

INTERSTITIAL WATER PATTERNS: A FACTOR INFLUENCING THE DISTRIBUTIONS OF SOME LOTIC AQUATIC VASCULAR MACROPHYTES

SHARON L. FORTNER and DAVID S. WHITE¹

*Great Lakes Research Division, Program in Water Resource Science and Biological Station,
University of Michigan, Ann Arbor, MI 48109 (U.S.A.)*

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ABSTRACT

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The distributions of 9 species of aquatic vascular macrophytes were examined in relation to interstitial water patterns (based on temperature) in the beds of three northern Michigan (U.S.A.) streams. *Ranunculus septentrionalis* Poir., *Caltha palustris* L. and *Nasturtium officinale* R.Br. were associated with areas of groundwater discharge. *Sparganium chlorocarpum* Rydb., *Veronica catenata* Penn., *Potamogeton filiformis* Pers. and *P. richardsonii* (Benn.) Rydb. occurred most often at the downstream end of a hyporheic zone (corresponding to the foot of a riffle) where interstitial water was of surface origin. *Sagittaria latifolia* Willd. occurred where interstitial temperatures were cool; the water origin was not determined. *Potamogeton gramineus* L. occurred most often where interstitial temperatures were warm, primarily at the upstream ends and middles of hyporheic zones (heads of riffles) in areas of surface-water infiltration. Complex patterns of interstitial water movement and related physicochemical complexity combined with differences in plant requirements, in part, may determine observed local distributions.

INTRODUCTION

Factors known to control the distribution and growth of lotic aquatic macrophytes include turbulence, light, surface-water chemistry, surface-water temperature, flow, sediment structure and chemistry, and other biota (Spence, 1967; Peltier and Welch, 1968; Kullberg, 1974; Hutchinson, 1975; Beal 1977; Haslam, 1978). Although often implied in habitat descriptions for lotic species (Muenscher, 1944; Fassett, 1969; Correll and Correll, 1972) or in general descriptions of lotic systems (Gray et al., 1983) the influence of interstitial water has received much less attention.

¹Author to whom correspondence should be addressed: Benthos Laboratory, 1061 North University Building, University of Michigan, Ann Arbor, Michigan 48109, U.S.A.

Interstitial water can be divided roughly into the categories of infiltrating surface water, underflow or hyporheic water, and groundwater based on primary origin of the water and flow patterns within the bed (Fig. 1). The boundaries between water types, however, are rarely distinct and more often are represented by vertical physicochemical gradients from surface water to groundwater. The depths of the gradients will be dependent on stream flow, bed permeability and changes in streambed elevation (Vaux, 1968; Thibodeaux and Boyle, 1987; White et al., 1987). Decreasing stream depth along the direction of flow (such as at the head of a riffle) causes surface water to enter the bed (infiltration), displacing existing interstitial water, and travel for some distance through the bed as underflow. Underflow then returns to the surface where stream depth begins to increase (Fig. 1). Interactions between surface water infiltration and bed sediments along underflow paths promote solute storage, creating sinks for nutrients and even very conservative ions (Wallis et al., 1981; Bencala, 1984; Grimm and Fisher, 1984), with the result that underflow areas, or hyporheic zones, often contain much higher concentrations of organic matter, phosphorus, nitrogen, ions, etc. than either the original surface water or the groundwater beneath.

The direct movement of groundwater into surface sources may occur in the form of distinct springs (often the source of first-order streams, Wisler and

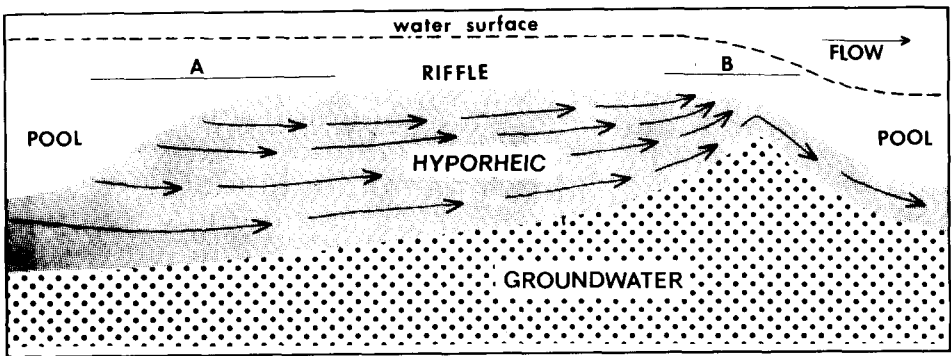


Fig. 1. Diagram of theoretical surface-water movement patterns (underflow) through the hyporheic zone of a streambed pool-riffle-pool sequence and the relation to groundwater distribution. Line A represents the region of surface-water infiltration, and Line B represents the region of underflow return to the surface (after Vaux, 1968; Thibodeaux and Boyle, 1987; White et al., 1987).

Brater (1959)), bank seeps where the water table slopes toward the stream (Bardach, 1964), or stream-bottom seeps which, in many streams, are found at the beginnings of pools as a consequence of returning underflow (Bilby, 1984; White et al., 1987).

One of the simplest methods of locating surface-water infiltration, hyporheic water and groundwater areas is by measuring interstitial temperatures (Freeze and Cherry, 1979; White et al., 1987), especially in warm-water streams in the summertime. Groundwater tends to remain near the mean annual temperature throughout the year (Freeze and Cherry, 1979), and, in northern Michigan, differences of nearly 20°C between surface water and groundwater are common.

Infiltrating surface water, underflow and groundwater seepage combine to form complex interstitial patterns along any reach of stream, particularly where riffle-pool sequences are well-developed. If macrophyte species have become adapted to utilizing some of the physicochemical properties of a particular type of interstitial water, then correlations with water type and distribution or abundance may be possible. Of particular interest in this study were species of *Potamogeton* which co-occur in many northern Michigan streams, in beds often separated by only a few meters and with no detectable differences in surface flow, depth, light or substratum type.

The objective of this study was to examine the types of interstitial water (based on temperature) occurring beneath 3 species of *Potamogeton* and beneath other common lotic macrophytes found in 3 northern Michigan (U.S.A.) streams. While the focus was on submerged taxa associated with flowing water, some lotic emergent and littoral taxa were examined as well.

STUDY SITES

This study was conducted in 3 similar-sized streams in northern Michigan, U.S.A. (Fig. 2). Lands surrounding all 3 sites contain primarily second-growth aspen (*Populus tremuloides* Michx. and *P. grandidentata* Michx.) with some northern hardwoods and mixed conifers. Soils in the area are sorted and unsorted glacial till up to 100-m deep, permitting unconfined groundwater movement. The first site was on the East Branch of the Maple River, a 5–10-m wide third- to fourth-order stream originating as outflow from Douglas Lake. Mid-summer stream temperatures (22–27°C) reflected surface-water temperatures of Douglas Lake. Discharge was 0.51 m³ s⁻¹ in mid-June and 0.36 m³ s⁻¹ in mid-August. The second site was on the West Branch of the Maple River, a 4–10-m wide third- to fourth-order stream originating in a large white-cedar (*Thuja occidentalis* L.) swamp. Mid-summer temperatures in the study site reflected the groundwater origin, ranging from 18 to 22°C. Discharge was 0.65 m³ s⁻¹ in mid-June and 0.46 m³ s⁻¹ in mid-August. Both the East and West Branches contain shallow riffles less than 0.5-m deep alternating with pools

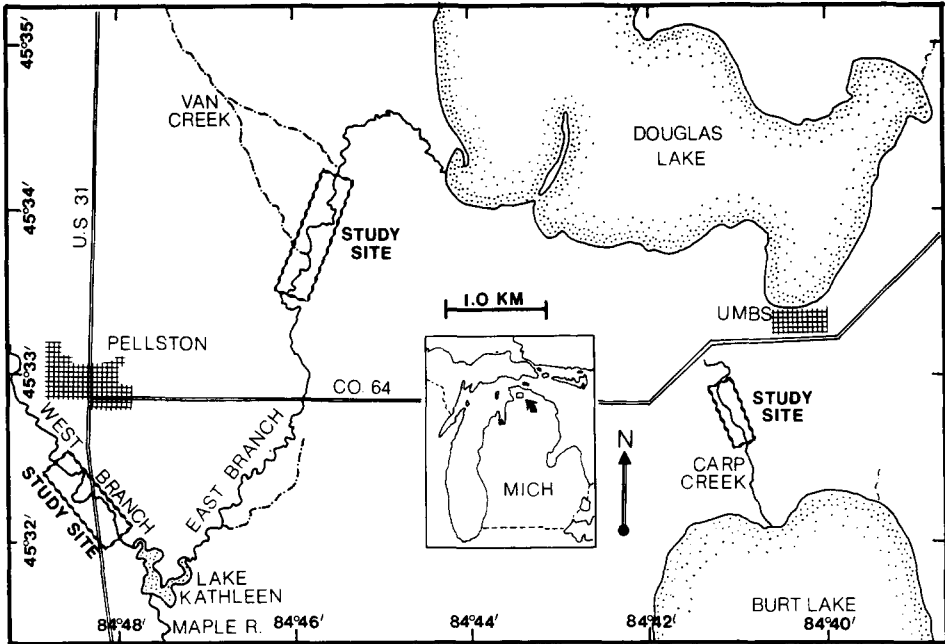


Fig. 2. Map of the study sites near the University of Michigan Biological Station (UMBS). Insert shows approximate location of study area in northern Michigan (U.S.A.).

up to 2.5-m deep. The streambed substrata in the East and West Branches vary from sand to gravel to cobble in the riffles and fast-flowing reaches, to sand with some accumulations of silt in the pools.

The third site was on Carp Creek, a 3–8-m wide first-order stream less than 3-km long fed by several hundred groundwater springs. The source of the springs is Douglas Lake surface and epilimnetic water. The springs create nearly constant year-round temperatures (10–12°C) and discharge (0.34–0.40 m³ s⁻¹) (Pringle, 1985). The bed of Carp Creek is primarily sand with little riffle-pool development. Mid-summer temperatures measured at 9 flowing springs in the Carp Creek basin averaged 11.5°C (s.d. = 1.2), approximately the mean annual air and Douglas Lake temperatures. Temperatures recorded from a 2-m deep well near the East Branch were slightly lower at 9.1°C (s.d. = 1.30).

Study sites in the West and East Branches were not heavily shaded, and cover was estimated to be less than 30% (Table 1). While there were some open areas on Carp Creek, most of the study site was shaded with cover greater than 80%. Shading, however, was not taken into account in the selection of plants to be analyzed.

Selected mid-summer physicochemical parameters for each stream and for a groundwater well are summarized in Table 1. The East and West Branches were similar except that the West Branch tended to have lower temperatures

TABLE 1

Mid-summer physicochemical characteristics of surface water at each study site and at a groundwater well near East Branch of Maple River. Data summarized from our measurements and from unpublished University of Michigan Biological Station records, 1982-1984; standard deviations in parentheses

	Surface water			Groundwater (<i>n</i> =5)
	East Branch Maple River (<i>n</i> =6)	West Branch Maple River (<i>n</i> =5)	Carp Creek (<i>n</i> =5)	
Temperature (°C)	24.5 (1.9)	19.8(1.6)	11.4(0.9)	9.1(1.3)
Carbonate alkalinity (mg l ⁻¹)	140 (4.5)	150 (5.0)	165 (3.5)	220 (6.8)
Conductivity (μmho cm ⁻¹)	230 (7.1)	250 (7.1)	330 (10.5)	320 (5.2)
Si (mg l ⁻¹)	2.8(0.2)	1.2(0.1)	2.9(0.2)	1.0(0.1)
PO ₄ -P (μg l ⁻¹)	3.3(0.2)	4.0(0.3)	4.0(0.1)	2.7(0.3)
NO ₃ -N (μg l ⁻¹)	9.1(2.7)	22.5(2.2)	35.2(4.0)	12.0(2.1)
Chloride (mg l ⁻¹)	3.6(0.1)	4.5(0.3)	2.4(0.1)	1.4(0.1)
Dissolved oxygen (% Sat)	100	100	100	<0.5
pH (range)	7.8-8.0	7.0-7.4	7.9-8.3	6.6-6.8
Estimated percentage cover	< 30	< 30	> 80	
Estimated mean width (m)	7	8	6	
Maximum depth (m)	2.5	2.5	1.5	
Discharge (m ³ s ⁻¹) (<i>n</i> =2)	0.36-0.51	0.46-0.63	0.36-0.37	

and pH and more inorganic nitrogen. Nutrient levels in the East Branch reflected surface water characteristics of Douglas Lake which become quite low in inorganic nitrogen in late summer (R. Glover, personal communication, 1986). Carp Creek differed from the other sites in higher conductivity and inorganic nitrogen and much lower temperatures. Groundwater from the well differed from the East Branch site in lower temperatures, dissolved oxygen and pH and in much higher alkalinity and conductivity.

MATERIALS AND METHODS

Individual plants were sampled at random from distinct plant beds. No more than 2-3 individuals were examined in any one plant bed. For most species, about 40 plants per stream were sampled (Table 2). Interstitial water temperatures beneath each plant were measured to the nearest 0.5°C at the streambed

TABLE 2

Numbers of emergent (E) and submerged (S) aquatic vascular macrophytes examined in the East Branch of Maple River (EBMR), West Branch of Maple River (WBMR), and Carp Creek, NP = not present. Mean surface-water velocity and standard deviation (cm s^{-1}) based on measurements taken in mid-bed; $n = 20$ (10 from measurements from each stream combined if present in more than one stream)

Taxon	Distribution				Velocity (cm s^{-1}) (s.d.)
	Form	EBMR	WBMR	Carp Creek	
Sparganiaceae					
<i>Sparganium chlorocarpum</i> Rydb.	S	41	40	NP	32 (8.2)
Potamogetonaceae					
<i>Potamogeton filiformis</i> Pers.	S	41	40	NP	51 (6.7)
<i>P. gramineus</i> L.	S	102	NP	NP	46 (8.2)
<i>P. richardsonii</i> (Benn.) Rydb.	S	104	40	NP	43 (7.3)
Alismaceae					
<i>Sagittaria latifolia</i> Willd.	E	40	40	NP	< 10
Ranunculaceae					
<i>Ranunculus septentrionalis</i> Poir.	E	NP	NP	40	< 10
<i>Caltha palustris</i> L.	E	NP	NP	40	< 10
Cruciferae					
<i>Nasturtium officinale</i> R.Br.	E	NP	40	40	< 10
Scrophulariaceae					
<i>Veronica catenata</i> Penn.	S	38	40	NP	22 (7.5)

surface and at depths of 5, 10, 15, 20, 30, 40 and 50 cm into the bed using a 95-cm long stainless-steel temperature probe and thermister (YSI series 400).

Surface-water velocity was measured in 20 beds of each species. If a species occurred in more than one stream, 10 beds were selected from each stream. At least 3 velocity measurements were taken in the center of each plant bed using a Pygmy-Gurley flow meter positioned at 60% of stream depth. Velocity estimates in flows less than 10 cm s^{-1} were highly variable using the Pygmy-Gurley and were recorded only as $< 10 \text{ cm s}^{-1}$.

To examine the differences between the species further, we attempted to measure root-penetration depths using a 10-cm diameter mechanical corer. Data are discussed for only *Potamogeton gramineus* L. and *P. richardsonii* (Benn.) Rydb., and these data must be considered preliminary because biomass was not taken into account, the depths of some of the smaller roots and root hairs may have been missed, and there were problems removing intact cores from sand-gravel substrata. Few roots of any species, however, appeared to penetrate much deeper than 15 cm. Therefore, analyses were based primarily on interstitial temperatures at the 10-cm depth interval. To determine if interstitial temperatures at 10-cm deep were significantly different between

species, data were analyzed by analysis of variance using the Statistical Analysis System (SAS). Significance levels were set at $\alpha = 0.05$. Plots of the number of individuals versus temperature at 10-cm deep for each species appeared Gaussian; therefore, for additional comparisons, the mean temperature and temperature range encompassing 95% of the distribution were estimated for each species using the Gaussian function given by Robbins et al. (1984).

Determining boundaries between infiltrating surface water, hyporheic water and groundwater is made somewhat more difficult by the thermal conductance produced from flow along the longitudinal gradient within the bed. For convenience, however, the hyporheic zone can be defined as some intermediate temperature range between surface water and groundwater over which surface-water characteristics remain dominant (Williams, 1984). Interstitial water was determined to contain primarily surface-water infiltration if temperatures were higher than the minimum surface-water temperature recorded over any 24-h period during the study time (17.5°C for the West Branch, 18.0°C for the East Branch, D.S. White, unpublished data, 1983–1985). A site was assumed to contain underflow if temperatures ranged between 13°C and the minimum surface water temperature. Unpublished mid-summer data (S.P. Hendricks, University of Michigan, 1984–1986; D.S. White, 1984–1986) showed that interstitial water warmer than 13°C usually contained dissolved-oxygen concentrations higher than 20% saturation and negligible free CO₂. Interstitial water cooler than 13°C was considered to be primarily groundwater. At that temperature, dissolved-oxygen concentrations were usually less than 5% saturation, and free CO₂ concentrations were often higher than 40 mg l⁻¹.

RESULTS AND DISCUSSION

Nine species of aquatic macrophytes typical of northern Michigan streams (Fassett, 1969; Voss, 1972, 1985) were common and widespread in one or more of the 3 study sites (Table 2). No attempts were made, however, to determine overall relative abundances of any species. One species, *Potamogeton gramineus*, was limited to the East Branch; 5 species were common to the East and West Branches; one species, *Nasturtium officinale* R. Br., was common to the West Branch and Carp Creek. While Table 2 lists *Ranunculus septentrionalis* Poir. and *Caltha palustris* L. from only Carp Creek, we since have found a few isolated specimens of both species at bank seeps along the West Branch; however, no interstitial temperature measurements were made.

Sparganium chlorocarpum Rydb. and *Veronica catenata* Penn. were often found together near the stream margins at the beginnings of pools and just out of the fastest flows (Table 2). Substrata were firm, coarse sands mixed with gravel. Well-developed beds of the three species of *Potamogeton* were found only in the fastest flowing reaches (Table 2). *P. filiformis* Pers. and *P. richardsonii* usually were found together near the center of the stream at the down-

stream end of riffles or beginnings of pools. Substrata were most often coarse gravels. Beds of *P. gramineus* were more scattered, occasionally occurring near beds of the other two *Potamogeton* species, but more often occurring near the head and mid-sections of the riffles. Substrata ranged from coarse sand to coarse gravel. *Sagittaria latifolia* Willd. was most common along the stream margins where there was little to no surface flow (Table 2). The top few cm of surface substrata were usually fine sand and silt grading deeper (5–10 cm) into very coarse gravel. *Ranunculus septentrionalis* and *Caltha palustris* usually occurred together along the stream margin in depositional areas with little to no surface flow (Table II) and near groundwater springs. Substrata were deep, fine sands. *Nasturtium officinale* beds also were located in sandy, depositional zones near the stream margin, but portions of the beds often extended into surface flows greater than 10 cm s⁻¹. Most beds were found near groundwater seeps or springs.

For species examined in the East Branch, the mean interstitial temperatures at the 10-cm depth were significantly higher beneath *Potamogeton gramineus* (19.5°C) than beneath beds of other species (14.6–16.2°C, Fig. 3) ($P < 0.001$). There were no significant interstitial temperature differences among the remaining species; however interstitial temperatures beneath *Veronica catenata* showed a much greater range than occurred in other East Branch species. For plants in the West Branch, the mean interstitial temperature at the 10-cm depth was significantly less beneath *Nasturtium officinale* (12.1°C) than beneath the other 5 species (14.8–16.0°C, Fig. 3) ($P < 0.001$), and again there were no significant interstitial temperature differences between the remaining species. Mean interstitial temperatures 10-cm deep beneath plants from Carp Creek were nearly identical at approximately 11.5°C (Fig. 3) which reflected the narrow temperature range between surface water and interstitial water in this stream.

Interstitial temperature differences between populations of species occurring in both the East and West Branches were not significant ($P < 0.001$), but the temperature ranges were slightly broader for some East Branch populations, particularly for *Veronica catenata* (Fig. 3). Only *Nasturtium officinale* occurred in both the West Branch and Carp Creek. The mean interstitial temperatures at 10-cm deep were not significantly different ($P < 0.01$) between populations, but again the range was slightly broader beneath plants in the warmer West Branch (Fig. 3).

When the distributions of *Sparganium chlorocarpum*, *Sagittaria latifolia*, *Veronica catenata* and the 3 species of *Potamogeton* were examined in relation to predicted interstitial water patterns beneath pool–riffle–pool sequences, all except *S. latifolia* and *P. gramineus* usually occurred in areas where underflow was expected to be returning to the surface (Segment B in Fig. 1). Although interstitial temperatures beneath *S. latifolia* were similar to several other species, the expected source (groundwater or underflow) was not determined. Beds

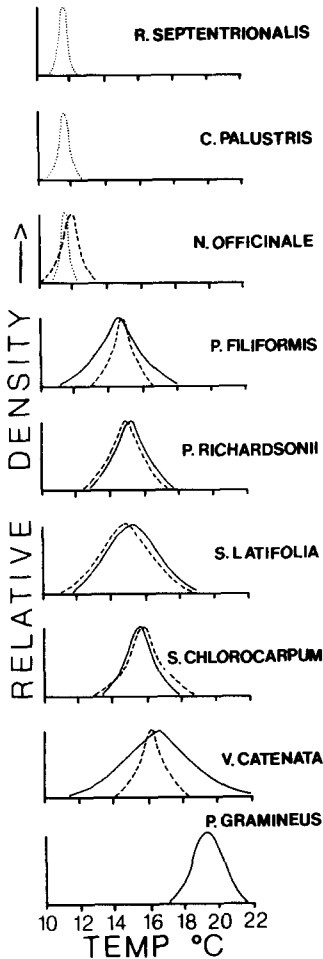


Fig. 3. Estimated distribution of each aquatic plant species in the East Branch of the Maple River (—), West Branch of the Maple River (- - -), and Carp Creek (· · ·) versus temperature 10-cm deep in the streambed. Lines represent Gaussian fits encompassing 95% of the calculated distribution for each species from the function described by Robbins et al. (1984).

of *P. gramineus* appeared to be more common only in areas of warm surface-water infiltration (Segment A in Fig. 1).

Studies by Wallis et al. (1981), Bencala (1984) and Grimm and Fisher (1984) have shown that streambed sediments and interstitial water in underflow areas contain much higher concentrations of nutrients and ions than surface waters, and it has been speculated that concentrations may increase with distance along the underflow gradient. Initial studies of the interstitial chemistry of the East Branch (S.P. Hendricks, unpublished data, 1987; also see Hendricks and White, 1988) show that underflow 10–20-cm deep may contain up to 10 times

more inorganic phosphorus ($\text{PO}_4\text{-P}$) and 3 times more inorganic nitrogen ($\text{NO}_3\text{-N}$) than surface water. N:P ratios also differed from 12.5:1 in surface water to 3.4:1 in underflow.

Although comparatively little is known of the biology of the studied species, uptake experiments have demonstrated that roots of many lentic taxa can absorb nutrients, ions and gases directly from sediments/interstitial water (Denny, 1972; Barko and Smart, 1980, 1981; Smith and Adams, 1986). Some species, including *Potamogeton pectinatus* L. (Huebert and Gorham, 1983), are able to meet all requirements for nitrogen ($\text{NO}_3\text{-N}$) and phosphorus ($\text{PO}_4\text{-P}$) from the sediments (Best and Mantai, 1978) which led Carignan and Kalff (1980) to characterize aquatic macrophytes as conveyor mechanisms for the transfer of nutrients between sediments and open water.

Potamogeton gramineus is morphologically quite similar to *P. richardsonii* except that *P. gramineus* possesses large stipules which may serve as sites of nutrient uptake from surface waters (Denny, 1972). Further, *P. richardsonii* has been shown to obtain sufficient quantities of sodium (Haslam, 1978), copper and zinc (Cushing and Thomas, 1980) from the sediments to meet plant requirements. *P. richardsonii* and *P. gramineus* also appeared to differ in root-penetration depth. Mean root depths were 14.2 cm (± 3.35 , range 10–22 cm, $n=40$) for *P. richardsonii* and 8.7 cm (± 2.85 , range 4–14 cm, $n=35$) for *P. gramineus*. Without experimental evidence from uptake studies and more extensive water column/sediment chemistry data, we cannot confirm that *P. gramineus* relies more on surface waters for nutrients, ions, etc., while *P. richardsonii* and other studied species rely on interstitial sources for one or more of these plant requirements.

In summary, *Ranunculus septentrionalis*, *Caltha palustris* and *Nasturtium officinale* were found where the interstitial water was primarily groundwater discharge. *Sparganium chlorocarpum*, *Veronica catenata*, *Potamogeton filiformis* and *P. richardsonii* were most common where the interstitial water was expected to be surface water that had passed through the streambed (underflow) and was returning to the surface. *P. gramineus* was more widely distributed along the riffles but was limited to warm interstitial temperatures in suspected areas of surface-water infiltration into the streambed. Infiltration, underflow and groundwater form complex interstitial patterns, particularly in third to fourth order streams with well-developed riffle-pool sequences. Differences in interstitial water temperature, nutrients, ions, etc., combined with differences in plant requirements and uptake sites may be important in establishing local distributions of lotic aquatic vascular macrophytes.

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