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Journal of Hydrology 244 (2001) 157–180

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Linking hyporheic flow and nitrogen cycling near the Willamette River — a large river in Oregon, USA

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Received 19 January 2000; revised 14 November 2000; accepted 24 January 2001

Abstract

Several approaches were used to characterize ground water/surface water interactions near the Willamette River — a large (ninth order) river in Oregon, USA. A series of potentiometric surface maps demonstrated the presence of highly dynamic hydraulic gradients between rivers and the adjacent aquifer. Hyporheic zone gradients extended on the order of hundreds of meters. River gains and losses at the river stretch scale (tens of kilometers) were consistent with fluxes implied by the potentiometric surface maps, and apparently reflect regional ground water/surface water interactions. Gains and losses of up to 5–10% of streamflow were observed at this scale. On the river reach scale (1–2 km), gains and losses on the order of 5% of streamflow were interpreted as representing primarily local hyporheic exchange.

Isotopic and chemical data collected from shallow hyporheic zone wells demonstrated interaction between regional ground water and river water. The origin of sampled hyporheic zone water ranged from a mixture dominated by regional ground water to water containing 100% river water. The common assumption that ground and river water mix primarily in the river channel is not applicable in this system. Isotopic and chemical data also indicated that significant (nearly complete) vegetative nitrate uptake and/or nitrate reduction occurred in water from 4 of 12 hyporheic zone sites. In these cases, it was primarily nitrate transported to the hyporheic zone in regional ground water that was removed from solution. Isotopes of water and nitrate indicated that hyporheic zone water sampled at two sites was composed of water originating as river water and demonstrated that significant vegetative nitrate uptake and nitrate reduction occurred along these hyporheic zone flowpaths. Thus, the hyporheic zone may, in some instances, serve to remove nitrate from river water. Additional investigations with chemical tools and microbial enzyme assays were conducted at one hyporheic site. A strong vertical redox gradient was observed, with nitrate-limited denitrification potential in deeper sediment and both nitrification and denitrification potential in shallower sediment. Since nitrogen cycling is strongly affected by redox conditions, nitrogen cycling in the hyporheic zone of this large-river system likely is affected by dynamics of ground water/surface water interactions that control fluxes of nitrogen and other redox species to hyporheic zone sediment. Published by Elsevier Science B.V.

Keywords: Hyporheic zone; Ground water/surface water interactions; Nitrogen cycling; Isotope hydrology; Willamette Basin; River reach

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0022-1694/01/$ - see front matter Published by Elsevier Science B.V.
PII: S0022-1694(01)00335-3

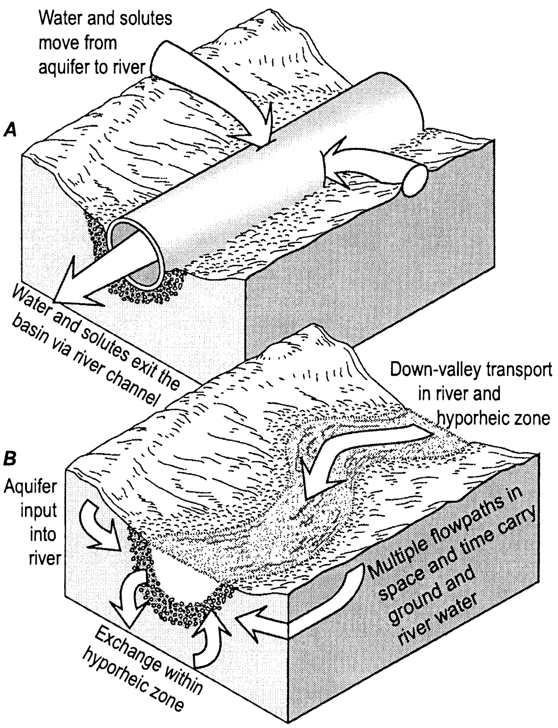

Fig. 1. (a) Common conceptualization of ground water/surface water interactions in a river with net overall gain in streamflow; (b) alternative conceptualization in which ground and river water interact in aquifer materials adjacent to the river (modified from Bencala, 1993).

1. Introduction

In early studies of interaction between ground and river water, interaction was conceptualized as unidirectional ground water discharge to gaining rivers or aquifer recharge from losing rivers. In the case of a river exhibiting a net gain in flow in the downstream direction, the river commonly was thought of as receiving discharge from the neighboring aquifer, but otherwise serving only as a conduit isolated from adjacent geologic material (Bencala, 1993; Fig. 1a).

Concepts of more complex interactions between ground and surface water eventually evolved. In particular, an understanding of the hyporheic zone has evolved over the past two decades (Winter, 1995). The hyporheic zone is defined as that part of the ground water/surface water continuum containing water originating both from the neighboring aquifer and from the river channel (Fig 1b; see also, Bencala, 1993; White, 1993; Winter, 1995). Recognition of the importance of the hyporheic zone to understanding ground water/surface water interactions evolved in response to field observations, as well as from the observation that solute transport in rivers often could not be described by simple advection and dispersion concepts. A variety of hydrochemical (physical, chemical, and isotopic) approaches have been developed to measure hyporheic exchange. Transient storage and aggregated dead zone models have been developed to simulate solute transport in rivers where solutes, in addition to responding to advection and dispersion, are retained in within-river and hyporheic 'storage' zones (Lees et al., 2000). These models have proven useful in quantifying hyporheic exchanges where within-river and hyporheic storage can be separately identified (e.g. Harvey et al., 1996).

In spite of recent increases in hyporheic research, advancement has been difficult because interaction between ground and surface water in the hyporheic zone is inherently dynamic both in space and time, reflecting spatially heterogeneous aquifer properties (Vaux, 1968; Valett et al., 1997), spatially (and, on the timescale of large floods, temporally) heterogeneous river-bed topography (Larkin and Sharp, 1992; Harvey and Bencala, 1993), and both spatially and temporally variable hydraulic gradients within and between ground and surface water zones (Pinder and Sauer, 1971). However, it is now believed that hyporheic zones are present, at some scale, in most aquatic ecosystems (Boulton et al., 1998; Edwards, 1998; Winter et al., 1998), and the importance of the hyporheic zone in hydrologic science is well established. Nevertheless, most studies of the hyporheic zone to date have been of hyporheic zones associated with lower order streams (Bencala et al., 1993; White, 1993; Winter, 1995; Dole-Olivier, 1998; Stanley and Jones, 2000). Evaluations of hyporheic zone processes in large river/aquifer systems have been few. White (1993) proposed that hyporheic zones should generally increase in size as stream order increases. Although largely untested, White's hypothesis suggests that the hyporheic zone may play an important role in large-river flow dynamics and water quality.

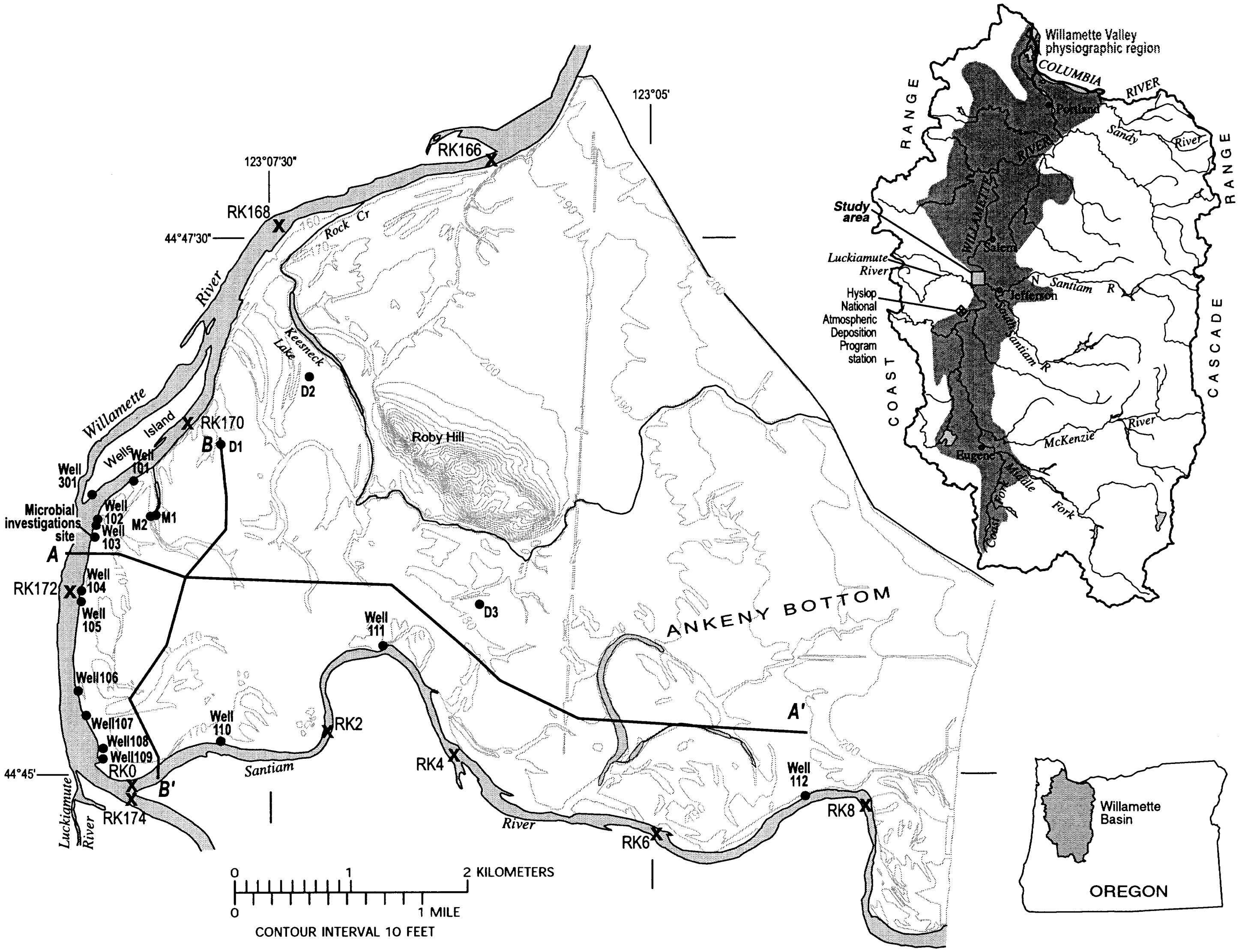

Fig. 2. Study area; lines A–A′ and B–B′ showing locations of geologic cross sections in Fig. 3 (RK, river kilometer).

The purposes of this paper are to: (1) use hydrochemical approaches to identify and quantify hyporheic interactions near a large river, and (2) use hydro-chemical and microbial approaches to identify processes occurring in a large river hyporheic zone that may affect water quality in receiving waters. Hyporheic fluxes of water and nitrogen dynamics were the foci of the study. The techniques applied are a step towards quantitative characterization of large river hyporheic zone processes needed for basin-scale water quality understanding, simulation, and management. In a separate paper, Laenen and Bencala (in press) provide insights into hyporheic exchanges in the same river basin from a transient-storage modeling basis.

2. Study area

The approximately 15 km^2 study area lies adjacent to the Willamette River — a ninth order (Sedell and Froggatt, 1984) river in Oregon, USA (Fig. 2). The 31 000 km^2 Willamette Basin (Wentz et al., 1998) is one of more than 50 study units in the USGS (US Geological Survey) National Water-Quality Assessment Program (Gilliom et al., 1995; US Geological Survey, 1999).

The temperate, marine climate of the Willamette Basin is characterized by cool, wet winters and warm, dry summers. Most precipitation falls during late fall, winter, and early spring, with 70–80% of the annual precipitation falling between October and March (Uhrich and Wentz, 1999). Streamflow reflects these seasonal variations. Summer and early fall reservoir releases augment natural streamflow. Mean annual precipitation for the period 1961–1990 ranged from about 100 cm in parts of the valley to as much as about 500 cm in some high elevation areas (Uhrich and Wentz, 1999).

Most land use in the Willamette Basin is characterized as forested or agricultural (Uhrich and Wentz, 1999). About 70% of the basin is covered by forest, primarily coinciding with bedrock areas. Several studies (D'Angelo et al., 1993; Wondzell and Swanson, 1996, 1999) have identified extensive hyporheic zones in relatively small streams in the forested headwater portions of the basin. Agricultural land covers about 22% of the basin, primarily in the Willamette Valley.

The Willamette Valley, a structural and erosional lowland, lies between the Coast Range (to the west) and Cascade Range (to the east). The Willamette Valley is filled with Tertiary and Quaternary clastic sediments of fluvial origin (Gannett and Caldwell, 1998). Holocene alluvium has been deposited near rivers and streams. Texture of the Holocene alluvium ranges from clean, well-rounded gravel and cobbles to fine-grained, often organic-rich sediment. Gravel and cobbles are common in the Holocene alluvium, and its permeability generally is greater than that of older alluvium in the Willamette Basin (Piper, 1942). The highly transmissive Holocene alluvium is the type of geologic material that would be expected to foster extensive hyporheic exchange (Stanford and Ward, 1988).

Most of the study area (Fig. 2) is underlain by a highly productive, relatively uniform, unconfined aquifer (Fig. 3). The lower part of the aquifer consists of about 6–12 m of Holocene (and Pleistocene?) gravel, sand, and cobbles. The upper part of the aquifer consists of the saturated portions of up to about 5 m of cobbly soil with layers of sand and silt. Aquifer permeability is high, and well yields typically range from 200 to 4000 l/min (Helm and Leonard, 1977). Measured depths to water range from near zero to approximately 6 m below land surface. The aquifer is uniformly underlain by relatively impermeable clay. Irrigation wells support land use dedicated predominantly to irrigated agriculture. For the most part, the western edge of the Willamette River near the study area is bounded by low-permeability Eocene siltstone and sandstone. The area immediately south of the Santiam River was not studied, but is geologically (and, presumably hydrogeologically) similar to the study area.

Portions of two rivers — the Willamette and Santiam Rivers — are included in the study area. The Santiam River is the largest Willamette River tributary, with a mean annual flow of about 221 m^3/s (Wellman et al., 1993).

In this paper, regional study area ground water is considered to be distinct from hyporheic water. Regional ground water residing in the shallow aquifer is the component of regional ground water that most actively interacts with rivers. This ground water is

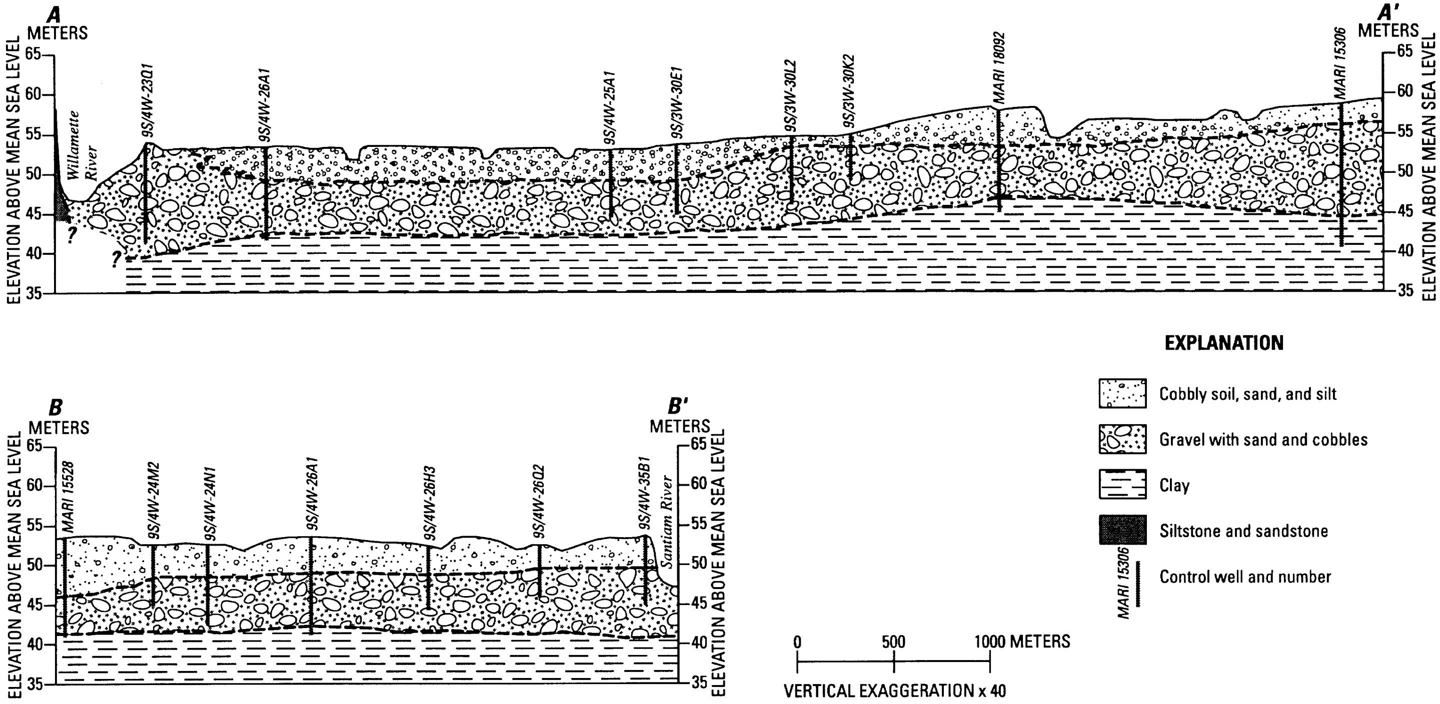

Fig. 3. Geologic cross sections of study area (well numbers reference Helm, 1968, or Oregon Water Resources Department database).

tapped by domestic wells and numerous irrigation wells in the study area. Regional ground water is presumed to originate as recharged precipitation.

3. Study design and methods

A combination of physical, chemical, and isotopic approaches was used to evaluate ground water/surface water interactions. Potentiometric surface maps were used to define hydraulic gradients between ground and river water. River gain and loss measurements were used to calculate fluxes between rivers and aquifers. Stable isotopes of water (D and ^{18}O) were used to identify components of river water and regional ground water in near-river hyporheic water. Chemical constituents (nutrients, or nitrogen and phosphorus compounds; chloride; iron), stable isotopes of water, ^{15}N of nitrate, and microbial enzyme assays were used to identify processes that may be affecting nitrogen in the hyporheic zone.

3.1. Potentiometric surfaces

Potentiometric surface maps were constructed by linear interpolation using 30–38 ground water levels measured every two months. River water elevations were estimated by extrapolation using measured study-area river-stage measurements, river-stage measurements from nearby USGS stream gaging stations, and published US Army Corps of Engineers river profiles (US Army Corps of Engineers, 1968a,b, 1971). Established procedures were used to measure ground water levels (Lapham et al., 1995) and to survey elevations of ground and surface water measurement points (Kennedy, 1990).

3.2. River gain and loss measurements

Measurements of net gains and losses in flow for individual river reaches were calculated by subtracting streamflow at the upstream end of the reach from that at the downstream end of the reach. Gain and loss measurements were adjusted for within-reach withdrawals and tributary inflows. Streamflow for the USGS gaging station on the Santiam River at Jefferson (station 14189000) at river kilometer (RK) 17.9 was determined from standard stage/discharge relationships (Rantz, 1982). All other streamflow measurements were made using Acoustic Doppler Current Profiler (ADCP) techniques (Morlock, 1996). Each ADCP-derived streamflow measurement used in the analysis represents the mean of 6–10 sets of ADCP measurements. Streamflow along the edges of ADCP cross-sectional transects was measured using conventional current-meter methods (Rantz, 1982). Standard errors were estimated using methods of Rantz (1982). The median standard error of ADCP-derived streamflow measurements was 2.0%. Standard error of gain and loss measurements (presented with data) account for the additive error of both the upstream and downstream streamflow measurements.

3.3. Isotopic, chemical, and microbial approaches

Twelve water samples were collected from the hyporheic zone along the right edge of water (looking downstream) of the Santiam and Willamette Rivers in June 1995 (wells 101–112; Fig. 2 and Table 1). These samples were collected from 3.2 cm-diameter drive-points (well 101, wells 104–112) and 5.2 cm-diameter augured PVC monitoring wells (wells 102–103). Samples were analyzed for stable isotopes of water, chloride, nutrients, and iron.

Additional investigation of processes affecting nitrogen in the hyporheic zone was conducted at two sites where observed hydraulic gradients indicated that river water was flowing into near-river gravels during site visits. Paired river and hyporheic zone water samples were collected. One site consisted of well 111 paired with the Santiam River at RK 2.9 (Fig. 2 and Table 1). The other site was located near the upstream (southern) end of Wells Island (Fig. 2). Here, a 3.2 cm-diameter drive-point (well 301) was paired with the Willamette River at Wells Island (Fig. 2 and Table 1). Samples were analyzed for stable isotopes of water, ^{15}N of nitrate, chloride, and nutrients.

A site in the hyporheic zone adjacent to the Willamette River at RK 171.5 (Fig. 2) was instrumented for microbial investigations. Arrays of closely spaced wells were installed. Five wells (WRS 1–5) were screened just beneath the top of the water table and six wells (WRD 2–7) were screened 2–3 m below the water table. The 3.2 cm-diameter PVC wells were screened for 76 cm at the bottom of the casing. Wells were sampled for DOC (nonpurgable dissolved

Table 1
Construction information for wells installed in hyporheic zone (date of physical measurements corresponds to date of sampling for chemical and isotopic constituents)

Site	Date	Depth from water table to top of screen (m)	Depth from water table to bottom of screen (m)	Shortest horizontal distance between river and well during sampling (m)
Well 101	06/13/95	0.33	0.40	2.9
Well 102	06/05/95	0.70	1.31	~ 6
Well 103	06/05/95	1.99	2.27	~ 6
Well 104	06/09/95	0.24	0.31	1.8
Well 105	06/09/95	0.20	0.27	2.1
Well 106	06/07/95	0.13	0.20	3.5
Well 107	06/07/95	0.39	0.46	2.7
Well 108	06/07/95	0.77	0.84	12.3
Well 109	06/07/95	0.23	0.30	10.1
Well 110	06/09/95	0.30	0.37	2.6
Well 111	04/20/95	0.72[a]	0.72[a]	2.3
Well 111	06/06/95	0.12[a]	0.12[a]	2.8
Well 112	06/09/95	0.09	0.55	1.5
Well 301	06/13/95	0.11	0.18	11.2
Well 301[b]	08/24/95	0.30	0.38	18.7

[a] Screen sheared during emplacement; drivepoint functioned as a piezometer (open only at bottom).

[b] Water table initially below bottom of screen on 08/24/95, so drivepoint driven deeper into gravels to obtain water.

organic carbon), DO (dissolved oxygen), nitrite-plus-nitrate, ammonium, ferrous iron, iron (ferrous-plus-ferric), and methane to study processes affecting redox and nitrogen biogeochemistry in the hyporheic zone. DOC also was determined for samples from two of the river sites and two of the regional ground-water sites described below. Laboratory microbial enzyme assays were done to estimate nitrification and denitrification potentials in both shallow and deep hyporheic sediments. Fresh sediment was collected using a bucket auger from the bank near the riparian well array on 20 May 1995. Sediment from the water table and 2–3 m below the water table was immediately returned to the laboratory for the assays.

The isotopic and chemical character of regional ground water was defined by analyses of water from wells presumed to be unaffected by river water dilution. Samples were collected from three domestic wells (D1, D2 and D3; Fig. 2) and two shallow augured monitoring wells (M1 and M2; Fig. 2). The monitoring wells, installed adjacent to a slough, were sampled during a period when the potentiometric surface had been observed to be rising quickly over several days and the local hydraulic gradient indicated regional ground water was discharging to the slough.

Eighteen samples for stable isotopes of water were collected from three river sites: Willamette River at RK 171.4 (right edge of water; every other month), Santiam River at RK 2.9 (right edge of water; two samples), and Santiam River at RK 9.8 (centroid of flow; every other month) (Fig. 2). Nine samples for chloride and nutrients were collected approximately quarterly for 1 yr from two of these sites (four from the Willamette River site, and five from the Santiam River at RK 2.9).

Arithmetic mean values of National Atmospheric Deposition Program (NADP) precipitation-weighted mean nitrate and chloride concentrations for calendar years 1994 and 1995 (National Atmospheric Deposition Program, 1997) for the Hyslop station (Fig. 2) were assumed typical of study area precipitation. Isotopic data are not routinely collected at NADP sites, but stable isotopic ratios of regional ground water are expected to be representative of stable isotopic ratios of local precipitation and were used to estimate the stable isotope character of precipitation recharging the shallow aquifer.

For microbial work, denitrification was assayed by the acetylene block technique (Balderston et al., 1976; Yoshinari et al., 1977). Thirty cm^3 of sediment were added to 250 ml Erlenmeyer flasks, slurried with 135 ml of ground water, flushed for 15 min with oxygen-free nitrogen, and sealed. Acetylene was added (15 ml) by syringe to the headspace of the flasks. Flasks were incubated at 25°C and 120 rpm for 15 min before the headspace was subsampled for initial nitrous oxide determinations. Nitrate, glucose, and nitrate plus glucose (1 mM final concentration per substrate) treatments allowed differentiation of carbon limitation from nitrogen limitation.

Nitrification also was assayed (Triska et al., 1990). Thirty cm^3 of sediment were added to 250 ml Erlenmeyer flasks and slurried with 135 ml of ground water. Triplicate unsealed flasks were incubated at 25°C and 120 rpm for 30 min before the water phase was sampled. Twenty ml of water was removed from the flasks at 15 h intervals, filtered, and analyzed for nitrate. Incubations were done at endogenous ammonium levels and with ammonium added (1 mM final concentration). Nitrapyrin (2-chloro-6-trichloromethylpyridine) was added to one set of slurries to inhibit ammonium oxidation (25 μl of a 20% solution). All flasks were amended with phosphorus to avoid potential nutrient limitations.

Procedures for ground water sample collection and processing were those defined by Claassen (1982). Surface water samples were collected as grab samples and processed in the same manner as ground water samples. DO was measured electrometrically in situ. Samples for nutrients, chloride, iron, and ferrous iron were filtered through in-line 0.45 μm filters. Samples for iron and ferrous iron at wells WRS1–5 and WRD2–7 were collected in-line in gas-tight glass syringes and stored on ice, in coolers, until analysis later the same day. DOC samples were filtered through 0.45 μm silver filters. Unfiltered samples for methane were collected with glass syringes and expelled into sealed serum bottles. Samples for D and ^{18}O in water were collected as unfiltered samples. Twenty-liter samples for ^{15}N in nitrate were filtered through 0.45 μm filters and extracted following procedures of Silva et al. (2000).

DOC was analyzed at the National Research Program (NRP) Organic Carbon Migration Laboratory in Boulder, Colorado, by wet oxidation (Aiken, 1992). Methane was analyzed at the NRP Biota-Solute Transport Interface (BSTI) laboratory in Menlo Park, California, by gas chromatography using flame ionization detection following headspace equilibrium. Iron and ferrous iron for wells WRS1–5 and WRD2–7 were analyzed near the study site using Hach chemical procedures (Hach Company, 1992). Ammonium and nitrite-plus-nitrate samples from wells WRS1–5 and WRD2–7 were analyzed at the NRP BSTI Laboratory by automated segmented flow colorimetry (Fishman and Friedman, 1989). Nitrate (microbial enzyme assay) was analyzed at the NRP BSTI Laboratory by ion chromatography (Fishman and Friedman, 1989). Nitrous oxide was determined at Oregon State University by gas chromatography using a ^{63}Ni electron capture detector (Smith and Duff, 1988). All other samples for nutrients and iron were analyzed at the USGS National Water Quality Laboratory in Arvada, Colorado, by automated segmented flow colorimetry (nitrite-plus-nitrate, nitrite, ammonium) and inductively coupled plasma/atomic emission spectrometry (iron) (Fishman and Friedman, 1989; Fishman, 1993). Chloride was analyzed at the NRP Flow and Geochemical Interactions Laboratory in Menlo Park, California, by ion-exchange chromatography (Fishman and Friedman, 1989).

In all samples that were analyzed for nitrite-plus-nitrate, nitrite concentrations consistently were negligible, so nitrite-plus-nitrate is henceforth referred to as 'nitrate'. The minimum reporting level (MRL) for nitrate ranged from 0.005 mg N/l (low level method) to 0.05 mg N/l (standard method). For plotting purposes, nitrate concentrations below the standard method MRL were plotted at one half of the MRL.

Stable isotopes of water (D and ^{18}O) were analyzed by mass spectrometry (NRP stable isotope laboratories in Reston, Virginia, and Menlo Park, California) and are reported in units of per mil (‰) relative to Vienna Standard Mean Ocean Water (VSMOW) on a scale normalized to standard light Antarctic precipitation (Coplen, 1994). Deuterium data were variably reported to either zero or one decimal, and are reported as such in this paper. Isotopes of nitrate were analyzed by mass spectrometry (NRP

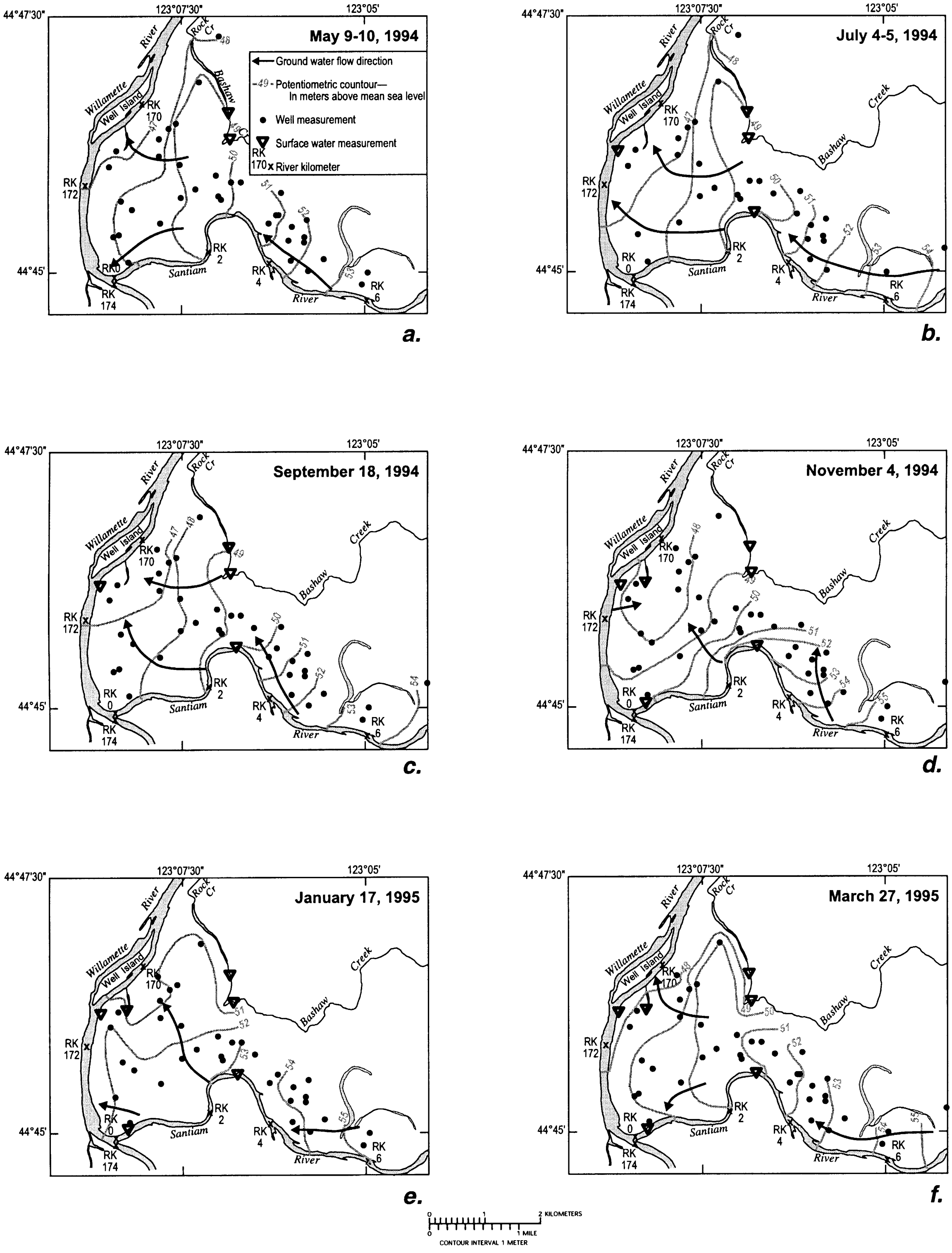

Fig. 4. Potentiometric surface maps of study area.

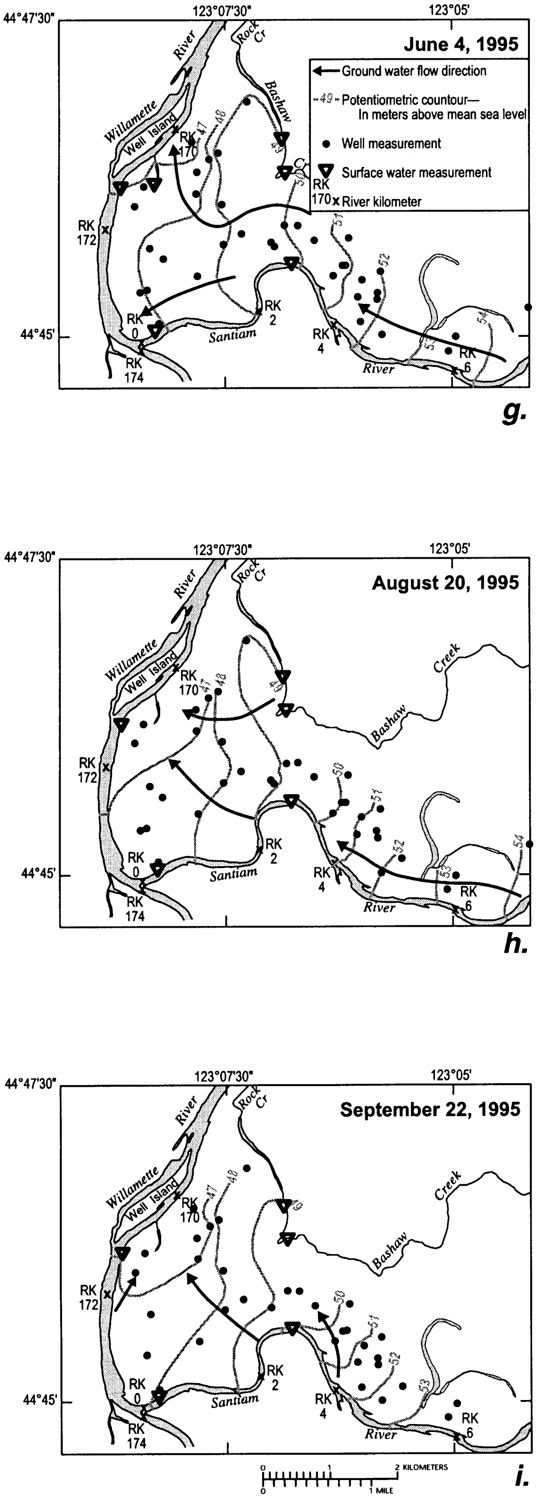

Fig. 4. (*continued*)

stable isotope laboratory in Menlo Park) and are reported in units of per mil relative to AIR (Coplen, 1993).

Fractionation of nitrogen isotopes during denitrification was simulated with the Rayleigh equation (Gat, 1981):

$$R_t = R_0[C_t/C_0]^{\epsilon/1000}, \quad (1)$$

where R_t is the isotopic ratio ($^{15}N/^{14}N$) at time t, R_0 the initial isotopic ratio ($^{15}N/^{14}N$), C_t the nitrate concentration at time t, C_0 the initial nitrate concentration, and ϵ is the isotopic fractionation factor, in ‰.

4. Results and discussion

4.1. Potentiometric surfaces

Potentiometric surface maps portray highly dynamic interactions between river and ground water (Fig. 4). Variable hydraulic gradients are particularly evident in the western half of the study area, where, in places, hydraulic gradients vary seasonally by up to almost 180° (e.g. compare Fig. 4a with Fig. 4d). Ground water in the western half of the study area appears to flow primarily towards the rivers during the spring (Fig. 4a, f and g). In early summer, gradients are characterized by flow from parts of the lower few kilometers of the Santiam River into alluvial materials (Fig. 4b). In some places, the gradients from river to ground water become better established as summer progresses (Fig. 4c and h). This regime, in which gradients favor movement of water from rivers to aquifers in at least parts of the western study area, also appears at times in the fall and winter in response to storm runoff events (e.g. events captured in Fig. 4d and e). Surface water stage usually rises farther and/or faster than ground water levels during rainfall events, and gradients conducive to flow from rivers into ground water can become steeper during the rainy season than during summer. Changes in river stage reflecting reservoir releases also can result in widespread gradients from rivers to aquifers (e.g. reservoir release event captured in Fig. 4i). Winter gradients are probably highly dynamic, in part reflecting rapid, storm-induced changes in surface water stage. However, in most of the western part of the study area, at most times, gradients are dominated by flow from aquifers to rivers, reflecting the net water balance in the Willamette Basin, in which rivers behave as regional drains for aquifers (Piper, 1942). Such patterns are well established in spring, as noted in Fig. 4a, f and g.

Hydraulic gradients in the eastern half of the study area are less variable than in the western half, and the predominance of down-valley ground water flow indicates an approximate balance between river and ground water. However, the hydraulic gradients in the eastern half of the study area sometimes contain flow components from the Santiam River towards ground water (e.g. Fig. 4d) and from ground water to the Santiam River (e.g. Fig. 4e) resulting from seasonal variations in precipitation, differences in the response to this precipitation in geologic materials versus rivers, and to some extent, timing of reservoir releases.

The potentiometric surface maps indicate the presence of a dynamic energy potential that may allow significant fluxes of river water to enter the aquifer. However, they do not quantify actual fluxes of water between rivers and ground water. River gain and loss measurements, the topic of Section 4.2, allow for quantitative characterization of exchanges of water between rivers and aquifers.

4.2. River gain and loss measurements

River gain and loss measurements were made to quantify exchanges of water between rivers and aquifers. River gain and loss measurements were interpreted at two scales: the ‘river reach’ scale, corresponding to individual measurement reaches of about 1–2 km, and the ‘river stretch’ scale, encompassing longer river sections (tens of kilometers). Four sets of measurements delineated reach-scale gains and losses along the lower 5 km of the Santiam River (Fig. 5). These data also were compared with river discharge data from the USGS gaging station at RK 17.9 to provide information over an 18 km stretch of river. Similarly detailed sets of measurements were made for a portion of the Willamette River (Fig. 6).

Patterns of gains and losses for the Santiam River are most obvious at the river stretch scale. The general pattern of gains and losses is consistent with interpretations of potentiometric surface maps (Fig. 4). For example, the overall gain in streamflow over the

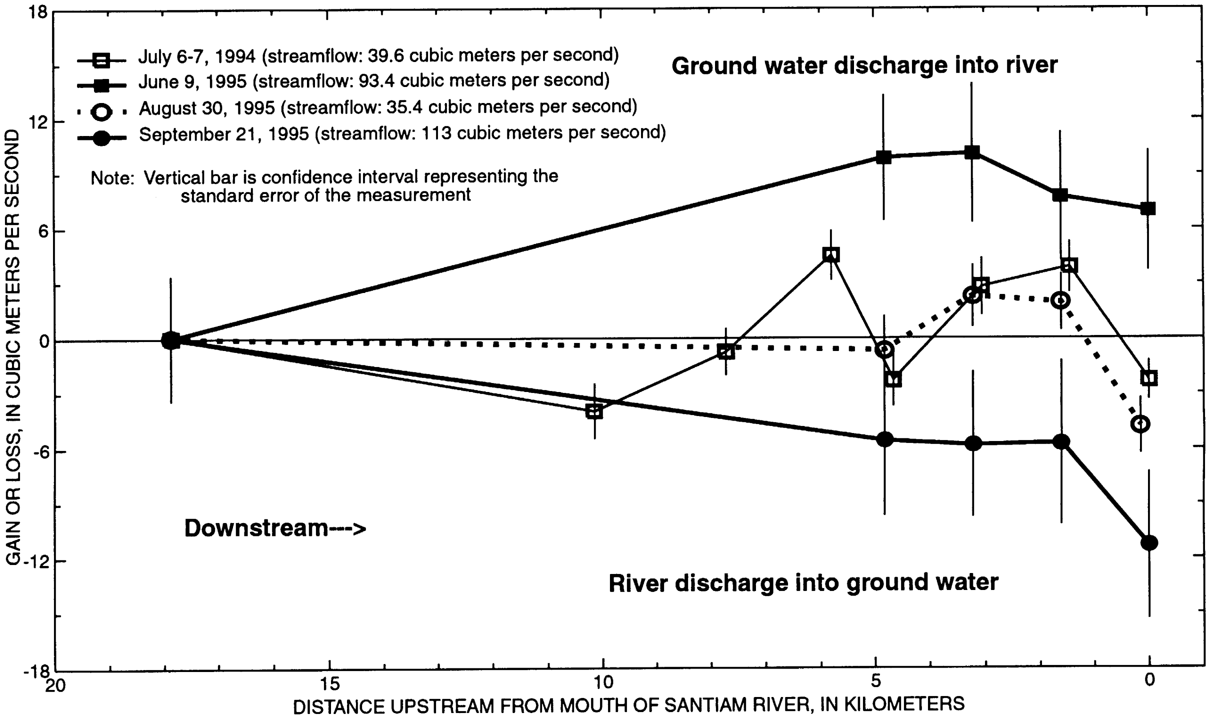

Fig. 5. Gains to and losses from the Santiam River (selected overlapping data offset by 0.1 km to allow better visual presentation).

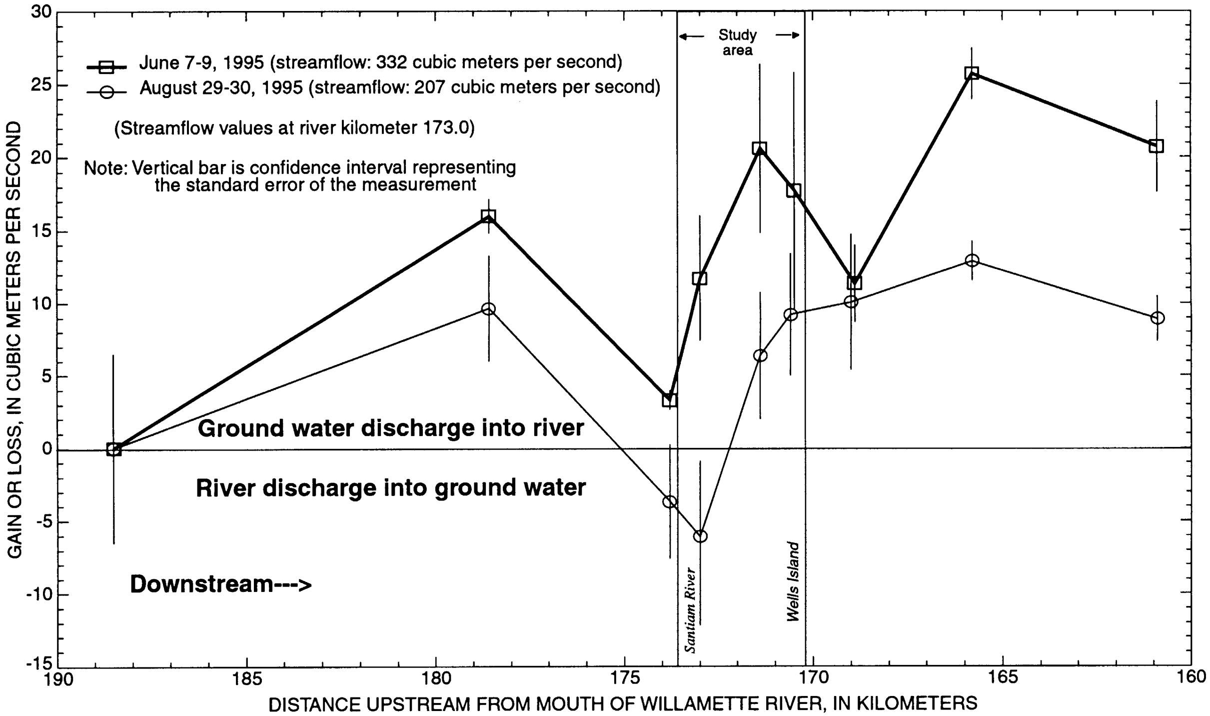

Fig. 6. Gains to and losses from the Willamette River (selected overlapping data offset by 0.1 km to allow better visual presentation).

18 km stretch of river in June 1995 (Fig. 5) is consistent with the potentiometric surface map (Fig. 4g) that shows high ground water levels relative to river levels. The net decrease in Santiam River streamflow over the 18 km stretch in September 1995 (Fig. 5) is consistent with the potentiometric surface map (Fig. 4i) that indicates high river levels relative to ground water levels. Periods of more neutral gradients between rivers and aquifers (e.g. Fig. 4b and h) correspond with smaller fluxes between river and ground water over the 18 km stretch (Fig. 5).

River-stretch scale gain and loss measurements for the Willamette River show overall gains in streamflow that result primarily from regional ground water discharge (Figs. 6, 4g and h). Greater gains in June 1995 than in August 1995 reflect greater ground water discharge to the Willamette River, as recently recharged ground water from winter rains emptied to rivers. By August 1995, effects of winter ground water recharge had weakened.

River-reach scale gain and loss measurements over the reach of the Santiam River just above the mouth (Fig. 5) correlate well with potentiometric surface maps. The small measured river loss in June 1995 corresponds with down-valley ground water flow on the north side of the Santiam River (Fig. 4g), whereas larger measured river losses for this reach in July 1994 and in August and September 1995 correspond with river-to-aquifer flowlines (Fig. 4b, h and i). However, other river reach gain and loss measurements on the Santiam River exhibit little correlation with potentiometric surface maps. This suggests that many of the ground water/surface water interactions at the river reach scale along the lower Santiam River are dominated by exchange with local rather than regional ground water systems. It is likely that some of the apparent river-reach scale gains and losses of up to several m^3/s reflect local fluxes between the Santiam River and near-river gravels, such as gravel bars, permeable islands, and the river bed. At the river reach scale, interactions between rivers and regional aquifers are difficult to observe in the presence of local fluxes (near-river gravels) and measurement errors.

Examination of Fig. 5 also indicates that gains and losses at the river reach scale were relatively greater during low flow (open symbols; flows on the order of $40\ m^3/s$) than during intermediate flow (solid symbols; flows on the order of $100\ m^3/s$). The apparently more significant gains and losses during low flow may be related to seasonal changes in magnitudes of local scale hyporheic flow. Pool-and-riffle structure of the Santiam River, which was observed to be significantly more pronounced during low flow than intermediate flow, could explain this pattern as stream water tends to enter the streambed hyporheic zone at the head of a riffle and re-emerge at the transition of the riffle to the next pool (Harvey and Bencala, 1993). Intermediate streamflow drowned (overflowed) the pool-and-riffle structure and inhibited hyporheic flow.

River reach scale gain and loss measurements along the Willamette River between RK 169 and 174 indicate generally gaining reaches in June and August 1995 (Fig. 6). Hyporheic interactions are not particularly evident. This is consistent with field observations of little pool-and-riffle structure. Also, hydraulic gradients along the east side of the Willamette River during June and August of 1995 appeared to be more favorable for discharge to surface water than was the case along the north side of the lowest several kilometers of the Santiam River (Fig. 4).

Ground water/surface water interactions can be measured at a variety of scales, but it has proven difficult to relate small-scale ground water/surface water interactions to basin-scale effects. Recently, Harvey and Fuller (1998) were able to extrapolate small-scale (sediment-grain scale through stream-reach scale) hyporheic data to basin-scale effects for a small creek. The results presented above, which demonstrated that river-reach and river-stretch gain and loss measurements apparently correspond to ground water/surface water interactions at local and regional scales, respectively, are a step towards developing an understanding of large-river-basin scale ground water/surface water interactions.

4.3. Mixing of water in the hyporheic zone: evidence from isotopes of water

Stable isotopes of water (Fig. 7) allow identification of sources of water to the hyporheic zone. Regional ground water is isotopically heavier than river water. This condition arises because isotopically lighter river water originates from a range of elevations (particularly the higher elevations) in the basin, whereas

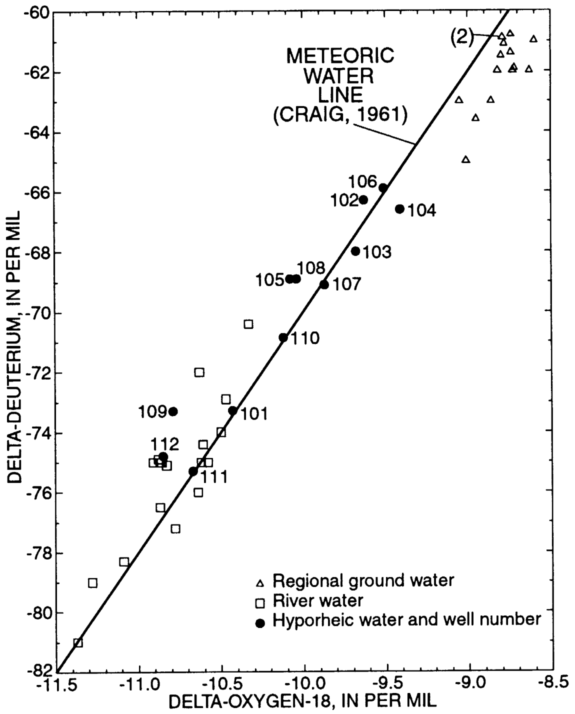

Fig. 7. Stable isotopes of water in regional ground water, river water, and hyporheic water.

isotopically heavier ground water originates as low elevation recharge. The differences in isotopic ratios reflect fractionation effects related to differences in elevation. For instance, decreases in $\delta^{18}O$ of 0.2–0.3‰ per 100 m of elevation gain generally are observed (Payne, 1983).

Hyporheic water samples fall along a mixing line between regional ground water and river water (Fig. 7). Three conclusions are immediately evident from these data. First, the isotopic data demonstrate mixing of water originating from regional ground water and river water sources within the hyporheic zone. Hyporheic exchange that would be expected based upon observed hydraulic gradients (Section 4.1) and that were observed in gain and loss measurements (Section 4.2) is clearly demonstrated by the isotopic data. Second, because all hyporheic samples contained measurable amounts of river water, interaction between regional ground water and river water apparently is not restricted to isolated sites. Hyporheic exchange is widespread in the study area. Third, patterns in the proportions of regional ground water and river water, as exhibited in the isotopic data, are consistent with June, 1995 potentiometric surface data (Fig. 4g). Specifically, samples from the hyporheic zone (collected during June 1995) alongside the Willamette River generally contain a greater proportion (median, 50%; $n = 9$) of regional ground water than do samples collected from the hyporheic zone alongside the Santiam River (median, 10%; $n = 3$). This result is consistent with the observation that, during early June 1995, much of the ground water adjacent to the Santiam River was flowing in the down-river direction (a condition expected to be relatively accommodating of hyporheic exchange), whereas ground water adjacent to the Willamette River largely was flowing towards the river (a condition expected to be less accommodating of hyporheic exchange) (Fig. 4g).

4.4. Nitrogen cycling in the hyporheic zone: evidence from water chemistry and isotopes of water

To evaluate chemical processes occurring in the hyporheic zone, both chemical and isotopic characterization of end member components (regional ground

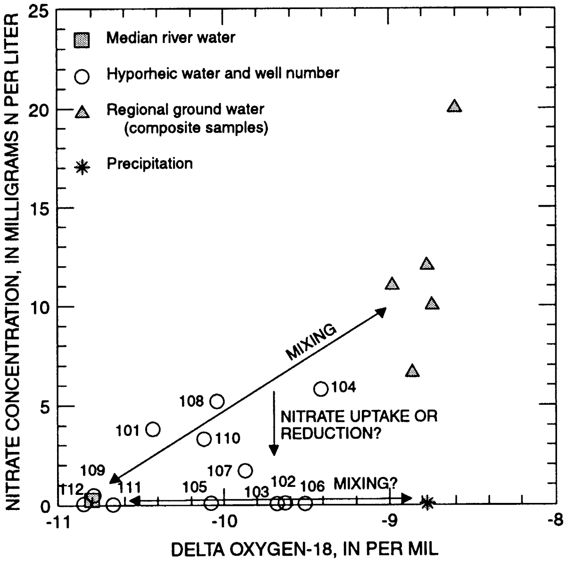

Fig. 8. Relationship between $\delta^{18}O$ values and nitrate concentrations for samples from regional ground water, river water, and hyporheic water.

water, river water, and precipitation) are useful. Samples for stable isotopes of water, nutrients, and chloride were collected from five wells tapping regional ground water. Median $\delta^{18}O$ was −8.77‰. Nitrate (6.6–20 mg N/l) and chloride (7.1–12.7 mg/l) concentrations in regional ground water were similar to those for oxic ground water from alluvial areas associated with irrigated agriculture throughout the Willamette Basin (Hinkle, 1997). In particular, Hinkle (1997) noted that near-river gravel aquifers with small amounts of overlying clay in areas of irrigated agriculture tended to have high nitrate concentrations (mg N/l to tens of mg N/l). Ammonium concentrations in water from the five wells were about 0.02 mg N/l.

River water was characterized as follows: $\delta^{18}O$, −10.80‰ (median of 18 samples, Fig. 7); nitrate, 0.25 mg N/l, and chloride, 1.3 mg/l (median of 9 samples each). (Ammonium was present at about 0.02 mg N/l.)

Local precipitation was characterized as follows. For $\delta^{18}O$, a value of −8.77‰ was assigned, based on the median $\delta^{18}O$ value for regional ground water (as described in Section 3.3). Nitrate and chloride concentrations in precipitation were assumed to be 0.04 mg N/l and 0.58 mg/l, respectively (also described in Section 3.3).

Although stable isotope data from hyporheic samples lie along a mixing line between regional ground and river water (Fig. 7), a plot of nitrate concentrations against $\delta^{18}O$ (Fig. 8) is not as straightforward. Nitrate concentrations for wells 102, 103, 105, and 106 are below the mixing line and near zero. Two explanations for these low nitrate concentrations are considered. One, they represent a mixture of river water and local precipitation that entered the hyporheic sediments so close to the river that agricultural impacts were absent (local mixing hypothesis). Two, these data reflect vegetative nitrate uptake or microbially facilitated nitrate reduction (denitrification or dissimilatory reduction of nitrate to ammonium), processes that may occur in the aquifer or in the hyporheic zone (nitrate uptake/reduction hypothesis).

Differences in chloride concentrations between regional ground water and precipitation (Fig. 9) allow rejection of the local mixing hypothesis. Although regional ground water and precipitation probably have similar isotopic signatures, precipitation contains significantly smaller chloride concentrations than does regional ground water. Hyporheic samples plot along a mixing line between regional ground and river water in Fig. 9. Mixing between

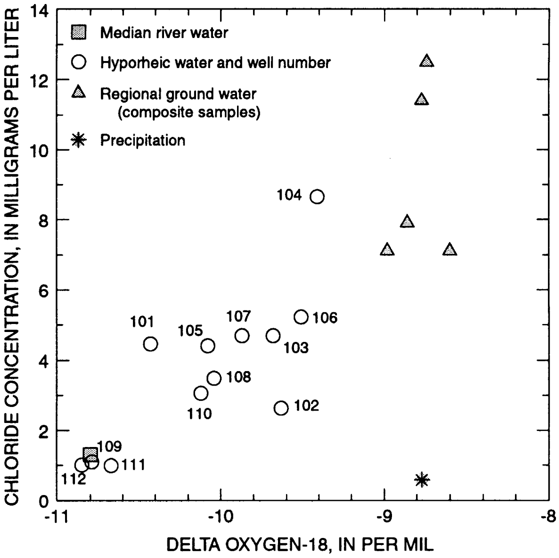

Fig. 9. Relationship between $\delta^{18}O$ values and chloride concentrations for samples from regional ground water, river water, and hyporheic water.

regional ground and river water also is supported by Figs. 7 and 8, however, data in Figs. 8 and 9 suggest that nitrate uptake or reduction occurred in some of the hyporheic water sampled.

Hyporheic zones commonly are associated with high levels of nitrate uptake and reduction (Duff and Triska, 1990; Bencala et al., 1993; Winter, 1995; McMahon and Böhlke, 1996; Mengis et al., 1999; Mulholland and DeAngelis, 2000). Nitrate uptake may occur in the hyporheic zone because the water table in the hyporheic zone typically is close to land surface. While Pinay et al. (1998) documented a case study in which hyporheic zone nitrate uptake was significant, high levels of hyporheic zone nitrate transformation also may be related to nitrate reduction resulting from frequent injection of readily assimilated organic carbon into hyporheic zone sediments (Von Gunten et al., 1991; Findlay, 1995; Cirmo and McDonnell, 1997; Schindler and Krabbenhoft, 1998). Injection of such organic carbon may occur by deposition of solid phase organic carbon during flood events or by advection of dissolved organic carbon in river water that flows into the hyporheic zone.

Support for the nitrate uptake/reduction hypothesis also is provided in Fig. 10. Some hyporheic samples fall along a mixing line between regional ground and river water, but several hyporheic samples (again, samples from wells 102, 103, 105, and 106) appear to fall below this mixing line. Low nitrate concentrations in samples from wells 102, 103, 105, and 106 cannot be ascribed to dilution with precipitation (Fig. 10), thus nitrate uptake or reduction remain the most likely explanations for the low nitrate concentrations.

Dissolved iron concentrations offer evidence supporting nitrate reduction in at least some of the water pumped from the hyporheic zone. Samples from two of the four wells exhibiting low nitrate concentrations also had high iron concentrations (wells 102 and 103; Table 2), which are indicative of conditions sufficiently reducing to have promoted nitrate reduction (Scott and Morgan, 1990).

4.5. Nitrogen cycling in the hyporheic zone: evidence from isotopes of nitrate

Paired river water/hyporheic water samples were collected at two sites: a Santiam River site and a site at Wells Island in the Willamette River (Fig. 2; Table 3). Observed hydraulic gradients for these pairs of samples were from river water to ground water, suggesting flow of river water into the hyporheic zone. Ratios of stable isotopes of water and concentrations of chloride for individual pairs of upgradient and downgradient samples were similar (Table 3), supporting the hypothesis of hyporheic linkages between upgradient and downgradient samples and ruling out regional ground water and local precipitation as contributing components. Nitrate concentrations, however, were lower in downgradient samples relative to upgradient samples (Table 3), suggestive of nitrate reduction and/or vegetative nitrate uptake.

Assimilation of nitrate by plants results in little fractionation of nitrate ^{15}N (Hubner, 1986). Large decreases in nitrate concentrations and small changes in $\delta^{15}N$ values from upgradient to downgradient Santiam River samples (Table 3) are consistent with nitrate uptake. However, apparent fractionation of ^{15}N in nitrate was observed between upgradient and downgradient Wells Island samples (Table 3), suggesting that a process other than or in addition to nitrate uptake was occurring at this site.

Biologically mediated nitrate reduction results in fractionation of nitrogen isotopes, with enrichment

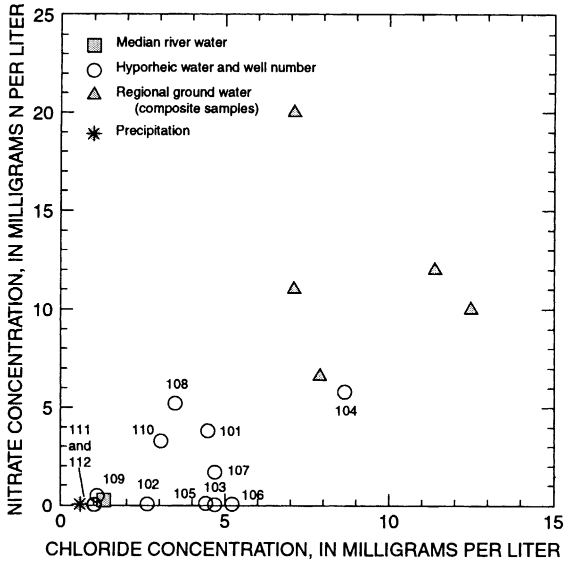

Fig. 10. Relationship between chloride and nitrate concentrations for samples from regional ground water, river water, and hyporheic water.

of the lighter ^{14}N in the product and enrichment of the heavier ^{15}N in the residual nitrate (Feast et al., 1998). An isotopic fractionation factor (ϵ) of −8.9‰ was calculated (Eq. (1)) for the apparent fractionation of nitrogen isotopes in nitrate for the pair of Wells Island samples. The value falls within the range typical of isotopic fractionation factors for denitrification (about −5 to −30‰; Mariotti et al., 1988; Bottcher et al., 1990; Smith et al., 1991). Thus, denitrification could explain nitrate loss between the upgradient and downgradient Wells Island samples. Other possible mechanisms of nitrate loss between the upgradient and downgradient Wells Island samples include dissimilatory reduction of nitrate to ammonium with subsequent sorption of ammonium, or a combination of nitrate uptake and nitrate reduction. Denitrification, however, is the most commonly observed nitrate reduction process in most environmental settings (Kinzelbach et al., 1991).

Table 2
Isotopic and chemical data for hyporheic water from wells 101–112

Site	Date	δD (‰)	δ^{18}O (‰)	Nitrate (mg N/l)	Ammonium (mg N/l)	Chloride (mg/l)	Iron (mg/l)
Well 101	06/13/95	−73.3	−10.43	3.8	0.02	4.5	0.54
Well 102	06/05/95	−66.3	−9.63	0.06	1.0	2.6	52
Well 103	06/05/95	−68.0	−9.68	< 0.05	1.7	4.7	58
Well 104	06/09/95	−66.6	−9.41	5.8	0.02	8.7	0.059
Well 105	06/09/95	−68.9	−10.08	0.07	0.02	4.4	0.11
Well 106	06/07/95	−65.9	−9.51	0.05	0.03	5.2	0.068
Well 107	06/07/95	−69.1	−9.87	1.7	0.02	4.7	0.10
Well 108	06/07/95	−68.9	−10.04	5.2	0.02	3.5	0.021
Well 109	06/07/95	−73.3	−10.79	0.49	0.02	1.1	0.018
Well 110	06/09/95	−70.8	−10.12	3.3	0.02	3.0	0.11
Well 111	06/06/95	−75.3	−10.67	0.014	0.02	1.0	0.039
Well 112	06/09/95	−74.8	−10.85	< 0.05	0.02	1.0	0.73

Table 3
Isotopic and chemical data for paired river water/hyporheic water samples (RK, river kilometer)

Site	Date	Nitrate (mg N/l)	$\delta^{15}N$ of nitrate (‰)	$\delta^{18}O$ of water (‰)	δD of water (‰)	Ammonium (mg N/l)	Chloride (mg/l)
Santiam R. at RK2.9 (upgradient)	04/20/95	0.24	+ 5.13	−10.33	−70.4	0.03	1.2
Well 111 (downgradient)	04/20/95	0.038	+ 4.03	−10.62	−73.8	< 0.015	1.0
Santiam R. at RK2.9 (upgradient)	06/06/95	0.16	+ 5.57	−10.78	−77.2	0.02	1.0
Well 111 (downgradient)	06/06/95	0.014	+ 2.15	−10.67	−75.3	0.02	1.0
Willamette R. at Wells Island (upgradient)	06/13/95	0.22	+ 6.74	−11.06	−77.9	0.03	4.3[a]
Well 301 (downgradient)	06/13/95	0.023	+ 27.25	−10.91	−77.2	0.03	4.3

[a] The high chloride concentration for the Willamette River at Wells Island relative to that for the right edge of water at RK 171.4 (2.1 mg/l on 5 June, 1995) reflects the influence of low-chloride Santiam River water along the right edge of water in the area immediately downstream from the confluence of the Santiam and Willamette Rivers.

4.6. Nitrogen cycling in the hyporheic zone: biogeochemical evidence

Water from both the shallow and deep well array at the site chosen for microbial investigations (Table 4) was chemically distinct from river water and from regional ground water. Nitrogen in river water and regional ground water was present primarily as nitrate (Section 4.4). DOC in river water ($n = 2$) and regional ground water ($n = 2$) was about 1 mg C/l. In contrast, nitrogen in samples from the well arrays at the microbial investigations site was present primarily as ammonium, and DOC concentrations were greater (2–18 mg C/l). High nitrate, low ammonium, and low DOC concentrations in river water and regional ground water are characteristic of oxygenated conditions. Hyporheic water at the microbial investigations site differed from these sources, having low DO. DOC in hyporheic water may be labile and available in sufficiently high concentrations to stimulate microbial respiration.

Deep and shallow hyporheic water differed drastically in the concentrations of ammonium and other reduced compounds present (Table 4). Ammonium in the deeper water may represent mineralization of organic nitrogen, or nitrate that was transported to the hyporheic zone from the regional aquifer and subsequently reduced at the prevailing redox conditions. On the other hand, low nitrate and ammonium concentrations in the shallow water at this site may indicate a dynamic zone of microbial respiration and element transformation near the top of the water table, where redox conditions vary in response to changing surface water/ground water gradients.

Nitrification and denitrification assays at the microbial investigations site indicate the potential for a dynamic interface for nitrogen transformations in the shallow hyporheic zone, but not in the deeper hyporheic zone. Deep hyporheic water lacked nitrification potential (data not shown) despite the presence of ammonium at concentrations on the order of 9 mg N/l. Deep sediments were capable of denitrification when nitrate was added to laboratory incubations (data not shown), and nitrate was not detected in the ground water (Table 4). These results for deeper hyporheic water are consistent with chemical evidence (high iron and methane concentrations) indicating strongly reducing conditions.

Table 4
Concentrations of redox species, nonpurgable dissolved organic carbon, and nutrients for environmental samples associated with microbial investigations (RK, river kilometer; DO, dissolved oxygen; DOC, nonpurgable dissolved organic carbon)

Site		Date	DOC (mg C/l)	DO (mg/l)	Nitrate (mg N/l)	Ammonium (mg N/l)	Ferrous Iron (mg/l)	Iron (mg/l)	Methane (mg C/l)
Shallow Wells	WRS 1	05/18/95	2.6	1.3	< 0.05	0.2	0.14	0.23	0.04
	WRS 2	05/18/95	2.6	0.9	< 0.05	0.1	0.30	0.39	0.08
	WRS 3	05/18/95	2.0	0.6	< 0.05	0.4	0.02	0.06	0.03
	WRS 4	05/18/95	2.9	0.8	< 0.05	0.3	0.11	0.14	0.02
	WRS 5	05/18/95	2.4	0.5	< 0.05	0.1	0.03	0.11	0.02
Deep Wells	WRD 2	05/18/95	14.9	< 0.5	< 0.05	9.5	108	105	21.2
	WRD 3	05/18/95	13.5	–	< 0.05	9.3	–	–	21.0
	WRD 4	05/18/95	13.7	< 0.5	< 0.05	8.5	122	116	21.2
	WRD 5	05/18/95	15.1	< 0.5	< 0.05	9.8	112	104	21.0
	WRD 6	05/18/95	14.7	< 0.5	< 0.05	9.6	114	108	21.0
	WRD 7	05/18/95	18.1	< 0.5	< 0.05	8.8	107	107	19.2

Nitrification was observed in incubations of shallow hyporheic sediments (Fig. 11) and was mildly stimulated by elevating ammonium levels. Nitrate production was not observed in hyporheic water alone, or when nitrapyrin was added to slurries to inhibit ammonium oxidation (i.e. to rule out other sources of nitrate). Rates of nitrification are likely regulated by the supply of ammonium and oxygen to the shallow hyporheic zone from river water and regional ground water, upward diffusion of ammonium from deeper hyporheic water, and oxygen diffusion through the unsaturated zone.

Denitrification was also observed in incubations of shallow hyporheic sediments (Fig. 12). Initial laboratory rates of nitrification and denitrification were similar (0.2–0.5 nmol N/cm^3 sediment/hr for nitrogen-amended slurries; Figs. 11 and 12). Thus, low dissolved inorganic nitrogen in shallow hyporheic water may be due to either of two causes. Absence of significant nitrate accumulation in shallow hyporheic water may indicate that nitrate was denitrified as rapidly as it was transported into this zone from river water and regional ground water or produced from nitrification. Alternatively, inorganic nitrogen may be rapidly assimilated by roots of riparian vegetation near the top of the water table.

5. Summary and conclusions

In this paper, hyporheic interactions near the Willamette River — a large (ninth order) river — were evaluated. Six major results were found:

- Potentiometric surface maps demonstrated the presence of highly dynamic hydraulic gradients between rivers and the adjacent ground water. Although flow of water often was from aquifers to rivers, hydraulic gradients also were observed from rivers into aquifers; these hyporheic gradients sometimes extended on the order of many hundreds of meters.
- River gain and loss measurements allow quantitative evaluation of exchanges of water between rivers and aquifers. River gain and loss measurements at the river stretch scale (tens of kilometers) agreed with flux directions shown by potentiometric surface maps. Gains and losses on the

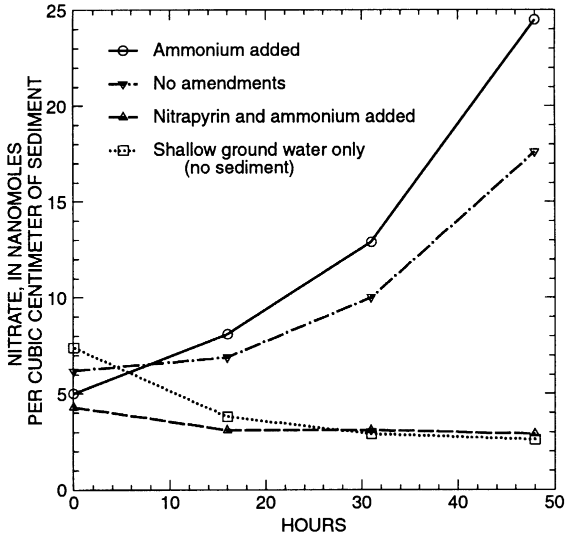

Fig. 11. Nitrification potential for shallow sediment, as indicated by nitrate production.

river stretch scale, therefore, appear to reflect interactions between regional ground water and rivers. Gains and losses of up to 5–10% of streamflow were observed at the river stretch scale. On the smaller river reach scale (1–2 km), measured gains and losses were interpreted to represent primarily local hyporheic exchange, probably occurring in near-river gravels. Exchanges over individual river reaches were on the order of up to 5% of streamflow. To some extent, these river reach fluxes alternately leave and return to the river, as would be expected for movement of water into and out of near-river geologic materials, such as gravel bars and islands and the river bed. Thus, the cumulative hyporheic flux from river-reach scale movement of water into and out of the hyporheic zone may exceed the net hyporheic flux that would correspond with gains and losses measured on the river stretch scale.

- Isotopic and chemical data from 12 shallow hyporheic zone wells also support ground water/surface water exchanges indicated by potentiometric surface maps and river gain and loss measurements. The origin of sampled hyporheic zone water ranged from a mixture dominated by regional ground water to 100% river water.
- In an assessment of 12 hyporheic zone samples, significant (nearly complete) nitrate uptake and/or reduction appeared to occur in at least four of the samples. It was primarily nitrate transported to the hyporheic zone in regional ground water that was removed from solution. Nitrate uptake and/or reduction, probably occurring in the hyporheic zone, suggests that the hyporheic zone of this

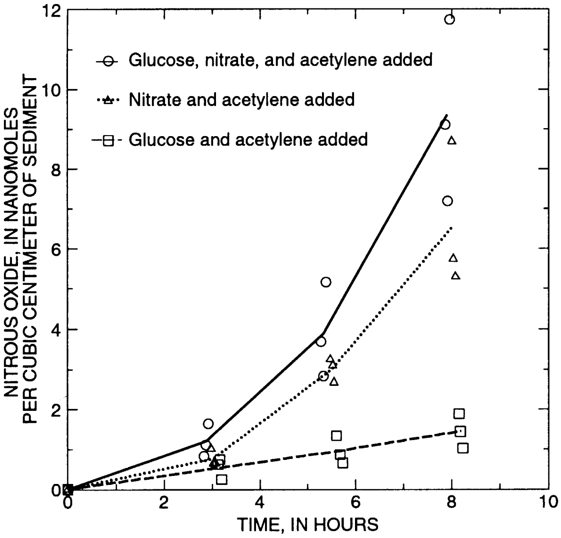

Fig. 12. Denitrification potential for shallow sediment, as indicated by nitrous oxide generation.

large river system is biologically and chemically active.

- Two case studies using ^{15}N of nitrate provided further evidence of chemical transformations in the hyporheic zone. Nitrate uptake and nitrate reduction appeared to occur along hyporheic zone flowpaths that originated in rivers, suggesting that the hyporheic zone may serve to remove nitrate from river water. Thus, removal of nitrate transported into the hyporheic zone both by regional ground water and by river water apparently occurs in parts of the study area hyporheic zone.
- Detailed investigation, using chemical and microbial techniques, further defined links between ground water/surface water interactions and cycling of transported nitrogen. Hyporheic water in a deeper hyporheic zone was distinctly more reducing than that at the water table. Hyporheic water >2 m deep was characterized by highly reducing conditions and high ammonium concentrations. This water exhibited high, nitrate-limited denitrification potential during microbial enzyme assays. In contrast, hyporheic water at the water table was mildly reducing, was low in both nitrate and ammonium, and exhibited both significant nitrification and denitrification potential. Thus, nitrogen cycling in the hyporheic zone, especially near the water table, may be particularly sensitive to shifts in redox resulting from dynamics of ground water/surface water interactions.

Results of this study have implications for a variety of water management issues. For example, uncertainties in measurement of streamflow resulting from variations in proportions of river water in open channels versus in hyporheic zones may have implications for management of water use and water rights. Similarly, large-river hyporheic zone fluxes may need to be considered in interpretation of streamflow data used to calculate boundary conditions for regional numerical ground water flow models.

Hyporheic zone processes also may need to be considered in the study and management of water quality of large rivers. The present work suggests the existence of a capability for nitrogen cycling (nitrate uptake and/or reduction; nitrification) in large-river hyporheic zones. Simulation of river solute loads based solely on tributary and ground water fluxes into rivers and in-river uptake/release/transformation may not match actual loads because advection of regional ground water and river water through hyporheic zone sediments can be accompanied by significant chemical or biological transformations. For example, calculation of ground water solute loads to large rivers based on regional ground water chemical characteristics, without accounting for hyporheic zone chemical and biological transformations, could result in significant errors.

Acknowledgements

We thank C.P. Cirmo, R.J. Hunt, J.J. McDonnell, and P.B. McMahon for insightful review comments on earlier versions of this manuscript. This work was funded by the USGS National Water-Quality Assessment Program and USGS National Research Program.

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