

A mini drivepoint sampler for measuring pore water solute concentrations in the hyporheic zone of sand-bottom streams

Abstract—A new method for collecting pore-water samples in sand and gravel streambeds is presented. We developed a mini drivepoint solution sampling (MINIPOINT) technique to collect pore-water samples at 2.5-cm vertical resolution. The sampler consisted of six small-diameter stainless steel drivepoints arranged in a 10-cm-diameter circular array. In a simple procedure, the sampler was installed in the streambed to preset drivepoint depths of 2.5, 5.0, 7.5, 10.0, 12.5, and 15.0 cm. Sampler performance was evaluated in the Shingobee River, Minnesota, and Pinal Creek, Arizona, by measuring the vertical gradient of chloride concentration in pore water beneath the streambed that was established by the uninterrupted injection to the stream for 3 d. Pore-water samples were withdrawn from all drivepoints simultaneously. In the first evaluation, the vertical chloride gradient was unchanged at withdrawal rates between 0.3 and 4.0 ml min⁻¹ but was disturbed at higher rates. In the second evaluation, up to 70 ml of pore water was withdrawn from each drivepoint at a withdrawal rate of 2.5 ml min⁻¹ without disturbing the vertical chloride gradient. Background concentrations of other solutes were also determined with MINIPOINT sampling. Steep vertical gradients were present for biologically reactive solutes such as DO, NH₄⁺, NO₃⁻, and dissolved organic C in the top 20 cm of the streambed. These detailed solute profiles in the hyporheic zone could not have been determined without a method for close

interval vertical sampling that does not disturb natural hydrologic mixing between stream water and groundwater.

A close connection exists between stream water and near-stream groundwater in stream catchments (Bencala et al. 1993). Water and solutes from stream channels exchange with pore water underlying the streambed, banks, and valley. The subsurface zone where stream water and shallow groundwater mix, called the hyporheic zone, exists wherever subsurface water consists of at least 10% stream water (Triska et al. 1989). Hyporheic exchange greatly increases the volume of sediment in contact with stream water (Harvey and Bencala 1993; Morrice et al. 1997).

The linkage between hydrologic transport and biogeochemical reactions in the hyporheic zone has the potential to modify the solute chemistry of shallow groundwater and channel water moving through the sediment. Chemically reduced solutes from groundwater and chemically oxidized solutes from surface water are brought together and mixed in the hyporheic zone. As a result, various oxidation-reduction reactions can be stimulated. Reactions include metal partitioning (Kennedy et al. 1984; Benner et al. 1995),

NH_4^+ sorption (Triska et al. 1994), Mn oxidation and trace-metal sorption (Harvey and Fuller 1998), physicochemical transformations (Hendricks and White 1991, 1995), and nutrient transformations (Duff and Triska 1990; Triska et al. 1990; Findlay et al. 1993; Holmes et al. 1994; Jones et al. 1995; Wondzell and Swanson 1996; Mulholland et al. 1997). Microbial processes in the hyporheic zone that can influence C, N, O, S, and P levels in the stream include dissolved organic C processing, SO_4^{2-} reduction, S/S^{2-} oxidation, Fe^{3+} reduction, Fe^{2+} oxidation, NO_3^- reduction, NH_4^+ oxidation, methanogenesis, and CH_4 oxidation. Because the biogeochemistry of lotic ecosystems is likely to be fundamentally linked to hyporheic processes, it is essential to determine water and solute gradients in the hyporheic zone.

Measurement of solute gradients in highly permeable streambeds requires a reliable method to obtain close interval samples without disturbing natural mixing processes. Diffusion equilibration (Hesslein 1976; Bottomley and Bayly 1984; Carignan 1984) and core sectioning followed by squeezing or centrifugation (Howes et al. 1985; Viel et al. 1991) have frequently been used to measure concentration gradients in fine-grained sediments dominated by diffusion, but they are less effective in streambeds composed of highly permeable sands and gravels. Diffusion equilibrators are most effective at characterizing pore-water chemistry where the primary transport vector is diffusion and solute velocities are low (millimeters per day). In contrast, horizontal water velocities in permeable sediments range from 0.01 to 2.4 m h^{-1} (Duff and Triska 1990; Valett et al. 1990; Harvey and Bencala 1993; Triska et al. 1993; Holmes et al. 1994). Placement and removal of cores can disturb natural gradients because of edge effects and redistribution of pore water during coring and handling. These methods may also be inadequate for measuring dissolved gases and organic matter.

The impetus for developing the MINIPOINT solution sampling technique was the difficulty we encountered delineating solute gradients in the hyporheic zones of the Shingobee River in north-central Minnesota and in Pinal Creek in central Arizona. Both streambeds consist of relatively high permeability, low cohesion, medium to coarse sands, and gravels. Originally, we used stainless steel drivepoints (0.64-cm inside diameter (ID)) with slots (0.04 \times 1.0 cm) sawn in the tube near the tip to remove pore water at 20-cm intervals to 2 m below the streambed. To resolve the chemical gradients where groundwater and stream water actually mixed in the subsurface, we found it necessary to develop methods for measuring our spatial sampling resolution within the top 20 cm of the streambed. To preserve natural solute gradients, the MINIPOINT sampler was designed to remove subsurface water from the bed in a reasonable length of time without disturbing streambed stratigraphy or the natural distribution of solutes. The purpose of this paper is to describe the design, evaluation, and use of the MINIPOINT technique for measuring in situ hyporheic solute concentrations.

Description of mini drivepoint sampler—The mini drivepoint sampler consists of six slotted 0.318-cm (= 1/8 in) outside diameter (OD) stainless steel tubes attached to a polycarbonate plastic frame that in turn attaches to a photographer's tripod (Fig. 1). The center post of the tripod

is inverted so the sampler can be mounted under the tripod and positioned vertically in the streambed. The plastic frame is a 1-cm-thick by 12-cm-diameter disk attached at its center to a rod 20 cm long and 2.2 cm in diameter. The free end of the rod is tapped to accept the standard 1/4-20-in. threads of a camera mount. Six holes in the disk, equally spaced on a 10-cm-diameter circle, hold Swagelok brand 1/8-in. bulk-head-mounting compression fittings. (The use of name brands in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.) Each fitting is drilled through to 0.325 cm (#30 drill) to allow the 0.318-cm (1/8 in.) tubes to pass easily. The tubes are retained in their fittings with nylon ferrules, which hold the tubes securely while allowing them to be repositioned easily. The mini drivepoints are made from various fixed lengths of 0.318-cm (1/8 in.) OD stainless steel tubing. The bottom of each tube is crimped shut. Water is drawn into the drivepoints through three slots about 0.8 cm long and 0.04 cm wide that are sawn into each tube near its crimped end.

To collect water samples, the tripod and sampler are placed on the streambed, and the sampler is plumbed and lowered, inserting the drivepoints to a fixed depth. The frame of the sampler remains above the water surface, except in very deep water, where the frame may be submerged but remains well above the sediment surface. Elastic tubes (Pharmed #13) are attached to the drivepoints and connected to a variable-speed peristaltic pump (we used a Masterflex 7549-32, 110 volts alternating current or Masterflex 7533-20, 12 volts direct current) equipped with a multichannel pump head (Masterflex L/S 7519-25 or Masterflex L/S 7519-06). Most AC pumps generate greater torque and thus accommodate a greater variety of pump heads, rollers, and tubing. However, in remote locations, a 12-VDC variable-speed peristaltic pump with a six- or eight-channel pump head is satisfactory. Pore water can be pumped into either syringes or test tubes immediately after placement. Pore-water samples also can be withdrawn manually with syringes, but it is difficult to control the rate of withdrawal. The internal volume of a drivepoint and the attached elastic tubing is approximately 2 ml.

Evaluation of the mini drivepoint sampler—To evaluate the MINIPOINT sampler, we performed streambed pumping rate tests during a chloride injection (see Stream Solute Workshop [1990] and Triska et al. [1993] for a discussion of whole-stream tracer injection techniques) in the Shingobee River and a bromide injection in Pinal Creek. During the injections, the average stream discharges of the Shingobee River and Pinal Creek were 225 and 250 liters s^{-1} , respectively. The top 15 cm of the Shingobee River consisted of 17% very coarse-grained sands (>1.0 mm), 78% medium- to coarse-grained sands (0.25–1.0 mm), and 5% fine-grained sands (<0.25 mm). Overall, sediment porosity was 0.35 ± 0.01 (standard error), and the average vertical hydraulic conductivity was $1.1 \times 10^{-2} \pm 6.0 \times 10^{-4}$ cm s^{-1} (standard error). Sediment particles in the top 30 cm of Pinal Creek consisted of 60% very coarse sands, 36% medium- to coarse-grained sands, and 4% fine-grained sands. The average sediment porosity in Pinal Creek was 0.31 ± 0.01 (stan-

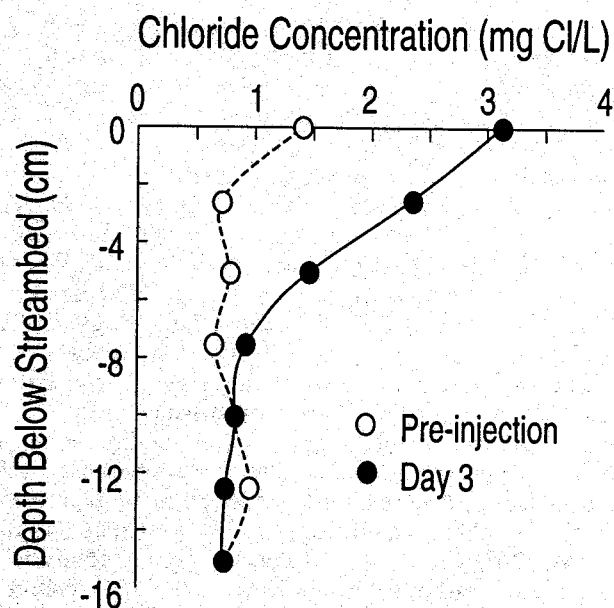
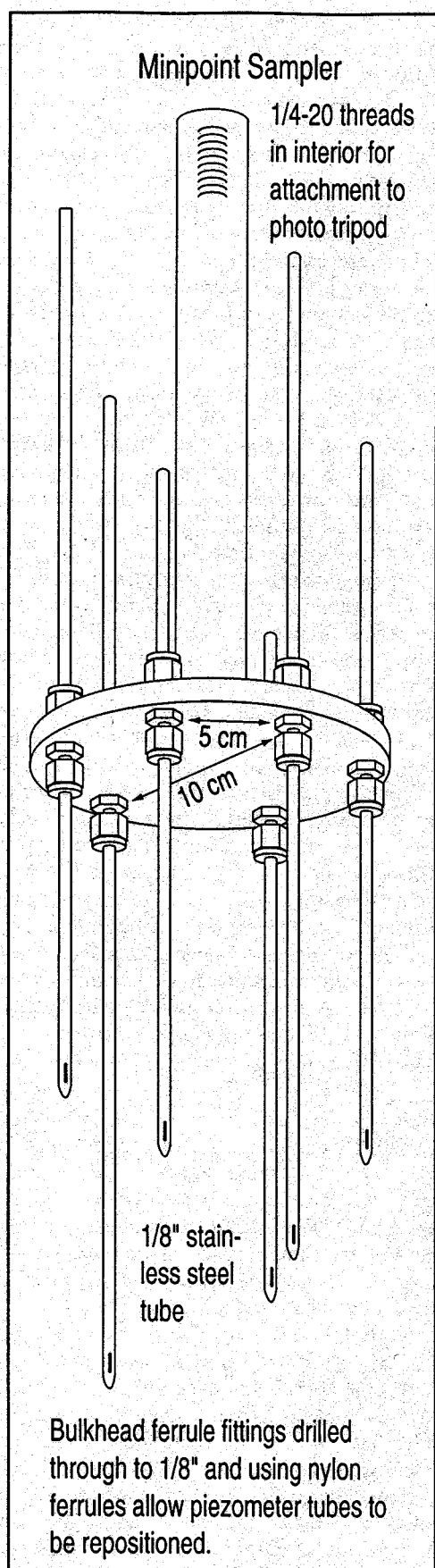


Fig. 2. Depth profiles of chloride concentration in the streambed of the Shingobee River collected every 2.5 cm with the MIDPOINT prior to (open circles) and during the third day (closed circles) of an uninterrupted chloride injection to the stream channel. Each data series represents one set of measured values.

dard error), and the average vertical hydraulic conductivity was 0.2 cm s^{-1} (range = $0.02\text{--}0.7 \text{ cm s}^{-1}$).

Because similar results were obtained with the MINI-POINT sampler in both injections, details of only the Shingobee River injection are presented for simplification. We elevated in-stream chloride levels threefold in the Shingobee River during a 3-d uninterrupted injection to create an artificial chloride gradient in the streambed that had reached steady state. The pumping rate test site was approximately 110 m downstream from the injection. Chloride profiles in streambed sediment before the start of the injection and during third day of the chloride injection are shown in Fig. 2.

The sampler was evaluated first by measuring the pore-water chloride concentration at six depths below the streambed surface (2.5, 5.0, 7.5, 10.0, 12.5, and 15.0 cm) while the pump rate of the mini drivepoint sampler was increased sequentially (0.3, 0.8, 1.5, 4.1, 9.0, 14.2, and 18.6 ml min^{-1}). All six drivepoints were pumped simultaneously at the same rate for each pumping speed. The pump was stopped and the sample collection vessels were changed prior to increasing the pump rate. Approximately 7 ml of water was collected from each depth at each pump rate. The first 2 ml was discarded, and the remaining 5 ml was analyzed for chloride by ion chromatography (Dionex 2010i with an AS4A column, Dionex Instruments). (There was a relative variability of 3.8% in the chloride measurements.) Overall, about 55 ml of water was withdrawn from each depth. The

Fig. 1. A three-dimensional view of the mini drivepoint sampler depicting six stainless steel drivepoints. The 1/4-20-tapped rod attaches to a photographer's tripod.

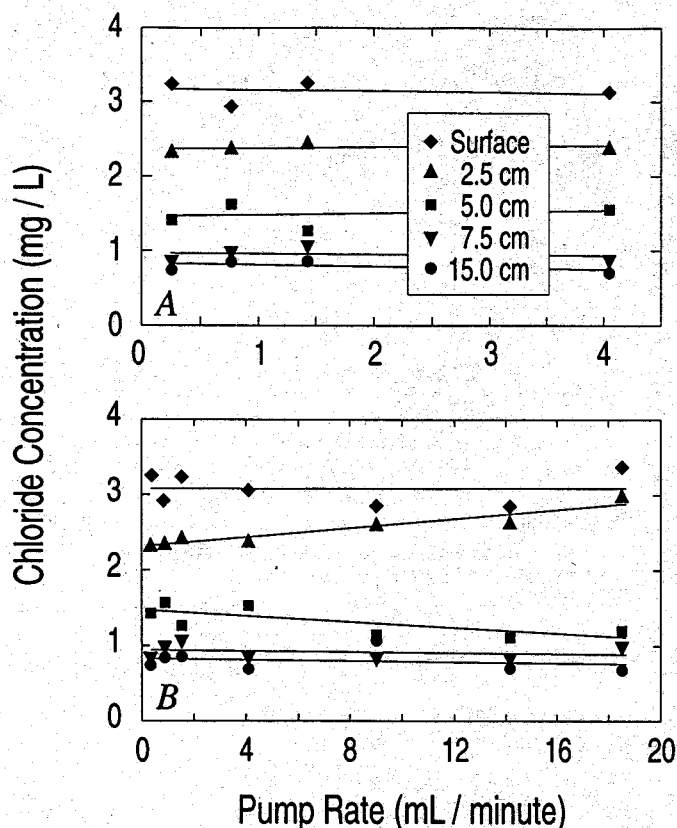


Fig. 3. Depth profiles of chloride concentration in the streambed of the Shingobee River collected with the MINIPOINT sampler during a pumping rate test in the third day of a chloride injection to the stream channel. (A) Linear-fit trend lines for pump rates between 0.3 and 4.0 ml min⁻¹. (B) Linear-fit trend lines for pump rates between 0.25 and about 19 ml min⁻¹.

duration of the pumping rate tests was about 42 min. Statistical significance of trends in pore-water chemistry was analyzed by regression analyses (Zar 1974). In the Shingobee River, four tests were conducted at two downstream locations. In Pinal Creek, two tests were conducted at two sites.

Figure 3A,B shows the trends in chloride concentration for samples collected from four depths in the streambed at seven pump rates. The artificial chloride gradient was maintained at pump rates <4.0 ml min⁻¹ (the slopes for each depth were not significantly different from zero) (Fig. 3A). Elevating the pump rate above 4.0 ml min⁻¹ caused the chloride concentration to increase in water samples collected 2.5 cm below the streambed (0.0005 < *P* < 0.001; *P* = 0.0007), suggesting that surface water was drawn into the streambed (Fig. 3B). Conversely, elevating the pump rate above 4.0 ml min⁻¹ caused the chloride concentration to decrease in water samples collected 5.0 cm below the streambed (0.05 < *P* < 0.1; *P* = 0.08), suggesting that low-chloride water was drawn from below. These results indicated that the artificial chloride gradient was unchanged when pore-water samples were withdrawn between 0.3 and 4.0 ml min⁻¹ for these sediments. Similar conclusions were reached from a comparable pumping rate test with the MINIPOINT sampler in Pinal Creek. There, artificially elevated depth profiles of bro-

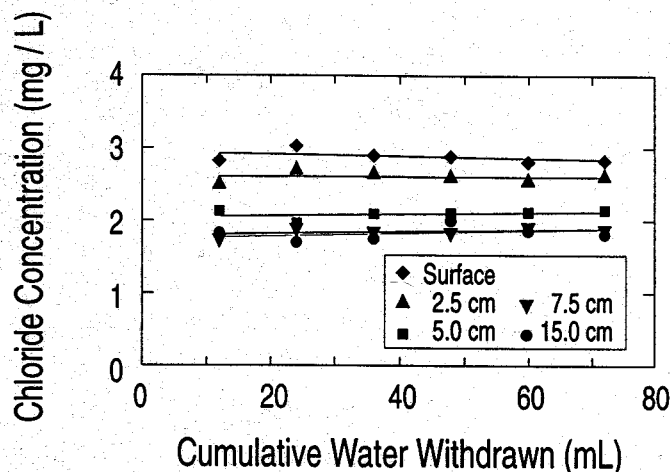


Fig. 4. Depth profiles of chloride concentration in the streambed of the Shingobee River collected with the MINIPOINT sampler during a pore-water volume pump test on the third day of a chloride injection to the stream channel. Linear-fit trend lines for pore-water withdrawal volumes are between about 10 and 72 ml.

mid concentrations were preserved at pumping rates up to 4.8 ml min⁻¹ (data not presented) but were disturbed at pumping rates ≥ 6.0 ml min⁻¹.

To determine empirically whether the increase in pore-water volume withdrawn affected the chloride concentrations, an evaluation of cumulative pore-water volume pumped was performed in the Shingobee River during a later injection (Fig. 4). Using a constant pump rate of 2.5 ml min⁻¹, >70 ml of pore water was withdrawn simultaneously from five depths with no significant change in the vertical chloride gradient (Fig. 4). In Pinal Creek, the vertical bromide gradient was unchanged after >140 ml of pore water was withdrawn (data not presented). The results combined from the pump rate tests and the pore-water volume tests suggest that vertical solute gradients are more sensitive to withdrawal rates than the volume withdrawn.

A total of 72 ml of pore water could be withdrawn from each drivepoint in the Shingobee River without changing the artificial chloride gradient in the streambed (Fig. 4). Assuming that this amount of water was withdrawn from a spherical zone of sediment around each sampling port (although the actual shape of the volume from which water was collected is unknown), the effective radius of the sphere of sediment would have been about 3.5 cm (Fig. 5), greater than the vertical distance between adjacent 2.5-cm depths. Removal of 70 ml of pore water without disturbing the artificial chloride gradient suggested that the volume of the streambed sampled might have been shaped like a horizontal disk or an oblate spheroid. This is consistent with the fact that sedimentary materials such as streambed sediments often show higher horizontal hydraulic conductivities than vertical conductivities (Freeze and Cherry 1979). In addition, adjacent depths in the mini drivepoint sampler are 8–10.5 cm apart because of the horizontal sampling array (Fig. 1). If the sampling ports were located vertically above one another, the spherical sampling zones would intersect at a radius of 1.25 cm, the same as withdrawing only 3 ml of sample. There-

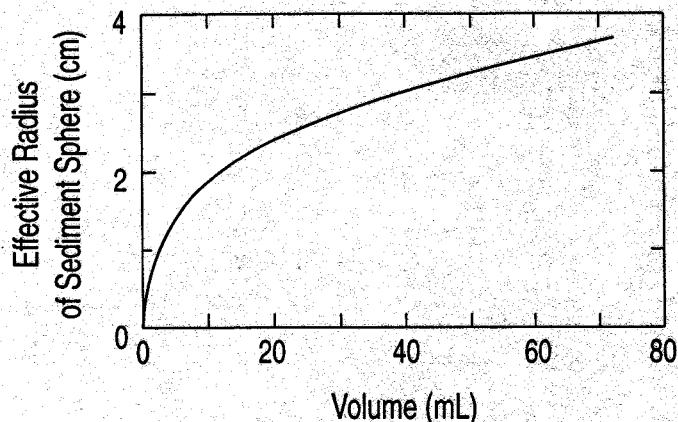


Fig. 5. Relationship between the effective radius of a sediment sphere and the volume of pore water withdrawn from the streambed of the Shingobee River with a porosity of 0.35.

fore, by keeping adjacent depths 8–10 cm apart, a greater volume of pore water can be drawn.

Field application of the mini drivepoint sampler—The MINIPPOINT sampler was used to delineate the lower boundary of the hyporheic zone in the Shingobee River and to reveal steep vertical gradients of biologically reactive pore-water solutes. Chemical data collected with the MINIPPOINT revealed steep vertical solute gradients in the top 20 cm of the streambed for common biologically reactive solutes (Fig. 6), whereas samples collected every 20 cm with stainless steel drivepoints (0.64-cm ID) showed relatively uniform solute concentrations below 20 cm (Fig. 6). Details of the hyporheic zone would have been missed without a mechanism for sampling pore water at closely spaced vertical intervals. The specific conductance profile (Fig. 6B) delimited the mixing zone between groundwater and stream water and the lower boundary of the hyporheic zone (extending to a depth of only about 10 cm). The steep solute gradients for DO, inorganic N, and organic C fell within the mixing zone (Fig. 6A,C,D), indicating the presence of a relatively thin but biologically active hyporheic zone.

We are unaware of other samplers that are in use to sample pore water at closely spaced intervals in highly permeable sediments characteristic of many stream and river bottoms. The mini drivepoint sampler is unique in that it is intermediate between large diameter (5–15 cm) cased wells that are used at spatial scales ranging from 1 to 10s of meters (Duff and Triska 1990; Triska et al. 1990), small-diameter cased wells (1 cm) that are used at the 0.1-m scale (Henry et al. 1994), and microsensors that are used in diffusion-limited sediments (Nielsen et al. 1990).

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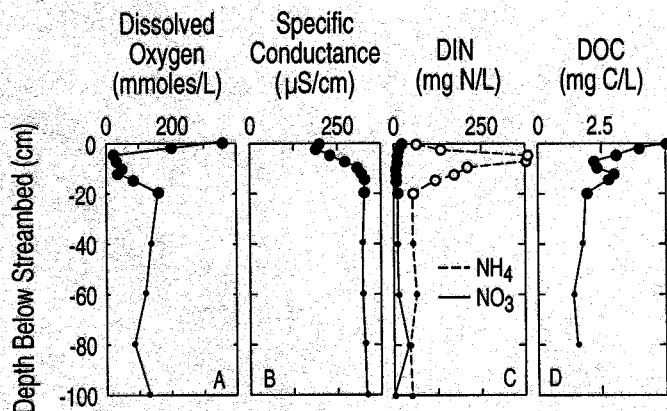


Fig. 6. Depth profiles of (A) DO, (B) specific conductance, (C) dissolved inorganic N (DIN), and (D) dissolved organic C (DOC) collected every 2.5 cm down to 15 cm with the MINIPPOINT sampler (large circles) and then every 20 cm with stainless steel dripepoints (0.64-cm ID) (small circles). Each data series represents one set of measured values.

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