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Geomorphology, hydrology, and aquatic vegetation drive seasonal hyporheic flow patterns across a gravel-dominated floodplain

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Abstract:

Across 1·7 km^2 of the Umatilla River floodplain (Oregon, USA), we investigated the influences of an ephemeral tributary and perennial 'spring channel' (fed only by upwelling groundwater) on hyporheic hydrology. We derived maps of winter and summer water-table elevations from data collected at 46 monitoring wells and 19 stage gauges and used resulting maps to infer groundwater flow direction. Groundwater flow direction varied seasonally across the floodplain and was influenced by main channel stage, flooding, the tributary creek, and the location and direction of hyporheic exchange in the spring channel. Hyporheic exchange in the spring channel was evaluated with a geochemical mixing model, which confirmed patterns of floodplain groundwater movement inferred from water-table maps and showed that the spring channel was fed predominantly by hyporheic water from the floodplain aquifer (87% during winter, 80% during summer), with its remaining flow supplied by upslope groundwater from the adjacent catchment aquifer. Summertime growth of aquatic macrophytes in the spring channel also influenced patterns of hyporheic exchange and groundwater flow direction in the alluvial aquifer by increasing flow resistance in the spring channel, locally raising surface water stage and adjacent water-table elevation, and thereby altering the slope of the water-table in the hyporheic zone. The Umatilla River floodplain is larger than most sites where hyporheic hydrology has been investigated in detail. Yet, our results corroborate other research that has identified off-channel geomorphic features as important drivers of hyporheic hydrology, including previously published modeling efforts from a similar river and field observations from smaller streams.

KEY WORDS Umatilla River, Oregon; alluvial aquifer and streams; groundwater and surface water interactions; hydrogeology; aquatic macrophytes; channel roughness

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INTRODUCTION

Patterns of surface water and groundwater exchange across floodplains are shaped largely by local and regional geomorphology and hydrology. Geomorphic structures, such as off-channel features (e.g. spring channels, side channels, backwaters) and topographic heterogeneity of the streambed, can alter hyporheic flux rates and patterns (Harvey and Bencala, 1993; Wondzell and Swanson, 1999; Kasahara and Wondzell, 2003; Anderson *et al.*, 2005; Gooseff *et al.*, 2006a,b; Poole *et al.*, 2006). Likewise, the timing, magnitude, and source of water delivery to a floodplain influence the direction and magnitude of groundwater flux within the alluvial aquifer (Wroblicky *et al.*, 1998; Malard *et al.*, 1999; Wondzell and Swanson, 1999). Although these interactions have been studied in small stream systems, few such hydrologic analyses have been completed on larger gravel-dominated floodplains (but see Poole *et al.* (2006)).

Several mechanisms by which vegetation influences floodplain hydrology are well known. Riparian vegetation is known to influence surface water hydrology indirectly by deflecting surface water flows and stabilizing banks (Tooth and Nanson, 2000; Bennett *et al.*, 2002; Gurnell and Petts, 2002; Coulthard, 2005). Riparian and aquatic vegetation can also directly alter water-table elevation via transpiration (Oveson, 2001; Bond *et al.*, 2002; Dahm *et al.*, 2002; Chen, 2007). Additionally, the growth of aquatic vegetation (such as macrophytes) in stream channels increases channel roughness, reduces water velocities, and alters stage–discharge relationships (Wilcock *et al.*, 1999; Champion and Tanner, 2000; Harvey *et al.*, 2003; Green, 2005; Cotton *et al.*, 2006; Naden *et al.*,

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2006). Where present, such vegetation-induced changes in surface water hydrology are apt to alter patterns of hyporheic exchange. Yet, these indirect effects of vegetation on floodplain groundwater hydrology appear to be poorly studied.

In this paper, we describe how the interactions among off-channel geomorphic features, surface water hydrology, and seasonal growth and senescence of aquatic macrophytes influence the seasonal groundwater hydrology of the Umatilla River floodplain (Oregon, USA). Specifically, we investigate the seasonal influences of an ephemeral tributary and perennial 'spring channel' (an abandoned river channel fed only by upwelling groundwater) on patterns of water flux in the alluvial aquifer. Our analysis relies on water-table elevation data from a well network distributed across the floodplain and a geochemical mixing model documenting the contributions of two groundwater sources to the spring channel. Additionally, we examine how the emergence and senescence of aquatic macrophytes affect the location and timing of hyporheic exchange in the spring channel.

STUDY SITE

The Umatilla River drains the mountains and high desert of northeastern Oregon, USA, and ultimately flows into the Columbia River near Hermiston, Oregon. Our study site (centered at latitude 45·6722 °N, longitude 118·6117 °W) is a 1·7 km^2 section of the Umatilla River floodplain (Figure 1) on the Umatilla Indian Reservation, and is about 14·5 km upstream from the town of Pendleton, Oregon. The site is upstream of the significant agricultural water withdrawals common in the lower section of the river. Unaffected by dams and large withdrawals, the river channel is naturally anabranched, a characteristic of many of the remaining free-flowing alluvial rivers in the western USA.

The lithology of the Umatilla River watershed is dominated by Columbia Plateau basalt. The river's hydrology is driven by distinctive winter and summer precipitation patterns. In the winter and spring, precipitation falls typically as rain on the floodplain (0·3 m $year^{-1}$) and as rain or snow in the surrounding Blue Mountains (0·8 to 1·8 m $year^{-1}$) (US National Oceanographic and Atmospheric Administration). Rain-on-snow and warm 'Chinook' winter wind events yield substantial but brief freshets and floods in late winter and early spring. In contrast, groundwater baseflow and occasional precipitation events in the Blue Mountains are the primary water sources for summertime stream flows. Long-term data show that the discharge of Umatilla River generally varies from $\sim$1 m^3 s^{-1} at baseflow to $>$50 m^3 s^{-1} during typical winter freshets and exceeds 300 m^3 s^{-1} during flood stage (US Geological Survey gauge 'Umatilla River at Pendleton, OR', ID = 14 021 000; period of record: 1904–1989; located $\sim$14·5 km downstream of our site). Discharge data for 2004, the year of this study, were similar to long-term conditions, though the annual peak flood was only $\sim$150 m^3 s^{-1} (Figure 2, US Geological Survey gauge 'Umatilla River at West Reservation Boundary near Pendleton, OR', ID = 14 020 850; period of record: 1997–present; location $\sim$9·5 km downstream of our site).

The main channel of the river runs along a bedrock valley wall on the northern edge of our study site (Figure 1). South of the main channel, groundwater emerges in a two abandoned channel traces once occupied by the main channel. These two 'spring channels' converge and skirt the southern edge of the floodplain for $\sim$1·0 km before rejoining the main channel. We refer to the two forks and combined channel collectively as Minthorn Spring Channel. South of the spring channel, a small spring set above the floodplain on the toe slope of the south valley

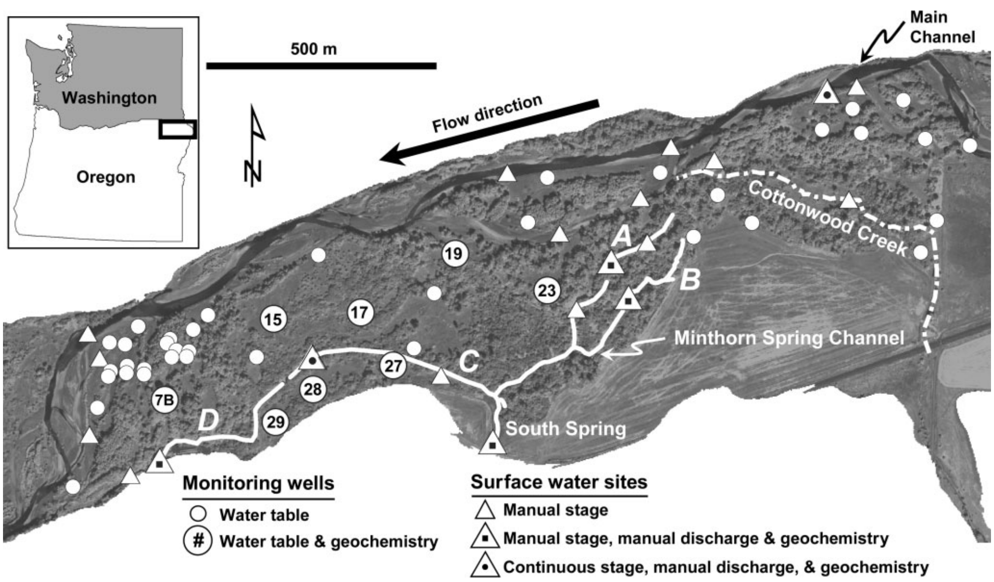

Figure 1. Quickbird imagery (collected on 4 July 2004 by the Satellite Imaging Corporation, Houston, TX, USA) of the Umatilla River floodplain study site in northeastern Oregon, USA. Locations are indicated for off-channel geomorphic features (Minthorn Spring Channel and Cottonwood Creek), monitoring wells, surface water sampling sites, and mixing model reaches (white line segments labelled A–D)

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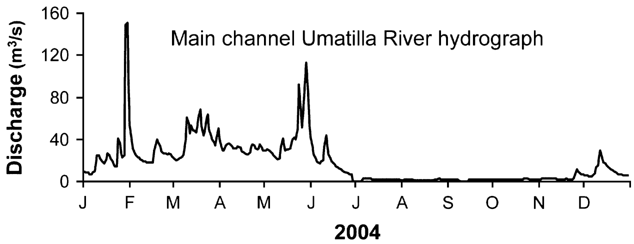

Figure 2. The 2004 discharge data for the main channel Umatilla River (US Geological Survey, gauge ID = 14 020 850, 'Umatilla River at West Reservation Boundary near Pendleton, OR')

wall (referred to as the 'South Spring') discharges catchment (upslope) groundwater into the spring channel. East and upstream of the spring channel's forks, Cottonwood Creek flows onto the floodplain from the south during winter, but is typically dry during summer.

Ground-penetrating radar surveys, domestic well log analyses, seismic refraction analysis, and backhoe excavation revealed that the floodplain alluvium is typically ~3 m thick and consists of basalt gravel, cobbles, and boulders intermixed with silt and sand lenses (Boer *et al.*, 2005). The main channel's alluvium rests atop basalt bedrock. Aquifer tests produced estimates of hydraulic conductivity ranging from 300 to 700 m day^{-1} (B. Boer, unpublished data). The streambed of the spring channel consists of finer-grained sediments covered by a muddy organic layer 0·10–0·20 m thick. Along Minthorn Spring Channel, we observed groundwater discharging from both the north and south banks, suggesting that the spring channel received water from the river's hyporheic zone to the north and the upslope catchment aquifer to the south. During spring and summer, aquatic macrophyte vegetation grows densely within the spring channel (Figure 3), especially in the lower reaches. During winter, only senesced, dormant plants remain and water flow in the channel is less restricted.

METHODS

We used two complementary approaches to explore seasonal changes in hydrologic interactions among the main river channel, floodplain groundwater system, and off-channel geomorphic features (Minthorn Spring Channel and Cottonwood Creek). First, we monitored and analysed the wintertime and summertime floodplain water-table elevation and surface water stage within the main channel, Minthorn Spring Channel, and Cottonwood Creek. Second, we used geochemistry data from monitoring wells, the South Spring, and Minthorn Spring Channel, combined with discharge data in the spring channel, to develop a mixing model of seasonal variation in hyporheic and catchment groundwater sources to the spring channel.

Hydrologic monitoring and data

As part of a larger study, 46 monitoring wells (either 2·54 cm or 10·16 cm in diameter) were installed from 1999 to 2003 in the floodplain, up to 3 m in depth, using either a pneumatic drill rig (Geoprobe 5400) or track-mounted excavator. The wells extended to (or nearly to) bedrock, fully penetrating the alluvial aquifer, and were perforated along their entire length except within ~0·3 m of the ground surface. Nineteen stage gauges were also installed, six in the river's main channel and 13 in off-channel features, including Minthorn Spring Channel and Cottonwood Creek. A professional surveyor determined the location and elevation of all monitoring sites (±1 cm) using a survey-grade global positioning system and an electronic theodolite. Field technicians recorded water-table elevation at all wells (plus/minus ~3 cm) and river stage at all gauges (plus/minus ~1 cm) monthly during baseflow and bimonthly during months where elevated flows occurred. Electronic data loggers (Solinst Levelloggers) recorded water stage (plus/minus

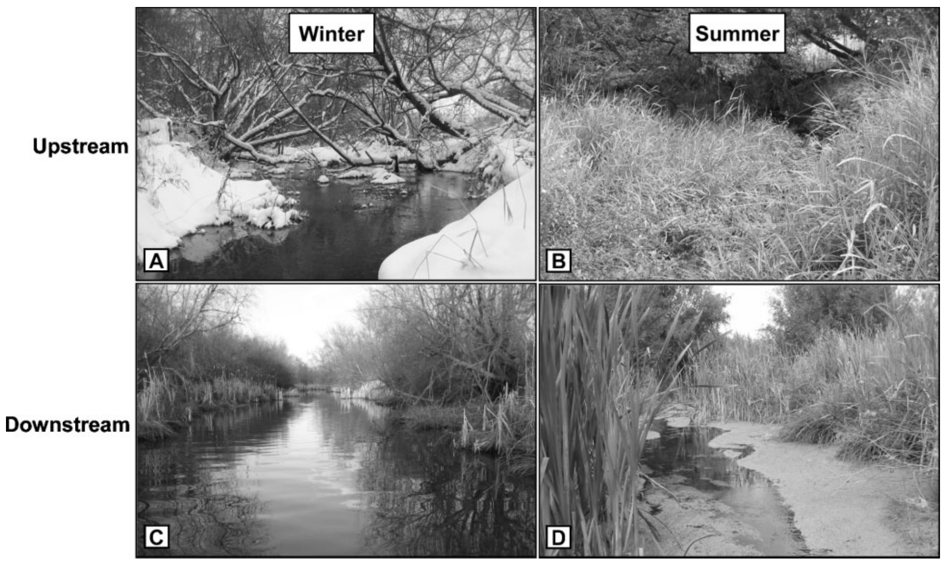

Figure 3. Repeat photographs documenting the seasonal growth of aquatic macrophytes from winter to summer in the Minthorn Spring Channel. Photographs were taken near the confluence of the spring channel forks ((A) and (B): 'upstream') and near the continuous stage recorder installed in the spring channel ((C) and (D): 'downstream') (labelled A–D in Figure 1)

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<3 cm) at one gauge in the spring channel and one gauge in the main channel (identified as 'continuous stage' sites in Figure 1). Following Gore (1996), measurements of spring channel discharge were collected in winter (14 March 2004) and summer (19 July 2004) with a Swoffer model 2100 current velocity meter. For Umatilla River discharge data on these dates, we used USGS data from the 'Umatilla River at West Reservation Boundary near Pendleton, OR' gauge (Figure 2). Lastly, we quantified the magnitude of the change in flow resistance (Manning's n) in the Minthorn Spring Channel (winter versus summer) using Manning's equation (Leopold *et al.*, 1964) combined with measurements of channel cross-section, discharge, and water surface slope collected near the spring channel's continuous stage recorder.

Analysis of seasonal water-table surfaces

To create groundwater potentiometric maps across the floodplain, field observations of water-table elevation and river stage from winter (10–11 March 2004) and summer (26 and 28 July 2004) were interpolated using a spline-tension technique (ArcGIS 9·1, ESRI, Redlands, CA). Because the surface water gauges were spaced sparsely and surface water formed the domain boundaries for the analysis, we used linear interpolation between gauges to estimate river stage every ~20 m along the main channel, spring channel, and Cottonwood Creek for both winter and summer. These estimated water stage data points were included in the spline analysis to reduce interpolation artifacts at the domain boundaries. Water-table equipotential contours for winter and summer were generated at 0·5 m intervals; we assume groundwater flow direction would be approximately perpendicular to these contour lines (Fetter, 1994). A map of seasonal variation in water surface elevation was calculated by subtracting the summer water-table elevation map from the winter water-table elevation map.

Geochemical sampling

We collected water samples seasonally from monitoring wells and surface water sites to characterize water sources and develop a geochemical mixing model (see next section) for the Minthorn Spring Channel. Two sets of water samples (winter and summer) were collected from the main channel Umatilla River, four sites along the spring channel, the South Spring, and eight wells distributed along the length of the spring channel (Figure 1). Winter and summer conditions were represented by samples collected during 5–7 March 2004 and 17–19 July 2004 respectively. Surface water samples were collected in the middle of the channel at half depth by hand submerging a clean 60 ml high-density polyethylene bottle. Groundwater samples were collected from floodplain wells after purging wells with a 5 hp gas pump for several minutes until pH stabilized (measured using an Orion pH meter); sample bottles were then filled from the pump outlet. Field duplicates (10%) and field blanks were collected for each sampling day. Cation samples were filtered with a Gelman 0·45 µm filter and analysed for Ca^{2+}, Mg^{2+}, and Na^{+} at the University of Montana's Murdoch Environmental Biogeochemistry Laboratory using a Thermo Elemental, Model IRIS, inductively coupled plasma emission spectrometer with ultrasonic nebulization (EPA Method 200·15). Unfiltered samples were analysed for Cl^{-} anion concentration using a Dionex Model DX400 ion chromatograph (AS15 separation column, 200 µl injection volume, modified EPA Method 300).

Mixing-model development

We used a two end-member geochemical mixing model (*sensu* Christophersen *et al.*, 1990) to determine seasonal variation in groundwater contributions to Minthorn Spring Channel from the alluvial aquifer and from the upslope catchment aquifer. We selected Ca^{2+}, Mg^{2+}, and Na^{+} as chemical constituents to use in the geochemical mixing model. Ideally, we would use anions such as Cl^{-} because advective transport of cations is often not conservative. However, laboratory errors resulted in the loss of Cl^{-} data for key sampling locations, including well 29 and the South Spring, which rendered our Cl^{-} dataset unsuitable for the mixing-model analysis. To determine whether cation advection was conservative (or nearly so) in this floodplain system, we calculated Pearson's correlation coefficient r (Zar, 1999) between the available Cl^{-} data (wells 7B, 15, 17, 19, and 23) and Ca^{2+}, Mg^{2+}, and Na^{+} values from the same wells in winter ($r = 0{\cdot}93$, 0·97, and 0·95 respectively) and summer ($r = 0{\cdot}79$, 0·88, and 0·93 respectively). The high correlations between Cl^{-} and each cation suggested that advection of these cations was very nearly conservative in the Umatilla River floodplain aquifer.

Spring channel discharge measurements (synoptic survey, ±5%) were obtained at the downstream end of each sampling reach (A–D, Figure 1) in both winter and summer. These data were combined with site geochemical data to complete the mixing model. The basic equation for the mixing model was simply a flow-weighted average of the cation concentrations for the three water sources:

$$[R_X] = \frac{[R_S]Q_S + [R_H]Q_H + [R_C]Q_C}{Q_X} \tag{1}$$

assuming continuity of flow:

$$Q_X = Q_S + Q_H + Q_C \tag{2}$$

where $[R_X]$ (mg l^{-1}) and Q_X (m^3 s^{-1}) represent respectively cation concentration and surface water discharge from sampling reach X. Q_S, Q_H, and Q_C are the rates of water influx to sampling reach X from upstream reaches, hyporheic groundwater, and catchment groundwater respectively. $[R_S]$, $[R_H]$, and $[R_C]$ represent the cation concentrations in these same water sources.

Discharge measurements revealed that Reach D lost water to the hyporheic zone during summer. Thus, we modified Equation (1) to represent loss to the hyporheic

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zone and applied the resulting equation to Reach D in the summer, instead of Equation (1):

$$[R_X] = \frac{[R_S](Q_S + Q_H) + [R_C]Q_C}{Q_X} \quad (3)$$

Note that the value of Q_H was negative in Reach D during summer; thus, flow is reduced when Q_H is summed with Q_S and Q_C in Equation (2), or with Q_S in Equation (3).

Empirical field data for each reach provided values for cation concentrations and surface water discharge in Equations (1)–(3) (Table I). $[R_H]$ was set equal to the mean cation concentration across floodplain wells to the north of the spring channel (Figure 1). We had intended to use the mean cation concentration in wells 27, 28, 29, and the South Spring to characterize catchment groundwater, but our geochemical sampling and potentiometric maps suggested that wells 27 and 28 were influenced by hyporheic water (see 'Results' section). Thus, $[R_C]$ was set equal to the mean cation concentration from the South Spring and well 29. Q_S was zero for Reaches A and B because these reaches had no upstream surface water contribution. For Reach C, Q_S and $[R_S]$ were calculated as the summed outflow and flow-weighted mean cation concentration from Reach A, Reach B, and the South Spring (Figure 1). The outflow and cation concentration from Reach C provided Q_S and $[R_S]$ for Reach D. This left Q_H and Q_C as the only two unknowns for each reach in the mixing model equations.

We calculated three estimates (one for each cation) of Q_H and Q_C for each reach (A–D) and each season (winter and summer) by minimizing the root-mean-square error of the observed and calculated $[R_S]$ using Equation (1) (or Equation (3) in the case of Reach D in summer), assuming continuity of flow (Equation (2)). We determined Q_H and Q_C for each of the three cations using the generalized reduced gradient non-linear optimizer in Microsoft Excel, and calculated the mean and standard error for Q_H and Q_C based on the three estimates.

RESULTS

Floodplain hydrology

Groundwater equipotential maps demonstrated that seasonal changes in water-table elevation varied spatially across the floodplain (Figure 4). In the eastern portion of the study site, associated seasonal changes in groundwater flow directions were principally controlled by the presence (winter) or absence (summer) of aquifer recharge from Cottonwood Creek. During winter, the elevated water-table surrounding Cottonwood Creek (Figure 4a) created hydraulic gradients away from both banks of the creek, approximately due north toward the main river channel and due west toward the head of Minthorn Spring Channel. In summer, Cottonwood Creek was dry. In the absence of associated groundwater recharge, the adjacent floodplain water-table was substantially lower than in the winter (Figure 4b). As a result, hydraulic gradients in this portion of the floodplain resulted simply from the difference between the main channel stage east of Cottonwood Creek and the water stage in the upper forks of Minthorn Spring Channel to the west of Cottonwood Creek (Figure 4a). Thus, summertime water-table elevations indicated that groundwater flowed in a westerly direction beneath the dry bed of Cottonwood Creek.

In the central portion of the study site, the elevation of the floodplain water-table was somewhat lower in summer than in winter (Figure 4b), reflecting the observed reduction in the main channel stage (Figure 5a). During both winter and summer, the slope of the water-table showed that water infiltrated the aquifer from the main channel and then flowed in a southwesterly direction toward the spring channel.

In the western ~0·5 km of the study site during winter, water-table contours revealed that main channel water infiltrated the floodplain aquifer from the north, flowed southward, and entered the spring channel. In summer, the contours in the same portion of the floodplain indicated that water infiltrating from the main channel started to flow south, but turned westward and flowed parallel to the spring channel. This pattern suggested that little hyporheic water entered the western portion of the spring channel during the summer.

Surprisingly, the water-table beneath the western portion of the spring channel was higher in summer than in winter. This finding is anomalous, since summer water-table elevations were lower than winter elevations across the remainder of the floodplain (Figure 4b). Similarly, despite a summertime reduction in discharge from Minthorn Spring Channel and low precipitation (Figure 5a and b), the spring channel stage was unexpectedly higher in the summer than in the winter (Figure 5a). Field observations revealed the dense growth of aquatic vegetation in the spring channel (Figure 3). This aquatic

Table I. Surface discharge and cation concentrations for each reach of the Minthorn Spring Channel (Figure 1) in winter (W) and summer (S) used as input to the geochemical mixing model

Spring channel reach	Surface outflow ($m^3 s^{-1}$)		Ca^{2+} ($mg\ l^{-1}$)		Mg^{2+} ($mg\ l^{-1}$)		Na^{+} ($mg\ l^{-1}$)	
	W	S	W	S	W	S	W	S
A	0·0200	0·0086	11·20	8·84	4·50	3·72	5·90	5·47
B	0·0581	0·0096	10·60	11·35	4·20	4·57	6·20	6·96
C	0·1627	0·0858	9·44	15·44	4·00	6·33	7·80	11·41
D	0·2093	0·0393	11·10	16·41	4·70	6·78	9·20	12·58

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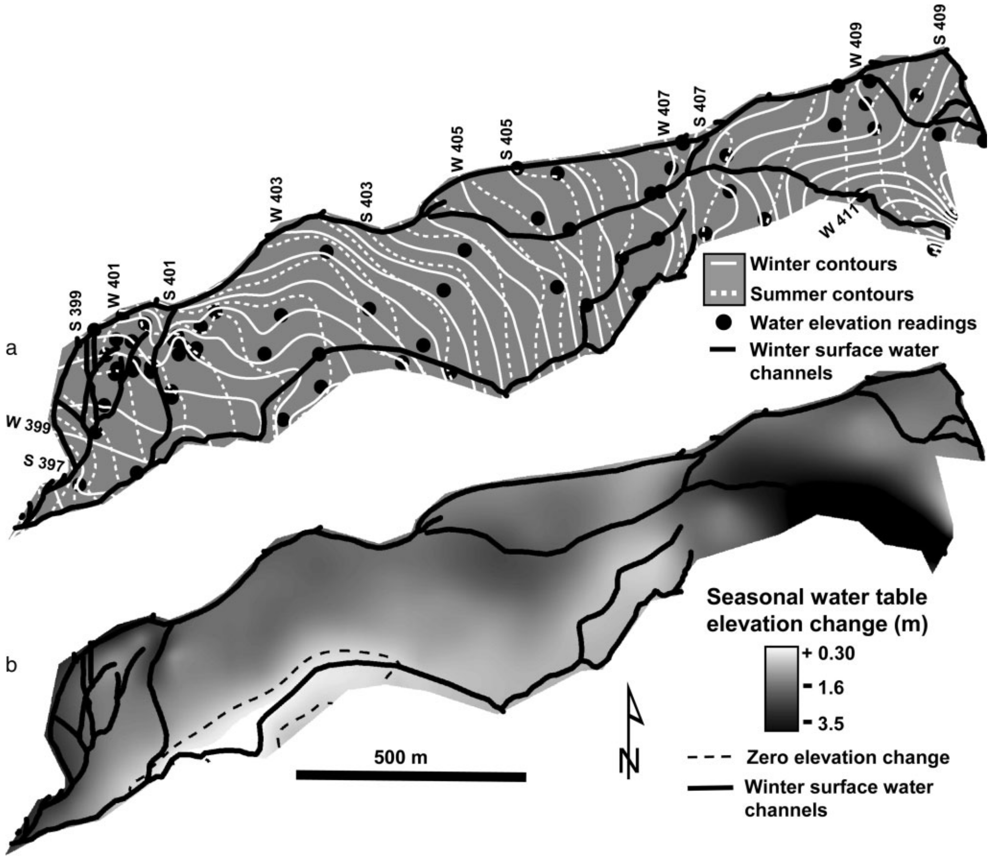

Figure 4. Winter and summer variations in water-table elevation. (a) Groundwater equipotential contours for winter and summer (contour interval: 0·5 m; in contour elevation labels, W is winter and S is summer). (b) Seasonal change in water-table elevation from winter to summer. Dotted line indicates zero elevation change between seasons. Inside this area, the elevation of the water-table was higher in summer than in winter

vegetation likely created higher summertime flow resistance in the channel (Wilcock *et al.*, 1999; Champion and Tanner, 2000; Green, 2005; Naden *et al.*, 2006) and, therefore, produced the observed inverse stage–discharge relationship. The magnitude of the change in flow resistance was substantial; our estimates of Manning's n in the spring channel were 0·030 in winter and 0·040 in summer.

Site geochemistry and mixing-model results

Cation concentrations were distinctly higher in catchment groundwater than in hyporheic water (Figure 6). Hyporheic water geochemistry was very similar to river geochemistry. Combined with the potentiometric maps, these results suggested that a large proportion of the groundwater found throughout the alluvial aquifer was derived from the river and, therefore, that the hyporheic zone permeated most of the alluvial aquifer. The spring channel's geochemistry fell between the hyporheic and catchment values.

Our geochemistry data suggested that wells 27 and 28, which were located south of the spring channel (Figure 1), contained a mixture of catchment and hyporheic water (Figure 6). Water-table maps (Figure 4a) revealed that these two wells might be intercepting flowpaths originating from Minthorn Spring Channel, indicating a mechanism for the mixing of hyporheic and catchment groundwater.

Results from the mixing model showed that the spring channel received both hyporheic and catchment groundwater inputs and that the contribution patterns varied among reaches and between seasons (Figures 7 and 8). In both winter and summer, hyporheic water dominated the inputs to all reaches of the spring channel, comprising 87% of groundwater reaching the spring channel in winter and 80% in summer. In winter, the spring channel rapidly and continually gained water as it flowed downstream. In summer, the relative patterns of flow in Reaches A and B were similar to winter patterns, albeit with reduced flow magnitude. Catchment groundwater discharge in Reach C was somewhat higher in summer than in winter, whereas discharge from the hyporheic zone showed the opposite trend. In summer, Reach D recharged the hyporheic zone, contrasting with the strong hyporheic discharge occurring in this reach in winter.

DISCUSSION

Hyporheic water derived from the main channel or as seepage from Cottonwood Creek comprised the majority of groundwater reaching the Minthorn Spring Channel (Figures 7 and 8). The remaining portion of spring channel discharge was derived from upslope catchment groundwater received via direct input along the

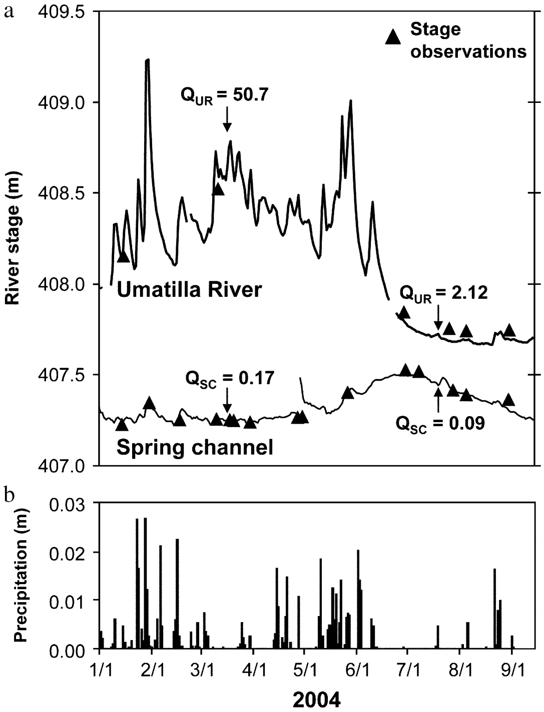

Figure 5. Hydrologic and precipitation data for the Umatilla River floodplain. (a) Solid lines represent stage levels recorded by loggers at 'continuous stage' locations in the main and spring channels (Figure 1). Triangles denote stage observations recorded by technicians and provide verification of logger stage data. Discharge measurements Q (m^3 s^{-1}) from the Minthorn Spring Channel and the main Umatilla River channel (USGS data, Figure 2) are labelled on the graph. Breaks in stage data indicate logger retrieval to download data and subsequent redeployment. Elevated spring channel stage at beginning of second deployment (mid May 2004) is a data anomaly of unknown cause. Yet, agreement between data logger and field observations suggests that the remaining data are accurate. (b) Daily precipitation values measured by a weather station deployed ~16·5 km upstream of our study site

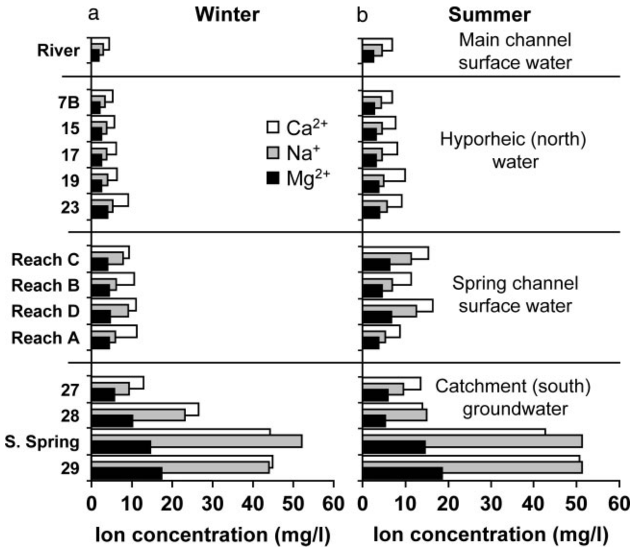

Figure 6. Concentrations of Ca^{2+}, Na^{+}, and Mg^{2+} in water samples collected from the Umatilla River channel, monitoring wells, Minthorn Spring Channel, and the South Spring (Figure 1) in (a) winter; and (b) summer

stream bank or from the South Spring. Water-table elevation maps and our mixing model suggested that the spring channel represented a local, partially penetrating hydrologic divide between the floodplain and catchment groundwater flow systems. Groundwater hydrology surrounding the divide, however, was complex, as indicated by the discharge of catchment groundwater into the north fork of the spring channel (Reach A, Figure 7) and by the mixing of hyporheic and catchment groundwater in two wells located south of the spring channel (wells 27 and 28, Figure 6).

Other researchers have reported similar interactions among floodplain- or catchment-scale geomorphology and hydrology (e.g. Wondzell and Swanson, 1996, 1999; Wroblicky *et al.*, 1998, Malard *et al.*, 1999, 2002). Based on these previously published studies, we expected that seasonal and spatial variations in the distribution of surface water and delivery of catchment groundwater to the Umatilla River floodplain would drive water-table elevations within the context of the floodplain's geomorphology (Figure 4). For instance, the summertime drying of Cottonwood Creek induced substantial changes in water-table elevation and associated hydrologic gradients in the alluvial aquifer (Figure 4), which in turn suggested seasonal shifts in patterns of hyporheic flow direction in the eastern portion of the study site. These changes allowed groundwater to flow from east to west under the dry creek bed during summer, whereas in winter the water infiltrated the aquifer from Cottonwood Creek and flowed from the creek bed either due north or due west

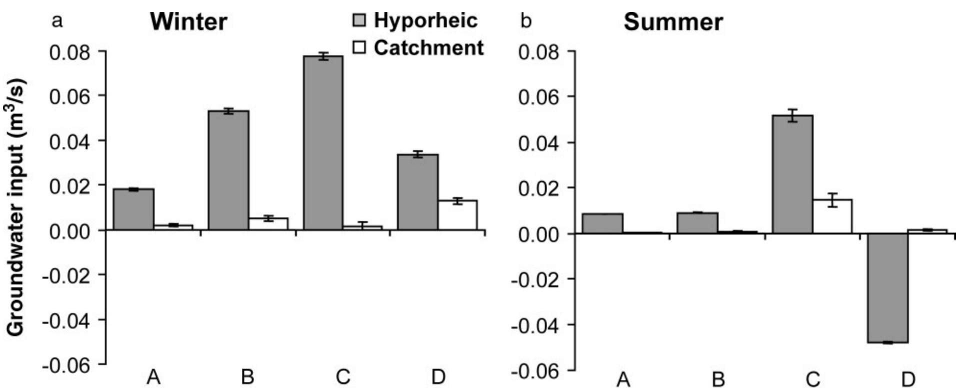

Figure 7. Spatial and seasonal variation in water sources to Reaches A–D (Figure 1) in the Minthorn Spring Channel. Columns represent mean values (plus/minus standard error) from three runs of a geochemical mixing model, each using a different cation, in (a) winter and (b) summer

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(Figure 4a). Wondzell and Swanson (1999) and Kasahara and Wondzell (2003) reported similar influences of off-channel geomorphic features (e.g. side channels, backwaters, and tributaries) on hyporheic flow direction in smaller streams. Thus, our results documented that many of the geomorphic and hydrologic interactions occurring in small streams also occur in larger alluvial rivers, albeit at coarser spatial scales. Additionally, our data provided empirical corroboration of model results presented by Poole *et al.* (2006), which demonstrated a restructuring of groundwater flow paths across a similar floodplain in response to interactions among geomorphology and seasonal flow variation on the Middle Fork Flathead River, Montana, USA.

Unlike the expected interactions between geomorphic features, hydrology, and groundwater exchange around Cottonwood Creek, the summertime increase in water-table elevation in the western portion of the Minthorn Spring Channel was unexpected (Figure 4b). Our data suggest that a cascade of hydrologic effects occurred in the Minthorn Spring Channel during the summer. Macrophyte emergence (Figure 3) yielded increased surface water flow resistance (Wilcock *et al.*, 1999; Champion and Tanner, 2000; Green, 2005; Naden *et al.*, 2006), and caused an inverted stage–discharge relationship (Figure 5), summertime reversal of vertical hydrologic gradients beneath the spring channel, and subsequent aquifer recharge zone in the spring channel (Figures 7 and 8). The associated summertime increase in water-table elevation near the spring channel (Figure 4) restructured hydrologic gradients in the alluvial aquifer and, thus, influenced patterns of groundwater flow direction across much of the western third of the study site. These results document how the localized effects of aquatic macrophytes spiralled upward in spatial scale (*sensu* Poole, 2002) and affected patterns of groundwater movement across a broader section of the floodplain.

CONCLUSIONS

Although Cottonwood Creek and the Minthorn Spring Channel are relatively small geomorphic features, they played disproportionate roles in establishing and seasonally restructuring patterns of hyporheic flow direction across the Umatilla River floodplain. Additionally, the seasonal emergence and senescence of macrophytes within Minthorn Spring Channel magnified the influence of the spring channel on seasonal variation in hyporheic hydrology. Our results supported other empirical studies citing off-channel geomorphic features as critical drivers of hyporheic flow dynamics (Wondzell and Swanson, 1999; Kasahara and Wondzell, 2003) and extended the applicability of these concepts to larger floodplain systems. Additionally, our empirical evidence corroborated results of hydrogeologic modelling experiments (e.g. Kasahara and Wondzell, 2003; Poole *et al.*, 2006), which suggested that the surface hydrology of

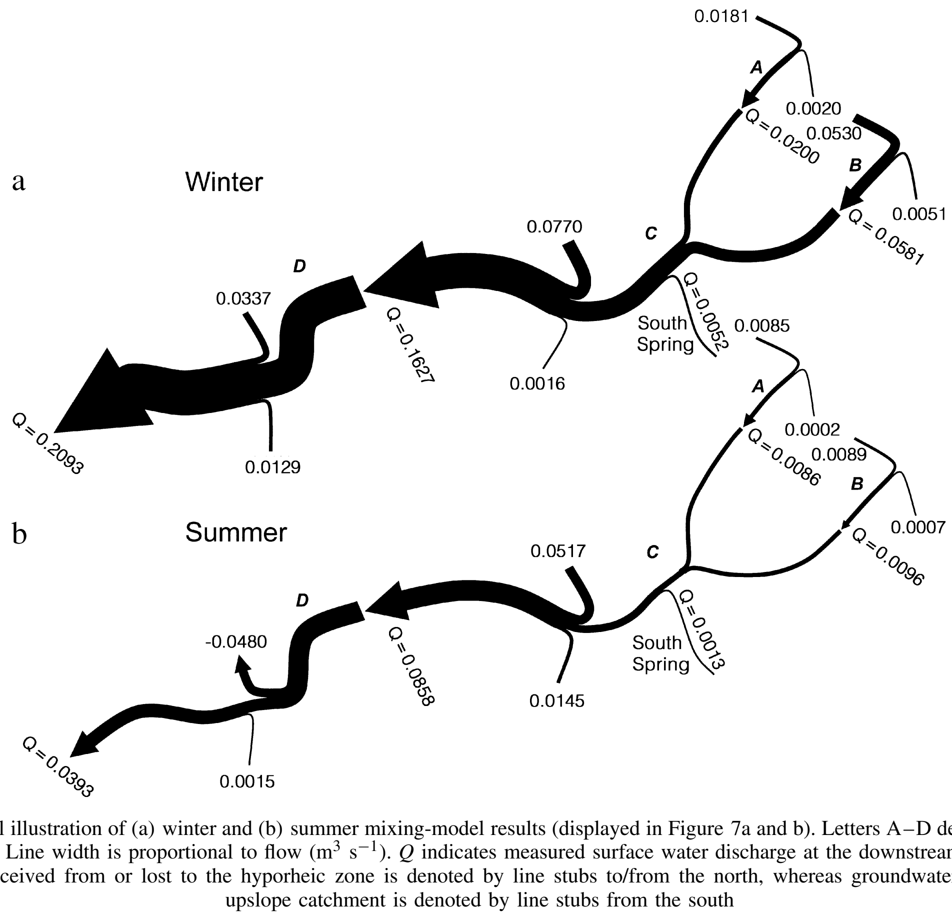

Figure 8. Graphical illustration of (a) winter and (b) summer mixing-model results (displayed in Figure 7a and b). Letters A–D denote spring channel reaches (Figure 1). Line width is proportional to flow (m^3 s^{-1}). Q indicates measured surface water discharge at the downstream end of each reach (Table I). Water received from or lost to the hyporheic zone is denoted by line stubs to/from the north, whereas groundwater received from the upslope catchment is denoted by line stubs from the south

off-channel features (e.g. spring channels, side channels, tributaries, backwaters, etc.) can create temporally dynamic deviations from the typical downstream orientation of hydraulic gradients within alluvial aquifers (Woessner, 2000) and, thus, alter water-table elevations and restructure hyporheic flow directions among seasons.

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