Effect of surficial disturbance on exchange between groundwater and surface water in nearshore margins

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[1] Low-permeability sediments situated at or near the sediment–water interface can influence seepage in nearshore margins, particularly where wave energy or currents are minimal. Seepage meters were used to quantify flow across the sediment–water interface at two lakes where flow was from surface water to groundwater. Disturbance of the sediment bed substantially increased seepage through the sandy sediments of both lakes. Seepage increased by factors of 2.6 to 7.7 following bed disturbance at seven of eight measurement locations at Mirror Lake, New Hampshire, where the sediment representing the greatest restriction to flow was situated at the sediment–water interface. Although the veneer of low-permeability sediment was very thin and easily disturbed, accumulation on the bed surface was aided by a physical setting that minimized wind-generated waves and current. At Lake Belle Taine, Minnesota, where pre-disturbance downward seepage was smaller than at Mirror Lake, but hydraulic gradients were very large, disturbance of a 20 to 30 cm thick medium sand layer resulted in increases in seepage of 2 to 3 orders of magnitude. Exceptionally large seepage rates, some exceeding 25,000 cm/d, were recorded following bed disturbance. Since it is common practice to walk on the bed while installing or making seepage measurements, disruption of natural seepage rates may be a common occurrence in nearshore seepage studies. Disturbance of the bed should be avoided or minimized when utilizing seepage meters in shallow, nearshore settings, particularly where waves or currents are infrequent or minimal.


1. Introduction

[2] Heterogeneity in the distribution of seepage flux across the bed of a lake, stream, wetland, or estuary is one of the more vexing problems associated with quantifying exchanges between groundwater and surface water [Keery et al., 2007; Malcolm et al., 2003; Rosenberry, 2005; Schneider et al., 2005]. Seepage meters are particularly useful for quantifying this exchange because they provide a direct measurement of flow across the sediment–water interface over a discrete area. Although simple in concept, results can be confusing or erroneous unless several common sources of error, including use of small-diameter baggie-connection hardware or thick-walled seepage bags, are addressed and reduced [Belanger and Montgomery, 1992; Cable et al., 1997; Fellows and Brezonik, 1980; Murdoch and Kelly, 2003; Rosenberry et al., 2008]. Some of the confusion and uncertainty historically associated with seepage-meter measurements may stem from inadvertently disrupting the sediment bed prior to measurement. In low-energy settings, particularly where flow is downward (from surface water to groundwater), an accumulation of a lower-permeability layer of fine-grained sediment can reduce the rate of flow across the sediment–water interface [Rosenberry and Pitlick, 2009a]. Disturbance of this veneer, whether by waves, currents, fish [Baxter and Hauer, 2000; Soulsby et al., 2001], or scientists, can substantially alter the seepage rate. Physical manipulation of the sediment–water interface (furrowing the bed with a garden rake) approximately doubled seepage rates along the nearshore margins of a lake in New Hampshire [Rosenberry and Morin, 2004]. Tests conducted in a laboratory test tank indicated that seepage flow can be restricted by a layer of silt deposited at the sediment–water interface only 1 mm thick, especially during downward seepage (from surface water to groundwater) [Rosenberry and Pitlick, 2009a].

[3] Seepage commonly is focused in these shallow, nearshore margins of lakes, wetlands, and estuaries because of (1) the concentration of flow paths at the break in slope represented by the shoreline [McBrade and Pfannkuch, 1975; Pfannkuch and Winter, 1984], (2) the frequent disturbance of the sediment caused by breaking waves and nearshore currents, and (3) the migration of the wave-washed littoral zone associated with changes in surface-water stage [Rosenberry, 2000]. Primarily because of convenience, most nearshore seepage measurement locations are accessed by foot; meters are installed and serviced while standing on the bed adjacent to the seepage cylinder. Unless care is taken to mark locations where investigators have stepped on the sediment bed, it is likely that subsequent seepage-meter installations will be made on portions of the bed that have recently been disturbed by accessing previously installed
seepage meters. This disturbance can dislodge and suspend fine-grained particles situated on or near the bed surface (in the interstitial spaces between larger-grained sediment situated on the bed), locally increasing vertical hydraulic conductivity. We hypothesize that subsequent seepage rates, measured where the bed was inadvertently disturbed, will be artificially fast. The intent of this paper is to describe settings and processes that lead to reduced exchange of water at the sediment-water interface, document the effect of bed disturbances on measured seepage rates in nearshore lacustrine settings, determine the significance of sediment disturbance on seepage rates, and provide guidance for minimizing this occurrence.

2. Settings Conducive to Substantial Alteration of Seepage Rates Following Bed Disturbance

[1] Seepage is controlled to a large extent by the lowest-permeability sediment along a groundwater flow path. If the lowest-permeability layer is at the sediment-water interface, substantial changes in seepage rate can occur in response to disturbance of the bed surface and disruption of the fine-grained sediments that are situated on the bed surface. If the governing sediment layer is located some distance beneath the sediment-water interface, disturbances at the sediment–water interface may not affect seepage rates. Several other factors also determine whether bed disturbance might alter seepage.

[2] 1. Seepage direction (upward or downward). Downward seepage can result in a greater degree of clogging of the bed by fine particles (colmation) because the seepage-force (FS) is in the same direction as, and therefore added to, the gravity-force (g) [e.g., Brunke, 1999; Rosenberry and Pitlick, 2009a; Schalchli, 1992; Veličković, 2005].

[3] 2. Seepage velocity. Seepage velocity (q) varies in response to hydraulic conductivity and porosity of the sediment, and hydraulic gradient:

\[ q = Ki \frac{\Delta h}{a}, \]  

where K is hydraulic conductivity, i is hydraulic gradient, and n is porosity. Seepage force on a sediment-grain scale is proportional to hydraulic-head difference [Freeze and Cherry, 1979]:

\[ F_S = \rho g \Delta h A, \]  

where \( \rho \) is density of water, \( g \) is acceleration of gravity, \( \Delta h \) is hydraulic-head difference across a sediment grain, and \( A \) is the cross-sectional area of the sediment grain on the axis perpendicular to the mean groundwater-flow vector. Assuming \( i \) is distributed across a spherical particle of diameter \( D \), substituting \( iD \) for \( \Delta h \), and assuming density of water is 1000 kg m\(^{-3}\), seepage force is proportional to hydraulic gradient and the cube of the grain diameter [Rosenberry and Pitlick, 2009a]:

\[ F_S = \rho g i D A = \frac{1000 g i D^2}{4} = 250 g i D^3. \]  

[7] Once FS approaches the weight of individual sediment particles resting on the bed, sediment can be mobilized and either pulled into the porous matrix given a downward force or even suspended with upward seepage if FS exceeds the weight force (FW):

\[ F_W = \frac{(\rho_s - \rho) g \pi D^3}{6}. \]  

Comparing (5) and (3), FS exceeds FW when i exceeds 1.1. Although i is rarely so large in most hydrogeologic settings, i can easily exceed 1.1 when distributed across nearshore sediment beds where sharp contrasts in K commonly occur [Rosenberry, 2000; Rosenberry and Pitlick, 2009a, 2009b].

[8] 3. Size of fine-grained clogging particles relative to a bulk porous medium matrix. Fine-grained sediments either accumulate at the bed surface or infiltrate the pore spaces between larger grains, depending on the size of the clogging sediments relative to the grain diameter of the bulk matrix. If the diameter of clogging particles is within an order of magnitude of that of the bulk matrix, clogging will usually occur at the sediment-water interface in the form of a “filter cake” (surface colmation) [Baveye et al., 1998; McDowell-Boyer et al., 1986; Ray et al., 2002]. If clogging particles are more than an order of magnitude smaller than the bulk matrix, particles more commonly will infiltrate the porous matrix and clog pore spaces some distance below the sediment-water interface (straining) [Bradford et al., 2005; Brunke, 1999]. Sediment mobility also influences the depth and degree of clogging. An immobile bed is more likely to clog at the surface, whereas a mobile bed can result in clogging particles extending deeper into the bed, potentially reducing the degree of clogging [Rehg et al., 2005].

[9] 4. Thickness of a fine-grained sediment veneer. A thicker layer of fine-grained particles can provide a more substantial and resistant barrier to exchange at the sediment-water interface.

[10] 5. Degree and orientation of sediment packing (i.e., hardness of the sediment bed). A sediment bed that is more resistant to erosion is more stable and less likely to be mobilized by shear forces, therefore, allowing colmation to reach its ultimate extent and create a maximum reduction in bed sediment hydraulic conductivity [Schalchli, 1992; Schubert, 2002].

[11] 6. Presence and density of biological organisms on and near the sediment bed. Bacteria, algae, and invertebrates living in the pore spaces of bed sediments can either reduce [Brugger et al., 2001; Goldscheider et al., 2007; McDowell-
3. Sediment Disturbance at Mirror Lake, New Hampshire

Mirror Lake is a small 0.15 km$^2$ lake situated in the White Mountains of New Hampshire, U. S. A. Rapid seepage occurs along a portion of the southwestern shoreline of the lake where water flows through unconsolidated coarse sand and gravel from the lake to Hubbard Brook (Figure 1) [Mitchell et al., 2008; Winter, 1984]. Seepage also exhibits substantial spatial variability both along the shoreline and with distance from shore [Asbury, 1990; Rosenberry, 2005]. Hydraulic conductivity averaged 13.8 m/d based on constant head permeameter measurements of 11 shallow cores collected along this shoreline. Geophysical [Gagliano et al., 2009; Mitchell et al., 2008] and well-log [Winter, 1984] data indicate that the sand-and-gravel unit exists beneath the shoreline reach from about 5 to about 55 m northwestward from an arbitrary origin near a swim beach on the southern shore (Figure 2). Artificial disturbance of the surface of the sediment bed associated with a previous study resulted in increases in seepage that ranged from 45% to 110% [Rosenberry and Morin, 2004], making this site a good candidate for more thoroughly testing the effects of bed disturbance associated with measuring seepage in shallow, nearshore sediments.
other from an adjacent area where the bed had not been disturbed. Cores were segmented into 1 or 2 cm increments, and grain size distributions were determined by dry sieving in a sediment lab.

[19] Pre-disturbance seepage measured 2 m from the shoreline along the study reach averaged −22.8 cm/d (negative indicating downward seepage). Seepage was considerably faster through the portion of the lakebed overlying the coarser sand-and-gravel unit (35 to 55 m from the origin) with an average flux of −51.7 cm/d compared to −17.4 cm/d along the shoreline interval 60 to 95 m (Figure 3a). Hydraulic gradients also were much larger along the shoreline interval 35 to 55 m (Figure 3b) indicating that the sand-and-gravel unit was acting as a substantial drain.

[20] Post-disturbance seepage rates were nearly always faster (Figure 3a). Ratios of after and before disturbance seepage rates ranged from 0.5 to 7.7 and averaged 2.7 (Table 1). The ratio at location 92 was 23.9, but the very small pre-disturbance values may have been altered by a leak in the seepage-cylinder seal with the sediment bed and were not included in the analysis. Largest changes in seepage associated with bed disturbance occurred over the sand-and-gravel unit where hydraulic gradients were largest. Only one instance of post-disturbance seepage decreasing relative to pre-disturbance seepage was recorded. Post-disturbance seepage at the 88 m location (−16 cm/d) was about half the pre-disturbance seepage rate (−31 cm/d).

[21] Once the bed was initially disturbed, subsequent disturbances both increased and decreased seepage but usually to a smaller extent compared to pre-disturbance seepage. At location 35, seepage following second disturbance increased from −76 to −166 cm/d. At location 40, seepage following second disturbance decreased from −200 to −166 cm/d. The median of nine measurements at locations 35, 40, and 42 following first disturbance was −201 cm/d.

Figure 3. (a) Distribution of seepage along a portion of the southwest shore of Mirror Lake. Thin, black bars indicate pre-disturbance rates; thick, gray bars indicate post-disturbance rates. (b) Distribution of hydraulic gradient across the shallowest 50 cm of sediment along the same shoreline segment of Mirror Lake.

Table 1. Seepage Rates 2 m From the Shoreline at Locations Along Mirror Lake Shoreline

<table>
<thead>
<tr>
<th>Meter Location</th>
<th>Bed Condition</th>
<th>Average (cm/d)</th>
<th>Standard Deviation (cm/d)</th>
<th>n</th>
<th>Disturbance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>Und</td>
<td>−29.3</td>
<td>1.1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Dist</td>
<td>−75.5</td>
<td>2.9</td>
<td>3</td>
<td>2.6</td>
</tr>
<tr>
<td>35</td>
<td>Dist&lt;sup&gt;b&lt;/sup&gt;</td>
<td>−166.1</td>
<td>2.0</td>
<td>2</td>
<td>5.7</td>
</tr>
<tr>
<td>40</td>
<td>Und</td>
<td>−25.9</td>
<td>3.1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>Dist</td>
<td>−199.5</td>
<td>2.5</td>
<td>2</td>
<td>7.7</td>
</tr>
<tr>
<td>40</td>
<td>Dist&lt;sup&gt;b&lt;/sup&gt;</td>
<td>−165.9</td>
<td>36.7</td>
<td>3</td>
<td>6.4</td>
</tr>
<tr>
<td>42</td>
<td>Dist</td>
<td>−252.0</td>
<td>4.9</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>Dist&lt;sup&gt;b&lt;/sup&gt;</td>
<td>−84.3</td>
<td>18.0</td>
<td>3</td>
<td>0.3&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>45</td>
<td>Und</td>
<td>−137.0</td>
<td>4.1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>47.5</td>
<td>Und</td>
<td>−51.9</td>
<td>0.8</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Und</td>
<td>−54.0</td>
<td>0.2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Dist</td>
<td>−60.5</td>
<td>2.1</td>
<td>4</td>
<td>1.1</td>
</tr>
<tr>
<td>52</td>
<td>Dist</td>
<td>−181.5</td>
<td>1.6</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>Dist</td>
<td>−105.5</td>
<td>11.5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>Und</td>
<td>−21.8</td>
<td>0.5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>Und</td>
<td>−16.5</td>
<td>0.4</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>Und</td>
<td>−8.7</td>
<td>2.9</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Und</td>
<td>−2.6</td>
<td>1.0</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Dist&lt;sup&gt;b&lt;/sup&gt;</td>
<td>−15.4</td>
<td>1.8</td>
<td>5</td>
<td>5.9</td>
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<tr>
<td>85</td>
<td>Und</td>
<td>−18.3</td>
<td>0.1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>Dist</td>
<td>−26.9</td>
<td>2.7</td>
<td>4</td>
<td>1.5</td>
</tr>
<tr>
<td>88</td>
<td>Und</td>
<td>−31.2</td>
<td>1.4</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>Dist</td>
<td>−15.7</td>
<td>3.0</td>
<td>9</td>
<td>0.5</td>
</tr>
<tr>
<td>90</td>
<td>Und</td>
<td>−35.9</td>
<td>1.7</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>Dist&lt;sup&gt;b&lt;/sup&gt;</td>
<td>−36.4</td>
<td>2.1</td>
<td>4</td>
<td>1.0</td>
</tr>
<tr>
<td>92</td>
<td>Und</td>
<td>−1.9</td>
<td>0.7</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>92</td>
<td>Dist&lt;sup&gt;b&lt;/sup&gt;</td>
<td>−45.4</td>
<td>0.4</td>
<td>3</td>
<td>23.9</td>
</tr>
<tr>
<td>95</td>
<td>Und</td>
<td>−5.8</td>
<td>0.2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>Dist</td>
<td>−6.8</td>
<td>0.2</td>
<td>3</td>
<td>1.2</td>
</tr>
</tbody>
</table>

<sup>a</sup>Und indicates undisturbed bed; Dist, disturbed bed. Disturbance ratio is the seepage rate through the disturbed bed divided by the seepage rate through the undisturbed bed.

<sup>b</sup>Sediment bed disturbed a second time.

<sup>c</sup>Ratio is relative to a previously disturbed bed.
compared to a median of eight measurements following second disturbance of \(-147\ \text{cm/d}\). For comparison, the median of six pre-disturbance measurements made in the sand-and-gravel unit at locations 35 and 40 was \(-29\ \text{cm/d}\).

4. Sediment Disturbance at Lake Belle Taine, Minnesota

[22] Lake Belle Taine is a 4.8 \text{km}^2 lake in northern Minnesota, U.S.A. at the downstream end of a chain of 10 lakes connected by Little Sand Creek (Figure 4). The lake receives an average discharge of 76,000 \text{m}^3/d from Little Sand Creek but has no outlet, losing all of that water to seepage through the lakebed along the southern shoreline. The large difference in lake-surface elevation (13.5 to 14.3 m difference) between Belle Taine and three lakes only about 1 km to the south, combined with the presence of coarse, clean sandy outwash between the lakes, results in such a substantial drain at the southern shoreline of Lake Belle Taine that sediments beneath portions of the lakebed, including the lakebed studied here, are unsaturated [Rosenberry, 2000]. Desaturation of sediments beneath the lakebed occurs about 20 to 30 cm beneath the lakebed at the interface between medium sand and the coarse to very coarse sand outwash below. Hydraulic conductivity of the lakebed sediments is quite large (about 7 to 9 \text{m/d}, based on two constant head permeameter tests; and 3 to 17 \text{m/d} based on Hazen analysis of sieved sediments within 25 cm of the sediment-water interface). However, hydraulic conductivity of the outwash is 1 to 2 orders of magnitude larger, ranging between 35 and 350 \text{m/d} [Rosenberry, 2000].

[23] Measurements made during an initial investigation of the site [Rosenberry, 2000] indicated seepage ranged from \(-0.1\) to \(-79\ \text{cm/d}\) and averaged \(-18.0\ \text{cm/d}\) (n = 14) between 4 and 30 m from the shoreline along a transect perpendicular to shore (Figure 5a). Seepage likely was faster between the shoreline and 4 m from shore, but the nearshore bed was too cobbly to allow installation of seepage meters. Hydraulic gradients within the thin layer of saturated sediments were exceptionally large, ranging from 5.0 to 5.7, indicating that hydraulic conductivity of the shallowest 20 to 30 cm of sediment was much smaller than deeper sediments. The bed material contained very few silt- or clay-sized sediments typically associated with reduced values of hydraulic conductivity [e.g., Okagbue, 1995; Uma and
Loehnert, 1994]. The sediment size for which 5% of the sediments were finer ranged from 0.07 to 0.17 mm, in the very fine- to fine-sand range.

[24] The top 30 cm of sediment was removed from discrete locations and seepage measured to determine the increase in seepage that would occur if the layer of smaller hydraulic conductivity was not present. Three 38 cm diameter, 50 cm lengths of PVC pipe were jetted approximately 30 cm into the sediment bed at locations shown in Figure 5a (P1–P3); the jetting process removed virtually all of the finest fraction, leaving some of the gravel and cobble grains on the bed. A 3.8 cm diameter pipe was extended through a PVC cap that was fitted over the upper end of the large-diameter PVC pipe, providing a means to attach a seepage bag (Figures 5b and 5c). Air bubbled out of the top of all three seepage cylinders for several to 20 min following installation, indicating that the meters had breached the saturated sediments and extended into the unsaturated sediments below. Seepage could not be measured with a standard seepage bag because seepage rates were too fast. Flow was so strong at P1 that a hand placed palm down over the opening was forcibly sucked onto the opening. Therefore, an inverted 0.56 m diameter plastic seepage cylinder was floated on the lake surface and connected to the seepage cylinder with a length of flexible 5.1 cm diameter pipe (Figure 5b). The floating cylinder was weighted to be as close to neutrally buoyant as possible. Change in volume of water contained inside of the floating water-measurement chamber was recorded along with the duration of flow to obtain a volume-per-time seepage measurement. Multiple measurements were made at each location to determine change in seepage in response to changing hydraulic conditions beneath the bed as well as the potential clogging of the sediment bed by particles entrained in the flow. During times when a seepage measurement was not being made, a submerged valve was opened to allow seepage flow to be maintained and prevent air from being sucked into the seepage cylinder.

[25] Initial seepage rates were measured within 2 h of meter installation at P3 and within a day at P1 and P2. Values were exceptionally large, ranging from −25,400 cm/d at P1 to −1800 cm/d at P3 (Figure 5a). Subsequent measurements usually indicated a rapid reduction in seepage rate in response to changing hydraulic conditions beneath the sediment bed (Figure 6). For example, seepage flux decreased from more than −25,000 to −20,000 cm/d at P1 within 60 min of initiation of flow through the seepage chamber (Figure 6). However, seepage did not decrease at P2 within the first hour following initiation of flow until measurements were conducted with a seepage bag as opposed to the floating chamber method. Although large, the 1.9 cm diameter connection hardware used to connect
Table 2. Seepage Rates at 3 Locations Along the Southern Shore of Lake Belle Taine

<table>
<thead>
<tr>
<th>Meter Location</th>
<th>Bed Condition</th>
<th>Average (cm/d)</th>
<th>Standard Deviation (cm/d)</th>
<th>n</th>
<th>Disturbance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early measurements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>Und</td>
<td>−22.5</td>
<td>0.7</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>Dist</td>
<td>−25.025</td>
<td>570</td>
<td>2</td>
<td>1112</td>
</tr>
<tr>
<td>P3</td>
<td>Dist</td>
<td>−20.6</td>
<td>2.9</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Late measurements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>Dist</td>
<td>−88.49</td>
<td>495</td>
<td>2</td>
<td>430</td>
</tr>
<tr>
<td>P2</td>
<td>Dist</td>
<td>−17.4</td>
<td>20.4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>Dist</td>
<td>−181.3</td>
<td>0</td>
<td>2</td>
<td>104</td>
</tr>
</tbody>
</table>

aUnd indicates undisturbed bed; Dist, disturbed bed. Disturbance ratio is the seepage rate through the disturbed bed divided by the seepage rate through the undisturbed bed.

bUndisturbed values from early measurements repeated here.

the seepage bag to the seepage cylinder still resulted in resistance to flow and a decrease of measured seepage rate from about −4000 to about −2000 cm/d (Figure 6).

[26] Seepage stabilized within about a day of meter installation at P3, even though flow through the meter was halted overnight between measurement periods. Repeat measurements indicated a reduction in seepage rate of 200 cm/d over a 20 min duration on 28 June, but that reduction was much smaller than the 1200 cm/d reduction that occurred during the previous 24 h period. Seepage rate was approximately the same the following day, on 29 June, at −660 cm/d.

[27] Seepage cylinders were capped after several days and reopened a month later. Measurements indicate that flow had stabilized at about −20,000 cm/d at P1. Seepage initially was much faster at P2 than during the June measurements a month earlier, starting at −9200 cm/d 10 min after flow was initiated and stabilizing at about −3500 cm/d 4.5 h later. Seepage at P3 had decreased to −38 cm/d, about the same as seepage rates measured where the bed was undisturbed. The seepage meter at P1 was left open to flow until the next site visit about 6 weeks later. Even after flowing for 47 days, seepage still was much faster than through the undisturbed bed, ranging from −1100 to −1900 cm/d.

[28] Disturbance ratios were orders of magnitude larger at the Belle Taine site than at the Mirror Lake site. For the post-disturbance measurements made soon after water was allowed to flow through the seepage chambers, disturbance ratios ranged from 104 at P3 to 1112 at P1 (Table 2). Disturbance ratios eventually decreased to 2.6 at P3, 52 at P2, and 72 at P1.

5. Discussion

[29] Conditions were favorable for substantial changes in seepage in response to sediment disturbance at both Mirror Lake and Lake Belle Taine but for different reasons. At Mirror Lake, the likely cause of substantial seepage increase was disturbance of a thin layer of lower-permeability material deposited at the sediment-water interface. Analyses of grain size distributions of shallow cores collected from disturbed and undisturbed portions of the bed at locations 35, 40, 42, and 50 showed an increase in median grain size of the top 5 cm of the disturbed sediment relative to the undisturbed sediment at three of the four sampling locations (Figure 7).

[30] As mentioned earlier, seepage flow can be restricted by a thin veneer of fine-grained sediment [Rosenberry and Pitlick, 2009a]. Such a thin silt layer would not be stable in many lakes and would frequently be dislodged and suspended in the water column in response to waves and currents. However, Mirror Lake is a relatively small lake situated in a steeply sloping basin that shelters the lake surface from atmospheric circulation, leading to long periods of calm to light winds and providing relatively few opportunities for the generation of waves or currents large enough to dislodge silt-sized sediments on the bed.

[31] The significance of sediment disturbance depends to some extent on the duration of the altered bed conditions and the time it takes for sediments to settle back to the bed and resume their clogging role. Once sediment is dislodged, duration of suspension in the water column is related to grain diameter and water depth. Time of suspension can be estimated by dividing settling distance by Stokes settling velocities (vs):

\[ v_s = \frac{(\rho_s - \rho)gD^2}{18\mu} \]

where \( \mu \) is dynamic viscosity. Assuming a water depth of 0.5 m and laminar flow associated with the settling particles, the finest sand-sized particles would settle to the bed within 2 min. Silt-sized particles would remain in suspension between 2 min and 10 h, and clay-sized particles would remain in suspension between 10 h and well over 1000 days. These durations do not consider the flocculating tendencies of silt- and clay-sized particles, which would result in faster settling rates and shorter suspension times. Waves or currents would increase these estimated settling times. Although sediment settling to the lakebed eventually restores the disturbance caused by walking on the bed, sediment would not be able to settle onto the portion of the bed covered by a previously installed seepage cylinder and would settle on top of the cylinder instead. Therefore, the portion of the bed covered by the seepage cylinder is essentially frozen in time and cannot evolve as the rest of the sediment bed does.

[32] Seepage decrease following initial disturbance at location 88 and following a second disturbance at locations 40 and 42 at Mirror Lake (Table 1) was unexpected. Although seepage decreased following disturbance at these three locations, post-disturbance seepage increased at adjacent seepage meters. One possible explanation for post-disturbance seepage decrease at some locations is that the distribution of seepage changed following widespread bed disturbance. If seepage was focused in a few specific locations
prior to disturbance, an increase in seepage over a broader lakebed area resulting from bed disturbance would temporarily increase lakebed hydraulic conductivity and reduce hydraulic gradients in that broader area. Therefore, seepage at what previously had been a focused-discharge location would decrease in response to the larger-scale reduction in hydraulic gradient. 

Seepage rates typically are largest nearest to the shoreline and measurements commonly are conducted in water less than 0.5 m deep, making installing and servicing seepage meters while wading in the water an easy and efficient option. Based on results from these two study sites, it is likely that walking on the bed to service seepage meters may be resulting in the measurement of unnatural seepage rates in many nearshore settings. In some instances, disturbance effects are easily visible (Figure 8). Even given this obvious bed disturbance, however, cores collected from within the disturbed portion of the bed and from an adjacent, but undisturbed, portion of the bed showed relatively small differences in sediment grain size distribution. Clogging sediments at the bed surface in Mirror Lake likely are a mix of organic and inorganic fine-grained particles that become primarily organic with greater lake depth and distance from shore. In addition to waves and currents, disturbance of this layer also could result from fish building spawning redds and perhaps from foraging ducks, both of which were common at the site. Because of the relative lack of wind and waves at Mirror Lake, the bed may go undisturbed for long periods and may be particularly susceptible to reductions in seepage resulting from surface colmation. These conditions also would be common in lake margins where emergent vegetation provides protection from the forces of wind and waves.

Lake Belle Taine is near the other end of the nearshore kinetic energy spectrum, commonly experiencing large, crashing waves along the southern shoreline in response to prevailing northerly winds. Walking on the bed likely would not cause a measurable change in seepage rate because clogging of the lakebed appeared to be the result of particle straining distributed over a depth of 20 to 30 cm rather than focused at the surface as it was at Mirror Lake. In addition, the fast seepage rates and exceptionally large hydraulic gradients appear to have compacted the bed, making it stable enough to support growth of aquatic plants in spite of the frequent large waves. A much more substantial disturbance, large enough to dislodge this 20 to 30 cm thick lower-hydraulic-conductivity layer, was required to create orders-of-magnitude increases in seepage at this location. Such a disturbance occurs naturally, on occasion, when ice is rafted against the shoreline during spring ice breakup, or is pushed into the shoreline during midwinter thermal expansion, at which times ice can scour the nearshore sediments to depths of 1 m or more [Gilbert, 1990; Gilbert et al., 1992].

The study sites at Mirror and Belle Taine were selected primarily because they both exhibited strong downward seepage, a characteristic that makes seepage alteration associated with bed disturbance more likely according to literature on induced infiltration. Although implications for seepage measurements are considerable in these types of settings, it remains to be determined whether physical disturbance of the sediment bed substantially alters exchange where seepage is upward. Colmation processes also occur in areas of upward seepage; however, studies of the influence of seepage associated with surface-water current in a controlled environment indicate the influence of bed disturbance likely is much smaller for settings with upward rather than downward seepage [Rosenberry and Pitlick, 2009a].

6. Conclusions

Disturbance of the lakebed substantially increased seepage in two nearshore lake settings where seepage was from surface water to groundwater. Seepage along a sandy
shoreline of a small, 0.15 km$^2$ lake increased following bed disturbance at seven of eight measurement locations where the sediment representing the greatest restriction to flow was situated at the sediment-water interface. Post-disturbance seepage averaged 2.7 and was as large as 7.7 times faster than pre-disturbance seepage at this location. At a larger 4.8 km$^2$ lake, where downward seepage was slightly smaller but hydraulic gradients were very large, disturbance of a 20 to 30 cm thick medium-sand layer resulted in increases in seepage of 2 to 3 orders of magnitude. Exceptionally large seepage rates, some exceeding 25,000 cm/d, were recorded following bed disturbance.

Surface colmation was responsible for reduced seepage rates at a small lake protected from wind and large waves and likely would be less developed where waves are more common. At a lake where large waves are a common occurrence, clogging particles were distributed through the top 20 to 30 cm of the bed, disturbance of which resulted in exceptionally large increases in seepage. In such a setting, walking on the bed likely would have little effect on seepage rates. However, natural disturbances, such as exceptionally strong winds, ice movement, or changes in shoreline location associated with substantial lake-stage change, could mobilize the bed and release fine-grained particles, altering seepage rates and creating seasonal or interannual changes in seepage rates and spatial distribution. These changes could bring into question the reproducibility of seepage measurements during subsequent field seasons.

It is likely that at least some, and perhaps many, of the seepage studies reported in the literature have been influenced by inadvertent disturbance of the sediment bed in the process of making measurements along the nearshore margins of lakes and wetlands and estuaries. Future studies should be designed to minimize bed disturbance, particularly in quiescent settings where seepage is from surface water to groundwater. Disturbance could be minimized by focusing bag measurement locations in one area away from seepage cylinders or by installing and servicing nearshore seepage meters while floating on the water surface, perhaps from a shallow draft boat or by swimming to the measurement locations in a buoyant wetsuit.

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