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Physical and chemical characteristics of the hyporheic zone of a Sonoran Desert stream

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Abstract. The hyporheic zone of three reaches of Sycamore Creek, Arizona consisted of an average 63 cm depth of predominantly sand or fine gravel (0.5-5 mm). Sediments were highly porous (19-23% interstitial space) and interstitial water volume was 3-4 times that of surface water. Spatial distribution of temperature, sediment organic matter, interstitial nutrients, and subsurface oxygen indicate that physical-chemical conditions vary greatly within the hyporheic zone. Much of the observed variability may be due to repeated disturbance by flash floods. Organic matter content of sediment was low (0.08% by weight), variable, and generally declined with depth in shallow portions of the hyporheic zone. Hyporheic water temperature was higher than surface temperature in regions beneath the wetted perimeter in summer. Nutrient concentrations of interstitial water were enriched compared to surface water; ammonium-N, SRP, and nitrate-N were 269%, 174%, and 327% of surface concentration, respectively. Sub-surface velocity was low (0.62 mm/s), but vertical exchanges were pronounced. Interstitial oxygen was high in regions of infiltration (downwelling), and was generally reduced in discharge regions (upwelling), but subsurface patterns were otherwise complex. Vertical linkages between surface and hyporheic zones provide a mechanism for mutual influences. Chief among these are replenishment of interstitial oxygen by downwelling (and enhancement of aerobic respiration), and nutrient enrichment of surface water at upwelling sites.

Key words: hyporheic, oxygen, ammonium, nitrate, phosphate, sediment, organic matter, hydrologic exchange.

Hyporheic zones of streams and rivers have received much attention as zoobenthic habitat (Coleman and Hynes 1970, Stanford and Gaufin 1974, Williams 1984, Stanford and Ward 1988) and as important sites for fish reproduction (Pollard 1955, Hansen 1975, Johnson 1980). However, less attention has been directed to ecosystem structure and functioning of hyporheic zones. Further, little is known about linkages between subsurface and surface systems and how these regions may influence each other.

Research emphasizing the role of groundwater in streams (Wallis et al. 1981, Hynes 1983, Rutherford and Hynes 1987) has focused on the interface of sub-surface and stream water in terms of nutrient dynamics and organic carbon processing. Sub-surface water may be high in dissolved organic carbon (DOC) (Wallis et al. 1981, Rutherford and Hynes 1987, Crocker and Meyer 1987, Ford and Naiman 1989) and groundwater that enters streams may enrich or dilute DOC depending on conditions in the aquifer and processes occurring in the hyporheic zone. Crocker and Meyer (1987) emphasized the role of hyporheic sediments in the generation of DOC from in situ decomposition of particulate matter. Hyporheic water may also be high in nitrogen and phosphorus (Grimm et al. 1981, Triska et al. 1989, Carr 1989, Coleman 1989). Bencala (1984) reported that stream water solute transport was strongly affected by intragravel flow and that solutes were retained by hyporheic sediments. Such processes of retention, production, and transformation may generate a chemical environment in the hyporheic zone that is very different from that of surface water.

Exchange between hyporheic and surface stream water is a dynamic feature of streams (Vaux 1962, 1968, Bencala et al. 1983, 1984, Grimm and Fisher 1984, Jackman et al. 1984, Kennedy et al. 1984, Savant et al. 1987, Thibodeaux and Boyle 1987). White et al. (1987) located regions of hyporheic-surface exchange in a Michigan river by mapping interstitial temperature. Mestrov and Lattinger-Penko (1977, 1981) reported linkage between a Yugoslavian river and sub-surface water of the hyporheic zone. They emphasized that distinct regions of the hyporheic zone were affected differently by river pollution, indicating variable interaction with surface water. Stanford and Ward (1988) addressed hyporheic-river interaction in Flathead River, Montana where food for abundant hyporheic fauna, located many kilometers laterad to the main river channel, may be supplied by hydrologic exchange.

The degree and location of exchange between hyporheic and surface water can be affected by the distribution of surface flora (Hendricks and White 1988). Conversely, the distribution of various aquatic macrophytes may be linked to occurrence of hydrologic exchange (Fortner and White 1988). Coleman (1989) attributed large mats of filamentous algae to nutrient rich interstitial water just 5 cm beneath the benthic substrata. The distribution and abundance of this benthic flora may partially depend on nutrient supply from the hyporheic zone.

Sonoran Desert streams are characterized by sparse canopies and broad channels. Streams are generally 'underfit' in that wetted perimeters occupy only a portion of the stream channel. Channel sediments are composed of sand to gravel size alluvium that is frequently reworked by flash floods (Graf 1988).

We define the hyporheic zone in Sycamore Creek as the saturated sediments and interstitial spaces of alluvial material underlying and lateral to the wetted perimeter where sub-surface and surface water are actively exchanged. Most biologists have defined hyporheic zones based on distribution of interstitial biota (Williams and Hynes 1974, Williams 1984, 1989). Some distinguish beween phreatic groundwater characterized by particular taxa (e.g., Bathynellaceans, Pennak and Ward 1986) and the overlying hyporheic zone; others recognize a distinct 'community' in the saturated sediments of the stream bank ('parafluvial' sensu Williams 1989). We recognize that different faunal habitats probably exist within the interstitial environment of Sycamore Creek (A. J. Boulton, E. H. Stanley, H. M. Valett, Arizona State University, unpublished data), but employ the above definition to emphasize our focus on water flow and its influence on physical-chemical features of the hyporheic zone.

The hyporheic zone in sand-dominated sediments of runs and pools is strongly influenced by discharge, but boulder and cobble substrata of riffles are more stable and flows competent to move these materials are very large and infrequent. Results reported here characterize portions of the hyporheic zone underlying regions of the stream that are affected by annual flash floods (Fig. 1).

The influence of the hyporheic zone on stream ecosystem function was addressed in Sycamore Creek by Grimm and Fisher (1984). Based on research at a single site they showed that hyporheic sediment to be an important metabolic component; apparently autotrophic conditions were actually heterotrophic when sub-surface components were included in measurements of stream respiration. On a larger scale, flood-mediated changes in distribution and volume of hyporheic zones through erosion and redeposition of large sand deposits have strong effects on whole-stream metabolism (Grimm et al., in press, S. G. Fisher, unpublished data).

Including hyporheic zones as part of stream ecosystems emphasizes functional linkages between the stream and sub-surface water. Regions of exchange have been identified in Sycamore Creek, but litle is known of their structure. Interstitial oxygen can be high (Grimm and Fisher 1984), but long periods of successional recovery generate large amounts of benthic organic matter that may affect interstitial conditions. Interstitial water of Sycamore Creek is high in inorganic nitrogen, but little is known about patterns of nutrient distribution in the hyporheic zone (Grimm et al. 1981, Grimm and Fisher 1984).

Objectives of research presented here were 1) to describe physical and chemical conditions in the hyporheic zone of Sycamore Creek, Arizona and, 2) to characterize regions of linkage between the hyporheic zone and stream surface.

Study Site

Sycamore Creek is located 32 km northeast of Phoenix, Arizona USA. Watershed area is 505 km^2 ranging from 2164 to 427 m elevation. The stream flows ca. 55 km from ephemeral headwaters to confluence with the Verde River. Longitudinal profiles of typical Sonoran Desert streams reveal three distinct components: ephemeral reaches high in the watershed; intermediate transitional sections; and usually dry alluvial stream beds at low elevation. Throughout the transitional region, water is alternately forced to the surface by outcroppings of impervious bedrock material or absorbed into

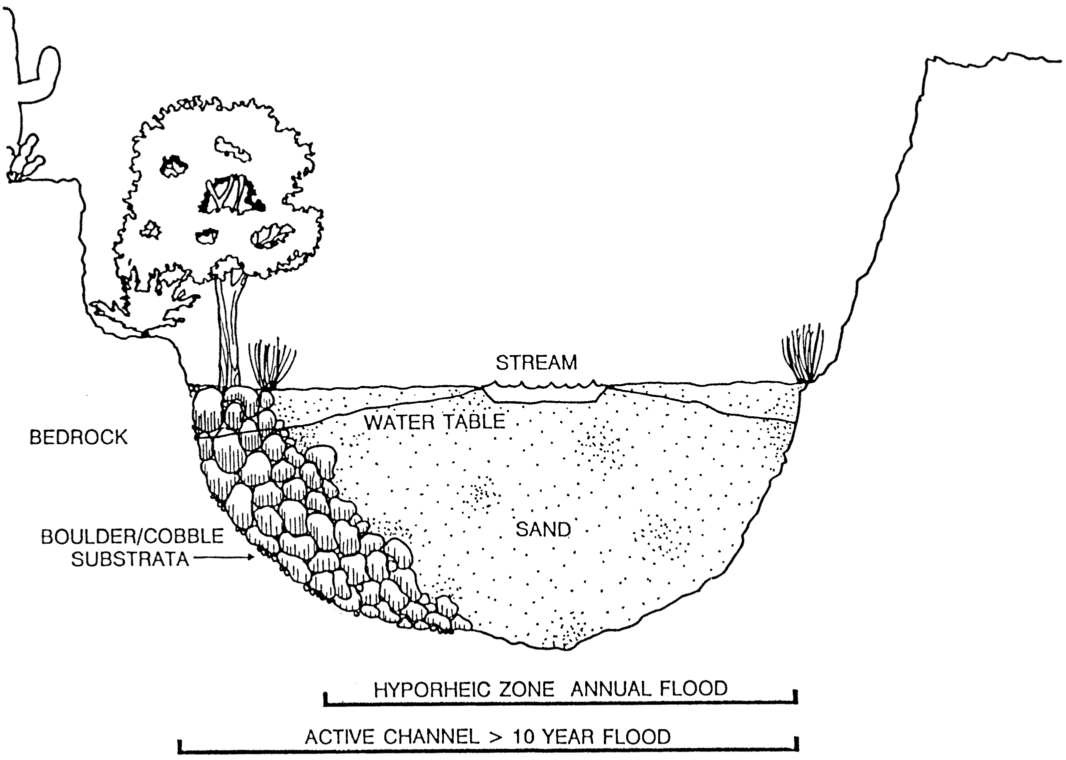

FIG. 1. Diagrammatic representation of the hyporheic zone, Sycamore Creek, Arizona. Vertical scale is exaggerated.

deeper regions of channel alluvium (Wertz 1963). Distinct reach types (runs, riffles, pools) are easily discernable within a 12 km transitional region of Sycamore Creek. At the time of this study, runs occupied 45% of total stream length within the transitional region. Riffles were as abundant as runs, while pools represented 10% of total length.

A single site was established at each of three runs at ca. 650 m elevation in the transitional region. Surface flow was continuous but of variable discharge at sites II and III during the study. Flow was intermittent at site I and streambed sediments were often dry.

Methods

Morphometry of sandy runs was determined with a series of permanent transects oriented perpendicular to the longitudinal axis of the stream and spaced 20 m apart. Surface topography was determined in reference to a level line between fixed points on each bank at each transect location. Sand depth was measured by sounding with a steel rod to boulder or bed rock surface. Hyporheic profiles for each transect were sketched on a graphics tablet and treated as a collection of serial cross-sections. Total sand lens volume and volume of the saturated zone were calculated from distance between transects and integration of serial sections using a digitized software program (PC3D®, Jandell Scientific, 605 Koch Road, Corte Madera, California 94925).

Hyporheic sediments were sampled using a series of 72.5 cm^3 cylindrical plexiglass cores (4.3 cm dia.). Sediment porosity (percent pore space) was estimated as water volume in saturated cores. Sediment size classes (small, <0.5 mm; medium, 0.5–5 mm; large, 5.0–9.5 mm; extra large, >9.5 mm) were determined by sieving after drying 48 hours at 60°C.

Physical-chemical features of the hyporheic zone were investigated by sampling a series of

TABLE 1. Morphometric characterization of the hyporheic zone in three runs of Sycamore Creek, Arizona. Widths, depths, and porosity are means ± SE.

Site	Length (m)	Width (m)	Sediment Depth (m)	Sediment Volume (m^3)	Porosity (%)	Hyporheic: % Total Sand Volume	Hyporheic: % Total Water Volume
I	120	16.0 ± 1.17	0.52 ± 0.02	1339.8	19.32 ± 0.83	87.2	63.0
II	95	14.7 ± 0.51	0.63 ± 0.04	1194.5	22.44 ± 0.67	83.7	83.9
III	141	13.1 ± 1.64	0.76 ± 0.05	1772.6	23.28 ± 0.89	99.5	81.5

wells constructed from PVC pipe (I.D. = 1.58 or 1.90 cm). Lateral perforations near the tip of the well were protected by Nitex mesh. Shallow wells (<20 cm) were fitted with impervious collars (20 cm by 20 cm) to restrict infiltration of surface water. Transects were established near the middle of sand reaches and samples were taken from depths of 10–135 cm. Wells were set either directly beneath the surface stream or lateral to it, beneath dry surface sediments within the stream channel. Wells were cleared of water, allowed to equilibrate 1–3 days, then cleared again before sampling with a manual vacuum pump.

Temperature was measured in water samples immediately after collection from wells. Dissolved oxygen was determined by Winkler method on samples obtained in 60 ml bottles placed in a sealed pumping apparatus to avoid contact with air. Water chemistry was determined on laboratory-filtered (pre-fired Whatman GF/F) samples. Ammonium-N was determined by the phenolhypochlorite method (Soloranzo 1969) within four to eight hours of collection. Samples were analyzed spectrophotometrically for soluble reactive phosphorus (SRP) using a molybdate-antimony method (Murphy and Riley 1962). Cadmium reduction, followed by colorimetric analysis of nitrite, was used to measure NO_3-N (Wood et al. 1967).

Points of vertical hydrologic exchange between interstitial and surface water were identified by injecting fluorescent dye 10–15 cm into sediments. After 15 minutes the dye was sought by digging. Sites were considered "stationary" if, after excavation, the dye was evident at the injection site. Loss of dye indicated "downwelling" or "lateral advection", and "upwelling" resulted in the appearance of dye at the sediment surface. Downwelling was verified by observing infiltration of dye injected on benthic substrata. Interstitial velocities were determined beneath the wetted perimeter or less than 2 meters lateral to the surface stream. Procedure included injecting dye to 10–15 cm depth 50 to 100 cm upstream from 20 cm deep trenches and measuring time of travel. There was no attempt to determine interstitial velocity at depths greater than 20 cm.

Sediment organic matter was determined by dichromate oxidation (Maciolek 1962). Earlier investigation of stream sediment indicated that more than 95% of total organic matter was accounted for by small- and medium-sized particles (S. G. Fisher, unpublished data). Results reported here are restricted to these size classes. Organic matter in the shallow portions of the hyporheic zone at each site was sampled in cores taken vertically to depths of 15–20 cm at midstream. Cores were sectioned into 2–4 cm thick subsamples and analyzed for organic matter. Deeper portions of the hyporheic zone were sampled by excavating two large pits (ca. 1.5 m deep and 30 m apart) in the dry mid-channel sediments at site I. Triplicate core samples were taken every twenty centimeters to depths of 120 and 140 cm, respectively.

Results

Morphometry and sub-surface flow

Sandy runs at sites I, II and III were approximately 118 m long and 15 m wide (Table 1). Sand depth at these sites averaged 0.63 ± 0.02 m, compared to 0.42 m average over the entire 12 km transitional reach (S. G. Fisher, unpublished data). Riffle substrates were located above and below each run.

Most hyporheic sediment in Sycamore Creek is coarse sand or fine gravel (0.5 to 5.0 mm), but sediment size varies with depth (Fig. 2). Each

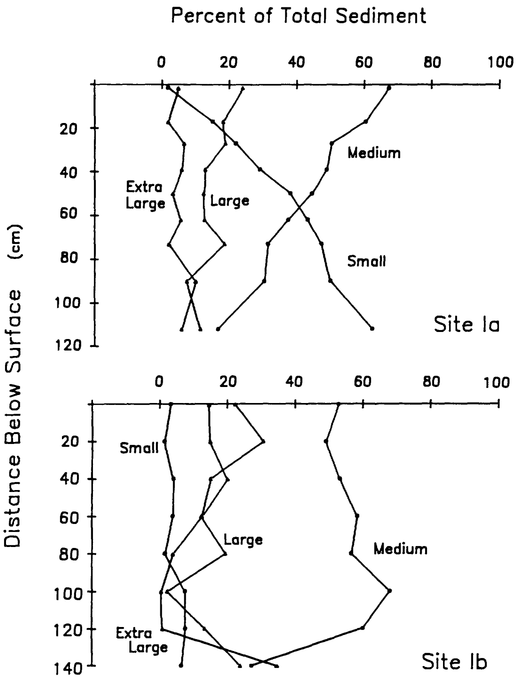

FIG. 2. Relative depth distribution of sediment size classes. Size fractions are: small (<0.5 mm), medium (0.5-5.0 mm), large (5.0-9.5 mm), and extra large (>9.5 mm). Samples were taken from 2 pits (a and b) 30 meters apart at site I.

study reach contained over 1000 cubic meters of sediment and porosity of sediment was high (19.3-23.3%, Table 1). At base flow conditions (site I = 0.033 m^3/s, site II = 0.040 m^3/s, site III = 0.046 m^3/s), interstitial water volume was more than three times surface water volume across three sites (Table 1). Interstitial water occupied from 83 to nearly 100 percent of sand lens volume at base flow, but size of the saturated zone varies with discharge.

Well transects at site I and III were located in "downwelling" or "recharge" zones where surface water enters the hyporheic zone. At site I, all sub-surface injections were transported to deeper regions of the hyporheic zone. Dye placed on the benthic surface adhered closely to the substratum before entering interstitial spaces. Injections at site III behaved similarly. In one case, dye injected 5 cm below surface sediments was collected the following day 2.5 meters downstream in well water at a depth of 80 cm.

Conversely, the well transect established at site II was located on an "upwelling" or "discharge" zone where hyporheic water reentered the surface stream. Dye placed on benthic substratum moved quickly into overlying water. Six of nine dye tracers upwelled at the sampling transect when injections were made 1, 3, and 5 m upstream.

Dye injections yielded an estimate of sub-surface flow as 0.62 mm/s (SE = 0.11, n = 16). Flow rate varied with location and ranged from 0.035 mm/s to 1.25 mm/s. Rates were highest beneath the wetted perimeter and declined laterally with increasing distance from surface water.

Organic matter

Average percent organic matter for sediment cores taken from 10 to 40 cm depth was low (Table 2). Small sediment contained an order of magnitude higher percent organic matter than medium sized sediment. However, small sediments represented less than 3 percent of total sediment mass in core samples. As a result of the paucity of small particles in stream bed alluvium, most organic matter in hyporheic sediment was associated with medium-sized particles (Table 2).

Particulate organic matter in the top 15 cm of bed material was variable, but declined with depth at all sites (Fig. 3). Profiles differed between sites. Total benthic organic matter was 5.7, 2.9 and 2.8 kg/m^3 at sites I, II and III, respectively. Concentrations decreased by 50% within 3 cm depth at all sites. Organic matter increased notably at 7 cm depth at site I and at 9 cm depth at site III, but decreased again at greater depth.

TABLE 2. Sediment size-class abundance and organic matter content in small (<0.5 mm) and medium (0.5-5.0 mm) size particles for all sites combined. Data are means ± SE (n = 69).

Sediment Size-class	% Organic Matter	% Sediment Weight	% Total Organic Matter
Small	0.29 ± 0.02	2.89 ± 0.13	24.50 ± 1.61
Medium	0.03 ± 0.001	71.80 ± 1.08	75.50 ± 3.59

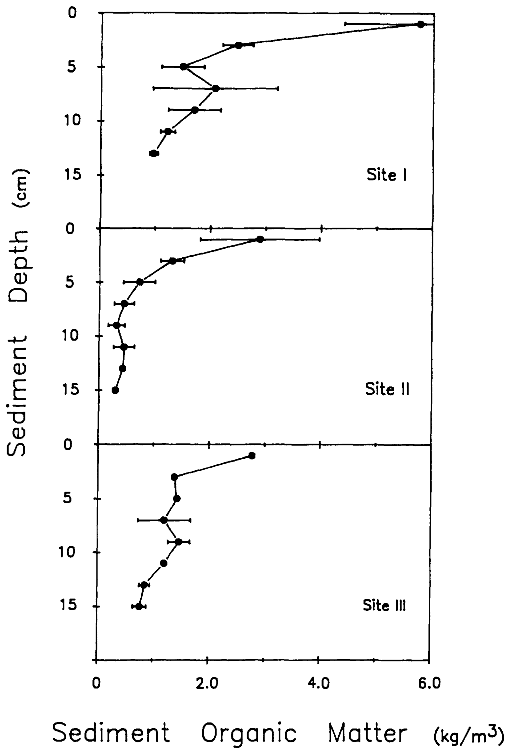

FIG. 3. Total organic matter for combined small (<0.5 mm) and medium (0.5–5.0 mm) size fractions. Cores were sectioned in two centimeter intervals. Data are means ± SE (n = 3).

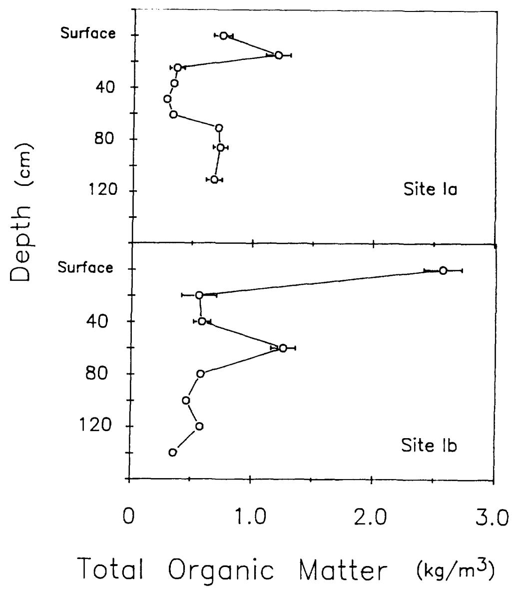

FIG. 4. Depth distribution of organic matter in deep hyporheic sediments. Total organic matter (kg/m³) for two locations at site I. Data are means ± SE (n = 3). Error bars may be within plot symbols.

In deeper sediments sampled at site I, total organic matter varied significantly with depth (one-way ANOVA, $p < 0.0001$, Fig. 4). At site Ia total organic matter at 15 cm depth was significantly higher than surface organic matter. No benthic material was visibly evident at site Ia at time of excavation. A significant and strong decrease in organic matter was evident between 15 and 25 cm depth at this site. At site Ib, total organic matter decreased significantly from surface to 20 cm depth. Significant increases in organic matter were present at 70 cm depth at site Ia and at 60 cm at site Ib (Fig. 4). Total organic matter remained high at site Ia to a depth of over 110 cm, but decreased significantly below 60 cm depth at site Ib.

Temperature

Samples taken in early morning hours during summer months revealed that interstitial temperature can vary greatly within the hyporheic zone (Tables 3–6). Temperatures measured during nutrient surveys (Tables 4–6), and on separate occasions during more extensive sampling of dissolved oxygen (Table 3), ranged as much as eight and nine degrees at sites I and II, but the range was much less at site III (Table 3). Temperature increased with depth beneath the wetted perimeter at all sites. Maximum water temperature occurred 80 cm beneath the stream at site I and 120 cm below surface water at site III. At site II temperature increased lateral to the wetted perimeter and maximum water temperature was recorded beneath exposed alluvium nearly 10 m from surface water.

Dissolved oxygen

Figures 5, 6 and 7 show isoclinal lines of dissolved oxygen for each sampling transect. Interstitial dissolved oxygen at sites I and III decreased with depth beneath the wetted perimeter. Conversely, oxygen concentration at site II was greatest in deepest portions of the hyporheic zone.

Interstitial oxygen patterns at site I were complex. Concentration decreased rapidly from 8.0 ppm (107% sat.) to less than 1.0 ppm (13% sat.)

TABLE 3. Interstitial water temperature (°C), Sycamore Creek, Arizona. Data are compiled from surveys carried out from 0700 to 1100 hours in April (Site I), July (Site II), and August (Site III), 1989. Depths range from 20 to 135 cm.

Site	Min	Max	Range	n	Mean	SD	Surface Temp
I	18.0	26.5	8.5	32	23.5	1.9	25.5
II	23.0	32.0	9.0	36	28.4	2.1	23.0
III	24.5	26.0	1.5	25	25.1	0.4	25.0

at 25 cm depth beneath the wetted perimeter (Fig. 5). Higher concentrations were present at greater depths lateral to the surface stream where 4 ppm (53% sat.) extended to 50 cm depth. Anoxic water was encountered in a single sample and values of less than 1.0 mg/L were measured in 23 of 42 total samples. Regions of less than 0.5 mg/L comprised 31% of hyporheic cross-sectional area (Fig. 5).

Interstitial oxygen at site II increased significantly ($r = 0.74$, $p < 0.0001$) with hyporheic depth (Fig. 6). Maximum interstitial oxygen was only 2.5 ppm (34% sat.) and was recorded at 135 cm depth (Fig. 6). Interstitial spaces immediately beneath benthic substrata contained less than 1.0 ppm (<13% sat.) dissolved oxygen. Minimum dissolved oxygen concentration of 0.30 mg/L (4.3% sat.) was located in shallow regions of the hyporheic beneath lateral exposed bed material. No anoxic regions were detected at this site. Regions of less than 0.5 mg/L comprised only 2% of total hyporheic cross-sectional area.

Oxygen concentration decreased exponentially with increased depth (log transformed depth, $r = 0.66$, $p < 0.0005$, Fig. 7) at site III. Water was highly oxygenated (5.5 to 6.8 ppm, 75–93% sat.) to depths approaching 25 cm. Concentrations dropped sharply in samples taken from 22 to 135 cm depth. Anoxic water was encountered in only one sample, but 19 of 28 samples at this site contained less than 1.0 mg/L (<13% sat.) dissolved oxygen. Regions of less than 0.5 mg/L comprised over half (51%) of hyporheic cross-sectional area at this transect (Fig. 7).

Overall patterns of interstitial oxygen reflect a decided reduction when compared with surface conditions. Local patterns of oxygen distribution may vary, but anoxic water was rare (2 of 105 samples). Low ambient oxygen (<1 ppm) occurred in 64 of 105 samples. Twenty six samples contained oxygen between 1 and 4 ppm. Dissolved oxygen from 4–11 ppm was present in 12 hyporheic samples.

Nutrient environment

Nutrient content did not vary predictably with depth or position in the hyporheic zone (Tables 4–6). Interstitial water was rich in inorganic nitrogen and phosphorus relative to surface water, but concentrations varied greatly from well to well.

Hyporheic water at site I contained 76 μg/L (SE = 24, $n = 10$) NO_3-N, 3.4 times more than surface water concentration. Hyporheic NH_4-N was 31 μg/L (SE = 8, $n = 10$), but NH_4-N concentration was very low in surface water (Table 4). Total inorganic nitrogen (TIN: NO_3-N + NH_4-N) was 32 μg/L in surface water and 107 μg/L in the hyporheic.

Surface water richest in TIN occurred at site II. Surface TIN was 72 μg/L and consisted of nearly equal amounts of NH_4-N and NO_3-N (Table 5). Concentration of interstitial inorganic nitrogen was much higher. Hyporheic NH_4-N was 59 μg/L (SE = 12, $n = 8$) and averaged 1.84 times surface water concentration. Sub-surface NO_3-N averaged 240 μg/L (SE = 65, N = 8), nearly six times surface concentration. Nitrate-N concentration was greater than 500 μg/L in two of eight wells at this site.

Interstitial NH_4-N was highest at site III (Table 6). Hyporheic NH_4-N averaged 130 μg/L (SE = 81, $n = 9$), but mean concentration was heavily influenced by a single well in which NH_4-N values were extremely high (well #9, Table 6). Surface NO_3-N was low and although hyporheic NO_3-N was least among all sites ($\bar{x} = 31$ μg/L, SE = 6, $n = 9$), interstitial concentration was still high compared to surface water (179%).

Interstitial water was rich in inorganic phosphorus at all sites; SRP was 189, 184 and 147

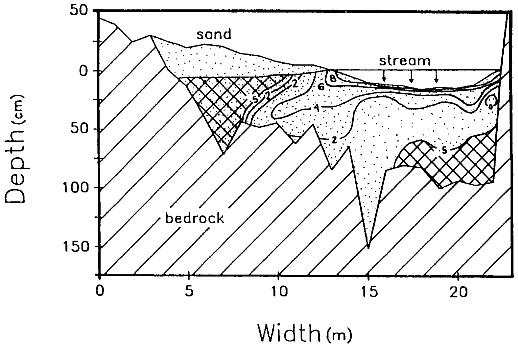

FIG. 5. Hyporheic dissolved oxygen (mg/L) isoclines for site I, a downwelling zone. Vertical scale is exaggerated. Cross-hatched areas are regions less than 0.5 ppm.

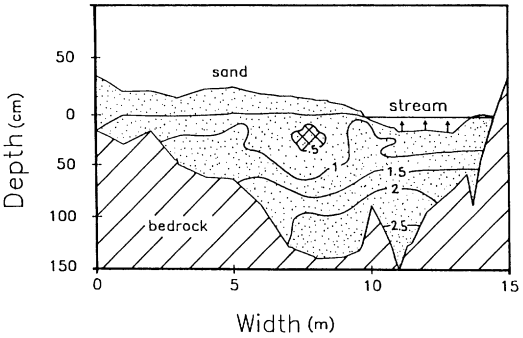

FIG. 6. Hyporheic dissolved oxygen (mg/L) isoclines for site II, an upwelling zone. Vertical scale is exaggerated. Cross-hatched areas are regions less than 0.5 ppm.

percent of surface water at sites I, II and III, respectively.

Mean values for all well water indicate that the hyporheic zone is rich in inorganic nitrogen and phosphorus and that sub-surface nitrogen is more variable than interstitial SRP (Table 7). Hyporheic NH_4-N averaged 268% (SE = 64.3, n = 27) and interstitial NO_3-N was 327% (SE = 67.6, n = 27) of surface water content. On average, interstitial SRP was 174% (SE = 11.9, n = 27) of water column SRP phosphorus. Coefficients of variation (CV) for hyporheic NH_4-N and NO_3-N are great (204 and 129%, respectively), whereas, variation in sub-surface SRP was comparable to that observed for surface water nutrients (CV < 60%, Table 7).

The surface water N:P atomic ratio was as low as 1.45 (Table 4), averaged 4.50, and varied only 5.32 units. Average N:P ratio in the hyporheic was twice as high at 8.97 (Table 7) and the atomic ratio varied greatly between wells, reaching a maximum of over 62.0 at site III (Table 6). Water with N:P ratios greater than 15, potentially phosphorus- rather than nitrogen-limited (Redfield 1958, Shanz and Juon 1983), occurred in 6 of 27 wells.

Discussion

Morphology and hydrology

The size of the hyporheic zone in Sycamore Creek depends on discharge, both in terms of water availability and sediment volume. Table 1 indicates that average interstitial water volume was nearly four times that of surface water; however, interstitial volume itself varied with discharge. Surface discharge rates in Sycamore Creek vary with season and storm intensity, but low surface discharge is typical for most of the year (Thomsen and Schumann 1968). Under these conditions the hyporheic zone encompasses a major portion of available aquatic environment (Table 1) and, as such, should be recognized as a substantial component of the stream ecosystem.

While most stream water is in the hyporheic zone at any given time, the vast majority of discharge takes place on the surface. The product of average rate of subsurface flow (0.62 mm/s), hyporheic cross-sectional area determined from Figures 1-3 (site I = 12.33 m^2, site II = 10.53 m^2, site III = 7.15 m^2), and % porosity (Table 1) results in sub-surface discharge rates

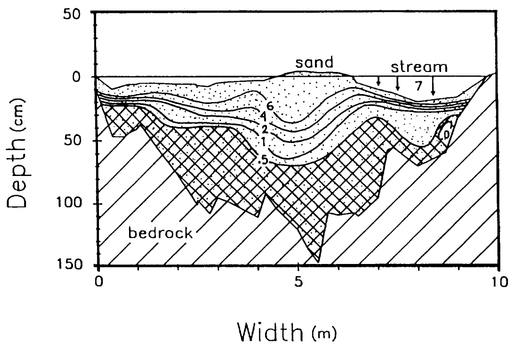

FIG. 7. Hyporheic dissolved oxygen (mg/L) isoclines for site III, a downwelling zone. Vertical scale is exaggerated. Cross-hatched areas are regions less than 0.5 ppm.

TABLE 4. Well locations, nutrient concentration ($\mu g/L$) and water temperature (0800–1000 hrs) of surface and interstitial water for Site I, Sycamore Creek, Arizona on April 11, 1989. Data are means ± SE (n = 3). SRP = soluble reactive phosphorus. "Lateral Position" = distance from left edge of stream channel looking downstream. Depths = depth below water table (depth below sand surface).

Well Location (cm)	Depth (cm)	Lateral Position (m)	Temperature (°C)	NH_4-N	NO_3-N	SRP	Atomic N:P
Surface	0 (0)	16.0	22.5	9 ± 2	23 ± 9	48 ± 2	1.45
Sand edge:		3.2					
Well 1	20 (45)	6.2	24.0	22 ± 3	7 ± 1	146 ± 2	0.43
Well 2	20 (40)	7.8	23.0	8 ± 2	74 ± 2	124 ± 1	1.46
Well 3	20 (35)	9.3	22.5	56 ± 10	7 ± 4	124 ± 1	1.13
Well 4	20 (30)	10.9	26.0	31 ± 17	224 ± 6	81 ± 1	6.99
Left stream edge:		12.8					
Well 5	20 (20)	12.8	18.0	8 ± 4	26 ± 1	40 ± 2	1.88
Well 6	68 (60)	15.0	26.0	15 ± 7	208 ± 6	77 ± 2	6.44
Well 7	30 (20)	15.6	23.5	34 ± 4	35 ± 1	76 ± 2	2.00
Well 8	33 (20)	17.2	24.0	33 ± 4	46 ± 3	76 ± 1	2.29
Well 9	33 (20)	19.0	23.0	89 ± 9	21 ± 6	80 ± 1	3.04
Well 10	45 (31)	19.1	22.5	14 ± 4	113 ± 17	87 ± 1	3.24
Right stream edge:		22.1					

an order of magnitude smaller than those for surface water. Surface water flux represented 95, 96, and 98 percent of total discharge at sites I, II and III, respectively. However, during periods without surface water 100% of stream discharge occurs as hyporheic flow.

Residence time of surface water in our study reaches varied between thirty and sixty minutes during summer low flow periods. This may be as short as 2 to 5 minutes at higher flows characteristic of winter. Hyporheic residence time is difficult to calculate because fluxes due to

TABLE 5. Well locations, nutrient concentration ($\mu g/L$) and water temperature (0800–1000 hrs) of surface and interstitial water for Site II, Sycamore Creek, Arizona on July 15, 1989. Data are means ± SE (n = 3). SRP = soluble reactive phosphorus. "Lateral Position" = distance from left edge of stream channel looking downstream. Depths = depth below water table (depth below sand surface).

Well Location (cm)	Depth (cm)	Lateral Position (m)	Temperature (°C)	NH_4-N	NO_3-N	SRP	Atomic N:P
Surface	0 (0)	12.00	22.0	32 ± 3	40 ± 6	30 ± 2	5.28
Sand edge:		0.00					
Well 1	12 (35)	5.30	29.0	26 ± 3	570 ± 19	47 ± 1	28.04
Well 2	125 (140)	6.95	26.2	24 ± 4	121 ± 2	39 ± 4	8.17
Well 3	10 (30)	7.10	25.6	54 ± 23	534 ± 129	72 ± 1	18.13
Well 4	20 (40)	7.40	26.5	117 ± 15	144 ± 10	38 ± 1	15.06
Well 5	20 (30)	8.35	25.5	19 ± 3	225 ± 5	46 ± 2	11.64
Well 6	10 (17)	9.35	23.0	97 ± 32	129 ± 3	57 ± 1	8.77
Left stream edge:		9.70					
Well 7	30 (20)	11.10	23.5	56 ± 5	131 ± 2	103 ± 23	3.98
Well 8	20 (10)	12.20	23.2	78 ± 6	65 ± 4	40 ± 1	7.97
Right stream edge:		13.50					

TABLE 6. Well locations, nutrient concentration (μg/L) and water temperature (0800–1000 hrs) of surface and interstitial water for Site III, Sycamore Creek, Arizona on June 28, 1989. Data are means ± SE (n = 3). SRP = soluble reactive phosphorus. "Lateral Position" = distance from left edge of stream channel looking downstream. Depths = depth below water table (depth below sand surface).

Well Location (cm)	Depth (cm)	Lateral Position (m)	Temperature (°C)	NH_4-N	NO_3-N	SRP	Atomic N:P
Surface	0 (0)	5.00	25.0	50 ± 7	17 ± 7	22 ± 1	6.77
Left stream edge:		0.00					
Well 1	25 (20)	0.40	24.5	51 ± 3	10 ± 3	18 ± 1	7.47
Well 2	35 (30)	0.72	24.0	47 ± 12	19 ± 7	35 ± 1	4.13
Well 3	35 (30)	1.15	24.5	3 ± 1	6 ± 1	53 ± 12	0.38
Well 4	95 (90)	2.82	25.5	30 ± 4	18 ± 2	37 ± 1	2.91
Well 5	82 (80)	4.20	25.0	44 ± 1	46 ± 1	34 ± 1	5.87
Well 6	104 (108)	5.50	26.0	46 ± 2	43 ± 1	36 ± 1	5.52
Well 7	40 (30)	7.35	25.0	47 ± 12	55 ± 9	24 ± 2	9.42
Well 8	35 (30)	8.27	25.5	93 ± 2	56 ± 8	24 ± 1	13.89
Well 9	15 (22)	9.60	25.0	812 ± 71	22 ± 2	30 ± 2	62.00
Right stream edge:		10.00					

vertical exchange are incompletely known. Based on velocities of interstitial water established during base flow conditions, residence time of hyporheic water in study reaches is between 42 and 110 hours; however, calculations based on oxygen demand (discussed later) are nearer 3 to 8 hours. Residence time of hyporheic water varies greatly because of incomplete mixing due to spatial variation in hydraulic heads and conductivities. In any event, contact time of hyporheic water with stream sediments is prolonged in compared to surface water. When both volume of flow and residence time are considered, surface and hyporheic sediments have approximately equal opportunities to influence physical and chemical charcteristics of water as it flows downstream.

Organic matter

Organic matter concentration in hyporheic sediments of Sycamore Creek is low compared to benthic standing crop. Hyporheic organic matter averaged 0.67 kg/m^3 (n = 69, SE = 0.030) in cores taken in the top 40 cm of sediment. Maximum benthic organic matter to 2 cm is 13 kg/m^3 (calculated from Table 3, Grimm and Fisher 1989).

Based on average sediment depth, hyporheic organic matter was 348 g/m^2, 422 g/m^2, and 509 g/m^2 at sites I, II and III, respectively. Maximum standing stock of benthic organic matter approaches 258 g/m^2 (Grimm and Fisher 1989), but varies greatly with successional time (Fisher et al. 1982). If average surface organic matter is 50% of maximum, then hyporheic sediments store more than three times the organic matter stored on the benthic surface.

Organic matter in shallow portions of the hyporheic zone is variably distributed. Results show a general trend of decreasing organic matter with depth, but values were very different among sites and within runs (Fig. 3). This variation probably reflects disturbance history both in terms of deposition of organic matter during floods and time for in situ utilization by heterotrophs.

Decreasing organic matter with increasing depth is a trend opposite to that reported in an Austrian stream where organic matter was lowest in the surface layers of stream bed sediments (Leichtfried 1985, 1988). In the above case small sediment particles (<1 mm) accounted for only 6–9% of total sediment weight, but represented up to 88% of total organic carbon. Small particles in the hyporheic zone of Sycamore Creek are equally scarce (≈3% of sediment dry weight) and represent one quarter of total organic matter (Table 2). Although the organic content of small particles in the hyporheic zone of Syca-

TABLE 7. Summary statistics for hyporheic and surface nutrient (μg/L) chemistry. Surface: n = 3 sites; Hyporheic: n = 27 wells. CV = SD/$\bar{x}$ × 100.

		Mean	SD	SE	CV (%)	Range
NH_4-N:	surface	30	17	10	55.3	41
	hyporheic	72	148	28	204.4	809
NO_3-N:	surface	27	10	6	36.5	31
	hyporheic	109	141	27	129.0	564
SRP:	surface	33	11	6	32.6	26
	hyporheic	61	33	6	54.5	128
N:P:	surface	4.50	2.24	1.29	49.9	5.3
	hyporheic	8.97	12.06	2.32	134.4	61.6

more Creek is low they may exert strong influence on interstitial biota. Bretschko and Leichtfried (1988) stress that because of high surface area and associated biofilm, small particles may be a main parameter governing distribution of the fauna of the hyporheic zone.

Other research reports hyporheic sediment much higher in organic matter than the 0.08% average for Sycamore Creek. Interstitial organic carbon averaged 7.5% in Oberer Seebach, Austria, and varied only slightly with depth (Leichtfried 1988, calculated from Fig. 5). An average concentration of 4.3 kg/m^3 (calculated from Table 2) was obtained from 60 cm sediment cores. Total organic carbon (bed sediment + interstitial water) increased with depth at all sites in Oberer Seebach.

In Hugh White Creek, North Carolina, organic matter ranged from 0.5% to greater than 2.0% in stream sediment (Munn and Meyer 1989). Organic matter was significantly greater in deep sediments (6–8 cm) than in shallower ones (0–2 cm).

Benke and Meyer (1988) emphasized the importance of fine-grained substrata in the low gradient Ogeechee River, Georgia. Exceptionally high benthic standing stock is mostly fine particulate organic matter, but samples included 24 cm of interstitial sediments. Volumetric calculations (from Benke and Meyer 1988, Table 2) yield an average 18 kg/m^3. Comparable samples (benthic and 24 cm hyporheic) from Sycamore Creek would contain closer to 7 kg/m^3.

Variable sediment distribution (Fig. 2) and differences in percent composition (Table 2) result in complex patterns of organic matter in deep regions of the hyporheic zone in Sycamore Creek (Fig. 4). At site Ia sediment weight in the medium size-class decreased with depth while smaller particles became more abundant. At site Ia larger sediments overlie smaller ones. Leopold et al. (1964) stated such a distribution occurs in a variety of channels in "quasi-equilibrium" and that sediment distribution may be explained by disturbance. During flash floods smaller sediment may be quickly entrained, but larger material may not be exported due to the relatively short duration or intensity of most floods (Frostick and Reid 1979). As such, the geomorphic effects of flooding may be manifested in the hyporheic zone as variable concentrations of sediment organic matter. Depending on flow patterns, reservoirs of organic matter deep in the hyporheic zone have the potential to greatly influence sediment respiration rates, affect dissolved oxygen and nutrient conditions, and alter stream metabolism profiles.

Temperature

Exposed alluvium may play an important role in the heat budget and metabolism of sandy bottom streams. Sand surface temperatures have been recorded as high as 50°C on exposed alluvium in Sycamore Creek. Cooling of surface water by evaporation is very high in the extremely low relative humidity of Sonoran Desert air in summer; however, evaporation rate in the interstitial environment of Sycamore Creek is greatly reduced (Thomsen and Schumann 1968). Exposed sediment undoubtedly transfers heat to the lateral portions of the hyporheic zone by conduction where interstitial temperatures can be quite high (e.g., site II).

High interstitial temperature contrasts markedly with conditions reported in northern temperate streams (Mestrov and Lattinger-Penko 1977, Hynes 1983, White et al. 1987, Fortner and White 1988, Hendricks and White 1988). Sub-surface temperature exceeded surface temperature in a Michigan stream only during winter when surface water temperature was as low as 2°C (White et al. 1987).

In Sycamore Creek, readings taken during morning hours in spring and summer indicate that sub-surface temperature can equal or exceed surface temperature during part of the day, even in hot weather typical of summer in the Sonoran Desert. Warm temperatures in the hyporheic zone promote rapid rates of biologic processing, including increased respiratory demand and potentially high rates of nutrient transformation. As such, the hyporheic zone in this desert stream may be an extremely active component of the stream ecosystem in terms of energy flow and nutrient cycling.

Dissolved oxygen

Photoautotrophic production in the hyporheic zone is zero, thus distribution of interstitial dissolved oxygen results from the interaction between the surface and hyporheic subsystems. Oxygen content varied from 0 to 107% saturation, and averaged 20%. Biologic oxygen demand averaged 0.753 g O_2 m^{-3} hr^{-1} (3.49 mg $O_2/L \cdot hr$) in hyporheic sediment (H. M. Valett, unpublished data), thus surface water entering the hyporheic zone with 10 mg/L dissolved oxygen would be rendered anoxic within three hours. The presence of measurable interstitial oxygen indicates replenishment by hydrologic exchange.

Patterns of variation in oxygen content with depth in the hyporheic zone correspond to differences in interstitial flow rates, sediment respiratory activity and sub-surface residence time. Direction of flow is also important. For example, surface water infiltration of sediments in downwelling regions may produce highly oxygenated interstitial water in shallow portions of the hyporheic zone. In upwelling regions deeper interstitial water must pass through hyporheic sediments on its way to the stream surface, thus producing the inverted oxygen profile observed at site II.

Conditions in the hyporheic zone that affect dissolved oxygen content probably reflect the influence of disturbance. Routes of sub-surface flow, permeability of interstitial spaces and degree and location of linkage between surface and hyporheic water may be altered by flash floods and may change during periods between disturbance events.

Variable distribution of dissolved oxygen has a significant effect on element cycling in the hyporheic zone (Dahm et al. 1987, Triska et al. 1989). Oxygen content of interstitial water was correlated with inorganic nitrogen species-composition in three New Mexican streams (Carr 1989). The geomorphology of these streams, and its effects on organic matter deposition, generated a physical mosaic supporting anaerobic, microaerophilic and aerobic processes. Sprent (1987) argued that limited opportunity for anaerobiosis is the most common constraint to nitrogen cycling in aquatic ecosystems. Close association of regions relatively low and high in oxygen content may provide opportunity for high rates of hyporheic nutrient transformation in Sycamore Creek.

Nutrient environment

Primary production of surface autotrophs is nitrogen limited in Sycamore Creek (Grimm and Fisher 1986). Thus, it is of significance that hyporheic water is 3-fold richer in TIN (Tables 3–7). Similar conditions were reported for three first-order New Mexican streams where interstitial water was 2-fold richer in inorganic nitrogen (Carr 1989). Hyporheic NH_4-N was much higher than found in Sycamore Creek (205 $\mu g/L$ vs. 72 $\mu g/L$), but interstitial NO_3-N was similar (108 $\mu g/L$ vs. 109 $\mu g/L$). High interstitial NH_4-N in these headwater streams of New Mexico reflects their retentive geomorphology and corresponds to widespread anaerobic conditions. Anoxic conditions were less common in Sycamore Creek (Figs. 5–7).

During dry summer months Sycamore Creek becomes spatially intermittent. Hyporheic water emerges at origins of isolated above-ground segments, is rich in nutrients (Grimm et al. 1981, Grimm et al., in press), but subsequent uptake by surface algal communities results in longitudinal gradients in surface water nitrogen content (Grimm et al. 1981, Grimm 1987). The gradient thus created by algal uptake may in turn influence community structure, since e.g., blue-green bacteria are more likely to colonize where inorganic nitrogen concentrations are low (N. B. Grimm, Arizona State University, unpublished data). Water column NO_3-N concentration is elevated at hyporheic discharge zones within continuous reaches of Sycamore Creek (Grimm et al., in press). Similarly, highest concentration of surface TIN was found in an upwelling region in this study (Table 4). Thus, nutrient supply from the hyporheic zone has potential to influence surface communities and processes by alleviating nitrogen limitation. Other researchers have also postulated that interaction between hyporheic and surface systems alters benthic conditions and may affect distribution and abundance of primary producers (e.g., Fortner and White 1988, Stanford and Ward 1988, Coleman 1989).

Conclusion

The hyporheic zone of runs in Sycamore Creek consists of the sandy sediment and interstitial spaces of stream alluvium located below the water table. As a reuslt of perennially low surface water volume and extensive amounts of hyporheic sediment, a substantial proportion of water resides in the hyporheic zone. During dry periods, surface flow is zero and water is found only in the hyporheic zone.

Organic matter of hyporheic sediment is low and varies greatly with location. Repeated flash flooding, scouring, and redeposition of sediments probably accounts for the high variation in sediment organic matter. Some regions deep in the hyporheic zone may act as reservoirs of stored organic matter with the potential to affect nutrient cycling and system metabolism.

The hyporheic zone in Sycamore Creek is a dynamic region that is closely linked with the surface water. Hyporheic conditions (dissolved oxygen, nutrient content) are strongly influenced by patterns of surface flow. Conversely, the surface stream may be influenced by upwelling of nutrient rich interstitial water. Because the potential for interaction between hyporheic and surface subsystems is substantial, it is essential that the structure and functioning of both be considered in attempts to understand stream ecosystem dynamics.

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