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Multiscale effects of surface–subsurface exchange on stream water nutrient concentrations

C. Lisa Dent[1], Nancy B. Grimm, and Stuart G. Fisher

Department of Biology, Arizona State University, Tempe, Arizona, 85287-1501 USA

Abstract. Stream–riparian ecosystems are landscapes composed of dynamic interacting terrestrial and aquatic patches. Patch composition and configuration affects both the form of transported materials and the amount of nutrient retention and export. We describe spatial patterns of nutrients in the surface water of an arid-land stream using surveys conducted at 3 different scales, ranging from 30 m to 10 km in extent and from 1 m to 25 m in grain. We then relate these patterns to connections with subsurface patches at channel subunit, channel unit, and reach scales. Our objectives were to compare spatial variation in nutrients across scales, to determine the causes of downstream changes in nutrient concentration in terms of intervening patches, and to investigate whether subsurface patches at different scales behaved similarly in terms of net nutrient processing.

Nutrients varied spatially at all scales sampled. The highest variation was observed in nitrate-N (NO_3-N) in the survey with the smallest grain (CV = 161%) and the lowest was observed in soluble reactive P (SRP) in the same survey (CV = 17%). We hypothesized that downstream changes in nutrient concentrations were caused by upwelling of high-nutrient water from the subsurface. To test this hypothesis, we identified locations of hydrologic inputs to surface water from the subsurface using geomorphic features of the stream such as gravel bar edges (channel subunit scale), riffle-run transitions (channel unit scale), and permanent groundwater sources (reach scale). As surface water passed over these locations, nutrient concentrations generally increased, particularly during late succession when subsurface patches acted as sources of NO_3-N at all 3 scales and as sources of SRP at the channel unit and reach scales. A hierarchical approach allowed us to decompose effects of subsurface upwellings at different scales and to consider interactions between them. Processes occurring in subsurface patches influenced surface water nutrient patterns at scales from a few meters to several kilometers.

Key words: nutrient retention, hyporheic zone, scale, hierarchy, nitrogen, phosphorus, stream.

Stream–riparian ecosystems are landscapes composed of dynamic interacting terrestrial and aquatic patches (Fisher et al. 1998a, Ward et al. 1999). Connections between patches occur in 3 spatial dimensions (Ward 1989): longitudinally, between upstream and downstream; laterally, between the channel, riparian zone, and floodplain; and vertically, between surface water and subsurface sediments. Although the flow of water is the dominant mode of connection, materials are also moved between patches by wind, gravitational forces, and organisms. Patch structure in stream–riparian ecosystems is dynamic in response to floods, drought, and other disturbances (Frissell et al. 1986, Grimm and Fisher 1992, Stanley et al. 1997). Interactions between structure, function, and temporal dynamics across multiple scales pose a challenge for understanding and managing these systems.

The patch configuration of any landscape is scale-specific; that is, different patches exist at different scales of observation. It has been argued that a more complete understanding of system dynamics is obtained by considering multiple scales and the interactions between them (Wiens 1989). One way to organize patches at different scales is to create a nested hierarchy in which patches at each level are composed of patches at the next lower level (Kotliar and Wiens 1990, Wu and Loucks 1995). Examples of analyses that consider patches at multiple scales are relatively rare, despite the theoretical utility of these approaches. We present a study of nutrient retention and transport in streams from a multiscale, patch-based perspective.

In stream–riparian ecosystems, some patches are nutrient sinks, whereas others are nutrient sources. For example, riparian zones are often sinks for inorganic N because high rates of de-

[1] Present address: Center for Limnology, University of Wisconsin, 680 North Park Street, Madison, Wisconsin 53706-1492 USA. E-mail: ldent@facstaff.wisc.edu

nitrification remove inorganic N from water as it moves from the catchment into the stream (Hill 1996). Other patches that may act as sinks of inorganic nutrients include organic-rich gravel bars (Pinay et al. 1994), algal assemblages (Grimm 1992), and sediments that adsorb P (Meyer 1979, Klotz 1988). Conversely, some patches may be sources of inorganic nutrients, such as gravel bars composed of coarse sediments (Holmes et al. 1994b) and hyporheic zones (Valett et al. 1994). As water moves downstream through a series of patches, the materials it carries are transformed and transported in different ways. Thus, patch composition and configuration influence both the form of transported nutrients and the amount of nutrient retention and export.

Spatial variation in rates of biogeochemical transformations creates spatial variation in nutrient concentrations. In streams, the flow of water often carries transformation products away from sites of origin, in contrast to soil systems where products mostly remain in place (Wagener et al. 1998). Thus, changes in nutrient concentration along flowpaths can be used to infer intervening biogeochemical processes. In addition, changes in nutrient concentration and the relationship of these changes to patch locations can be observed at multiple scales. We describe spatial patterns of nutrients in stream surface water at 3 scales, ranging from 30 m to 10 km in *extent* (the maximum distance encompassed by the survey) and from 1 m to 25 m in *grain* (the distance between individual samples) (sensu Turner et al. 1989). In a previous analysis of nutrient patterns from the coarsest of these surveys (the 25-m grain survey), we hypothesized that downstream decreases in surface water nutrients were caused by algal uptake, whereas increases might be caused by upwelling of nutrient-rich water from subsurface sediments (Dent and Grimm 1999). Here, we test predictions of the latter part of the hypothesis.

Hydrologic connections between surface and subsurface patches are associated with scale-dependent geomorphic and topographic features (Fig. 1). Variation in features such as stream slope, sediment permeability, and valley width can cause water to move in and out of subsurface sediments at scales from a few centimeters to thousands of meters (Thibodeaux and Boyle 1987, White 1990, Gregory et al. 1991, Larkin and Sharp 1992, Harvey and Bencala 1993, Stanford and Ward 1993). We begin by describing the conceptual hierarchy of surface–subsurface connections that serves as the basis for our investigation, allowing us to identify subsurface patches at several scales. We then address 3 central questions: 1. How does spatial variation in surface water nutrient concentration change with survey scale? 2. Are increases in surface water nutrient concentration associated with subsurface patches, and if so, at what scales? 3. Do subsurface patches at different scales behave similarly in terms of net nutrient processing (source or sink)?

A hierarchy of surface–subsurface connections

Our conceptual hierarchy (Fig. 1) is largely consistent with previously published hierarchical descriptions of stream systems (Frissell et al. 1986, Gregory et al. 1991, Grimm and Fisher 1992, Stanley et al. 1997, Boulton et al. 1998, Dahm et al. 1998, Fisher et al. 1998a, Baxter and Hauer 2000), but focuses on exchange between surface water and subsurface patches.

The entire river drainage is divided into *segments* (Fig. 1), defined by major changes in slope and substrate (Gregory et al. 1991, Stanford and Ward 1993). We did not consider this largest scale in our work. A segment consists of *reaches,* which can be classified as either constrained or unconstrained depending on the relative widths of the valley and the active channel (Gregory et al. 1991). Unconstrained reaches are characterized by deep alluvial deposits with high water storage potential, in contrast to constrained reaches, where water storage capacity is much lower. Therefore, subsurface water comes to the surface at the transition from unconstrained to constrained reaches, and returns to the subsurface at transitions from constrained to unconstrained reaches (Gregory et al. 1991, Stanford and Ward 1993, Stanley et al. 1997). Locations where water moves from subsurface to surface (at any scale) are called upwellings, whereas locations where water moves from the surface to the subsurface are downwellings (Fig. 1). Permanent groundwater sources may also exist at the reach scale. Upwellings from subsurface patches at this scale are often sources of inorganic nutrients because of high nutrient concentrations in deep groundwater (Stanford and Ward 1988, Ford and Naiman 1989, Hendricks and White 1991). A reach, whether constrained

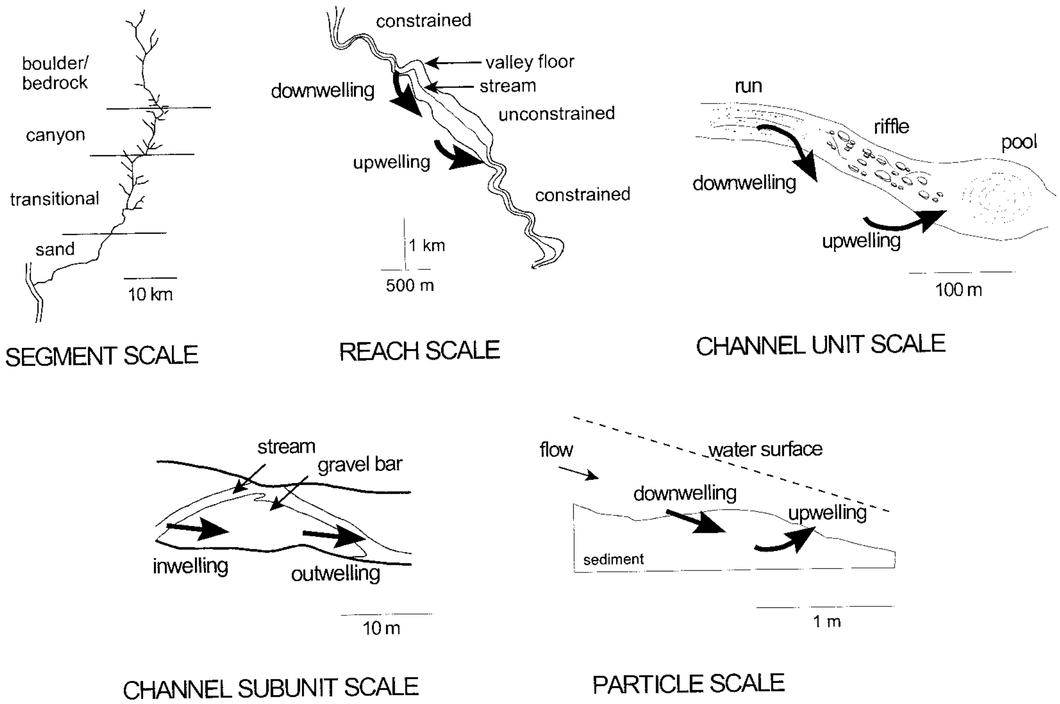

FIG. 1. A hierarchical decomposition of patches in a stream ecosystem, emphasizing connections between surface water and subsurface sediments at each scale. The segment scale divides the drainage (illustrated here by Sycamore Creek, Arizona) into segments defined by major changes in slope and substrate. At the reach, channel unit, channel subunit, and particle scales, heavy arrows show where water moves from surface to subsurface (downwelling or inwelling) and from subsurface to surface (upwelling or outwelling). See text for details.

or unconstrained, consists of a linear sequence of *channel units* of type run, riffle, or pool. Riffles are steeper in slope than pools and runs, leading to a tendency for water to flow from surface to subsurface at the tops of riffles and from subsurface to surface at the tops of runs or pools (Vaux 1962, White et al. 1987, Harvey and Bencala 1993, Valett et al. 1994, Wroblicky et al. 1998). In the vertical dimension, subsurface patches in channel units are shallower than those at the reach scale, so whether they are sources or sinks of nutrients for the surface stream depends on sediment characteristics (Jones and Holmes 1996). Coarse, well-oxygenated sediments favor nitrification and are more likely to be nutrient sources (Valett et al. 1994, Hendricks and White 1995, Jones et al. 1995a), whereas fine, organic-rich sediments favor denitrification and may be nutrient sinks (Duff and Triska 1990, Pinay et al. 1995). Stream meander bends create another possible subsurface connection at the channel unit scale (Vervier et al. 1993, Wroblicky et al. 1998), although they may also be viewed at the reach scale (Boissier et al. 1996). Channel units are divided into subunits, defined by structures creating local hydraulic features at scales less than the channel width, such as boulders, logs, gravel bars, or plant hummocks (White 1990, Gregory et al. 1991). We focused on runs only, where we define surface–subsurface connections at the *channel subunit* scale as movement of water between gravel bars and surface water. Water moves into gravel bars from the surface at inwellings and out of gravel bars to surface water at outwellings (Fig. 1). Gravel bars at the subunit scale may be sources (Triska et al. 1993, Holmes et al. 1994b, Wondzell and Swanson 1996b, Claret et al. 1997) or sinks (Pinay et al. 1994, Claret et al. 1997) of nutrients. Although we did not address patterns below the subunit scale, smaller-scale (*particle*) movement between surface and subsurface sediments may occur as a result of changes in bedform (Savant et al. 1987, Thibodeaux and Boyle 1987).

Study Site

Our work was conducted at Sycamore Creek, a tributary of the Verde River located in the lower Sonoran Desert 32 km northeast of Phoenix, Arizona. The stream drains a catchment of 505 km^2 that ranges in elevation from 427 m to 2164 m. Annual precipitation ranges from 39 cm/y at a rain gauge station located at 510 m to 51 cm/y at 1040 m, and peaks bimodally in winter and summer. Pan evaporation in the area is 313 cm/y; thus, the stream is frequently intermittent, especially in summer.

The study site is a 10-km stretch of stream dropping from 700 m to 600 m elevation. Stream substrates consist primarily of coarse sand and gravel that can be several meters deep. Riparian vegetation is sparsely distributed along an active stream channel that is generally >20 m wide, leaving the streambed unshaded much of the day. Periphytic algae are abundant, especially in summer, and primary productivity is high (≥10 g O_2 m^{-2} d^{-1}) (Grimm 1987). Nitrogen limits primary production during baseflow (Grimm and Fisher 1986). Intense flash floods remove algae from the stream channel several times a year. When flood waters recede, algae returns to predisturbance levels in a predictable successional pattern over a period of weeks or months (Fisher et al. 1982, Grimm and Fisher 1989).

Surface water and subsurface water in Sycamore Creek sediments are closely connected. Water may move rapidly through subsurface sediments with interstitial velocities averaging >1 m/h during baseflow (Valett et al. 1990, Holmes et al. 1994b). Subsurface sediments are generally oxic and support high rates of respiration (11.9 g O_2 m^{-2} d^{-1}) and nitrification (0.2 g NO_3-N m^{-2} d^{-1}) (Jones et al. 1995a, 1995b). Concentrations of inorganic nutrients in subsurface sediments are often higher than in surface water (Valett et al. 1990, Grimm et al. 1991).

Sycamore Creek is an ideal site to study the interactions between geomorphology, hydrology, and biogeochemistry because much is already known about the hydrology and biogeochemistry of particular surface and subsurface patches, yet this information has not been synthesized into a multiscale, geomorphically based framework. When placed into a hierarchical framework, previous work on the biogeochemistry of Sycamore Creek suggests that subsurface patches at reach, channel unit, and channel subunit scales may act as sources of inorganic nutrients to the surface water. High surface water nitrate-N (NO_3-N) concentrations have been observed at sources or springs (locations where water emerges downstream of a dry channel; reach scale) (Grimm et al. 1981, Grimm 1992). At the channel unit scale, concentrations of NO_3-N within subsurface sediments were higher at upwelling zones (bottom of a riffle) than at downwelling zones (bottom of a run) (Valett et al. 1992), and surface water NO_3-N concentrations were also elevated near upwellings (Valett et al. 1994). At the channel subunit scale, both NO_3-N and soluble reactive P (SRP) concentrations increased along subsurface flowpaths through gravel bars within a run (Holmes et al. 1994b, Holmes 1995), and surface water concentrations of NO_3-N at outwellings were elevated compared to surface water concentrations where water entered gravel bars (Holmes et al. 1994a). These patterns suggest that subsurface sediments act as sources of inorganic nutrients at several scales; however, these initial studies were limited to a few subsurface flowpaths in select portions of the stream.

Methods

Field sampling and laboratory analysis

Stream nutrient concentrations were surveyed at 3 different grain sizes: 25 m, 2.5 m, and 1 m (Fig. 2, Table 1). For the 25-m survey, samples were taken in the middle of the stream 25 m apart over a downstream distance of 10 km on 3 dates: 22 May 1995, 2.5 mo after a 6 March 1995 flood, 7 December 1995, 9 mo after the same flood, and 17 March 1997, 2 wk after a 28 February 1997 flood (Dent and Grimm 1999). These dates were representative of middle, late, and early successional conditions in the stream, respectively (Fisher et al. 1982). For the 2.5-m survey, samples were taken 2.5 m apart over a downstream distance of 105 m on 24 June 1996, 15.5 mo after the 6 March 1995 flood, during very late stages of succession. For the 1-m survey, samples were taken 1 m apart over an area of 30 m (downstream distance) by ~3 m (width) on 25 June 1997, 4 mo (late succession) after the

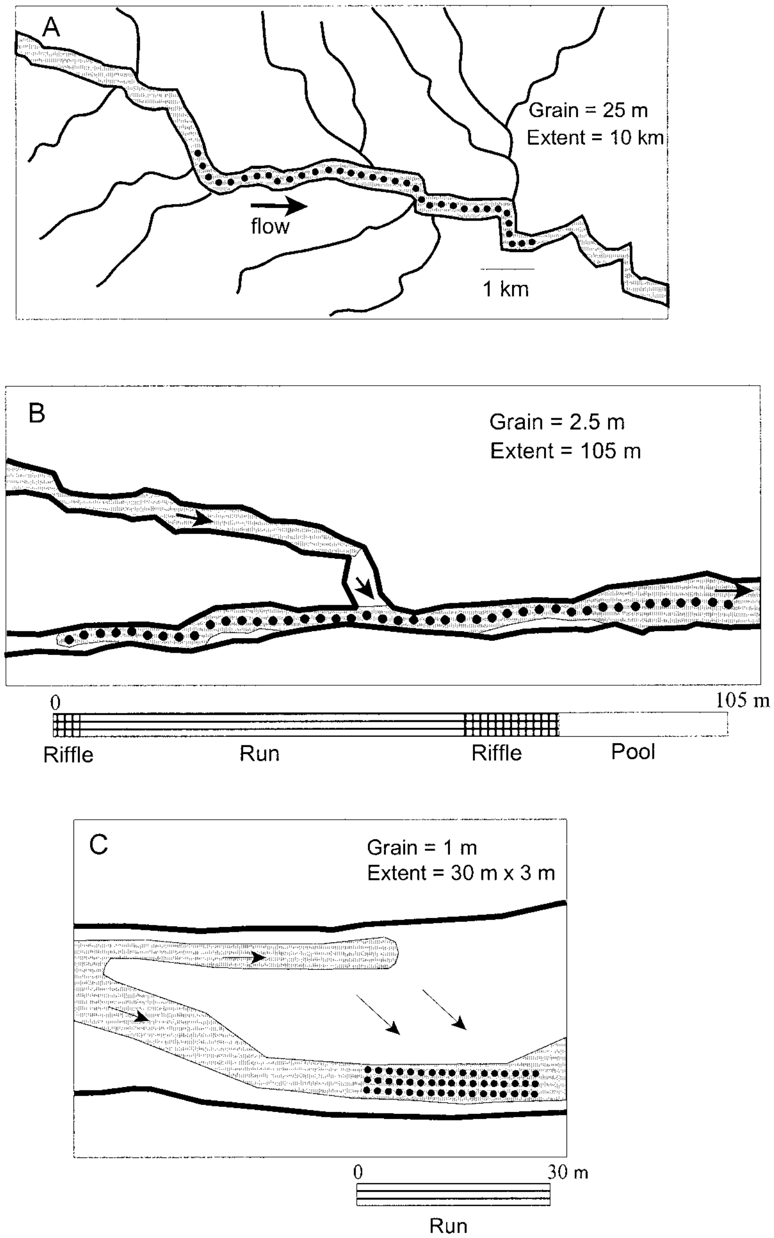

FIG. 2. Spatial structure of stream water nutrient surveys in Sycamore Creek, Arizona. Heavy lines indicate channel edge; shaded areas are wetted; open areas within the channel are dry sediment (gravel bars). Arrows indicate direction of surface and subsurface flow. Channel unit type (run, riffle, or pool) of the sampled channel is given below (B) and (C). Dots indicate representative (not actual) sample locations. A.—25-m survey. Samples were taken from the thalweg at locations 25 m apart over a total of 10 km. Stream width has been artificially expanded. B.—2.5-m survey. Samples were taken from the thalweg at locations 2.5 m apart over 105 m. C.—1-m survey. Samples were taken at the left edge, middle, and right edge of the wetted channel (~1 m apart) at locations separated by 1 m in the downstream direction over a distance of 30 m.

TABLE 1. Characteristics of surface water nutrient surveys. MPF = months post flood, Q = discharge.

Survey and grain (m)	Date	Extent (m)	MPF	Q (L/s)	Post-flood successional stage
25	17 March 1997	10,000	0.5	400	Early
25	22 May 1995	10,000	2.5	150	Middle
25	7 Dec. 1995	10,000	9	5	Late
2.5	24 June 1996	105	15.5	10	Late
1	25 June 1997	30 × 3	4	10	Late

28 February 1997 flood. The 2.5-m and 1-m surveys were contained within the 10-km extent of the 25-m survey, but did not overlap with each other. On each date, duplicate samples of surface water were collected in 60-mL bottles from the stream's thalweg (where velocity is maximal). For the 1-m survey, samples were also taken at the left and right edges of the stream ~1 m from the thalweg, and where necessary samples were drawn directly from algal mats with a syringe. Samples were taken at points longitudinally separated by the grain of the survey, and were collected over as short a time as possible (e.g., the 25-m survey samples were taken within 3 h by 10 to 14 assistants) (Dent and Grimm 1999).

Water samples were analyzed for NO_3-N and SRP within 24 h of collection. Ammonium-N (NH_4-N) concentrations in Sycamore Creek surface water are very low (Fisher et al. 1982, Grimm and Fisher 1986, Holmes et al. 1996), so we did not measure NH_4-N. Nitrate-N was determined by colorimetric analysis following reduction to nitrite (Wood et al. 1967) on a Bran and Luebbe TRAACS 800© autoanalyzer. Molybdate-antimony analysis was used to determine SRP concentrations (Murphy and Riley 1962). Nitrate-N values below the detection limit (1 μg/L) were set to 0.5 μg/L for statistical analysis. Analytic variability was low, with SDs for replicate samples usually <10% of mean values.

Identification of subsurface patches

Several methods were used to identify subsurface connections at the reach, channel unit, and channel subunit scale. Subsurface upwellings at the reach scale occur at transitions from unconstrained to constrained valleys and at locations where bedrock nears the surface (Brunke and Gonser 1997, Stanley et al. 1997). In the 10 km of stream we examined, there were only 2 clear transitions from unconstrained to constrained valleys (in each case valley width decreased by >100 m). However, there were several other locations where we consistently observed water emerging from subsurface sediments during dry periods. We were unable to directly observe changes in depth to bedrock, so we used locations where water emerged downstream of a dry streambed, which we called *sources,* as locations of reach-scale upwellings. We assumed that water was always upwelling from subsurface sediments at these locations, but was only visible when the stream was drying. We mapped source locations during a particularly dry period, in December 1996, when the stream had not flooded for >18 mo. We assumed that sources would remain spatially fixed through most bed-moving floods and, therefore, we used the same source locations for all comparisons with nutrient surveys.

At the channel unit scale, we identified likely locations of subsurface upwelling according to changes in substrate and according to changes in the slope of the streambed. At each water sample location, we recorded the reach type (run, riffle, or pool) using the dominant substrate: coarse, mixed gravel-boulder substrate (riffle); coarse, sandy substrate (run); and fine substrate with deeper, slow-moving water (pool). We then classified a location as upwelling if the upstream substrate was riffle and the downstream substrate was either run or pool (sensu Harvey and Bencala 1993). These data were collected during all nutrient surveys except the late-succession 25-m survey. In addition, we surveyed the slope of the streambed along the entire 10-km stream section during December 1996 and January 1997 using a tripod, a surveyors level, and a telescoping rod. We

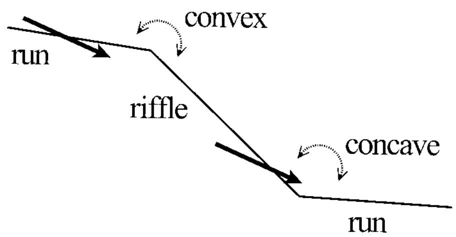

FIG. 3. Depiction of *convex* and *concave* locations at the channel unit scale. Convex locations are those where streambed slope becomes steeper (increases) by >1%. Concave locations are those where streambed slope becomes flatter (decreases) by >1%. Because riffles tend to be steeper in slope than runs, transitions from runs to riffles tend to be associated with convex locations, whereas transitions from riffles to runs or pools are associated with concave locations. Bold arrows indicate water movement; water moves from the surface to the subsurface at convex locations, and from the subsurface to the surface at concave locations.

measured slope changes every 25 m in the middle of the stream. Because a reduction in slope causes subsurface water to upwell to the surface (Harvey and Bencala 1993), we designated locations as upwelling sites if the slope decreased (became flatter) by >1% (Fig. 3). We called these locations *concave,* and locations where slope steepened by >1%, *convex*. No bed-moving floods occurred from May 1995 to January 1997, so the slope data were assumed to be applicable for the 25-m middle and late successional surveys. Slope data were not used for the 25-m early succession survey because it was conducted after a bed-moving flood in March 1997. Because slope data were collected at a grain of 25 m, they were not used for the 1-m and 2.5-m surveys.

At the channel subunit scale, we identified subsurface flow out of stream edges into surface water by adding flourescein dye to shallow holes or wells installed in dry sediments near the edge of the stream at 1-m intervals and observing whether the dye moved into stream surface water. These data were collected for the 1-m survey only. The stretch of stream covered by the 1-m survey was entirely a sandy run with no sources or side channels (Fig. 2C).

For the 2.5-m and 1-m surveys, we also estimated the potential for subsurface upwelling by measuring vertical hydraulic gradient (VHG). VHG was determined by dividing the difference in hydraulic head between water drawn from a minipiezometer inserted 20 to 30 cm into the streambed and surface water by the depth of the piezometer (Lee and Cherry 1978). Positive VHG could indicate upwelling at any scale. We measured VHG at each water sample location in the 2.5-m survey except those too rocky to allow insertion of a piezometer, and at sample locations in the thalweg in the 1-m survey.

Data analysis

For the 25-m survey, we classified survey locations as described and then compared nutrient concentration changes at different classes of locations (e.g., locations with concave slope) in 2 ways. First, we determined whether mean nutrient concentrations increased at each location type by testing whether the concentration at each location minus the concentration from the upstream location was significantly >0 (Student's *t*-test for paired comparisons, Sokal and Rohlf 1995). Second, we used contingency tables with a χ^2 test to determine whether increases in concentration were more likely to occur at particular location classes than expected, by classifying changes in concentration as positive, negative, or 0 (<1 μg/L) and comparing observed with expected frequencies for each location type. The distribution of nutrient increases at source locations (i.e., reach scale) could not be assessed in this manner because of low sample numbers (n = 11 sources).

For the 2.5-m survey, mean nutrient concentrations were compared for locations differing in VHG (upwelling, downwelling, and no exchange) using 1-way ANOVA. For the 1-m survey, mean nutrient concentrations were compared for locations where outwelling occurred vs other locations using a Student's *t*-test, and for locations in the right, middle, and left of the channel using 1-way ANOVA.

Results

Spatial variation in nutrient concentrations at different scales

In the early succession 25-m survey, mean NO_3-N concentration was high (219 μg/L) and variability low (CV = 72%) (Table 2). Nitrate-N increased dramatically at the site of an off-channel gravel pit operation that was pumping high-nutrient water into the main channel (Fig. 4),

TABLE 2. Nitrate-N (NO_3-N) and soluble reactive P (SRP) concentrations (μg/L) in Sycamore Creek surface water at 3 survey scales. All values are calculated on the basis of *n* sample locations; values at each sample location are based on 2 analytical replicates. Stage = successional stage, SD = standard deviation, CV = coefficient of variation, bdl = below detection limits.

Grain (m)	Stage	Location	*n*	Mean	SD	Min.	Max.	Range	CV (%)
NO_3-N									
25	Early	Thalweg	398	219	158	46	543	497	72
25	Middle	Thalweg	399	6	6	bdl	39	39	104
25	Late	Thalweg	260	35	51	bdl	279	279	145
2.5	Late	Thalweg	43	6	9	bdl	51	51	143
1	Late	All	91	13	15	bdl	66	66	116
1	Late	Middle	31	7	7	bdl	26	26	100
1	Late	Left	30	23	16	bdl	66	66	69
1	Late	Right	30	6	10	bdl	35	35	161
SRP									
25	Early	Thalweg	398	17	7	4	38	34	42
25	Middle	Thalweg	399	28	6	12	38	26	20
25	Late	Thalweg	260	28	13	2	59	57	44
2.5	Late	Thalweg	43	41	10	21	70	49	25
1	Late	All	90	18	5	6	31	25	25
1	Late	Middle	30	20	4	10	26	16	17
1	Late	Left	30	15	4	6	20	14	29
1	Late	Right	30	19	4	10	31	21	21

and declined gradually downstream from that point. Earlier analyses showed that the CV was not overly affected by the large increase at the gravel pit site (Dent and Grimm 1999). Spatial variability in NO_3-N in this survey increased during middle succession (CV = 104%) and was highest during late succession (CV = 145%), whereas mean values declined dramatically during middle succession (6 μg/L) and rebounded slightly during late succession (35 μg/L) (Table 2, Fig. 4). In contrast, mean SRP concentration in the 25-m survey was lowest in early succession (17 μg/L) and rose slightly during middle and late succession (28 μg/L) (Table 2, Fig. 5). The effect of the gravel pit, although clearly evident, was less dramatic for SRP compared to NO_3-N (Fig. 5). Although some spatial variation in SRP was observed in all three 25-m surveys, the amount of variation was consistently lower than for NO_3-N (e.g., 42% vs 72% in early succession; Table 2).

In the 2.5-m grain survey, concentrations of both NO_3-N and SRP were highest at the upstream sampling point (Fig. 6A, B). Concentrations decreased downstream, rapidly falling below detection limits for NO_3-N, before increasing further downstream. Mean NO_3-N concentration was low (6 μg/L) and CV was high (143%). The amount of spatial variation in NO_3-N was as great at this scale as in the late succession 25-m survey (Table 2). SRP concentrations were again much less variable than NO_3-N (CV = 25% and 143%, respectively). The mean SRP concentration in the 2.5-m survey was the highest of any survey (41 μg/L).

For the 1-m grain survey, NO_3-N concentrations declined gradually with distance downstream in the middle and right sides of the channel (Fig. 7A). At the same time, NO_3-N concentration increased dramatically from meter 5 to 11 on the left side of the channel before declining again over the next 10 m (Fig. 7A). Mean NO_3-N concentration was higher on the left side of the channel than in the middle and right sides (23 μg/L vs 7 and 6 μg/L; $p < 0.05$), whereas CV was lowest on the left side (69%), higher in the middle (100%), and highest on the right side (161%) (Table 2). SRP concentrations were lower on the left side of the channel than in the middle and right side (15 μg/L vs 19 and 20 μg/L; $p < 0.05$) and showed no longitudinal pattern (Fig. 7B). CV for SRP was generally low in the 1-m survey, with the highest variation oc-

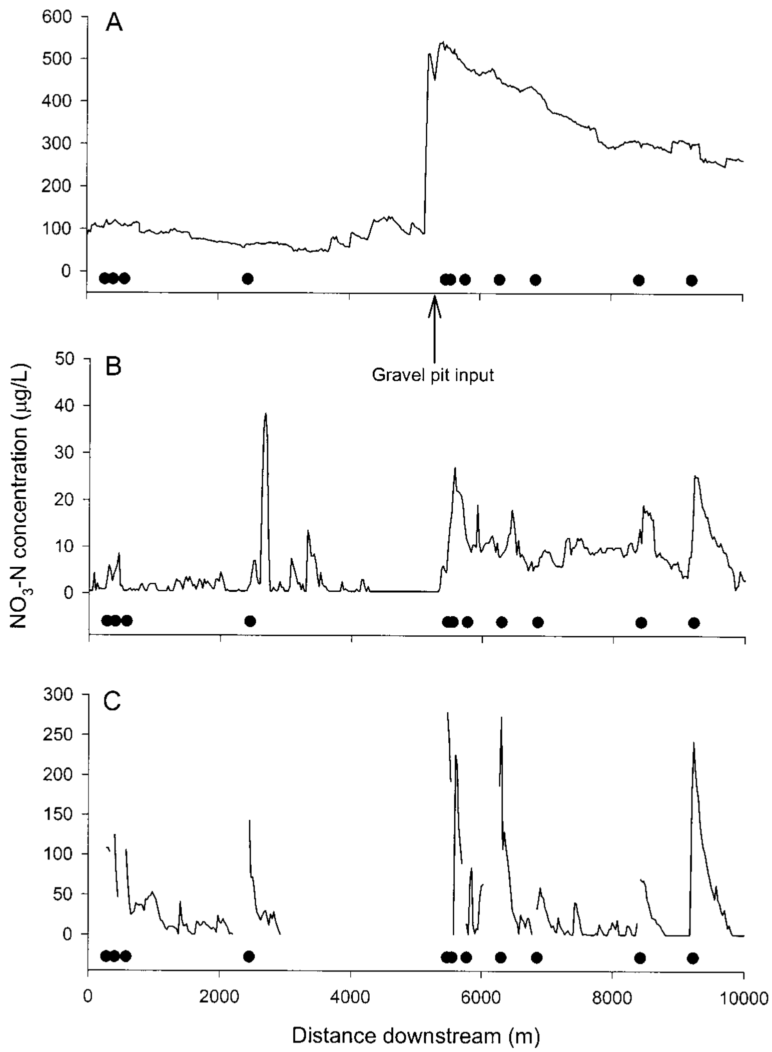

FIG. 4. Spatial variation in nitrate-N (NO_3-N) over 10 km of Sycamore Creek, Arizona. Data are means of duplicate samples taken during the 25-m survey. Dots indicate locations of subsurface upwellings at the reach scale (sources). A.—Early succession (2 wk post flood). Arrow indicates location of inflow of water to the stream from a gravel pit operation. B.—Middle succession (2 mo post flood). C.—Late succession (9 mo post flood). Missing data indicate a lack of surface water at those locations.

curring in samples from the left side of the channel (29%).

Comparing all 3 surveys, CVs ranged from a low of 17% for SRP in the 1-m survey to a high of 161% for NO_3-N in the same survey. Nitrate-N was more variable than SRP in all surveys, with CVs ranging from 1.7 to 5.7 times greater for NO_3-N than for SRP. For both NO_3-N and SRP, CV of thalweg samples decreased with survey grain during late succession, but there was no pattern with scale when maximum CVs for each survey were compared (Table 2).

Identification of surface–subsurface connections

Reach scale.—Drying patterns identified 11 locations of subsurface upwelling (sources) at the reach scale. Two of the sources corresponded to transitions from wide to narrow valleys and 1 to a (dry) tributary junction, but there was no

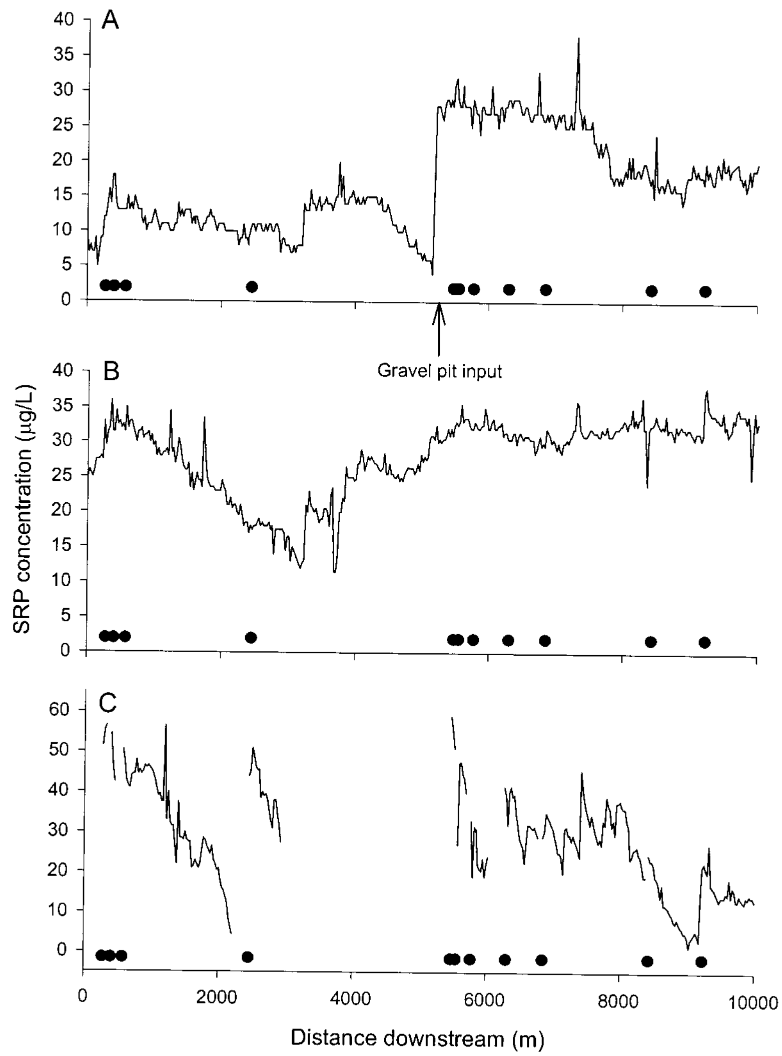

FIG. 5. Spatial variation in soluble reactive P (SRP) over 10 km of Sycamore Creek, Arizona. Data are means of duplicate samples taken during the 25-m survey. Dots indicate locations of subsurface upwellings at the reach scale (sources). A.—Early succession (2 wk post flood). Arrow indicates location of inflow of water to the stream from a gravel pit operation. B.—Middle succession (2 mo post flood). C.—Late succession (9 mo post flood). Missing data indicate a lack of surface water at those locations.

single morphological indicator for all sources. Sources were distributed throughout the 10 km studied (Fig. 4), although they were more common in the downstream 5 km. Five of the 11 source locations were concave in slope and therefore were also considered upwellings at the channel unit scale.

Channel unit scale.—Change in bedslope across 25-m intervals ranged from −6% to +6% with a mean of −1%. Out of 400 slope changes, 73 were classified as concave and 77 as convex. The number of morphological transitions from riffles to runs or riffles to pools (55) was lower than the number of concave locations (74). Most riffle–run or riffle–pool transitions corresponded to concave locations (~72%), but concave locations were identified as substrate-based transitions just 50% of the time.

Channel subunit scale.—In the 1-m survey, dye movement indicated strong outwelling from sediments lateral to the left side of the stream into surface water, from ~5 to 22 m down-

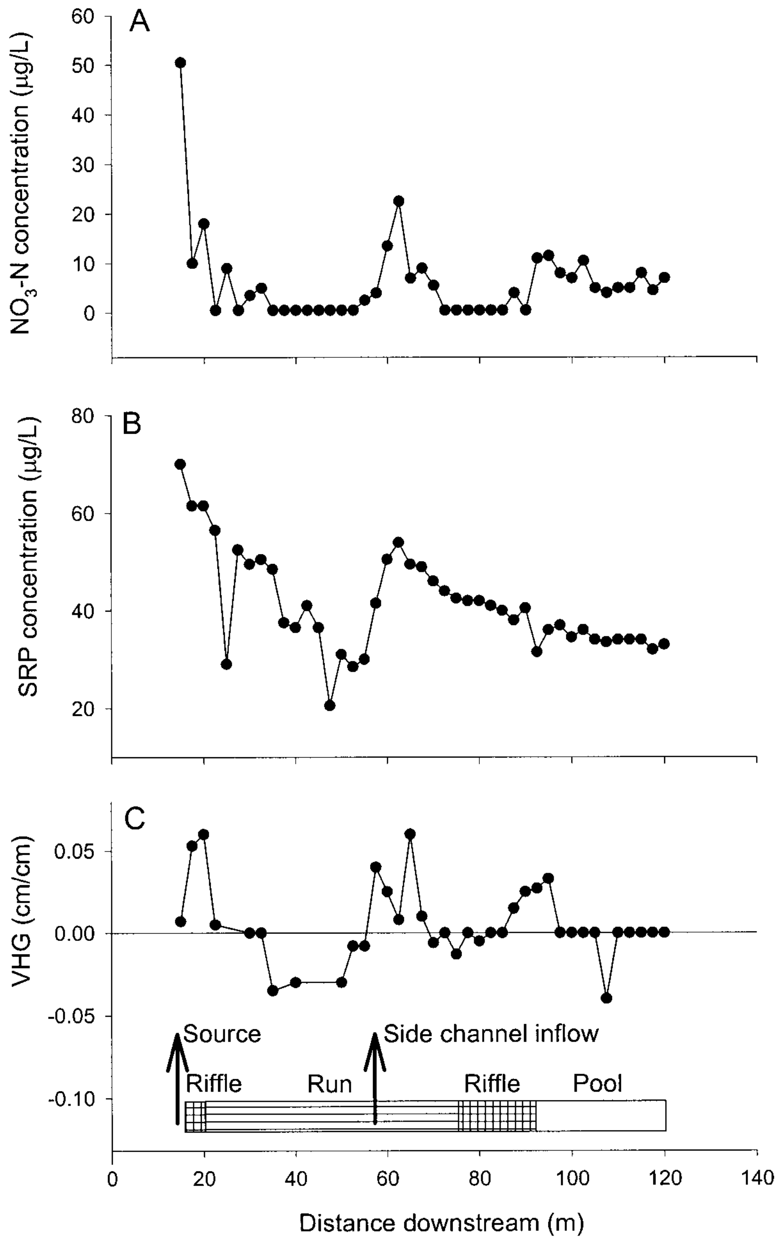

FIG. 6. Late successional spatial variation in (A) nitrate-N (NO_3-N), (B) soluble reactive P (SRP), and (C) vertical hydraulic gradient (VHG) over 105 m of Sycamore Creek, Arizona, from the 2.5-m survey. Positive VHG indicates upwelling of subsurface water into the surface; negative VHG indicates downwelling. Channel unit type (run, riffle, or pool) is depicted below VHG along with the locations of a reach-scale upwelling (source) and side channel inflow, marked by arrows.

stream of the head of the survey. No outwelling occurred from sediments on the right side.

VHG measurements identified 3 upwellings along the 2.5-m survey, one near the upstream sampling point where there was both a source and a riffle–run transition (reach and channel unit scale), one ~60 m downstream at the junction with a subsurface side channel (channel

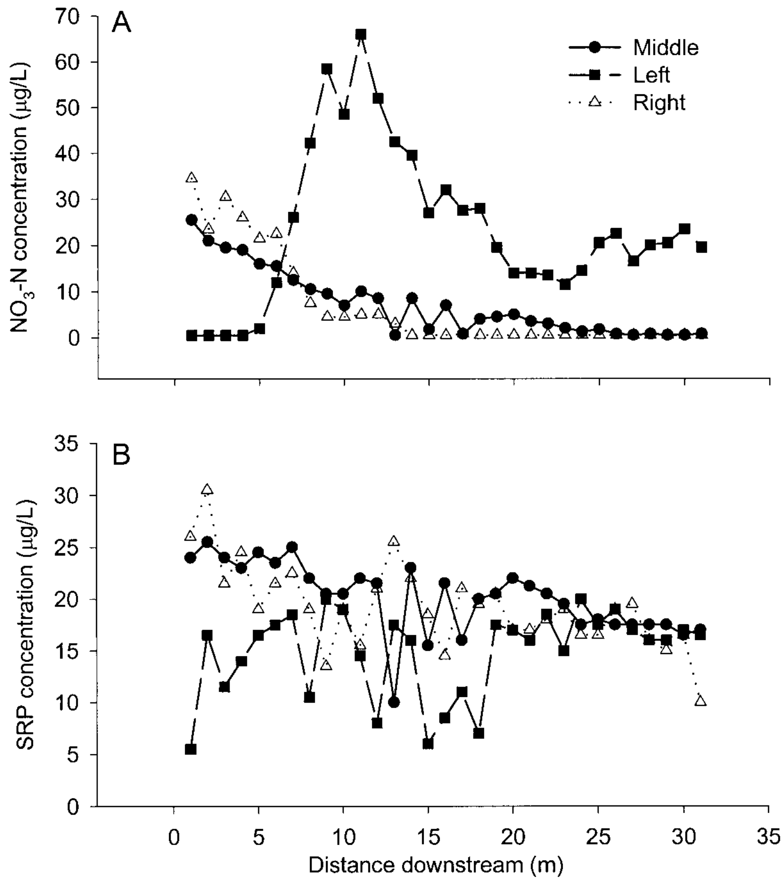

FIG. 7. Late successional spatial variation in (A) nitrate-N (NO_3-N) and (B) soluble reactive P (SRP) over 30 m of Sycamore Creek, Arizona, from the 1-m survey. Samples were taken in the middle of the stream, near the left edge, and near the right edge.

unit scale), and one ~90 m downstream at a riffle–pool transition (channel unit scale) (Fig. 6C). No locations within the 1-m survey were upwelling, but there was a strong upwelling ~10 m upstream of the most upstream 1-m sample. We considered this upwelling to be at the channel subunit scale because it occurred within a single run.

Effect of subsurface patches on surface water nutrient concentrations

For all 25-m surveys, NO_3-N increased at source locations (reach scale), but this increase was only significantly positive during late succession (Fig. 8). SRP also increased significantly at source locations in late succession. Nitrate-N concentrations increased significantly at concave locations in the middle and late succession 25-m surveys (channel unit scale; Fig. 8), whereas SRP concentrations increased significantly at concave locations only during late succession. The mean NO_3-N increase at the channel unit scale was 1 μg/L in middle succession and 17 μg/L in late succession (increasing ambient concentrations by 17% and 49%, respectively). For all successional stages, the mean change in nutrient concentration for all sample locations and the mean change for convex locations was not significantly different from 0. Using substrate transitions instead of slope changes as indicators of subsurface upwelling at the channel unit scale produced similar results for the middle succession survey, the only survey for which both measures were available (Fig. 8). By either measure, NO_3-N concentrations increased sig-

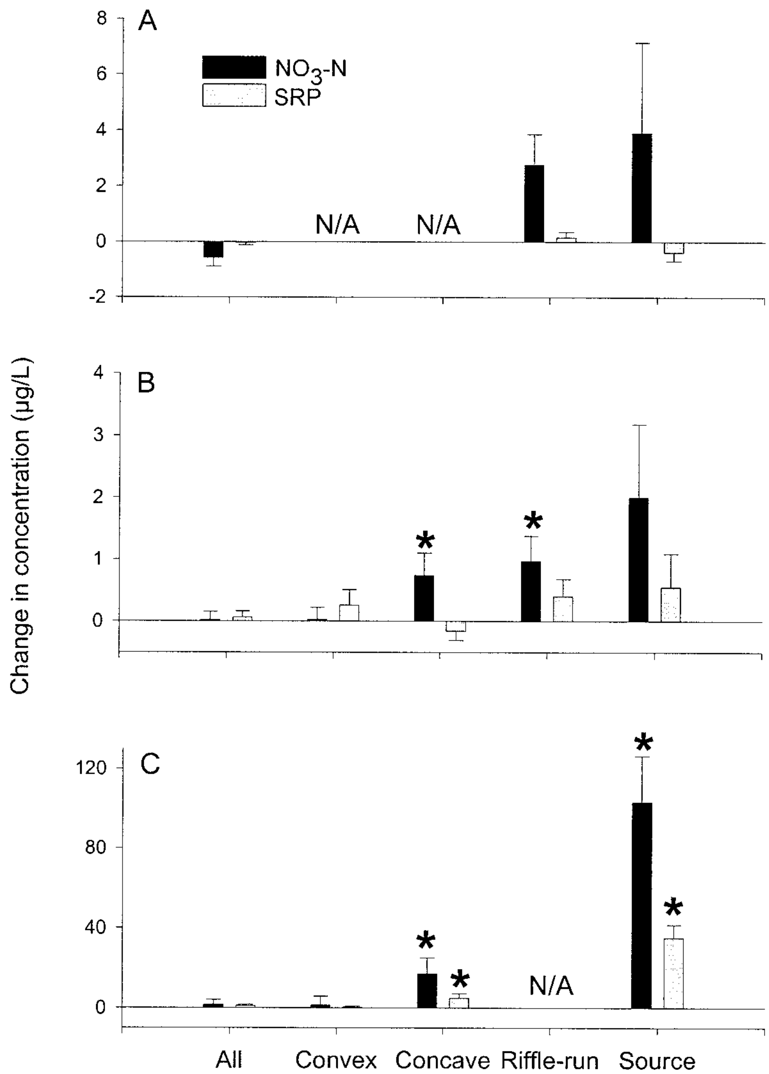

FIG. 8. Change in nitrate-N (NO_3-N) and soluble reactive P (SRP) concentration between adjacent survey sites associated with different types of subsurface connections along the 25-m survey during (A) early, (B) middle, and (C) late succession. Locations are *all* (all pairs of sites), *convex* (sites at convex locations, where channel unit scale downwelling should occur), *concave* (sites at concave locations, where channel unit scale upwelling should occur), *riffle–run* (sites at transitions from riffles to runs or pools, where channel unit scale upwelling should occur), and *sources* (sites at locations of flow origin during spatially intermittent conditions, where reach scale upwelling should occur). N/A = not available. Error bars are + or −1 SE. * = change is significantly >0 at the $p = 0.05$ level.

nificantly at channel unit transitions, whereas SRP concentrations did not.

Contingency tables showed that the distribution of increases, decreases, and no change in concentration depended on location type for NO_3-N. Increases in NO_3-N were more likely than expected to occur at concave locations for middle and late succession, and at riffle–run transitions in middle succession (χ^2 test, $p < 0.05$). Increases in SRP, however, were not more likely to occur at concave locations, despite the significantly positive SRP change found at concave locations in late succession.

Although nutrient concentrations often in-

TABLE 3. Nitrate-N (NO_3-N) and soluble reactive P (SRP) concentrations ± 1 SE in surface water at locations differing in surface–subsurface exchange. For the 2.5-m survey, locations were classified as downwelling ($n = 9$), no exchange ($n = 23$) or upwelling ($n = 13$). For the 1-m survey, locations were classified as no exchange ($n = 75$) or outwelling ($n = 18$). Superscript letters indicate significant differences between locations ($p < 0.05$). – = not measured.

Surveyed nutrient	Concentration (µg/L) Down-welling	No exchange	Up- or outwelling
2.5-m survey			
NO_3-N	1.7 ± 0.6^a	3.7 ± 0.7^a	12.5 ± 3.6^b
SRP	37.6 ± 2.5^a	39.0 ± 1.7^a	49.2 ± 3.2^b
1-m survey			
NO_3-N	–	7.8 ± 1.1^a	30.7 ± 4.4^b
SRP	–	18.9 ± 0.5^a	14.4 ± 1.1^b

creased at locations identified as upwellings, the presence of upwellings did not explain all nutrient concentration increases. For example, in the middle succession 25-m survey, there were 47 stretches of surface water where NO_3-N concentration increased as water moved downstream, ranging in length from 25 m to 125 m. Of these, 22 (47%) were correlated with locations of subsurface upwelling, as identified by our indicators.

In the 2.5-m survey, maximum concentrations of NO_3-N and SRP were found at the upstream end of the survey, near a source and a riffle–run transition (Fig. 6). Concentrations declined downstream but increased at the site of the side channel junction ~60 m downstream. Nitrate-N also increased at the riffle–pool transition ~95 m downstream. Mean NO_3-N concentrations were significantly greater at locations of subsurface upwelling (VHG > 0) than at locations of downwelling (VHG < 0) or locations lacking vertical exchange (VHG = 0) (Table 3). Average SRP concentrations were also significantly greater at upwelling locations than at downwellings and locations without vertical exchange. Because upwellings in the 2.5-m survey corresponded with channel unit features, surface water concentrations of NO_3-N and SRP in this survey were affected by channel unit upwellings.

In the 1-m survey, both SRP and NO_3-N concentrations were high at upstream sampling points in the middle and right side of the stream, close to the upstream upwelling zone (Fig. 7). Nitrate-N concentrations were significantly higher at outwellings (located on the left side of the channel), whereas SRP concentrations were lower in areas influenced by outwelling than in those lacking lateral inputs (Table 3). Therefore, surface water concentrations of NO_3-N in this survey were increased by upwelling at the channel subunit scale, whereas concentrations of SRP were decreased.

Discussion

Pattern and variation in surface water nutrients

Stream water nutrient concentrations varied spatially at all scales. The amount of spatial variation depended more on the specific nutrient and the temporal (successional) context than on spatial scale. Nitrogen, the nutrient known to limit primary production in this system (Grimm and Fisher 1986), was consistently more variable than P at all scales and was most variable late in succession. Considering only samples from the thalweg in late succession, range and CV for both NO_3-N and SRP declined as survey grain decreased, indicating that thalweg nutrients varied less at finer sampling grains. Semivariogram analysis of the 25-m survey (restricted to thalweg samples) suggested that spatial variation at grains finer than 15 m would be low compared to larger scales (Dent and Grimm 1999). The decreases in range and CV with scale found in the current surveys support this conclusion. On the other hand, expansion of sampling grain to 2 dimensions would be expected to increase variance, as it did in the 1-m survey where lowest CV was found when analysis was restricted to thalweg samples only (Table 2). In many cases, the nutrient concentrations varied over an order of magnitude between sampling locations. In the late succession 25-m survey and in the 1-m survey, NO_3-N concentrations were below the concentration thought to indicate N limitation (55 ug/L, Grimm and Fisher 1986) in some locations but above it in others, suggesting spatial variation in N limitation of primary production. The high spatial variation observed at all scales illustrates the importance of choosing an appropriate sampling strategy when characterizing stream nutrient patterns. Spatial variability of this type is also expected to affect abundance and/or diversity of primary producers and consumers, as well as system productivity and retention (Dent et al. 2000).

Effect of subsurface patches on surface nutrient patterns

We used indirect measures of subsurface upwelling such as drying patterns and slope breaks to test the hypothesis that downstream increases in surface water nutrients were caused by upwelling of high-nutrient water from subsurface sediments. Therefore, support for the hypothesis required both that these indicators actually identified subsurface upwellings, and that upwellings were associated with nutrient increases. We found that our measures of subsurface upwellings were associated with increases in surface water nutrients at the reach, channel, and channel subunit scales, consistent with our hypothesis. Our results indicated that processes occurring in subsurface sediments are a major factor in determining surface water nutrient patterns in Sycamore Creek, but other processes also play a role. Increases in concentration not associated with our indicators of upwelling may have been caused by unidentified upwelling of subsurface water, by mineralization and nitrification of organic N in other patches (e.g., in algal mats or side pools), or by leakage from N-fixing cyanobacteria. The observed pattern of surface water nutrient concentrations results from interactions between processes occurring in surface and subsurface patches as water flows back and forth between them. Feedbacks between surface and subsurface processes are likely. For example, Jones et al. (1995a) suggest that organic N from N-limited periphyton communities (in the form of algal leachate or decomposition products) is carried into the hyporheic zone, where it is then mineralized to inorganic N, thereby increasing concentrations of inorganic (available) N in subsurface patches. Upwelling of N-rich interstitial water may then alleviate N limitation in surface water (Valett et al. 1994).

Our model of multiscale surface–subsurface connections should be applicable to many different stream systems. As we define them, patches of subsurface sediment begin at downwelling zones, where water moves from surface to subsurface, and end at upwelling zones, where water returns to the surface. Water does not flow between surface and subsurface at all locations; rather, there are spatially restricted zones where exchange occurs, followed by areas with little or no exchange. This model works well for arid-land streams such as Sycamore Creek that are generally losing systems (i.e., recharge to groundwater aquifers occurs through channel sediments). Streams of more mesic regions experience more extensive lateral inflow of groundwater (Fetter 1994), along with surface–subsurface exchange of the types we have described. The importance of local exchange of water between surface and subsurface sediments versus inflow of groundwater varies, but both types of hydrologic flux occur and should be considered when addressing nutrient dynamics in lotic ecosystems (Larkin and Sharp 1992, Pinay et al. 1998).

Floods can radically alter the physical structure of a stream channel, causing major changes in surface–subsurface exchange patterns at some scales (Wondzell and Swanson 1999). Between floods, however, the locations of geomorphically controlled exchange points are fairly stable (Wondzell and Swanson 1996a, Wroblicky et al. 1998). Often, changes in discharge do not affect the locations or the roles of subsurface patches (whether they are sources or sinks), although the magnitude, and potentially direction, of surface–subsurface connections may change (Harvey and Bencala 1993, Vervier et al. 1993, Valett et al. 1994, Morrice et al. 1997). Exceptions have been reported. For instance, Wondzell and Swanson (1996b) described a flowpath through a gravel bar that ceased to be a NO_3-N source when water levels dropped below the alder rooting zone. In addition, large decreases in discharge may change a source to sink (Stanley and Boulton 1995), or magnify small-scale variation within a subsurface flow path because of lower dilution (Vervier et al. 1993). However, over a wide range of hydrologic conditions, geomorphically determined sites of surface–subsurface exchange should have an important and consistent influence on surface water nutrient dynamics, and more generally on biodiversity and production (Stanford and Ward 1993).

Role of subsurface patches: sources or sinks?

Spatial patterns in Sycamore Creek surface water were affected by subsurface–surface connections at the channel subunit, channel unit, and reach scales. Subsurface patches at all 3 scales were sources of NO_3-N in late succession, and patches at the channel unit scale were also sources of NO_3-N in mid succession. Subsurface patches were a source of SRP only during late succession, and only at the channel unit and reach scales. When subsurface patches acted as nutrient sources, increases observed in the surface water were not necessarily large. However, because samples were taken in the overlying water column and at regular intervals rather than directly at subsurface–surface connections, effects of upwellings were likely masked by algal uptake of nutrients at the point of discharge and as water flowed downstream to the sample point. Measured differences, therefore, represented the net effect of exchange. Algal uptake can mask elevated nutrients at upwellings even in water sampled close to a subsurface–surface connection (Jansson 1980, Triska et al. 1990). Indeed, in the 1-m survey, NO_3-N concentrations were elevated in the left side of the stream at outwellings, but not in the middle of the stream despite direct hydrologic connection between these points.

Subsurface patches acting as sinks should decrease surface water nutrients at locations of subsurface–surface upwelling because of dilution by lower-nutrient water. We did observe decreases at some locations, although they were not consistently related to identified upwelling sites, except for SRP in the 1-m survey. Decreases in nutrient concentration may have been caused either by upwelling of low-nutrient water or by benthic algal uptake. Microbial denitrification (the conversion of NO_3-N to atmospheric N) is one process that would cause a patch to act as a sink for inorganic N. Denitrification potentials are high in riparian bank sediments in Sycamore Creek (Holmes et al. 1996), and NO_3-N concentrations are low in riparian zones compared to surface water (Martí et al. 2000), making riparian zones likely candidates for nutrient sinks in this system. Hydrologic connections between surface water and riparian zones have been demonstrated during floods and baseflow (Dent 1999, Martí et al. 2000), with flow directed predominantly from the stream to the riparian zone rather than the reverse as is typical of mesic areas (Fetter 1994). More detailed hydrologic information is required to better understand how riparian zones affect surface water nutrients and how these patches fit into our hierarchy of subsurface–surface connections. Denitrification rates may also be high in patches smaller than the subunit scale that act as C sources, such as algal mats (Joye and Paerl 1994, N. B. Grimm, unpublished data), downwellings within sand bars (Holmes et al. 1996), and shrubs growing on sand bars (Schade et al. 2001). Thus, patches within a sand bar may act as sinks of nutrients, diminishing the role of the bar as a nutrient source. It has also been suggested that long subsurface flowpaths may become sinks of nutrients because of oxygen depletion, and that this may happen even in short flowpaths during late succession (Fisher et al. 1998b). Our results suggest that for a single gravel bar addressed at the scale of the channel subunit, effects of denitrification did not change the role of the bar as a source of nutrients to the surface water.

The hierarchical nature of surface–subsurface exchange

The hierarchy we have described here, based on the phenomenon of surface–subsurface exchange, fits well with previously published hierarchical descriptions of stream systems (Frissell et al. 1986, Gregory et al. 1991, Grimm and Fisher 1992, Stanley et al. 1997, Boulton et al. 1998, Dahm et al. 1998, Fisher et al. 1998a). In general, different phenomena (e.g., surface–subsurface exchange vs fish habitat preferences) lead to differences in the hierarchies used to study them (O'Neill et al. 1986, Urban et al. 1987, Fisher et al. 1998a, King 1999). However, the most useful hierarchies are those for which breaks occur at similar places for several phenomena of interest. We feel that these common scale breaks may occur in stream systems because of strong physical constraints.

Surface–subsurface exchange affects many aspects of the biology of surface waters (Dent et al. 2000), but rarely is the multiscale nature of surface–subsurface exchange considered. Recent work by Baxter and Hauer (2000) found that bull trout redds were associated with upwelling sites at large scales (segment and reach) and with downwelling sites at smaller scales (channel unit and channel subunit). Thus, a hierarchical perspective was necessary to understand the interaction between hyporheic exchange and bull trout spawning.

The hierarchical paradigm allows a focus on processes at one scale while accounting for processes occurring at other scales (Urban et al. 1987). The complexity of multiple scales and processes is resolved into a focal scale, a set of mechanisms, and a set of constraints. Knowledge of the effects of subsurface upwellings at multiple scales may be required to explain patterns observed at any one scale. For example, within a single reach, surface water nutrient patterns over a series of runs and riffles (channel unit scale) are directly affected by processes affecting water chemistry along subsurface flowpaths that emerge at channel unit slope breaks, but not by processes occurring in deep sediments along flowpaths that are connected with the surface at the larger reach scale. Reach scale processes, however, may be constraining those observed at the channel unit scale. For example, subsurface upwellings at larger scales may mask increases caused by subsurface upwellings at smaller scales by elevating nutrient concentrations such that small increases are no longer distinguishable. Such masking might be more dramatic if patches at different scales had acted in opposition to each other, i.e., if some had been sinks and others sources. In addition, processes that vary at larger scales may limit the magnitude of smaller-scale inputs by affecting total nutrient availability, volume of subsurface sediment, amount of shading, and so on. Processes occurring in lower hierarchical levels, such as channel subunits, may help to explain differences among channel units; for example, one run may have a single large sand bar, whereas another may have many small sand bars that together result in higher nutrient inputs to the surface (Fisher et al. 1998a).

Spatial patterns in stream water nutrient concentrations yield insight into biogeochemical transformations that occur as water moves materials downslope. Processes occurring in surface and subsurface patches affect surface water nutrients and, thus, retention and export, at several scales of observation. Our study demonstrates the importance of subsurface processes to surface stream nutrient dynamics at scales from a few meters to several kilometers.

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