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Use of Seepage Meters to Measure Groundwater Flow at Brook Trout Redds

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Abstract.—Anomalous influxes of water into unfilled collection bags can greatly overestimate volume and flow rate data from seepage meters. From static tank trials, initially empty collection bags (4,500 mL capacity) attached to seepage meters gained significantly more water relative to bags prefilled to 1,000 mL. Data from a study of groundwater flow at redds of brook trout *Salvelinus fontinalis* in Scott Lake, Ontario, indicate that the use of unfilled bags biases seepage meter data. At these redds, the anomalous influx of water into unfilled bags was significant (intercept of regression equation, y = 275 mL); however, this influx was sufficiently reduced when prefilled bags were used (y = 34 mL). Our data suggest that even at high flow rates (22–169 $mL \cdot m^{-2} \cdot min^{-1}$), seepage measures can be inflated by an order of magnitude when initially empty bags are used. Because of this anomaly, previous measures of groundwater flow at brook trout redds with unfilled bags are probably not representative of natural flow rates. Our estimates of groundwater flow at brook trout redds in Scott Lake (6–296 $mL \cdot m^{-2} \cdot min^{-1}$) are very similar to the range in groundwater flow found in lake and stream redds (4–340 $mL \cdot m^{-2} \cdot min^{-1}$) by other methods. We suggest the use of prefilled collection bags (filled to 1,000 mL) and conformity in measurement units ($mL \cdot m^{-2} \cdot min^{-1}$) when groundwater flow is measured with seepage meters.

Spawning areas of brook trout *Salvelinus fontinalis* are generally characterized by groundwater seepage which provides elevated temperatures for embryo development (Embody 1934). Adult females appear to select these areas to construct redds and deposit eggs (Benson 1953; Witzel and MacCrimmon 1983). Although the association between spawning sites and groundwater seepage has long been recognized (e.g., White 1930), few studies have quantitatively measured naturally occurring rates of seepage at brook trout redds.

A variety of methods have been used in the past to detect the seepage sites associated with brook trout spawning. Various field studies have used differences between ambient stream temperature and redd site temperature during fall and winter (White 1930; Benson 1953; Fraser 1985), field observations of adjacent riparian seepage areas (Hazzard 1932; Witzel and MacCrimmon 1983), dispersion of dye placed on the substrate (Fraser 1982), standpipes (Reiser and Wesche 1977), piezometers (Curry 1993), and seepage meters (Carline 1980; Snucins et al. 1992). Only the last three methods provide quantitative measures of groundwater flow.

A seepage meter is the end section of a barrel (15 cm long × 57 cm in diameter), the open end of which is pushed into the substrate. The upper closed end is bored; a stopper is placed in the hole, and a plastic tube is inserted through the stopper. An empty plastic bag attached to the exposed end of the tube is used to collect groundwater samples (Lee 1977). The seepage meter allows a direct measure of the upward flux of water at the substrate–water interface but provides no information on the hydraulic conditions beneath the substrate (Lee 1977). Seepage meters are inexpensive, easy to install, and provide data on water quantity as well as large numbers of samples in a relatively short amount of time (Lee 1977; Belanger and Mikutel 1985). However, one anomalous feature of the method has been detected; an empty plastic bag attached to a seepage meter creates a hydraulic potential resulting in a short-term influx of water into the bag (Shaw and Prepas 1989). This influx of water appears to be due to the mechanical properties of the bag and can seriously bias estimates of groundwater flow by the seepage meter method. Using plastic bags partially prefilled with water can alleviate this problem (Shaw and Prepas 1989).

The objective of this study was to characterize the flow rates of natural brook trout redds in a lake and to determine the potential bias of the seepage meter method when groundwater flow is recorded at brook trout redds. This bias is particularly acute at low flow rates and may diminish with increasing flow rates (Shaw and Prepas 1989). Because groundwater seepage in brook trout redds can be relatively high (Carline 1980; Snucins et al. 1992), the potential bias may be relatively small. Also, collection time may be relatively short where high flow rates exist, a situation that Shaw and Prepas (1989) did not fully address. In a more general context, the use of seepage meters may become more widespread given their ease of use and the growing interest in the role of groundwater discharge as a component of fish habitat. Therefore, we believe the solution to the problem of anomalous data being generated when the seepage meter method is used needs to be more widely appreciated (Shaw and Prepas 1989).

Methods

We determined the amount of short-term anomalous influx of water into seepage meters in the lab and field. Seepage meters were constructed similar to those of Lee (1977), the main difference being that the drums were made of plastic and the closed end had a 3.6-cm-diameter hole for the rubber stopper and attachment of the bag assembly. Other differences to note are as follows: (1) No-name® polyethylene bags, 4,500 mL capacity, were attached with an elastic band to Tygon® tubing (length = 6.0 cm, 0.80 cm inner diameter); and (2) a plastic connector (length = 6.3 cm, 0.65 cm inner diameter) tapered at each end (0.80–1.3 cm outer diameter) was embedded flush to the bottom (depth = 2.5 cm) of a number 8 rubber stopper. In both the lab and field trials, seepage meters were allowed to equilibrate before insertion of the rubber stopper assembly, which was attached about 15 min before attachment of the bag and tubing assembly. For trials with both unfilled and prefilled bags, the end of the flexible Tygon tubing was blocked by a finger and the tubing was gently pushed over the tapered plastic connector to achieve a snug fit. To remove the plastic bags, the tubing was pinched and pulled off the plastic connector and a finger was placed over the open end of the tubing so no water could escape. The resulting volumes were measured to the nearest milliliter with 500- and 1,000-mL graduated cylinders. We used the flow rate calculation of Shaw and Prepas (1989) where q, in $mL \cdot m^{-2} \cdot min^{-1}$, is calculated as $q = 392 \Delta V/t$; ΔV is the change in volume of water (mL) in the polyethylene bag when the bag is removed after a given period of time, t (min). The constant, 3.92, converts the area covered by the seepage meter ($2{,}550\ cm^2$) to $1\ m^2$.

Tank experiment.—Tank experiments were conducted at Harkness Laboratory of Fisheries Research, Ontario, 1–2 September 1994. Three seepage meters were placed in a 630-L rectangular tank (length, 2.01 m; width, 0.57 m; depth, 0.55 m) filled with lake water and were left for about 16 h before measuring water flow. One measure of seepage at each seepage meter was recorded at 5, 10, 15, 30, 45, and 60 min with unfilled polyethylene bags and bags prefilled to 1,000 mL. The tank was refilled and allowed to settle between subsequent time trials. The seepage meters rested on the bottom of the tank but did not create a seal, such that water could move into the meters.

Field study.—Field measures of groundwater seepage were conducted at Scott Lake, Algonquin Provincial Park, Ontario (45°29'N, 78°43'W), 5–21 September 1994. Scott Lake is 28 ha in surface area, has a maximum depth of 24 m, and contains a naturally reproducing population of brook trout. In total, four seepage meters were placed in redds where brook trout had previously spawned in 1993 (P.J.B., personal observation); sites ranged in depth from 1.4 to 1.6 m. The meters were inserted by divers to a depth of 12 cm beneath the substrate surface and were allowed to settle for about 16 h before seepage was measured. Seepage meters were sampled at 5, 10, 15, 30, 45, 60, and 120 min. For comparison to Shaw and Prepas (1989), site-specific data were pooled by time period and were used in linear regressions of V on t for unfilled bags (N = 103) and bags prefilled to 1,000 mL (N = 77).

For tank and field trials, we tested the null hypotheses that (1) the slope of the regression of volume on time was equal to zero (linear regression), and (2) the volume of water entering into prefilled and unfilled bags was equal (analysis of covariance). All analyses were performed on untransformed data.

Groundwater flow was measured at 36 sites just before brook trout spawned in Scott Lake, 4–17 October 1994. Twenty-three sites represented actual redds where spawning took place during the 1993 season. The remaining 13 sites represent random sites chosen close to spawning redds and contained similar substrate. Spawning occurred at 10 of the 23 redds during the 1994 season. For comparative purposes, we considered the redds where spawning occurred as "used" (N = 10) and grouped the remaining sites as "unused" (N = 26).

Seepage meters were installed in the same manner as described for the field experiment. All measurements of groundwater flow were made in triplicate and lasted 120 min; collection bags were prefilled to 1,000 mL. At one spawning site, the collection time was reduced to 15 min due to extensive flow. One seepage meter remained at one site during the entire collection period to determine the extent of day-to-day variability in groundwater flow. For comparative purposes we converted other published data of groundwater flow at brook trout redds, obtained from seepage meters attached to unfilled bags, from units of centimeters per hour to units of milliliters per square meter per minute (Carline 1980; data were provided by E. Snucins). We calculated our flow rate estimates in the units just noted to produce a conversion factor (166.6). To present unbiased measures of groundwater flow, we divided the flow rates from other studies by a factor of 9.57 because this is the ratio of mean volume of water present in unfilled bags (215 mL) versus prefilled bags (23 mL) from our 5-min time period (unfilled : prefilled = 9.57:1). This time period was most representative because previous measures of groundwater flow were collected over periods of 1–7 min (Carline 1980). We multiplied other published data of groundwater flow at brook trout redds, collected by different methodology, by our conversion factor of 166.6, to change units of centimeters per hour to units of milliliters per square meter per minute (Reiser and Wesche 1977; Curry 1993). We prefer the latter measure of flow, because this incorporates an associated volume which is far more understandable.

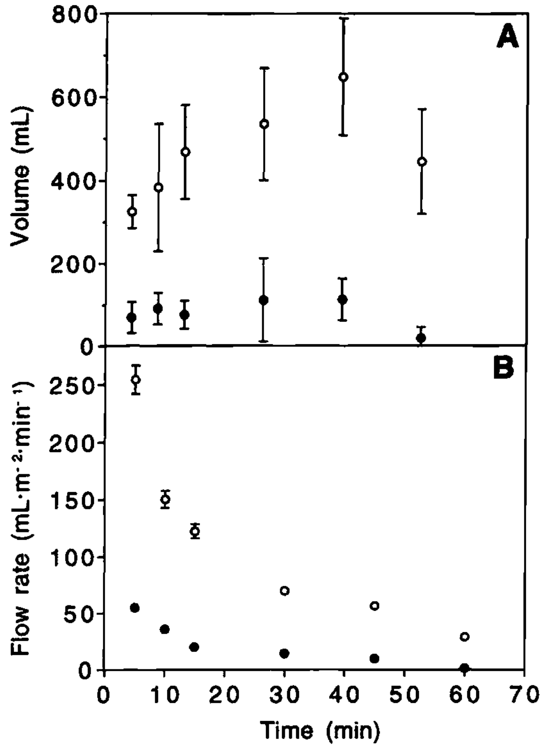

FIGURE 1.—(A) Volume of water collected and (B) flow rate of initially empty (○) and prefilled (●) bags in a water-filled tank versus time interval. Each circle is the mean (± SD) of three trials, one per seepage meter.

Results and Discussion

There was no linear increase in water volume with time for unfilled bags in a static environment (r^2 = 0.18; F = 3.5, df = 1,16; P = 0.08; Figure 1A). The volume of water present in unfilled bags increased as a function of time up to t = 45 min and thereafter showed a marked decrease in volume at 60 min. Overall there was a significantly greater influx of water into unfilled bags than bags prefilled to 1,000 mL (F = 109.3; df = 1,33; $P <$ 0.001). The additional volume of water present in prefilled bags was relatively constant with time. Over the comparable time period (up to t = 60 min), our data are consistent with those of the tank experiments of Shaw and Prepas (1989) when unfilled bags are used. Tank trials performed by Shaw and Prepas (1989) with bags prefilled to 1,000 mL showed an increase in V with t. In contrast, in our study, V did not increase significantly with t (r^2 = 0.04; F = 0.61; df = 1,16; P = 0.44) suggesting that attachment of the bag to the seepage meter regulates the flow of water entering the prefilled bag (Figure 1A). The most likely explanation is that water must travel from a much greater distance to reach the bag and is somewhat restricted by the bottom of the seepage meter resting on the tank floor. As flow rate is a function of volume, there was essentially a logarithmic decrease in flow rate with time when unfilled bags were used (Figure 1B). The pattern was similar with prefilled bags, but to a much lesser degree, whereby the flow rate at 60 min was 1.3 mL·m^{-2}·min^{-1} (Figure 1B). These data suggest that equilibrium is reached at this point and that prefilling 4,500-mL bags to 1,000 mL is a sufficient volume to reduce short-term influxes during collection periods of 60 min.

Volume of water collected increased linearly with t in field trials for both unfilled and prefilled bags; however, the volume collected differed greatly (Figure 2A): unfilled $V = 275 + 3.95t$ (r^2 = 0.76; F = 316.9; df, 1, 101; $P <$ 0.001) com-

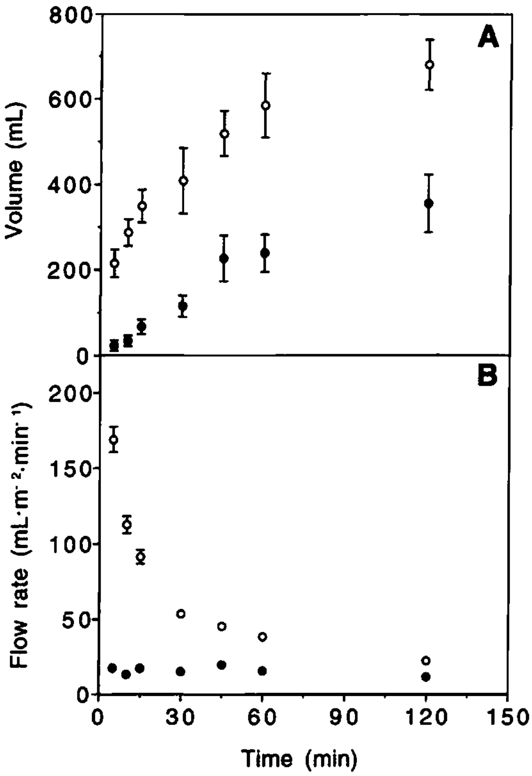

FIGURE 2.—(A) Volume of water collected and (B) flow rate of initially empty (○) and prefilled (●) bags at four brook trout spawning redds versus time interval. Each circle represents the mean (±SD) of 2–21 seepage measures pooled per time period (initially empty: N = 103; prefilled: N = 77).

TABLE 1.—A comparison of three studies in which seepage meters were used to determine groundwater flow at brook trout redds. Groundwater flow was measured at redds ("used") and at nearby random sites ("unused"). Flow rates from other studies have been reduced by a factor of 9.57 to account for the collection of groundwater with unfilled bags.

Study	Spawning site		Groundwater flow ($mL \cdot m^{-2} \cdot min^{-1}$)	
	Type	Number	Mean ± SD	Range
This study	Used	10	49 ± 83	6–296
	Unused	26	7 ± 6	0–22
Carline (1980)	Used	5	430 ± 294	200–780
	Unused	11	40 ± 23	17–139
Snucins et al. (1992)	Used	1		167–1,075

pared with prefilled $V = 34 + 293t$ ($r^2 = 0.80$; $F = 298.6$; df, 1, 75; $P < 0.001$). If we compare the y-intercepts of the regression equations for unfilled ($y = 275$) and prefilled ($y = 34$) trials, there is an excess of 241 mL entering the unfilled bags. This is consistent with the regression analyses of data from Narrow Lake, Alberta (Shaw and Prepas 1989), where the difference in anomalous short-term (30 min) influxes of water from unfilled (237 mL) and prefilled (9 mL) trials was 228 mL. The compatibility of these two studies provides further evidence that the use of initially empty bags on seepage meters can seriously overestimate rates of groundwater flow.

Our data show that anomalous influxes of water occur at relatively high seepage rates as well as at low seepage rates. Data from Buffalo Lake (Shaw and Prepas 1989) indicated that volume of water in initially empty bags increased linearly with t: $V = 106 + 2.23t$ (df = 2; $r^2 = 0.97$; $P < 0.05$), such that the y-intercept of 106 mL was not significantly greater than zero (df = 2; $t = 1.8$; $P > 0.1$). From these data they determined that a "high" flow rate (8.7 $mL \cdot m^{-2} \cdot min^{-1}$) may not affect short-term influxes of water into unfilled bags. However, from our volume data there was a significantly greater influx of water into unfilled bags than bags prefilled to 1,000 mL ($F = 735.3$; df = 1, 177; $P < 0.001$) with flow rates ranging from 22 to 169 $mL \cdot m^{-2} \cdot min^{-1}$. Therefore, it is important to note that the bias is substantial even with the relatively high flows at redds. In fact, the mean volume recorded from the unfilled bags (424 ± 158 mL) is essentially triple that of the prefilled bags (152 ± 106 mL). The critical finding of this study is that when collection bags (4,500 mL) are prefilled (to 1,000 mL), flow rate remains constant over t (Figure 2B).

With prefilled bags, our rates of groundwater flow at brook trout redds in Scott Lake (6–296 $mL \cdot m^{-2} \cdot min^{-1}$) appear to be considerably lower when compared to previous seepage meter studies in lentic systems (Table 1). This may, in part, be due to the generality of our conversion factor, or perhaps seepage rates in Scott Lake are naturally lower. Flow rates of about 500 mL in 1–7 min observed by Carline (1980) are very high and may not be directly comparable due to the various sizes of seepage meters used. Flow rates reported by Snucins et al. (1992) were determined from April to July and were inflated due to spring snowmelt and increased levels of precipitation. Mean groundwater flow is positively and significantly correlated with mean daily precipitation (Downing and Peterka 1978). Measures of groundwater flow at brook trout redds determined with standpipes and piezometers were in the range of 4–340

TABLE 2.—A comparison of three methods used to determine groundwater flow at brook trout redds.

Study	Aquatic system	Method	Range of groundwater flow ($mL \cdot m^{-2} \cdot min^{-1}$)
This study	Lake	Seepage meters (prefilled bags)	6–296
Curry (1993)	Lake and stream	Mini-piezometers (bundles)	4–279
Reiser and Wesche (1977)	Stream	Standpipes	4–340

$mL \cdot m^{-2} \cdot min^{-1}$ (Reiser and Wesche 1977; Curry 1993), which is very similar to the gradient in groundwater flow we found at Scott Lake, 6–296 $mL \cdot m^{-2} \cdot min^{-1}$ (Table 2). This lends further evidence that the use of prefilled bags with seepage meters provides a more realistic measure of natural groundwater flow at brook trout redds.

Piezometers provide the most extensive analysis of hydraulic conditions in groundwater discharge areas (Lee 1988). However, their use depends on substrate conditions for proper installation and often requires an assumption of homogeneous substrate to facilitate discharge calculations (Lee 1977; Curry 1993). The use of piezometers to examine groundwater discharge in brook trout spawning habitat can be difficult in some cases because redds can be found in a variety of substrates (Carline 1980; Fraser 1982) and may not be sensitive enough to detect differences in flow among spawning redds (e.g., Curry 1993). Seepage meters cover a much larger area of substrate than piezometers and incorporate a much greater area of any redd when determining groundwater seepage in brook trout spawning habitat. Although seepage meters (modified barrel ends) have limited use, they provide an excellent method for seepage estimates in terms of water quantity (Downing and Peterka 1978; Belanger and Mikutel 1985), if used with prefilled collection bags (Shaw and Prepas 1989; this study). We suggest the use of 4,500-mL collection bags prefilled to 1,000 mL and collection periods of 60–120 min for measuring groundwater flow at brook trout redds with seepage meters. Shorter collection periods (10–15 min) are recommended for redds with high flow rates.

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