MEASUREMENT OF FLUX AT THE GROUNDWATER/SEDIMENT INTERFACE
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ABSTRACT
Accurately measuring water flow across the sediment-water boundary in rivers and streams where contaminated sediments are present is necessary to assess contaminant transport and bio-degradation, and the efficacy of various remedial measures, such as the placement of sub-aqueous caps. A versatile, durable, and accurate apparatus and methodology was developed and field tested to measure this interfacial flow. The system was calibrated to accurately measure Darcy velocities in the range 1.5 - 4.3 cm/day in either direction, however using a flow addition method the measurement of lower velocities also was accomplished, and calibration at higher flow rates up to 14 cm/day was possible. The Darcy velocities measured with the device and hydraulic head differences measured with a series of river-sediment piezometers and stream gauges at 6 locations within the Grand Calumet River in Indiana (USA) were used to calculate the hydraulic conductivity of the sediment through application of Darcy’s Law.

1. INTRODUCTION
Depending on the temporal local and regional hydrology, sections of rivers and streams may either recharge groundwater from the stream or discharge groundwater to the stream across the sediment-water boundary. Groundwater discharge (or seepage) to or from a stream will occur whenever the local pressure head within the sediment, as measured with a piezometer, is different than the elevation of the stream. The rate of discharge is affected by this head difference and by the properties of the sediment deposits (i.e., heterogeneity, bulk porosity, pore fluid, and particle size). The conventional design for measuring in situ seepage across sediments consists of a submerged chamber (e.g., an inverted dome or shallow pan), connected to a thin plastic bag through a piece of tubing. The volume of water flowing across the sediment-water interface is determined by the change in weight or volume of the bag after some time has elapsed (Lee and Cherry, 1978; Lee, 1977). The value of the specific discharge measured by this method, however, is often highly variable due to the head loss resulting from deformation of the collection bag due to stream flow and other factor (London et al., 2001). Kelly and Murdoch (2003) modified this method by pumping water from the submerged chamber at the steady-state discharge rate, measuring the difference in head within the sediment under the chamber with a short piezometer-manometer apparatus, from which the vertical hydraulic conductivity was calculated directly. This method is useful in cases where the stream or lake is shallow and the discharge rate is relatively high, although besides these constraints, considerable effort is expended to make each measurement. In this paper, we describe and alternative approach for making measurements of both seepage and vertical hydraulic conductivity using an innovative heat-pulse flow tube as an integral component of an overall system. We first describe the overall interfacial-flow measuring system and its calibration, describe the installation of a series of sediment piezometers within the Grand Calumet River in Northern Indiana where the devise was used, and finally present results of our measurements. Values for both the Darcy velocity across the sediment/water interface and the vertical hydraulic conductivity through the sediment are reported for measurements made at six locations along a 400 ft reach of the river over a period of several months. The specific reach in which measurements were made is the same one located at a former manufactured gas (MPG) site for which extensive sediment chemical composition data were previously reported (Jafvert et al., 2006).
2. THE INTERFACIAL FLOW METER DESIGN

The interfacial flow meter system is illustrated in Figure 1. It consists of a cylinder, dome with flow tube and gas vent, circuit board, and computer. The cylinder is a high-density polyethylene (HDPE) cylindrical tank (22” OD, and 0.25” wall thickness), cut 10” below the rim. The rim extends 1.0” out, and 1.25” up, providing a 24” OD flange with a 1.0” rim on which to attach the dome. The stainless steel dome has an OD of 22-5/8”, is 7-1/2” high, and has a volume a 7.5 gallon. A 1/2” PVC pipe is attached to the top of the dome with a bulk-head flange and is of sufficient length to extend above the water surface, allowing water to rise within the pipe to the river’s water table level and serves as a gas vent. Once the cylinder is pushed into the sediment, four 5-ft stainless steel cables, connected to the outside of the cylinder, are then connected to the pipe at a location above the water surface, holding the dome onto the cylinder. Closed-cell polyurethane foam, attached to the rim of the dome ensures a water-tight seal.

Within the dome is a 0.5” ID by 13” long ‘flow tube’ that has a heating element, and thermocouple, located at its midpoint, and two thermocouples located on each side of the midpoint. One end of the tube is open within the dome and the other end is open to the river through a bulk-head fitting on the dome. This allows water to freely flow either direction between the river and the inside of the dome at a volumetric rate equal to the rate across the sediment-water interface. In operation, the temperature of the heating element is raised about 1º C for 3 seconds, raising the local water temperature within a few seconds. As water flows through the tube, the four thermocouples positioned within the tube, at different positions along the tube, sense the temperature change as a function of time; whereas the thermocouple located in the centre detects the heater temperature. The volumetric flow rate in the tube is calculated from the time-dependent temperature profile measured by the two thermocouples downstream from the heater, as described latter. The differential temperature at each thermocouple wire is determined via potential difference with a thermocouple reference junction co-located with a linear temperature measuring integrated circuit (LM35) that measures the absolute temperature of the reference junction. The microvolt level thermocouple signals are amplified using precision instrumentation amplifiers, housed within a 2-3/4” OD cylinder that surrounds the flow tube that is filled with an epoxy resin that acts as a heat insulator and water barrier. The signals are transmitted through a shielded 12 conductor cable to a land based PC-interface. The PC-interface includes a PMD-1608FS I/O Module (Measurement Computing Cooperation, Middleboro, MA) to convert the analog data to digital data, protection circuitry, and switching logic used to operate the heater through the PMD-1608FS I/O Module. Data are collected simultaneously from the 6 data channels (5

![Figure 1. Components of the interfacial-flow measuring system (not to scale).](image-url)
to \( Q \). For each measurement in the lab and in the field, the heater was activated for 3 sec with 19 W, recording the temperature change at all 6 channels at a data acquisition rate of 200 samples per second per channel. Exponential function calibration curves were developed for each thermocouple at \( Q = 2.5 \) to 7 mL/min. Since volumetric flow rates measured in the field were low, only the data from the thermocouple closest to the heater on the downstream side was used in calculations. The calibration for this thermocouple was \( r^2 > 0.99 \),

\[
Q = 16.64 \cdot e^{-0.608 T_m}
\]  

[1]

where \( Q \) is expressed in units of mL/min and \( T_m \) in units of min. The specific discharge (i.e., Darcy velocity), \( q \) (cm/day), is calculated by dividing \( Q \) by the cross sectional area of the cylinder placed in the sediment, \( A \) (cm\(^2\)),

\[
q = \frac{Q}{A}
\]  

[2]

Because the area enclosed by the cylinder is 2,342 cm\(^2\), the calibration curve spans Darcy velocities of 1.5 to 4.3 cm/day.

2.2 Installation of piezometer and stream gauge clusters.

Piezometers were constructed from 1.75” OD polyethylene pipe with 20 holes (3/8” diameter) drilled into the pipe within 6” of the capped end. The section of the pipe with holes was wrapped with a porous geotextile and wire mesh to avoid sediment inflow and clogging. The stream gauges were constructed in a similar manner with the holes and screen located within a 2 ft” segment at a sufficient distance from the capped end to assure they would be located above the sediment-water interface after installation. The piezometers and stream gauges were installed manually by pushing to the target depth. Six river clusters (RC) were installed in the river, with each cluster consisting of two piezometers pushed to depths of 4 and 8 ft below the sediment-water interface, and one stream gauge, each located approximately 10-18” apart. The location of each RC is shown on Figure 2. River clusters 1 to 4 (RC1 to RC4) were installed near the center of the river at an interval of approximately 80 ft from upstream (RC1) to downstream (RC4). River clusters RC2S and RC2N where installed at the same downstream distance as RC2, approximately 3-4 ft from the south and north banks of the river, respectively. Two additional stream gauges, SG1 and SG2, were installed approximately 250 ft upstream of RC1 and 100 ft downstream of RC4 to measure the total horizontal hydraulic head gradient of the river. A photograph of the RC1-RC4 stick-ups in the center of the river are shown in Figure 3.

At each cluster, the vertical hydraulic head gradient through the top 8 ft of sediment was calculated by measuring the head differences between the piezometers and stream gauge. Water levels in all piezometers and stream gauges were measured manually on a weekly basis with an electronic water level meter (Model 101, Solinst Canada Ltd, Ontario, Canada), and were measured at RC1-RC4 every 4 hrs with pressure transducers (Levelogger, Model 3001 Levelogger, Solinst Canada Ltd, Ontario, Canada) installed 6 ft down from the top of each riser.

2.3 Measuring water flow across the sediment-water boundary

The flow of water across the sediment-water interface was measured with the interfacial flow meter within 1-2 ft of each RC on at least two different days at each location. At each location, the cylinder was pushed into the sediment and the dome was secured with the four cables. After making several flow measurements, the dome was removed leaving the cylinder in the sediment, returning...
generally a week later to make measurements at the same location by re-attaching the dome to the cylinder. After placing the dome on the cylinder, measurements were delayed for about 1 hr to allow the thermocouples to reach thermal equilibrium with the surrounding water. During each series of field measurements, water levels in the associated stream gauge and piezometers were measured manually.

When the measured value of $T_m$ exceeded the maximum value on the standard calibration curve, a flow-addition method was employed. In this 'active' measurement method, water was pumped into the dome through the PVC pipe with a peristaltic pump at a constant known flow rate such that the total flow was within the calibration range. The actual flow rate was determined as the difference between the measured Q and added flow. In streams with high seepage rates, this method can be modified by pumping water from the dome at a constant rate such that the actual flow rate is the arithmetic sum of the measured Q and the pumped flow.

3. RESULTS AND DISCUSSION

The sediment in the river is composed largely of silt-sized particle with very high percent organic matter content. The organic matter is composed of both natural organic matter and coal tar components, as previously reported (Jafvert et al., 2006). Below the 8-12 ft organic muck layer is a 1-2 ft layer of fine to medium grain sand over a continuous impermeable clay layer. The sand layer was present at most locations where soundings with a ¼”-fibreglass rod were made within the river, and appeared to be extensive enough to be connected. Except during major storm events, water within the sand layer always exhibited a hydraulic head greater than the river elevation, suggesting a potential regional component to the flow within this layer and an upward vertical component to flow through the organic layer.

3.1 Temporal and spatial variation of hydraulic head

The piezometric head, $h$, is a measurement of the total hydraulic head at the point of measurement. Values of $h$ measured in the stream gauge and two sediment piezometers at RC1 and RC3 are reported in Figure 4 and are somewhat typical of the data collected at the other RCs. In all clusters, all three values of $h$ generally decrease proportionally over the three months of continuous measurement from August 1 to late October, 2005.

Vertical hydraulic head gradients, $i$, were calculated from the water elevations measured in the 4 and 8 ft deep piezometers and steam gauges at RC1-RC4,

$$i_{j-k} = \frac{h_k - h_j}{dz}$$

where $j$ and $k$ refer to the position in feet within the sediment where the head is measured in relation to the sediment-water interface (i.e., 0, 4, 8) and $dz$ is the distance between measurement position elevations (i.e, 4 or 8 ft). Note that at RC1 and RC3 (Figure4), the head difference between the 8 ft piezometer and the stream gauge, averages approximately 1 ft over the measurement period, leading to values of $i_{0.8}$ averaging about 0.13. At RC2 and RC4, the difference in head was approximately 0.5-0.8 ft, hence $i_{0.8} \approx 0.06$-0.1. As Figure 4 shows, the temporal changes in the gradients were minimal, except after high rainfall events when the change in elevation of the river was much more

![Figure 4. Variation in stream gauge and piezometer heads at RC1 and RC3 from August 1 to October 16, 2005.](image-url)
significant than the changes in water levels within the piezometers. The vertical gradients, $i_{0-4}$ and $i_{4-8}$ clearly indicate upward vertical flow of water through the sediment at the sediment water boundary at all times except during several short duration storm events when $i_{0-4}$ was negative.

3.2 Water flow across the sediment-water boundary

The vertical Darcy velocities (i.e., specific discharges), $q$, measured at each river cluster position are reported in Table 1. The reported standard deviations on $q$ are the result of at least 3 replicate measurements, except for 2 active method measurements (RC2N on 8/23 and RC2S on 8/15) for which only 1 and 2 measurements were made, respectively. Also reported in Table 1 are values of $i$ (ft/ft) measured manually at each respective RC location on the same day when $q$ was measured. Over all measurements, the range in the specific discharge, $q$, was 0.3-2.63 cm/day.

Note that reported values of $q < 1.5$ cm/d for the passive method require extrapolation below the minimum flow rate on the calibration curve. When this occurred, the active method was employed to confirm the actual Darcy velocity. In all active method measurements, the target total flow through the tube, $Q$, was in the range 3.5~4.5 cm$^3$/min, approximately at the midpoint of the calibration curve. In general, values of $q$ measured with the passive method were within 50% of each other, with 9 of 12 measurements occurring between 1.14 and 2.0 cm/day. This same variation in the measurements over spatial and temporal scales occurred using the active flow addition method; however the reproducibility of the results at each location and time were greatly improved as indicated by the much smaller standard deviations on these values.

3.3 Vertical hydraulic conductivity

Assuming that flow is vertical, values for the vertical hydraulic conductivity, $K_v$ (cm/d), within the top 4 ft sediment layer were calculated by dividing $q$ by the corresponding hydraulic head gradient, $i_{0-4}$.

$$K_v = q \times i_{0-4}^{-1}$$

The calculated values of $K_v$ are reported in Table 1. The values of $K_v$ measured by the active method ranged from $1.75 \times 10^{-5}$ to $1.99 \times 10^{-4}$ cm/sec, and for the passive method are $2.31 \times 10^{-5}$ to $2.39 \times 10^{-4}$ cm/sec. These values are within the range expected for silty sedimentary material, such as that found at the site. Considerations of regional flow directions have been made through generation of flow nets perpendicular to the river, which incorporate data not presented in this paper, to provide a more comprehensive indication of flow through the sediments.

The major advantage of the interfacial flow meter system described in this study is the ease with which it can be deployed to measure very low flow rates across the sediment-water boundary. Placing the collar into the

### Table 1. Darcy velocities ($q$), hydraulic conductivities ($K$), and vertical gradients ($i$) at each location.

<table>
<thead>
<tr>
<th>ID</th>
<th>Date</th>
<th>Passive Method</th>
<th>Active Method</th>
<th>$i$ (ft/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$q$ (cm/day)</td>
<td>$K$ at 0-4 ft (cm/sec)</td>
<td>$q$ (cm/day)</td>
</tr>
<tr>
<td>RC1</td>
<td>9/6/05</td>
<td>1.90 (0.85)$^a$</td>
<td>1.31×10$^4$</td>
<td>1.49 (0.07)$^a$</td>
</tr>
<tr>
<td>RC2N</td>
<td>8/23/05</td>
<td>1.89 (0.30)</td>
<td>1.44×10$^4$</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>8/29/05</td>
<td>0.31 (0.038)</td>
<td>2.31×10$^5$</td>
<td>0.36 (0.05)</td>
</tr>
<tr>
<td></td>
<td>8/15/05</td>
<td>1.14 (0.49)</td>
<td>8.52×10$^5$</td>
<td>0.155</td>
</tr>
<tr>
<td>RC2</td>
<td>8/23/05</td>
<td>1.66 (0.38)</td>
<td>1.45×10$^4$</td>
<td>0.133</td>
</tr>
<tr>
<td></td>
<td>10/3/05</td>
<td>1.27 (0.16)</td>
<td>1.16×10$^4$</td>
<td>0.128</td>
</tr>
<tr>
<td></td>
<td>8/10/05</td>
<td>2.63 (0.38)</td>
<td>2.39×10$^4$</td>
<td>0.128</td>
</tr>
<tr>
<td>RC2S</td>
<td>8/15/05</td>
<td>2.00 (0.13)</td>
<td>1.03×10$^4$</td>
<td>0.30 (0.26)</td>
</tr>
<tr>
<td></td>
<td>9/26/05</td>
<td>1.29 (0.49)</td>
<td>5.89×10$^5$</td>
<td>1.13 (0.04)</td>
</tr>
<tr>
<td>RC3</td>
<td>9/12/05</td>
<td>1.46 (0.42)</td>
<td>2.12×10$^4$</td>
<td>0.080</td>
</tr>
<tr>
<td></td>
<td>9/20/05</td>
<td>0.93 (0.40)</td>
<td>1.24×10$^4$</td>
<td>0.088</td>
</tr>
<tr>
<td>RC4</td>
<td>9/12/05</td>
<td>1.15 (0.55)</td>
<td>1.33×10$^4$</td>
<td>1.09 (0.04)</td>
</tr>
</tbody>
</table>

$^a$ Numbers in parenthesis are standard deviation of replicates.

$^b$ Not determined because the piezometric head in 8 ft piezometer did not reach at steady-state.
sediments introduces minimal disturbances, and the interfacial area encompassed by the cylindrical collar was sufficient to produce the desired flow rates through the tube, albeit at the low end of the standard curve.

Although the intent of the gas vent was to eliminate accumulation of gas under the dome during periods of extended measurement, it became obvious that gas was released as bubbles breaking at the surface of the water within the vent pipe causing shifts in the thermocouple reading as the heat passed through the flow tube, due to the minor turbulence caused by this phenomenon. The infrequency of this event and lack of visual observation of gas bubbles suggested the production of gas under the dome negligibly affected the measurements. In the future, the volume of gas exiting the pipe will be measured for further confirmation.

Combining automated data collection via the passive method with automated pressure head measurements made with pressure transducers over extended time periods would allow accurate determination in the temporal change in $q$ and $K_v$ with change in river conditions (i.e., storm events). The use of flow nets, based on additional piezometric data adjacent to the steam sediments, potentially could be used for determining total flow values within the sediment, and consequently support better design of an effective sub-aqueous cap.

4. ACKNOWLEDGEMENTS

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References


