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INCREASING RIVER FLOW EXPANDS RIPARIAN HABITAT: INFLUENCES OF FLOW AUGMENTATION ON CHANNEL FORM, RIPARIAN VEGETATION AND BIRDS ALONG THE LITTLE BOW RIVER, ALBERTA

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ABSTRACT

With river regulation, water withdrawal is common, reducing instream flows. The opposite alteration, flow augmentation, is less common and could reveal a mechanistic coordination between flow regime, channel form, and riparian ecosystems. The Little Bow River, a naturally intermittent prairie stream in Southern Alberta, has experienced flow augmentation since the late 1890s, and the Little Bow/Highwood Project of 2004 enabled a tripling of diversion flows from 2.9 to 8.5 m^3/s. We investigated the subsequent responses by assessing the channel form and riparian vegetation based on aerial photographs taken in 2000 versus 2010, and riparian birds were assessed between 2005 and 2013 to investigate associations with riparian vegetation. Following recent flow augmentation, the mean channel width increased from 12.2 to 13.5 m, while sinuosity was relatively unchanged. Streamside zones with true willows (especially *Salix exigua* and *Salix bebbiana*) increased from 7 to 11% of the river corridor, and the facultative riparian wolf willow (*Elaeagnus commutata*) zones increased from 16 to 20%, while grassy zones decreased from 64 to 52%. Avian species richness and Shannon–Wiener index increased, while species evenness was relatively unaltered, suggesting an increase of rarer bird species in response to the increased habitat structure and diversity following the expansion of riparian shrubs and woodland. This study revealed responses to the recent flow augmentation over the first decade of implementation, and alterations following flow augmentation would likely continue for decades until the river and riparian zones adjust to the new flow regime.

KEY WORDS: avian; flow regulation; habitat heterogeneity; instream flows; shrubs; sinuosity; willows

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INTRODUCTION

River regulation is prominent worldwide, with flow regimes having been altered in nearly all major river systems in the Northern Hemisphere (Leyer, 2005). River systems are typically altered through damming and water diversion, often resulting in reduced summer flows and peak flow attenuation. Less commonly, regulated rivers may undergo flow augmentation, in which annual flows are increased, especially during the summer months for the conveyance of water for irrigation agriculture (Bradley and Smith, 1984; Rood *et al*., 2005).

There have been relatively few studies following flow augmentation, and these have generally focused on the responses in river channel form. After more than a decade of augmentation, with increases ranging from 1.5 to 4 times the base flow discharge (Q_{base}), channel widths increased along the Milk River, Alberta (Bradley and Smith, 1984); Upper Arkansas River, Colorado (Dominick and O'Neill, 1998); La Poudre Pass Creek, Colorado (Wohl and Dust, 2012); and a few other Canadian rivers (Kellerhals *et al*., 1979). Channel bed substrates often coarsened as stream power increased (Dominick and O'Neill, 1998; Wohl and Dust, 2012) and meander cut-offs decreased planform sinuosity (Kellerhals *et al*., 1979). While channel expansion was generally consistent in the prior studies, the responses of different rivers to flow augmentation will probably also reflect the particular geology, hydrology, and ecology of the river system.

The responses of riparian ecosystems to flow augmentation have had very limited investigation. Following substantial augmentation (>3× Q_{base}), the Nechako River in British Columbia became entrenched, and this depressed the alluvial groundwater table, resulting in the dieback of riparian willows (Kellerhals *et al*., 1979). Along the Upper Arkansas River in Colorado, the total vegetated riparian area decreased, while the floodplain was restructured (Dominick and O'Neill, 1998). Alternately, under moderate augmentation (<2× Q_{base}), inundation-tolerant sedges increased along the South Fork Middle Crow Creek in Wyoming (Henszey *et al*., 1991).

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The phreatophytic nature of obligate riparian shrubs and trees, such as willows and poplars (Rood *et al.*, 2011a, 2011b), suggests that these woody plants could benefit from increased water availability with increasing streamflows. For other plants, the stabilization of water table fluctuations might transition drought-tolerant species up the elevational profile away from the stream, while inundation-tolerant species could increase at the lower positions (Bendix, 1999; Leyer, 2005). As flow augmentation would elevate and stabilize the alluvial water table through the summer season, similar outcomes would be predicted, with obligate riparian trees and shrubs benefiting and possibly out-competing facultative riparian shrubs (Rood *et al.*, 2010). Subsequently, because native woody vegetation with high levels of habitat heterogeneity produce the greatest diversity of bird species (MacArthur and MacArthur, 1961; Scott *et al.*, 2003), moderate flow augmentation might increase avian diversity (Rood *et al.*, 2003a).

To investigate the responses of channel form, riparian vegetation, and riparian birds to flow augmentation, this study was undertaken along the Little Bow River in Southern Alberta. Longitudinal patterns were investigated to consider possible transitions in channel characteristics, vegetation, and avian communities along this corridor that links sequential elevational ecoregions (Samuelson and Rood, 2011). Our study extended over a decade, allowing the identification of initial responses to the most recent flow augmentation. At the onset of the most recent project, we predicted that (1) the channel would widen to accommodate the increased flow and sinuosity would decrease following meander cut-offs; (2) riparian vegetation would generally increase and there would be a transition from facultative to obligate riparian species following the increased water availability; and (3) avian communities would increase in abundance and diversity in response to the expansion of riparian shrubs and trees.

METHODS

Study river

The Little Bow is a small prairie river, with the First Nations name, 'Namaghty', or the 'Naked River'. This reflected the natural absence of riparian shrubs or trees, probably due to a naturally intermittent flow regime. The river has a very unusual origin, as it commences directly in the town of High River, Alberta (Figure 1). The Little Bow River is an under-fit stream and flows along a relatively large valley, as it may represent a prior path of the adjacent and much larger Highwood River (Rood *et al.*, 2005). Below High River, the Little Bow receives inflow from snowmelt and rainfall run-off from the east slope of the Porcupine Hills, a foothill extension east of the Rocky Mountains. The Little Bow River drains 1963 km^2 of the mixed grassland natural sub-region, and land use is predominately cattle grazing with some dryland and irrigation agriculture.

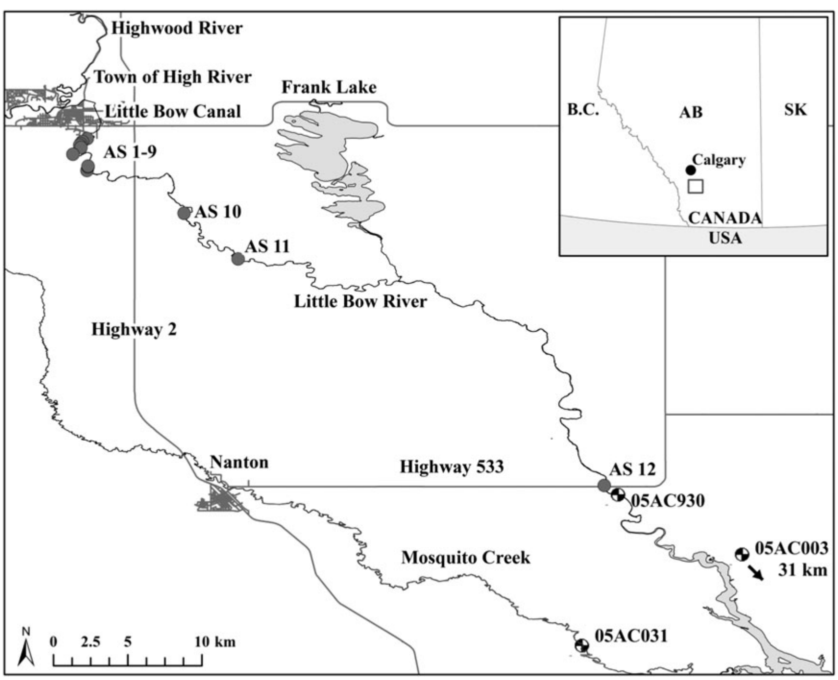

Figure 1. Study area along the Little Bow River, Alberta with avian survey sites (● AS 1-12) and streamflow gauging stations (05AC003, 05AC031, and 05AC930) indicated

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The Little Bow River is interconnected both naturally and artificially with the Highwood River in the Town of High River. Naturally, the Little Bow River conveys some groundwater contributions, and overland flood flows from the adjacent Highwood River. Artificially, diversion of water from the Highwood River through the 4-km-long Little Bow Canal and into the Little Bow River commenced in the late 1890s. The diversion headworks and canal were periodically upgraded, and in 2004, the Little Bow/Highwood Project (the most recent 'Project') was implemented, increasing the diversion capacity from 2.85 to 8.5 m^3/s. Augmentation of flows occurs primarily during the summer growing season (May to October) but occasionally persists into the winter months pending environmental flow requirements. This study was subsequently undertaken along 57.5 km of the upper Little Bow River, from the outflow of the expanded Little Bow Canal, downstream to the Highway 533 Bridge, which is located shortly upstream from the new Twin Valley Reservoir, an additional component of the Project (Figure 1).

Hydrologic record

Historic discharges along the Little Bow River were assessed from the gauging station near Carmangay (#05AC003; from Environment Canada on-line HYDAT archive), downstream from the outflow of Mosquito Creek (Figure 1). Since the new Twin Valley Dam regulated flows at that location, comparable discharges after the Project implementation were calculated by adding flows at a newer gauging station at Highway 533 (#05AC930) and Mosquito Creek at the Mouth (#05AC031). Seasonal (May to October) minimum and mean discharges, and annual maximum daily discharges (peak flows; ice-free intervals only) were compiled for 58 years from 1955 to 2012.

Analyses of aerial photographs

Aerial photographs from 2010 were obtained from the Alberta Environment Air Photo Record System (#AS5517/5518; 1:20 000 Colour). These were georectified to an orthophoto mosaic with coverage of the study area in 2000, distributed by North Western Geomatics (Calgary; 1:50 000 Colour). Georectification involved a minimum of 30 ground control points and maximum root mean square error of 2.5 m.

Channel form along the Little Bow River was investigated through the delineation of channel width and calculation of sinuosity index from aerial photo datasets for 2000 and 2010. Channel widths were measured from wetted perimeters at 100-m intervals. Sinuosity index was calculated over 400-m intervals, representing the current channel form rather than the larger paleo-channel meanders (Bigelow, 2006).

Predominant riparian vegetation types were classified at 100-m intervals from the aerial photo datasets. The interpretation was validated by field visits to multiple transect sites that had been established along the river (Rood *et al*., 2003b), combined with photographs from an airplane flight at 200 m above the river, which provided sufficient resolution to discriminate the shrub types. Subsequently, the predominant vegetation type along both right and left banks of each interval was classified as one of five categories: (1) riparian woodland (with trees); (2) true willows (*Salix* spp.); (3) wolf willow (*Elaeagnus commutata*); (4) graminoid or grass-type zone (with grasses (Poaceae) and grass-like plants, including sedges (Cyperaceae) and rushes (Juncaceae), USDA Plants, http://plants.usda.gov/growth_habits_def.html); or (5) cattail (*Typha latifolia)*. Classifications were converted to the proportion of each vegetation type per kilometre segment.

Bird surveys

Avian communities were surveyed in 2005, 2006, 2007, and 2013 at 12 sites representing the range of riparian vegetation types (Figure 1). Waterfowl were excluded from surveying, because populations along the Little Bow River are supplemented by the adjacent Ducks Unlimited project at Frank Lake. Fixed radius point surveys of 10-min duration and 50-m radius employing both sight and sound were conducted twice during the breeding season (late-May and mid-June), each at two locations per site. Surveys were conducted within the first 3 h of daylight and under clear weather conditions.

Assessed avian site characteristics included distance downstream from the Little Bow Canal, alterations to the channel width, cattle grazing regime (ungrazed, previously grazed, or grazed), prominent vegetation type, and subsequently relative vertical structure, coded as riparian woodlands (4), true willows (3), wolf willow (2), or grass-type/cattails (1).

Statistical analyses and ordination

Statistical analyses with SPSS Statistics v.19 (IBM, 2010) provided outcomes categorized as not significant (n.s.: $p > 0.1$), trend (t: $p < 0.1$), significant (*: $p < 0.05$), or highly significant (**: $p < 0.01$). From regression or model coefficients of determination (R^2), we assessed associations as strong (>0.5; >50% correspondence), moderate (0.5 to 0.2), slight (0.2 to 0.1), or weak (<0.1). For channel and vegetation characteristics, analyses of covariance (ANCOVAs) were undertaken with the distance downstream from the Little Bow Canal as the covariate. Year was the primary factor in comparing pre-Project (2000) versus post-Project (2010) conditions.

Avian survey data were compiled in PC-ORD v.16 (McCune *et al*., 2002), considering species richness and evenness, and the Shannon–Wiener index, a composite

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measure of diversity (both richness and evenness). ANCOVAs assessed the baseline (2005) versus post-Project (2013) diversity measures, with log-transformed distance as the covariate and excluding the 57.5-km site that was only surveyed in 2013. Avian community structure at survey sites was visualized within ecological space, to account for the limitations of the Shannon–Weiner index in dealing with rarefaction. Non-metric multi-dimensional scaling (NMDS with PC-ORD; Sorenson distance, 500 iterations, maximum three dimensions) visualized the baseline (2005), intermediate (2006/2007), and post-Project (2013) avian community compositions at sites, based on species sightings (McCune *et al*., 2002). Species sightings were relativized by the observed maximum for each species, equally weighting rare and common bird species, and accounting for variation in the detectability of certain species (McCune *et al*., 2002). Analysis was paired with an explanatory matrix of site characteristics. Survey sites were plotted within species abundance space, with associations of sites being further explained by vectors of site characteristics.

To further explore bird species associations, canonical correspondence analysis (CCA with PC-ORD; WA scores, maximum two dimensions) was undertaken (McCune *et al*., 2002). This constrained ordination was guided by the life history characteristics of each species, including riparian dependency (obligate, dependent, or facultative), story of occupation (under, middle, or upper), nesting substrate (ground, shrub, tree, cavity, or structure), diet (granivorous, insectivorous, omnivorous, or carnivorous), and migratory nature (resident, short distance, medium distance, or long distance). Provisional riparian dependencies were determined from previous classifications (Bureau of Land Management, 1998) and life history characteristics (Ehrlich *et al*., 1988; Cornell Lab of Ornithology, 2015). Species abundances were relativized by the maximum sighting of each species. Sora (*Porzana carolina* L.) sightings were removed from this analysis since this bird uniquely utilizes floating nests and was a distant outlier in ordinations, compressing the plotting of the other species. Associations of species were plotted within site space, and explanatory life history characteristics ($R^2 > 0.1$) were indicated with vectors.

RESULTS

Hydrologic record

Diversions of water from the Highwood River into the Little Bow River and into Mosquito Creek commenced in 1898 before any discharge gauging of the Little Bow River. As a consequence, the natural flow pattern can only be deduced, and the entire hydrologic record reflects flow augmentation.

The annual maximum (peak) flows declined in the half-century prior to the Project (Figure 2). This partly reflects diking along the larger Highwood River to reduce overland flows around the Town of High River and into the Little Bow River. Following the Project, there were apparently

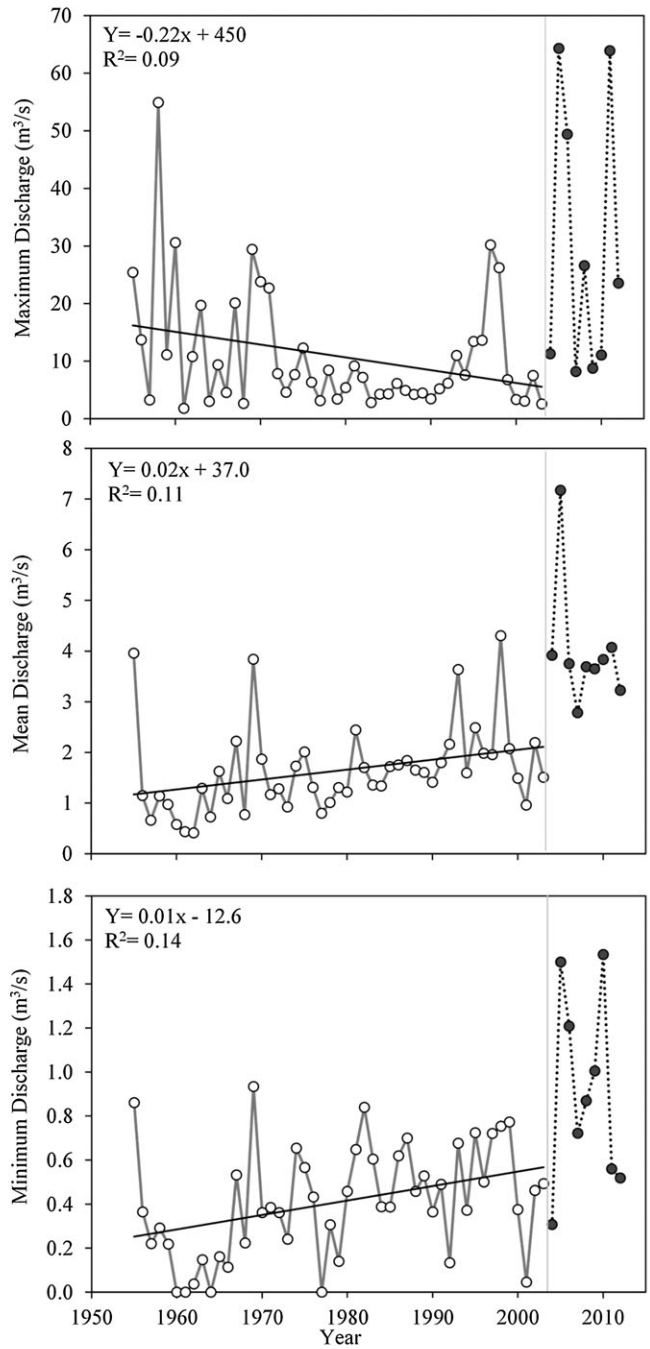

Figure 2. Annual maximum daily (top), seasonal (May–October) mean (middle), and seasonal minimum (bottom) discharges along the Little Bow River, Alberta. Pre-Project discharges (○, 1955 to 2003) were gauged at Carmangay, while post-Project discharges (●, 2004 to 2012) are calculated (refer to the "Methods" section) and not directly comparable, especially for the maximum discharges. Linear regressions are for the pre-Project interval

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higher peak flows, but this record is confounded because there would be peak broadening as pulses extended downstream from the location of the new gauge (Highway 533) to the longer term Carmangay gauge (Figure 1). In the region, major floods occurred in 1995 and 2005, and these are reflected in the peak flow record. Both the 2000 and 2010 aerial photographs would thus have been taken about 5 years after flood flows.

The seasonal mean and minimum discharge records (Figure 2) would be less confounded than the peak flow record and are more comparable in the pre-Project versus post-Project intervals. In the half-century prior to the Project, seasonal mean flows progressively increased, reflecting increases in the extent of augmentation and downstream irrigation demands. Seasonal mean flows abruptly increased following the Project implementation in 2004 and remained elevated thereafter. The pattern for the minimal flows during the plant growth interval also displayed progressive increase in the half-century prior to the Project and then further increase in the post-Project interval.

Channel form responses to flow augmentation

Channel width was somewhat variable along the Little Bow River and progressively increased downstream, with widths nearly doubling between High River and the Highway 533 Bridge (Figure 3). Channel widths increased following the implementation of the Project (mean = 13.5 ± 0.26 vs. 12.2 ± 0.30 m; $F_{(1,1150)} = 12.21$, $p < 0.01$), with relatively consistent widening along the downstream corridor. The sinuosity index progressively decreased along the study reach (Figure 3), and the post-Project index (mean = 1.22 ± 0.02) remained comparable with the pre-Project conditions (1.21 ± 0.02; $F_{(1,288)} = 0.25$, $p = 0.62$).

Riparian vegetation

Along the river, the five dominant riparian vegetation types displayed longitudinal patterns (Figure 4). Within the first 10 km downstream from the Little Bow Canal inflow, there were patches and bands of riparian woodlands consisting of primarily naturally seeded balsam poplar (*Populus balsamifera* L.) and trembling aspen (*Populus tremuloides* Michx.) and at a few locations introduced box elder (or Manitoba maple; *Acer negundo* L.). The riparian woodlands dropped off abruptly with only a few small patches downstream associated with farmstead or shelterbelt plantings.

There was a progressive longitudinal pattern for riparian shrublands with true willows, primarily composed of facultative riparian Bebb's willow (*Salix bebbiana* Sarg.) and obligate riparian sandbar willow (*Salix exigua* Nutt.) (Figure 4). The true willows were most abundant just downstream from the woodlands and subsequently declined along the study reach.

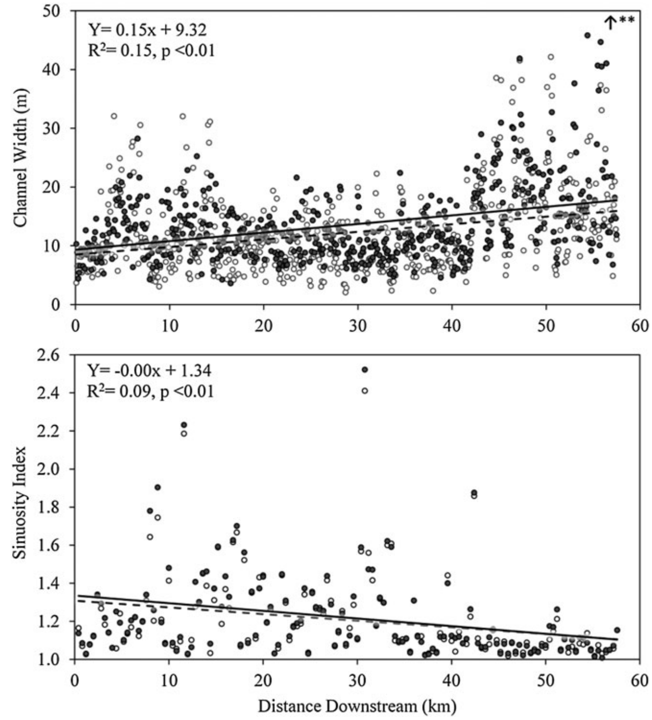

Figure 3. Channel width (top) and sinuosity index (bottom) along the Little Bow River in 2000 (○, dashed lines) and 2010 (●, solid lines) following river flow augmentation. Linear regressions lines are plotted, and equations are provided for the 2010 results, and for the channel width, ANCOVA indicated increased width in 2010 (↑**: $p < 0.01$)

Wolf willow (*E. commutata* Bernh.), a facultative riparian shrub, was variable but often abundant along the river (Figure 4). This shrub was fairly common along the full study reach, often representing a quarter to one half proportion of the riparian segments, with a trend towards declining occurrence downstream. Grassland zones provided the most common vegetation type along the river (Figure 4), and these included a combination of native and introduced grasses and other graminoids, and particularly sedges (*Carex* spp.) and rushes (*Juncus* spp.) in lower and wetter positions. Along slack water areas, the emergent cattail (*Typha latifolia* L.) occurred especially in the lower segments (Figure 4), where the stream gradient declined.

In comparing the pre-Project (2000) versus post-Project (2010) vegetation, there was little evidence of change in the woodland occurrence ($F = 0.03$, $p = 0.87$; vegetation ANCOVAs, $F_{(1,114)}$; Figure 4). The true willows increased substantially ($F = 4.36$, $p = 0.04$), almost doubling. Wolf willow displayed an increasing trend ($F = 2.76$, $p = 0.10$), with apparently consistent change along the study reach. Opposing these increases in the two shrub communities, the proportion of riparian grassland declined ($F = 14.36$, $p < 0.01$), typically by about one quarter along the reach. Finally, the cattail segments displayed an increasing trend ($F = 2.68$,

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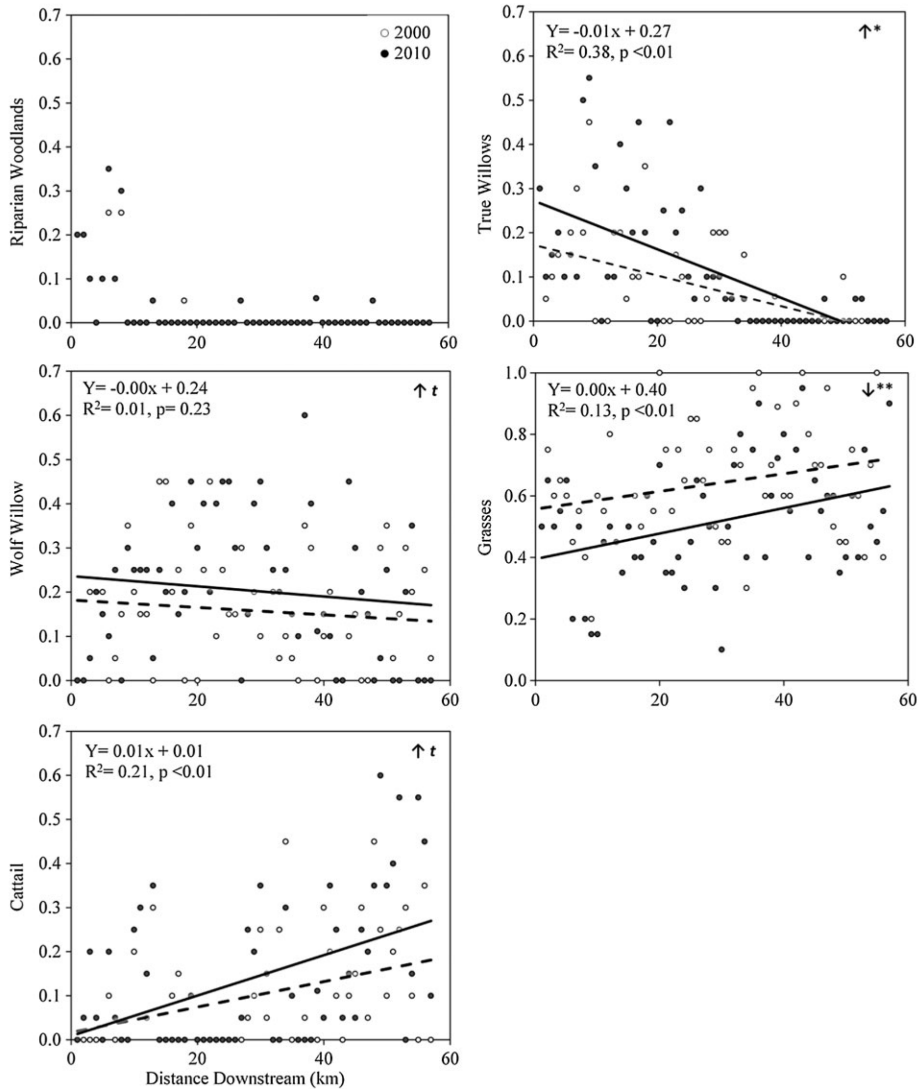

Figure 4. Riparian vegetation types along the Little Bow River in 2000 (○, dashed lines) and 2010 (●, solid lines) following additional river flow augmentation. Linear regression lines are plotted, and equations are provided for the 2010 results. The arrows (↑↓) indicate increases or decreases in 2010, with ANCOVA significance (t: $p < 0.1$; *: $p < 0.05$; **: $p < 0.01$)

$p = 0.10$), which was apparently greater along the downstream zones.

Riparian birds and avian response to flow augmentation

We observed 44 bird species along the Little Bow River (Table I). Of these, 32 were observed in association with the woodlands, which included riparian trees along with shrubs. Twenty-six species were observed in the shrubland zones that included true willows, and 18 species were observed in the other vegetation habitat types. Most of the birds are assessed as facultative riparian birds, with 29 species, while 7 species are assessed as riparian dependent and 8 are considered as more restricted, obligate riparian species. The avian communities along the Little Bow River were composed of both migrant and resident species.

Although there were more bird species observed at the woodland and willow zones that occur at the upstream end of the study reach (Figure 4), across the subsequent sites, the richness or species numbers did not display a consistent pattern along the longitudinal corridor (Figure 5). Due especially to single species in two upstream sites in 2005, there was an apparent decreasing longitudinal trend in evenness ($R^2_{2013} = 0.13$, $p = 0.07$; not shown) and subsequently the integrative Shannon–Wiener index (Figure 5). The trend prompted the ANCOVAs with river distance as the covariate, which revealed a highly significant increase in species richness from the baseline assessment in 2005 to the post-

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Table I. Avian species identified along the Little Bow River, Alberta between 2005 and 2013, with information about reported riparian habitat preferences and observed occurrences

	Alpha code	Common name	Scientific name	Habitat occupation		
				OTR	TRW	PRW
Facultative	amcr	American crow	*Corvus brachyrhynchos*		X	X
	amro	American robin	*Turdus migratorius*	X	X	X
	bais	Baird's sparrow	*Ammodramus bairdii*			X
	baor	Baltimore oriole	*Icterus galbula*		X	X
	bbma	Black-billed magpie	*Pica hudsonia*		X	X
	brbl	Brewers blackbird	*Euphagus carolinus*	X	X	
	brth	Brown thrasher	*Toxostoma rufum*	X		X
	bhco	Brown-headed cowbird	*Molothrus ater*		X	
	chsp	Chipping sparrow	*Spizella passerina*			X
	ccsp	Clay-coloured sparrow	*Spizella pallida*	X	X	X
	clsw	Cliff swallow	*Petrochelidon pyrrhonota*	X		
	eaph	Eastern phoebe	*Sayornis phoebe*		X	
	eust	European starling	*Sturnus vulgaris*			X
	hosp	House sparrow	*Passer domesticus*		X	X
	kill	Killdeer	*Charadrius vociferus*	X	X	X
	lcsp	Le Conte's sparrow	*Ammodramus leconteii*		X	
	lefl	Least flycatcher	*Empidonax minimus*		X	X
	modo	Mourning dove	*Zenaida macroura*		X	X
	osfl	Olive-sided flycatcher	*Contopus cooperi*			X
	rtha	Red-tailed hawk	*Buteo jamaicensis*	X	X	X
	rbgu	Ring-billed Gulled	*Larus delawarensis*			X
	rnep	Ring-necked pheasant	*Phasianus colchicus*		X	X
	savs	Savannah sparrow	*Passerculus sandwichensis*	X	X	X
	swha	Swainson's hawk	*Buteo swainsoni*			X
	vesp	Vesper sparrow	*Pooecetes gramineus*	X		
	weki	Western kingbird	*Tyrannus verticalis*			X
	weme	Western meadowlark	*Sturnella neglecta*			X
	wcsp	White-crowned sparrow	*Zonotrichia albicollis*			X
	wbnu	White-breasted nuthatch	*Sitta carolinensis*			X
Dependent	Amgo	American goldfinch	*Carduelis tristis*	X	X	X
	Bcch	Black-capped chickadee	*Poecile atricapillus*			X
	Eaki	Eastern kingbird	*Tyrannus tyrannus*	X	X	X
	Howr	House wren	*Troglodytes aedon*		X	X
	Rwbl	Red-winged blackbird	*Agelaius phoeniceus*	X	X	X
	Nsts	Sharp-tailed sparrow	*Ammodramus nelsoni*		X	
	Wewp	Western wood peewee	*Contopus sordidulus*			X
Obligate	BANS	Bank swallow	*Riparia riparia*	X		
	COYE	Common yellowthroat	*Geothlypis trichas*	X	X	X
	GRCA	Grey catbird	*Dumetella carolinensis*		X	
	SOSP	Song sparrow	*Melospize melodia*	X	X	X
	SORA	Sora	*Porzana carolina*	X		
	SPSA	Spotted sandpiper	*Actitis macularius*		X	
	YEWA	Yellow warbler	*Dendroica petechia*	X	X	X
	YHBL	Yellow-headed blackbird	*Xanthocephalus xanthocephalus*	X		

Habitats occupied included true willows (TRW), riparian woodlands (PRW), and other vegetation types (OTR).

Project condition in 2013 ($F = 16.56$, $p < 0.01$; avian ANCOVAs $F_{(1,22)}$). Species evenness remained comparable ($F = 2.35$, $p = 0.14$) and the Shannon–Wiener index increased ($F = 11.50$, $p < 0.01$), reflecting the increased richness.

To consider the community patterns over the three assessment intervals, the NMDS indicated fairly consistent placement and association of sites within species space (Figure 6). However, the solution strength was moderate to poor, with a final stress of 19.7. Goodness of fit was slight for axis 1 ($R^2 = 0.14$) and increased to moderate following the second axis ($R^2 = 0.22$), with vertical structure as the primary explanatory variable ($R^2 = 0.11$, axis 1). A third axis did not provide substantial improvement ($R^2 = 0.23$, not

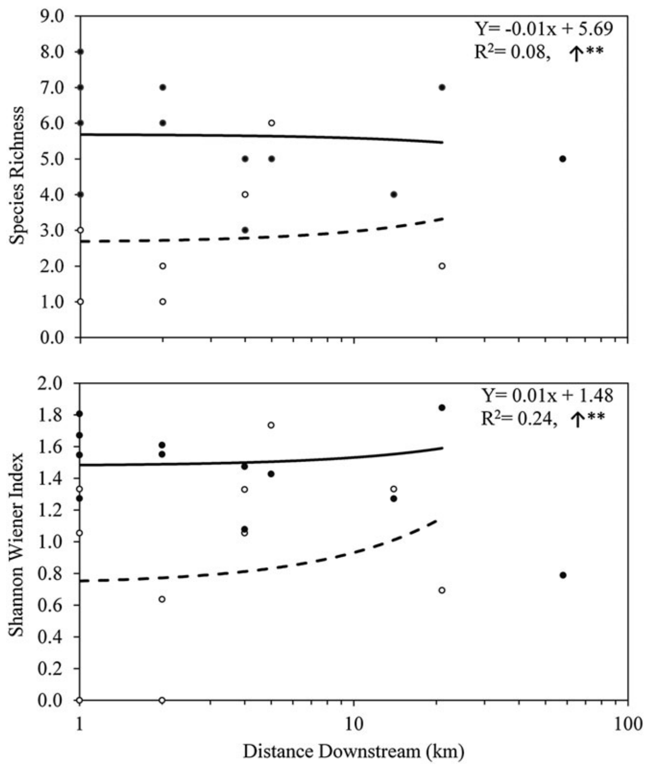

Figure 5. Riparian bird diversities along the Little Bow River in 2005 (baseline, ○, dashed lines) and 2013 (post-Project, ●, solid lines). Linear regressions are plotted, with curving reflecting log scaling for distance. The arrows indicate highly significant increases in 2013 (↑**: $p < 0.01$)

shown). With this ordination, the positioning of the riparian woodland sites shifted between 2005 and 2013, suggesting increasing vertical habitat structure (Figure 6). The true willow survey sites did not show consistent transitions, and there were fewer sites for the other vegetation types.

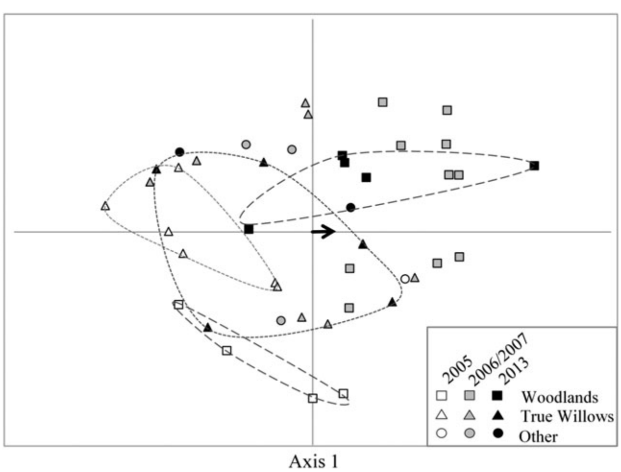

Figure 6. Non-metric multi-dimensional scaling (NMDS) of sites with riparian birds along the Little Bow River. The sites were grouped as woodlands, true willows, or other vegetation with plotted points for each site assessed three times: baseline (2005), early-Project (2006/2007), and post-Project (2013). The arrow indicates increasing vertical structure of vegetation

The CCA provided a stable two-dimensional solution but only explained 9.4% of the variation in avian species associations (Figure 7). For the environmental factors, axis 1 represented 4.9% of the variation and was paired with the explanatory life history characteristics of structure nesting, obligate riparian species, shrub nesting, and resident species ($R^2 = 0.43$, 0.17, 0.12, 0.11, respectively). Axis 2 represented 4.5% of the variation and was associated with ground nesting, story of occupation (middle, upper, and under), and structure nesting ($R^2 = 0.52$, 0.37, 0.31, 0.26, 0.16, respectively). Obligate riparian species were clustered mainly within the lower zone of axis 1, while the facultative and dependent riparian species were interspersed.

DISCUSSION

As we expected and has been consistently observed for other rivers (Kellerhals *et al*., 1979; Bradley and Smith, 1984; Dominick and O'Neill, 1998; Wohl and Dust, 2012), the channel along the Little Bow River widened in response to the additional flow augmentation. The extent of widening was modest, around 10%, but the extent of flow

Figure 7. Canonical correspondence analysis (CCA) for avian species along the Little Bow River. Codes are in accordance with Table I, with capitalization indicating riparian affiliation. * indicates a slight offset for legibility

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augmentation was also modest, reflecting a lag in irrigation expansion because of lower demand for downstream water than had been anticipated during Project planning. In contrast to our second prediction relative to channel form, we did not observe any trend towards decreasing sinuosity. Sinuosity declined within a decade along another small flow-augmented stream (Kellerhals, 1979) but that may have involved more extensive flow alteration. It will be useful to undertake further assessment after a longer interval and with the anticipation of increasing flow augmentation following irrigation expansion.

As we anticipated, there were changes in riparian vegetation following the flow augmentation and channel responses. There was limited apparent change in the woodland (tree) component, but a decade would be minimal for new trees to establish and reach the 4-m height criterion. As we predicted, there was an increase in the true willows, the obligate riparian sandbar willow, and the facultative Bebb's willow. The facultative shrub wolf willow also increased, somewhat in contrast to our expectation of transition from wolf willow to true willow because of the supplemental water. We did observe this predicted transition along some of our monitoring transect sites (Figure 8), but the greater response was the establishment or increase of wolf willow in some prior grassland, or grass-type sites. Thus, the primary early changes involved transition from riparian grassland to shrubland.

With flow augmentation, the elevation of the groundwater table and associated increase in substrate moisture should result in drought-tolerant species transitioning to higher positions, while inundation-tolerant hydric species flourish (Bendix, 1999; Leyer, 2005). Following the increased minimum and mean river flows, there would have been greater inundation stress and mortality, and a corresponding decreased extent of the bank proportions dominated by more xeric species within the graminoid category. Additionally, reduced drought stress would have favoured the riparian true willows, consistent with the observed increase. Wolf willow communities probably also benefited from reduced drought stress, and the observed expansion could be an intermediate response, as the wolf willow may display moisture adaptation that is intermediate between the drought-tolerant grasses and phreatophytic true willows.

As anticipated, an increasing trend was observed for cattail communities, as there would have been expanded slack water zones, which were favoured by this emergent vegetation, particularly in the lower segments. Conversely, cattail communities were scoured in some locations following the 2005 flood (Bigelow, 2006), opposing the expansion at other locations.

Some river systems may respond to flow augmentation with increases in sedge communities in only a few years (Henszey *et al*., 1991), while a longer transient stage of a decade or more may be required for other vegetation types (Johnson, 1998). Following the intermediate transient state, river systems may undergo rapid transitions in vegetation communities, such as the decline in total vegetated area along the Upper Arkansas River following 53 years of

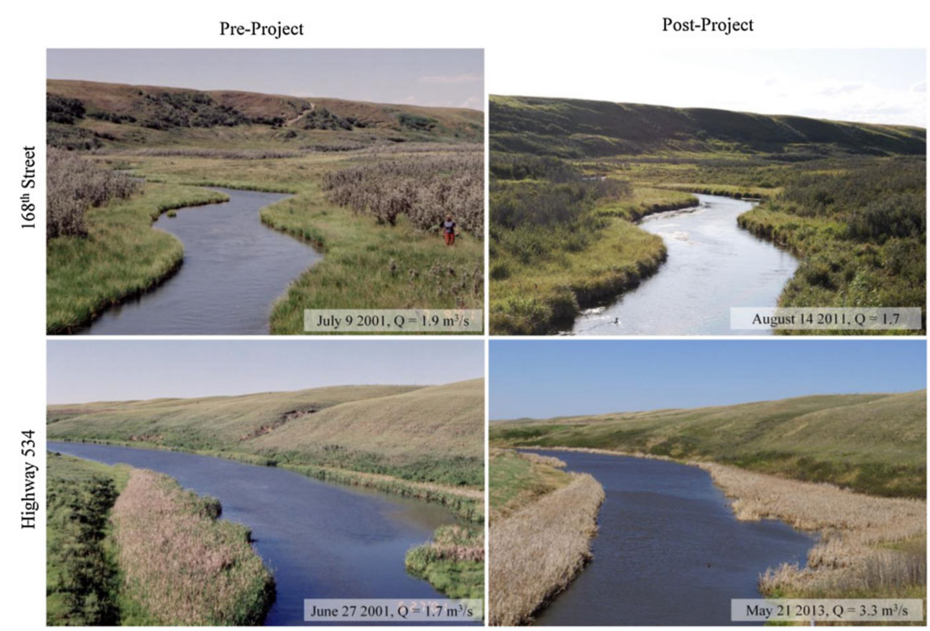

Figure 8. Photographs facing upstream from bridges over the Little Bow River, before (left) and after (right) the additional flow augmentation. The 168 St. pair (top) display a site with expansion of true willows, whereas wolf willow expanded near Highway 534 adjacent to the cattail zone (bottom, along left side of photo). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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augmentation (Dominick and O'Neill, 1998). Consequently, the Little Bow River may persist in a transient state, requiring time to equilibrate to the new hydrologic balance, before the broader transition occurs, from facultative to obligate riparian vegetation.

Following the implementation of the Project, the avian community diversity was slightly altered. Although species richness and Shannon–Wiener index increased, as predicted, species evenness remained comparable between baseline and post-Project conditions. Avian diversity is largely dependent on habitat heterogeneity and to a lesser degree on patch geometry and resource availability (MacArthur and MacArthur, 1961; Scott *et al*., 2003). Thus, increases in species richness in response to the accumulation of rare specialist species supported increases in the Shannon–Wiener index following the transitioning of some grassland zones to shrublands.

The NMDS suggested the increased development of vertical habitat structure along the riparian woodland sites. This was not extensive across all site types but provides another potential explanation for increases in species richness and Shannon–Wiener index due to niche expansion. Further, the CCA of species associations along the Little Bow River supported the importance of habitat heterogeneity in terms of story of occupation and nesting substrates, rather than emphasizing dietary or migratory characteristics. Thus, transitions in vegetation communities from grasslands to shrublands and the maturation of existing woodlands probably contributed to the increases in avian species richness and Shannon–Wiener index.

Riparian areas possessing high levels of structural complexity and native woody vegetation provide the greatest breeding bird abundance and diversity (Scott *et al*., 2003). However, a century may be required to develop maximum vertical structure of riparian woodlands in semi-arid regions (Scott *et al*., 2003). As vegetation transitions along the Little Bow River, the potential for habitat diversification also exists, and the avian communities may continue to increase in diversity and abundance. Alternatively, avian diversity might reach a maximum during the transient period, in accordance with the intermediate disturbance hypothesis (Roxburgh *et al*., 2004). Future monitoring will be informative, relative to the longer term changes in the riparian vegetation and avian communities.

Along our study reach, alterations in channel form, vegetation, and avian communities following flow augmentation were confounded with varying land-use management, particularly locally intensive cattle grazing. Pugging of banks (perforation with hooves), as well as trampling and browsing of riparian vegetation, could mask alterations along some segments while accelerating change along others (Bigelow, 2006). Ungrazed riparian areas in Colorado possessed 8.5 times greater willow coverage than grazed areas (Schulz and Leininger, 1990), and reduction in both ground and shrub cover in Oregon reduced associated riparian bird populations (Heltzel and Earnst, 2006). Following the implementation of the Project, intensively grazed locations exhibited localized channel widening that was catalysed by decreased vegetation coverage and pugging (Bigelow, 2006). Subsequently, these impacts would also suppress avian diversity in response to decreased vegetation cover.

The utilization of aerial photograph analysis in this study also limited the detection of changes to a landscape level. Vegetation was classified and compared between observable categories; however, changes within these observable categories were undetectable through this methodology. The graminoid category possessed the families of grasses, sedges, and rushes, but each family and particular species may respond differently to alterations in the riparian environment and water availability. As a preliminary assessment of riparian response, analysis of aerial photographs was an appropriate method to assess a large spatial area. Field-based approaches focusing on species of interest would provide a complementary study approach to assess smaller scale consequences of flow augmentation.

Our analyses of the Little Bow River focused on the responses of channel form, vegetation, and avian communities between pre-Project versus post-Project conditions. Although significant alterations occurred during this time interval, a historical comparison that extended the time frame from 1967 to 2013 indicated that there were also natural variations that reflected disturbance and expansion sequences associated with flood events (Hillman, 2014). The study timescales are thus important in understanding management impacts that are superimposed on natural variations.

MANAGEMENT IMPLICATIONS

The case study of the Little Bow River provides insight into the environmental responses of river systems to flow augmentation within semi-arid prairie ecoregions and also provides direction for riparian conservation and restoration. The enhancement of riparian ecosystems could be regarded as providing net environmental benefit, particularly in regards to the promotion of native riparian shrubs and trees, such as willows and poplars. These expand habitat heterogeneity, benefiting birds and terrestrial wildlife. The prospect of river flow augmentation as a mechanism for water conveyance, rather than the development of artificial canal systems, could be utilized to enrich ecosystem services, as well as enabling the desired water relocation. Augmentation projects typically involve increasing seasonal discharge, and refinements to the augmentation regime might even further enhance the environmental benefits. These refinements could also contribute to environmental flow requirements

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of downstream river systems, providing benefits to both the aquatic and terrestrial environments.

This river system also provides an interesting case study relative to the merits of 'pristine' versus 'productive' river ecosystems. In the native state, the Little Bow or Naked River had an intermittent flow regime and subsequently lacked riparian shrublands or woodlands. Following a century of flow augmentation that has produced a perennial flow regime, there has been progressive development of shrub zones with both obligate and facultative willows. The willows provide substantial wildlife habitat, and the treed woodlands would further increase the riparian habitat. We believe that the regional residents strongly favour the current condition with a flowing river system that supports artificial but productive aquatic and riparian ecosystems, as opposed to the natural, relatively barren valley. Subsequently, the flow-augmented river system provides valued ecosystem services, and we might expect that flow augmentation could provide environmental enrichment along other rivers, especially those with naturally intermittent flow regimes.

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