channel edges using a line-point intercept method to sample along transects perpendicular to flow spaced at regular intervals. For each study reach, we established 10 transects, with 10 evenly spaced sampling points along each transect, resulting in 100 sample points per study reach. Transects extended twice the channel width on either side of the channel, with a minimum distance of 5 m and a maximum distance of 10 m to ensure adequate representation of the riparian community. A laser pointer mounted on a pole was aligned directly over each sampling point. Each plant touched by the laser was recorded and then moved out of the way until ground cover was reached. Each plant sampled was identified to species in the field when possible, or collected for later identification. Each species (or taxon) was assigned to a USFWS Wetlands Indicator Category (Lichvar *et al.*, 2012). Each vegetation sampling point was associated with a field-identified geomorphic surface (i.e. depositional bar, secondary channel, floodplain, or terrace). Distance from and elevation above bankfull stage were also recorded for each vegetation sampling point.

Data analysis

All statistical analyses were checked for compliance with assumptions associated with the test. Paired tests were used unless otherwise noted. Biological diversity metrics utilizing a paired Student's *t*-test were evaluated for normality using the Shapiro–Wilk test and transformed if necessary to assure compliance with statistical assumptions. If transformations were not successful in normalizing the data, the Wilcoxon–Signed rank test for paired, non-parametric data was implemented. All statistical analyses were completed in R, unless otherwise noted (R Development Core Team, 2011).

For channel morphology, response variables tested included D_{50}, bankfull width, average bankfull depth, width/depth ratio, cross-sectional area, sinuosity, channel gradient, and entrenchment. Predictor variables included valley slope, valley width, lithology, drainage area, dominant riparian vegetation type, and group (control or diverted). To test H1, two sets of mixed effects models were developed, with the response variables tested separately in each model. One set accounted for both the control reaches with a paired diverted reach and the control reaches without a paired reach. The second mixed effects model took the uneven pairing into account as the mixed effect, as well as using valley type factors, lithology, and vegetation as different treatments. Univariate mixed effects models were run using the GLIMMIX procedure in SAS to compare each response variable between diverted and control groups. We determined that the univariate mixed effects model was the best approach, because there were not enough data to support using a multivariate or MANOVA-type analysis method (Blaschak, 2012). Results from the mixed model analyses were evaluated using *p*-values and associated least-squared mean estimates, which compare the diverted and control groups by using the estimated differences between their means.

For riparian vegetation, we conducted community-level analyses and population-level analyses focused on individual species to test H2. For community-level analyses, we examined one set of metrics commonly used for biological diversity (richness, evenness) and another set for vegetation composition analysis. For biodiversity, we considered species richness, which is the total number of species occurring within a given sampling unit. We also examined two diversity indices, the Shannon index and the Simpson index (Pielou, 1969, 1977; Smith and Wilson, 1996; Krebs, 1999; Magurran, 2004). Additionally, total abundance of species was calculated by totaling the number of all 'hits' sampled at a study reach, and compared using a paired Student's *t*-test. Species abundance distributions are another method to understand diversity and differences between sampling units, or communities. Two commonly employed examples are species accumulation curves (SAC), which generally compare the species richness of data sets (Magurran, 2004), and rank/abundance models, capturing richness and evenness/dominance within the sampling unit (Kent, 2011).

For vegetation composition analyses, we used analysis of similarity (ANOSIM; Clarke, 1993), multi-response permutation procedures (MRPP; Mielke and Berry, 2001), and permutational multivariate analysis of variance (function *adonis*) in R-Cran to test for significant differences in species composition between groups of samples. To test the differences in group means, we used the Vegan function *adonis*, a non-parametric, multivariate, permutational analysis of variance based on distance matrices (Anderson, 2001; Oksanen, 2011). We also examined the homogeneity of groups through the *betadisper* function, and then used analysis of variance to test the model fit (Anderson *et al.*, 2006). Decision to reject the null was based upon $\alpha = 0.05$.

For population-level analyses, we used a chi-square analysis to compare frequency of occurrence of individual species upstream and downstream from diversion. Each point was considered an observation, and the total number of observations where a species was present was divided by the number of observations where a species was absent. A significance level of 0.01 was used with a Bonferonni correction (Sokal and Rohlf, 1994).

We assigned each species to a Wetland Indicator Category (Lichvar *et al.*, 2012), which is a qualitative ecological classification that categorizes plant species based on occurrence in wetlands. Obligate species (OBL) almost always occur in wetlands. Facultative wetland (FACW) species usually occur in wetlands and are associated with near-channel, seasonally-flooded environments. We used the OBL and FACW species as indicators of hydric, moist conditions, and as evidence of geomorphic settings where soil is saturated through seasonal flooding, typical of functioning riparian environments. On the opposite side of the indicator spectrum are facultative upland (FACU) species, commonly occurring on drier, mesic soils, and Upland (UPL) species, most frequently occurring in non-wetlands, in soils that are mesic to xeric. We used the FACU and UPL species as indicators of geomorphic settings that are disconnected from the channel, or at least not subject to seasonal flooding. FAC species occur in both wetlands and non-wetlands. We then used the richness, diversity, abundance, and composition metrics to analyze the species classified as OBL or FACW, comparing control to diverted reaches. We examined the species classified as UPL or FACU and compared the control to the diverted reaches using the same metrics.

To test for differences in vegetation above and away from the stream (H3), we assigned topographical coordinates to each vegetation sampling point by interpolating based on known points from the survey. We stratified the data by creating bins of elevation at 0.25 m intervals up to 1·5 m above the active channel. Diversity metrics were tested for difference between upstream and downstream from diversions. We used relative abundance for all diversity metrics to avoid bias, rather than absolute abundance. The number of points in each topographical zone between upstream and downstream was similar, with magnitude being close to 10% difference. Similarly, zones of

lateral distance away from the active channel at every 0·5 m resulted in six zones up to 3 m away from the channel. In addition to diversity analysis, these lateral and vertical zones were used to test for community composition differences using ANOSIM, MRPP, and *adonis*. Chi-square analysis was again employed to test for differences in species frequency upstream and downstream from diversions.

To investigate the response of species and wetland indicator classes to topography, we plotted the probability of species occurrence as a function of lateral and vertical distance from the active channel using logistic regression. This analysis relates the probability of species or Wetland Indicator Category to elevation or distance to the channel, and tests whether this topographical relationship differs between upstream and downstream from diversions (Merritt and Wohl, 2006; Polvi, 2009). Based on presence–absence data for each point, we fit logistic regression equations, separately, for vertical elevation above active channel (EL) and horizontal distance away from the active channel (DIS). We also added a variable for upstream versus downstream (DIV) and an interaction term (DIV*DIST or EL).

Results

Channel geometry

Comparing group variables

Table I summarizes morphologic characteristics of the study reaches. Boxplot comparisons and summary statistics of the channel geometry variables show some differences between the means and medians of the control and diverted groups: sinuosity, slope, width, width/depth, entrenchment and cross-sectional area all have slightly higher mean values for the control group (Fig. 2A). The D_{50} value has slightly greater mean and median values in the diverted group, and depth does not differ between the groups (Blaschak, 2012). The only variable that differs significantly between groups, however, is sinuosity (Fig. 2B), based on a paired *t*-test ($p = 0{\cdot}0054$), non-parametric Wilcoxon signed-rank test ($p = 0{\cdot}0156$), and unpaired *t*-test ($p = 0{\cdot}0205$).

Mixed models

Only sinuosity is significant ($p = 0{\cdot}005$) in the first set of mixed models, which compares reach response variables between the diverted and control groups. The second set of mixed models, which included valley slope, valley width, vegetation type, drainage basin area and lithology as predictor variables revealed significant differences in three response variables. Stream width ($p = 0{\cdot}0013$), depth ($p = 0{\cdot}005$), and cross-sectional area ($p = 0{\cdot}0068$) were significantly less in diverted channels (Table II).

The output of the mixed models includes the least-squared mean estimates of the response variables, which are calculated by subtracting the diverted group from the control group, after adjusting for all other effects in the model. Type III tests of fixed effects, which include *F*-values and corresponding *p*-values, were used to examine which predictor variables were influential on the response variables. The significant variable for depth was drainage area ($F = 9{\cdot}54$, $p = 0{\cdot}005$). The significant variables for channel width were drainage area ($F = 12{\cdot}93$, $p = 0{\cdot}0013$) and lithology ($F = 5{\cdot}01$, $p = 0{\cdot}0324$). The significant variables for cross-sectional area were valley width ($F = 8{\cdot}45$, $p = 0{\cdot}0068$), lithology ($F = 4{\cdot}08$, $p = 0{\cdot}0524$), and drainage area ($F = 14{\cdot}37$, $p = 0{\cdot}0524$). These relations were used to standardize response variables in order to remove the effects of variables not related to diversion: channel width was standardized by drainage area using the transformation $w/A^{0{\cdot}6}$ to account for potential non-linear increase in channel width with larger drainage area. Using the transformed width variable in the mixed effects model still resulted in a significant difference between control and diverted groups.

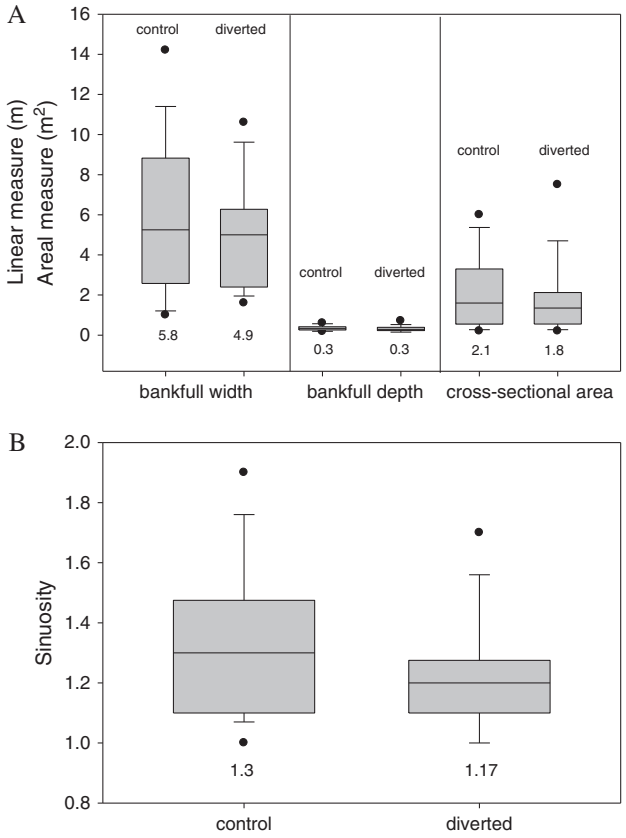

Figure 2. (A) Boxplots illustrating distributions for bankfull channel width, bankfull depth, and bankfull cross-sectional area upstream and downstream from diversions. Mean value of each population is listed below the box. (B) Boxplot illustrating differences in channel sinuosity between reaches upstream from diversions (control) and reaches downstream from diversions (diversion). Sinuosity differs significantly between the groups. Mean value of each population is listed below the box. For all box plots, $n = 18$ for the control reaches and $n = 20$ for the diverted reaches.

In summary, the results partially support H1 by indicating significant differences in some channel morphologic parameters between control and diverted reaches.

Riparian vegetation

From all 37 reaches, encompassing 3700 sampling points, a total of 238 plant taxa were recorded. Vegetation characteristics of the study reaches are summarized in Table III.

With respect to riparian vegetation community composition upstream and downstream of diversions (H2), results on the whole indicate significant differences. Mean species richness, species accumulation curves, and heterogeneity tests using the Shannon, Simpson, and Inverse Simpson indices are all higher downstream from diversions, although the differences are not significant (Caskey, 2013). Evenness, as indicated by the Shannon and Simpson indices, is significantly greater downstream from diversions (Fig. 3). ANOSIM, MRPP, and permutational MANOVA analyses testing for species composition differences indicate significant difference between upstream and downstream vegetation communities ($p = 0.01$), when analyzed at a point level. Difference between species composition is not significant when points are aggregated into reach-level data, where all 100 points for a reach are distilled into one

Table II. Results of mixed effects model for channel morphologic variables showing differences of group least squared means and adjustment for multiple comparisons with Tukey–Kramer

Variable	Estimate	Standard error	df	*t* Value	Pr > t	Adjust *p*
D_{50}	−7·1596	6·9855	30	−1·02	0·3136	0·3136
Entrenchment	−0·0071	0·4776	17·6	−0·01	0·9883	0·9883
Depth	*0·0552*	*0·0262*	*20·3*	*2·11*	*0·0478*	*0·0478*
Sinuosity	0·0752	0·0596	14·1	1·26	0·2277	0·2277
Width	*1·2221*	*0·4825*	*19·6*	*2·53*	*0·02*	*0·02*
Width/depth	0·8931	1·8832	19·4	0·47	0·6406	0·6406
Cross-sectional area	*0·6107*	*0·3091*	*20·1*	*1·98*	*0·0621*	*0·0621*
Gradient	0·0027	0·0021	32	1·29	0·2046	0·2046

Note: significant variables shown in italic typeface.

Table III. Vegetation characteristics of study reaches (16 control, 16 diverted)

Reach	Species richness	Diversity	Evenness	OBL	FACW	OBL + FACW	FAC	FACU	UPL	FACU + UPL
Control										
Beaver	42	3·12		114	55	169	29	45	0	45
Chedsey	32	2·81	0·81	135	1	136	12	32	0	32
Jolley	18	2·08	0·72	101	5	106	3	53	0	53
Little Muddy	32	3·00	0·87	89	8	97	44	107	9	116
Muddy	19	2·42	0·82	71	0	71	16	12	0	12
Service	10	1·35	0·59	127	0	127	2	3	0	3
Slater	19	1·95	0·66	113	2	115	5	4	0	4
Slater #2	35	2·90	0·81	98	4	102	25	58	0	58
South Fork Big	39	2·90	0·79	160	54	214	15	37	1	38
Red Dirt	31	2·76	0·8	88	22	110	27	25	0	25
West Fork	25	2·63	0·82	111	34	145	16	19	0	19
Summit	26	2·64	0·81	124	3	127	11	17	0	17
Rock Willow	27	2·64	0·8	92	3	95	36	60	0	60
Newcomb	33	2·94	0·84	58	28	86	28	49	0	49
Grizzly	34	2·79	0·79	99	87	186	12	19	0	19
Trout	31	2·90	0·84	94	50	144	57	34	0	34
Diverted										
Beaver	26	2·53		123	2	125	18	16	0	16
Chedsey	39	3·21	0·88	62	10	72	16	52	0	52
Jolley	12	1·95	0·79	94	17	111	0	26	1	27
Little Muddy	37	2·97	0·82	53	16	69	54	103	0	103
Muddy	30	2·90	0·85	75	9	84	14	40	0	40
Service	10	1·27	0·55	136	0	136	6	9	0	9
Slater	35									
Slater #2	26	2·83	0·87	88	19	107	16	69	0	69
South Fork Big	35	3·22	0·91	56	37	93	29	65	0	65
Red Dirt	28	2·84	0·85	112	15	127	18	28	5	33
West Fork	22	2·63	0·85	105	25	130	15	4	2	6
Summit	23	2·60	0·83	89	8	97	12	33	0	33
Rock Willow	40	3·13	0·85	71	19	90	19	77	3	80
Grizzly	41	3·18	0·86	72	30	102	20	46	2	48
Newcomb	30	2·82	0·83	49	38	87	14	33	0	33
Trout	36	3·03	0·85	85	60	145	52	64	3	67

Note: OBL, FACW, etc. indicate abundance of these categories of species, respectively. Gaps indicate missing data.

frequency value for each species. Chi-square analysis of overall species frequency, by species, indicates that seven of the eight wetland species (OBL or FACW) have significantly higher abundances upstream from the diversion, including three species in the genus *Salix* (willow) and one species in the genus *Carex* (Table IV). Additionally, six of the eight non-wetland, FACU or UPL species have significantly higher abundances downstream from the diversion. Significant increases in occurrence of upland species downstream of diversion include the forbs *Chamerion angustifolium*, and *Geranium richardsonii*, the grasses *Poa pratensis* and *Poa* spp., and *Pinus contorta*, the only conifer significantly different upstream and downstream from diversions. *Taraxacum officinale*, one of the few facultative (FAC) species in Table IV, is significantly more abundant downstream from diversions.

Grouping species by Wetland Indicator Category reveals a significantly higher frequency of wetland species upstream from diversion ($p = 0{\cdot}03$), and a marked increase (although not significant) in upland species downstream of diversion ($p = 0{\cdot}12$) (Fig. 4).

In summary, evenness is significantly greater downstream from diversions. Species composition at a point level differs significantly between control and diverted vegetation communities. Seven of the eight wetland species are significantly more abundant upstream from diversions, and six of the eight upland species are significantly more abundant downstream from diversions.

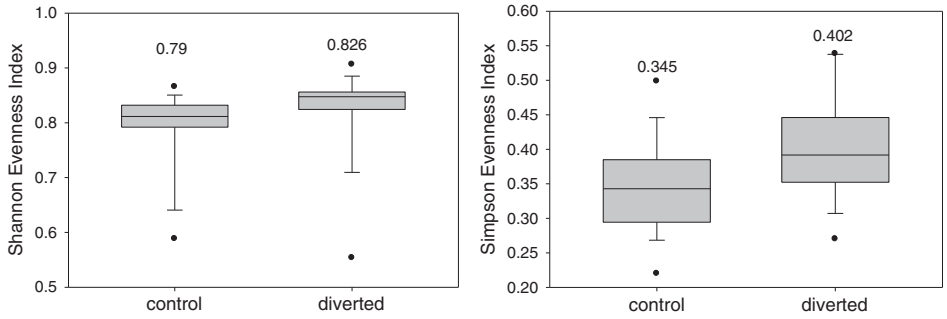

Figure 3. Shannon and Simpson evenness indices upstream and downstream of diversions. Mean value of each population is listed above the box. Sample size is 16 for all analyses.

Table IV. Results of chi-square analysis, sorted by wetland indicator status

Taxa	Life history	Wetland Indicator	*p*-Value	Frequency above	Frequency below	Direction of change
Carex utriculata (Northwest Territory sedge)	P	OBL	0	337	222	−
Mertensia ciliata (mountain bluebells)	P	OBL	0·003	34	13	−
Salix monticola (park willow)	W	OBL	0·008	30	12	−
Salix planifolia (diamondleaf willow)	W	OBL	0	90	47	−
Salix wolfii (Wolf's willow)	W	OBL	0	117	64	−
Veronica americana (American speedwell)	P	OBL	0·004	10	0	−
Deschampsia cespitosa (tufted hairgrass)	G	FACW	0	192	86	−
Equisetum arvense (field horsetail)	P	FACW	0	47	94	+
Ligusticum spp.		FAC	0·008	24	8	−
Ribus parviflorus (thimbleberry)	P	FAC	0·001	15	1	−
Taraxacum officinale (dandelion)	P	FAC	0·003	67	106	+
Abies lasiocarpa (subalpine fir)	W	FACU	0·002	36	13	−
Bromis inermis (smooth brome)	G	FACU	0·002	12	0	−
Chamerion angustifolium (fireweed)	P	FACU	0·005	8	25	+
Geranium richardsonii (Richardson's geranium)	P	FACU	0·009	19	40	+
Pinus ponderosa (ponderosa pine)	W	FACU	0·006	12	31	+
Poa pratensis (Kentucky bluegrass)	G	FACU	0	3	31	+
Poa spp.	G	FACU	0	37	83	+
Unknown	G	FACU	0	0	28	+

Note: Native plants are in bold font.
Under life history, G is graminoid, P is perennial, and W is woody.
OBL is obligate wetland species; FACW is facultative wetland species; FAC is hydrophyte species that occurs in both wetland and non-wetland habitats; FACU is facultative upland species.
Frequency above refers to frequency of this species above diversions (control reaches); frequency below refers to below diversions (diverted reaches).
Direction of change is + if species became more abundant downstream from diversion, − if species became less abundant downstream from diversion

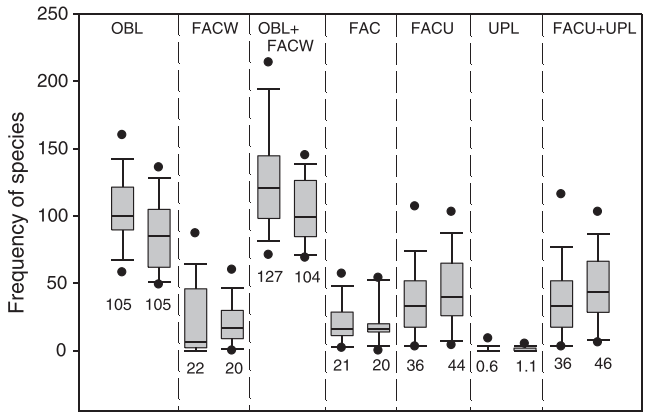

Figure 4. Number of occurrences of Wetland Indicator Categories for species upstream and downstream from diversions. In each set of box plots, the first box is upstream and the second is downstream. Sample size is 16 for each box, and mean value is given below the box.

With respect to differences in lateral and vertical zonation of riparian species (H3), the results indicate some significant differences. Diversity indices are not significant in any of the zones, although they are noticeably higher in the downstream of diversion group at the less than 100 cm above channel (elevation), and less than 300 cm away from channel (distance) (Table V). Evenness is significantly greater downstream from diversion for the less than 100 cm elevation above active channel, and the less than 200, 300, and 400 cm distance away from channel groups. Relative abundance of wetland species is significantly higher upstream from diversions, in all elevations zones tested except those closest to the channel, and all distance zones except for 100 to 200 cm distance away. Relative abundance of upland species is significantly higher downstream of diversion in one distance zone (200–300 cm distance) and is noticeably higher, although not significant, in almost every zone analyzed except for those closest in elevation and distance to the active channel. Species accumulation curves for the elevation and distance zones show a trend

Table V. Metrics with corresponding *p*-values for each elevation and distance zone analyzed

	Elevation or distance ranges (cm)	Simpsons diversity index	Simpsons evenness index	Wetland species relative abundance	Upland species relative abundance
Elevation above channel	< 25	0.926	0.503	0.352	0.872
	< 50	0.959	0.694	*0.000*	0.978
	< 75	0.156	0.176	*0.012*	0.128
	< 100	0.128	*0.020*	*0.019*	0.077
	25–75	0.147	0.338	*0.037*	0.226
	75–100	0.869	0.314	*0.021*	0.116
	75–150	0.778	0.493	*0.042*	0.140
Distance away from channel	< 100	0.573	0.173	*0.022*	0.698
	< 200	0.183	*0.049*	*0.019*	0.318
	< 300	0.063	*0.012*	*0.009*	0.083
	< 400	0.084	*0.033*	*0.008*	0.078
	100–200	0.333	0.309	0.098	0.093
	200–300	0.119	0.078	*0.005*	*0.037*

Note: significant values, $\alpha < 0.05$, are shown in italic typeface.
Wetland species = OBL + FACW.
Upland species = FACU + U.

starting with upstream of diversion having higher species richness at less than 25 cm above the channel. Richness is then increasingly greater downstream of diversion going from the < 50 cm to < 75 cm zones, becoming closer to even at the < 100 cm zone (Fig. 5).

Species frequency analyses through chi-square testing for several elevation zones indicates that, at 25 cm, only one species (*Salix wolfii*) has significantly higher frequency upstream from diversions (Caskey, 2013). At < 50 cm above active channel, four species have significantly higher frequencies upstream from diversions; *Carex utriculata*, *Deschampsia cespitosa*, *Salix planifolia*, and *Salix wolfii*. No species has significantly greater frequencies downstream of diversion in this elevation zone. At < 75 cm above active channel, *Pinus contorta*, *Poa pratensis*, and an unknown graminoid, which are all upland species, occur only downstream from diversion. Additionally, the weedy generalist species *Taraxicum officinale* is more abundant downstream from diversion.

Species accumulation curves for the distance zones of < 1 m, 2 m, 3 m and 4 m indicate a trend from higher species richness nearest to the channel upstream of diversion, to similar in the < 2 m zone, to slightly higher richness downstream of diversion in the < 3 m zone, and a noticeably higher richness downstream of diversion in the < 4 m zone (Caskey, 2013).

ANOSIM, MRPP, and permutational MANOVA analyses show no significant differences in species composition between upstream and downstream reaches based on vertical distance above or lateral distance away from active channel.

Logistic regression for elevation above the channel indicates a higher probability of occurrence of wetland vegetation species upstream from diversions, as well as greater difference in probability closer to the channel, decreasing with increasing elevation above active channel (Fig. 6). The *p*-values associated with the topography variable for elevation (EL – β1) show that all of the Wetland Indicator Categories except UPL species are significantly related to elevation above the channel,

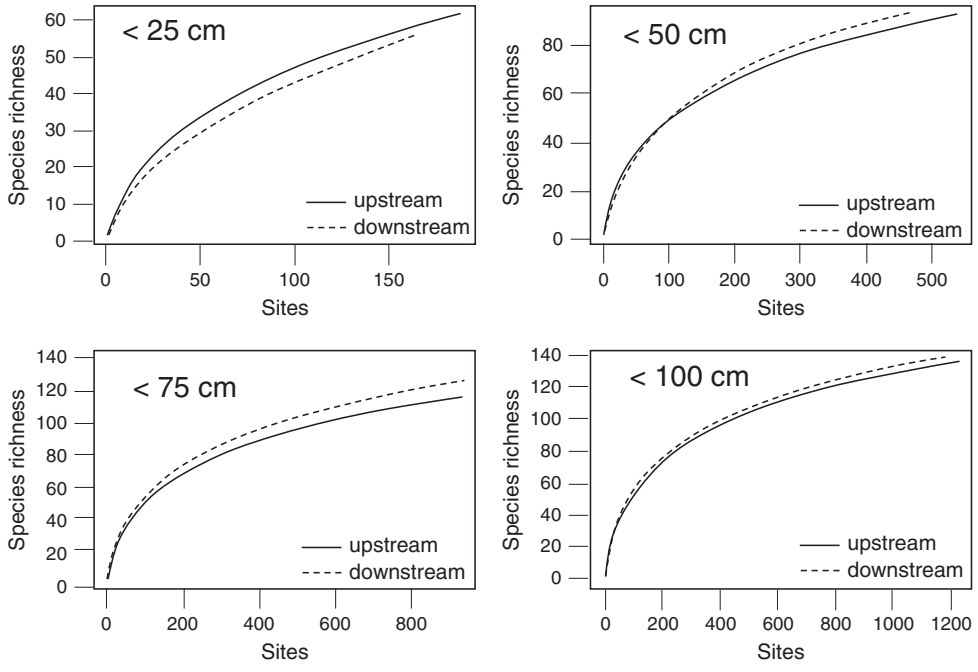

Figure 5. Species accumulation curves for four zones with respect to elevation above the channel.

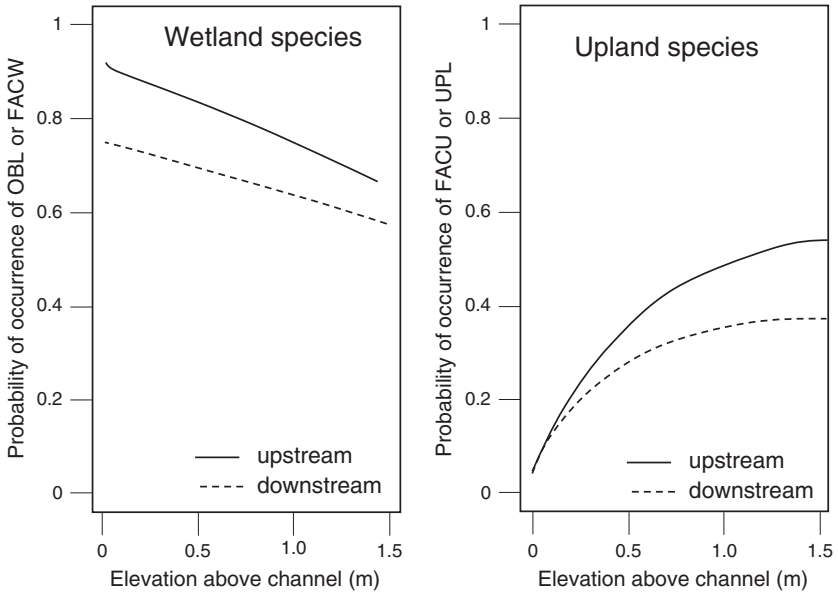

Figure 6. Logistic regression fits for probability of species occurrence versus distance above channel.

although none are significantly different between upstream and downstream from diversion, as indicated by the *p*-value of the interaction term (EL*Div – β3) (Table VI). We evaluated elevation significance of the logistic regression for all species, and 31 plant species are significantly related to elevation above the channel (Caskey, 2013). Significant difference between species probability as a function of elevation above the channel between upstream and downstream from diversion was found in 14 species (Caskey, 2013). The obligate hydrophyte and facultative wetland species *Carex aquatilis* and *Deschampsia cespitosa* have higher probability of occurrence upstream from diversion up to 1 m above the active channel, whereas the non-hydrophyte *Achillea millefolium* has a greater probability of occurrence near the channel downstream of diversion, with zero probability of occurrence upstream below 0·4 m elevation.

Logistic regression for distance from channel indicates that FACU, FAC and FACW species have probabilities of occurrence significantly related to distance from the channel, with the Wetland Indicator Category of FACW species also being significantly different upstream and downstream from diversions as a function of distance from the channel (Table VII). Fig. 7 indicates that the FACW group actually has a higher probability of occurrence as a function of distance up to 3.9 m, where the curves intersect and upstream from diversion probability becomes greater.

In summary, some species typically considered wetland or upland indicators differ significantly in lateral and vertical zonation between reaches upstream and downstream from diversions. Evenness is significantly greater downstream of diversion for some laterally and vertically zoned groups, but not all. Relative abundance of wetland species is significantly higher upstream from the diversions in almost all elevation and distance zones. Upland species relative abundance is significantly higher downstream of diversion in one zone. A few wetland species are significantly more frequent upstream from diversions, whereas three upland species are significantly more frequent downstream from diversions. Two wetland species have higher probability of occurrence upstream from diversions, whereas one upland species has a greater probability of occurrence near the channel downstream of diversions. Wetland and upland species have probabilities of occurrence significantly related to distance from the channel.

Discussion

Channel geometry

The statistical analyses indicate that diversions can have a discernible effect on the channel geomorphic parameters measured

Table VI. Wetland indicator status logistic regression coefficients and *p*-values

	Intercept (β_0) $p <$		Elevation (β_1) $p <$		Diversion (β_2) $p <$		Elev*div (β_3) $p <$	
OBL	−1·4575	0·0000	−0·4762	0·0040	−0·8281	0·0000	0·1847	0·4044
FACW	−1·0560	0·0000	−0·5619	0·0034	−0·1198	0·5151	0·3005	0·2576
FAC	−1·7840	0·0000	0·6156	0·0004	0·3065	0·1053	−0·4798	0·0544
FACU	−1·4561	0·0000	0·8375	0·0000	0·1814	0·2850	0·2977	0·1854

Table VII. Logistic regression coefficients and *p*-values for significant wetland indicator groups as a function of distance from the channel

Species	Intercept (β_0) $p <$		Distance (β_1) $p <$		Diversion (β_2) $p <$		Dist*div (β_3) $p <$	
FACW	−1·6358	0·0000	0·0812	0·0043	0·3908	0·0122	−0·1142	0·0053
FAC	−1·6156	0·0000	0·0722	0·0115	0·0658	0·6799	−0·0204	0·6165
FACU	−1·2086	0·0000	0·0920	0·0003	0·5586	0·0000	−0·0486	0·1668

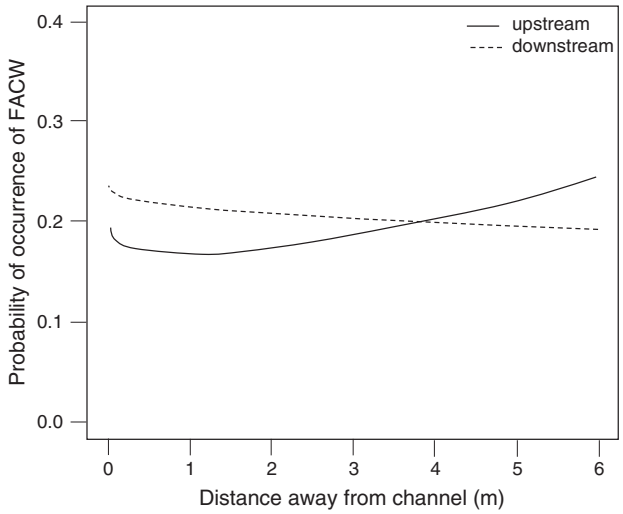

Figure 7. Logistic regression plot for FACW species as a function of distance from the channel.

in this study. The group comparisons indicate that diverted streams become slightly less sinuous, with the most pronounced changes in willow-dominated riparian zones. Reduced sinuosity in these diverted streams may reflect lower ability to locally erode the banks and preserve meander bends. Width, depth, and cross-sectional area differ significantly between control and diverted streams in the second set of mixed effects models, which adjusted for drainage basin size. We emphasize the results from this model, rather than from the group comparisons or first set of mixed effects models, because we believe the second set of mixed effects models more realistically evaluates the complex relationships among interacting variables that influence patterns in channel morphology upstream and downstream from diversions. In summary, diverted streams appear to become narrower and more homogeneous, as suggested by narrower variance for width, depth, and cross-sectional area in the diverted group than in the control group of streams.

The significance of these statistical analyses is particularly interesting given three factors that might have reduced potential differences between control and diverted streams. The first of these is the wide range of alterations in flow associated with diversions in the study area. Diversions completely dewater channels such as Little Muddy and Service Creeks for some portion of the year, whereas observations during the 2011 and 2012 field seasons suggest minimal reductions in peak flow along other channels. The second potential complication was the fact that the year 2011 was among the highest magnitude and most sustained peak flows on record at gaged sites throughout this area of northern Colorado. During the first year of data collection, we suspected that these high flows might have re-set channel morphology altered during preceding years of reduced peak flows. Because the flow diversions in the study area are primarily for local irrigation, diversion is seasonal and proportionally lower during wet years or years of abundant snowmelt. Finally, groundwater inputs downstream from the diversion point might be expected to ameliorate some of the effects of reducing stream flow (McCarthy, 2008). The Service Creek Reach, for example, is located in a wet meadow. Despite these potentially complicating effects, stream reaches downstream from diversions display significant alterations in channel morphology.

Riparian vegetation

The numerous statistical analyses conducted on the riparian vegetation data indicate clear differences in riparian communities downstream from diversions. Species richness does not change significantly downstream from diversions, but this likely reflects the increased presence of upland species in the riparian areas downstream from diversions. Seven of the eight wetland species examined are significantly more frequent upstream from diversions, and six of the eight upland species are significantly more frequent downstream, as is one weedy, invasive, generalist species (*Taraxicum officinale*). The change in species dominance downstream from diversions is an important indicator of a systemic shift in riparian community composition and suggests that riparian areas downstream from diversions are becoming terrestrialized as a result of flow alteration. Riparian vegetation may have responded more strongly to flow diversion than did channel geometry because the high flows that maintain key components of channel geometry are less influenced by diversions, particularly when occasional high flows are allowed to bypass diversions during years of abundant snowmelt, whereas diversion during warm, dry periods can particularly stress riparian vegetation.

Exposure to physical processes that can structure riparian communities, including frequency, magnitude and duration of inundation and erosion and deposition of substrate, varies in relation to elevation above and distance away from the channel. Analyses of riparian vegetation in relation to elevation and distance suggest that much of the shift in community composition is occurring between 0·25 and 1 m above the channel. The abundance of wetland species closest to the channel ($<0{\cdot}25$ m above the channel) does not differ significantly between control and diverted reaches, and the most significant differences occur in the zones $<0{\cdot}75$ m above the channel. Distance from the active channel does not determine species composition patterns as strongly as elevation. For distances of 2 to 4 m from the channel, however, the decreasing frequency of wetland species downstream from diversions becomes more significant with increasing distance from the channel. This suggests that wetland species are being outcompeted as upland species encroach in response to increasing habitat suitability, likely a decrease in soil moisture. Elevation above and distance away from the channel are interrelated, but the results support H3 in suggesting that moisture gradients downstream from diversions favor upland species at the expense of wetland species.

Management implications

Collectively, the hundreds of thousands of intrabasin and transbasin diversions throughout the American West have cumulative effects on riparian ecosystems that would be difficult to quantify. These effects could collectively account for changes similar to those imposed by large dams in terms of areal extent of conversion from obligate and facultative wetland-dominated riparian areas to more xeroriparian areas. Many, mostly smaller, diversions extract water from streams without impounding and storing significant volumes of water. On those run-of-river diversions that pass peak flows, the magnitude and timing of peak flows may be little altered, but the low flow segment of the hydrograph may be significantly altered. In contrast, large storage facilities, which commonly reduce the magnitude of peak flows significantly and alter the timing of the attenuated peaks that pass, potentially increase base flow, and alter daily variability in flows. Several studies have shown that large storage facilities may reduce the frequency of creation and the extent of open patches which colonizing riparian species rely upon to become established, while at the same time increasing the duration of flooding near the channel and enhancing habitat for hydric species (e.g. Merritt and Cooper, 2000). Downstream from diversions, however, regenerative habitat may be available, but the

low flows to support extant native hydric vegetation may be altered. This could favor ruderal, weedy species and explain the reduction in obligate wetland species downstream from diversions. Obligate riparian species tend to be ecological specialists with life history traits that are closely tied to the natural hydrologic regime. Obligate plants could thus be predicted to be more vulnerable to diversion, whereas some facultative plants could actually benefit, as our results indicate. This is consistent with patterns of downstream impacts from river damming (Rood *et al.*, 2010).

Our findings suggest that diversion-induced flow alteration is altering channel geometry and riparian vegetation communities in the lower gradient stream segments of this semi-arid, mountainous region. Natural patterns of lateral and longitudinal connectivity are integral to sustaining populations of many riverine species (Bunn and Arthington, 2002), but our results indicate that both channel geometry and vegetation in the study area are becoming homogenized downstream from diversions, similar to the homogenization of flow (Poff *et al.*, 2007), fish (Moyle and Mount, 2007), and wetlands (Lougheed *et al.*, 2008) in environments around the world. As hydrophytic species decrease in abundance downstream from diversions, this could impact processes such as allochthonous energy inputs, stream temperatures, and the ability of exotic species to colonize riparian zones (Bunn and Arthington, 2002). The effects of flow diversion could also potentially be exacerbated by climate change, which is projected to result in warmer temperatures and earlier snowmelt peaks in the study area (Stewart *et al.*, 2005). Because many riparian species have dispersal, germination or other reproductive traits adapted to the timing of peak flows, the stresses associated with flow diversions could influence riparian community composition even more in the future (Lytle and Poff, 2004). Although our study did not evaluate how far downstream from each flow diversion the observed changes exist, the large number of diversions on streams in the study area and in other mountainous watersheds of the western United States suggests that the cumulative effects of diversion-induced changes in river systems are likely to be substantial.

Management of diversions and mitigation of their effects could focus on quantifying the effects of individual diversions on flow regime by installing discharge gages, developing a record of daily flows upstream and downstream from diversions, or just within the diversions, and using a comparative analysis such as Indicators of Hydrologic Alteration (Richter *et al.*, 1996). Stream segments likely to have greater biodiversity, such as partly confined and unconfined valleys, could be targeted for protection from future diversions or for moving existing diversions to less sensitive stream segments. Finally, ensuring that diversions have proper oversight, especially during periods when hydrograph triggers are most important for riparian species, could help to ensure that at least some peak flows are allowed to reach stream reaches downstream from the diversion.

Conclusions

Many of the world's rivers are affected by direct flow alteration, primarily by dams and diversions, yet the impacts of the latter on channel geometry and riparian plant community composition and diversity have received little attention and are not well understood.

Diversions extract water from streams without impounding flow. Diversions do not necessarily alter the shape of a hydrograph, but they can reduce peak and base flow, thereby changing the abiotic factors to which stream and riparian ecosystems have adjusted. Many riparian plant species are adapted to the unique timing, magnitude and duration of the natural flow regime, implying that changes in flooding disturbance and water availability could lead to decreased suitable habitat and invasion by upland and/or exotic species (Bunn and Arthington, 2002; Naiman *et al.*, 2005). Developing an understanding of the effects on riparian vegetation by diversion-induced flow alteration is important to better managing the timing, magnitude and duration of withdrawals in order to sustain native riparian communities and beneficial ecosystem services, and to focus future study on specific thresholds of hydrologic alteration resulting in community change.

Many studies have examined the effects of dams on riparian areas, but this work is the first to investigate changes in plant community composition as a result of diversion. We found that several channel morphologic parameters, and the proportion of the riparian vegetation community composed of characteristically wetland versus upland species, differ significantly downstream from diversions. Our findings that diversions significantly alter downstream channel morphology and riparian vegetation communities at the local scale suggests that the cumulative, watershed-scale effects of diversions on numerous headwater channels are likely to be important. More intensive, site-level studies quantifying the hydrology and functional characteristics of the plants are necessary to characterize the particular aspects of the flow regime necessary to sustain healthy riparian plant communities and populations, as well as identifying the response thresholds at which effects of altered hydrology significantly influence the composition and functioning of these ecosystems. Further, such information may be used to encourage minor adjustments in the management of diversions that provide for specific life history requirements of riparian species and encourage ecological recovery with little cost in terms of quantity of flow.

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