Surface-ground water interaction: From watershed processes to hyporheic exchange

July 17-22, 2017, University of Calgary

Day 1: Scale – matching the study to the setting
Geology, heterogeneity
Flowpaths
Time of travel

Typical physical setting – some general terms

First, some general terms. The water table is the upper surface of the saturated zone. The water table meets surface-water bodies at or near the shoreline of surface water if the surface-water body is connected to the ground-water system.
Determining GW flow

A. Install wells and determine water-table elevation
B. Contour the data, creating "equipotential" lines
C. Draw perpendicular flowpath lines, creating approximately rectilinear squares

This is the beginning of a flow-net analysis for quantifying GW flow that will be discussed later.

Using known altitudes of the water table at individual wells (A), contour maps of the water-table surface can be drawn (B), and directions of groundwater flow along the water table can be determined (C) because flow usually is approximately perpendicular to the contours.

GW flow in cross section – piezometers indicate potential for flow

All wells have the same head no matter the screen depth
The deeper the well the lower the head
The deeper the well the higher the head

If the distribution of hydraulic head in vertical section is known from nested piezometer data, zones of downward, lateral, and upward components of groundwater flow can be determined.
Flow systems can be nested and much more complex

- The **scale** of the flow path or system and the **travel time** can be widely variable


You will explore this more using Topodrive software.

Scales of interest

**Nationwide scale** (percent river flow as baseflow)

Baseflow separation

There are many methods available for quantifying GW-SW exchange. We need to fit the method to the scale of the interest.

Wolock, 2003, USGS OFR 03-146
Regional scale

The groundwater-flow model MODFLOW was used to calculate distribution of discharge directly to the Great Lakes. The modeled area was 250,000 km².

Watershed scale

Gains or losses in streamflow provide a value for net groundwater recharge or discharge integrated on a sub-watershed scale.

Hoaglund et al., 2002, *Ground Water*

Donato, 1998, USGS WRIR 98–4185
Seepage run to measure change in river discharge

More later on Thursday or Friday

Net GW discharge can be determined for each reach and for the entire watershed. The difference between August and October demonstrates the effect of irrigation on the lower reaches of the river. Irrigation during August reduces flow in the river by about 1/3 along reaches 11 and 12.

Lakebed scale

Karst

Mountain Lake, FL

Belanger and Kirkner 1994

very labor intensive

This whole-lake-scale contour map of seepage rates required a huge effort made possible by many enthusiastic graduate students. Seepage is not distributed uniformly but is focused in two areas in the lake. Without the rich dataset, one would assume much smaller losses of water from the lake.

EXPLANATION

AREA OF POTENTIAL SEEPAGE INTO LAKE

LINE OF EQUAL SEEPAGE POTENTIAL IN MILLILITERS PER SQUARE METER PER HOUR (mL m⁻² hr⁻¹)

Belanger and Kirkner, 1994, Lake & Reservoir Mgmt.
Large-lake scale

\[ G_t \pm \epsilon = \frac{V \Delta C_t}{\Delta t} + (C_W - C_R)P + (C_W - C_{S1})S_t + (C_W - C_{ET})O_t + (C_{ET} - C_W)ET \]

From Rosenberry & Hayashi, 2013

For large lakes a water-budget or combined water and chemistry budget is a good option.

Lakes can be challenging

Lake O’Hara, Alberta, Canada

Masaki gets to work in some ridiculously beautiful areas. His students and he used a water-budget approach to show that groundwater provided even more input to the lake than did snowmelt and streamflow.

In fractured-rock settings, groundwater discharge often is distributed based on the distribution of networks of inter-connected fractures. Thermal infra-red often can be used to determine where to focus efforts. More on this on Day 4 in the measurement-method section.

BWCA-Quetico, northern MN, southwestern Ontario

FLIR thermal camera – a great reconnaissance tool

Upper Delaware River

Briggs et al., 2013, ES&T
Flow on a one to several meters scale can be obtained with a dense network of seepage meters. Each seepage-meter measurement integrates seepage flow over about 0.25 m of the sediment-water interface.

Need to scale measurements and methods to match the scale of concern

You would not want to use seepage meters, for example, to quantify groundwater discharge to the Great Lakes surrounding Michigan.
Ground-water flowpaths vary in length, depth, and travel time from points of recharge to points of discharge

The Age of Ground-Water Discharge to a Stream Channel Can Vary Widely

Local sources of ground water discharge near streambanks and are relatively young; regional sources of ground water discharge to the center of the stream channel and are relatively old.

Modica, 1999, USGS Fact Sheet
Jud Harvey convinced me!

Diagrams like the one on the previous slide are nice, but they often do not reflect the real world. Would you really be able to detect different ages of groundwater discharge based on distance from the shoreline of a stream, such as the one in this photograph? I was skeptical. How could we ever see differences in groundwater age with all of the geologic heterogeneity in and near the streambed and all of the hyporheic exchange? It turns out you sometimes can, and do. Jud Harvey’s data indicate that groundwater discharging at the center of this stream is much older than groundwater that discharges at the edge of the stream channel.

Ground-Water Discharge Becomes Increasingly Older with Distance Downstream

Why?

Groundwater that discharges farther downstream commonly is older (but not always) because the contributing area is getting larger with distance downstream, providing longer flowpaths and longer travel times.

Modica, 1999, USGS Fact Sheet
Heterogeneity is one of the largest problems for measurement and interpretation of flows between groundwater and surface water. Because of the numerous processes that occur in these areas, heterogeneity often is even larger at the interface between groundwater and surface water than in other aquifer environments.

Near-shore processes + geological variability

Here we show heterogeneity due to multiple influences. Surface water is flowing to groundwater near the shoreline because water removal caused by evapotranspiration (ET) has pulled down the water table. Groundwater is discharging to surface water beyond the local influence of ET. Farther from shore, beyond a low-permeability layer that isolates different portions of presumably higher-K sediments, a drain somewhere beyond the view shown here is resulting in surface water flowing into the aquifer.
Krabbenhoft and Anderson, 1986, *Ground Water*

This was a nice example from the literature that indicated a gravel lens was transmitting a much larger volume of seepage to the lake than were the surrounding sandy sediments.


*Fast seepage through sinkholes*

This lake is situated in sand with limestone beneath.

**Geologic controls on heterogeneity**

Mountain Lake, FL
Refuge managers wanted to draw down the level of ponds to expose mud flats so plants that benefit trumpeter swans could germinate. But they needed to be able to bring the water level back up as soon as swans were nesting to protect the eggs from predators. Therefore, they needed to know how much groundwater was discharging to the wetlands to determine how quickly the water level would rise once they reduced flow from the dam.

Groundwater discharge was slow except for places like you see here, where discharge was orders of magnitude faster. If we didn’t know about these areas, we would greatly underestimate total groundwater discharge. These springs may be related to a fault that extends beneath the edge of the lake.
Mirror Lake, NH, USA – GW seepage distribution varies greatly on a local scale.

The four meters to the southeast indicate seepage ranges from -4 to -12 cm/day (negative means flow from the lake to groundwater). But if you walk 15 meters along the shoreline to the northwest, seepage is much faster, up to -153 cm/day. And look at the positive values farther from shore. This complexity will be explained in greater detail in a subsequent lecture.

Heterogeneity in GW-SW exchange is very common in lakebeds and streambeds. Here is another example, this one from a lake in Denmark, where the degree of heterogeneity is revealed differently depending on the measurement method.
What rates of exchange are common?

Table II. Seepage rates for upward seepage (exfiltration) and downward seepage (infiltration) at 108 lakes across the world

<table>
<thead>
<tr>
<th></th>
<th>Exfiltration average</th>
<th>Exfiltration maximum</th>
<th>Infiltration average</th>
<th>Infiltration maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
<td>109</td>
<td>59</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.005</td>
<td>0.019</td>
<td>0.001</td>
<td>0.15</td>
</tr>
<tr>
<td>25th percentile</td>
<td>0.73</td>
<td>0.76</td>
<td>0.18</td>
<td>0.92</td>
</tr>
<tr>
<td>Median</td>
<td>0.74</td>
<td>5.10</td>
<td>0.60</td>
<td>1.64</td>
</tr>
<tr>
<td>75th percentile</td>
<td>2.59</td>
<td>13.30</td>
<td>1.88</td>
<td>30.5</td>
</tr>
<tr>
<td>Maximum</td>
<td>124.1</td>
<td>745.0</td>
<td>37.0</td>
<td>263.0</td>
</tr>
</tbody>
</table>

Data culled from the literature are average and maximum values reported for particular lakes. Values are in centimetres per day.

This study summarized seepage for lakes. Our best estimate is that values for hyporheic settings will be 1 to 2 orders of magnitude larger.

 kennedy et al., 2008, Jhydrol.
 genereux et al., 2008, Jhydrol.
Best and worst of 120 alternate maps based on random sub-sampling distributions.

Our interpretation also is greatly influenced by the density of our measurements.

Kennedy et al., 2008, Journal of Hydrology

40 vertical temperature profilers

Sachin Karan, 2014, WRR
Table 4 – Review of techniques commonly used for estimating groundwater-surface-water interactions

<table>
<thead>
<tr>
<th>Method</th>
<th>Spatial scale</th>
<th>Temporal scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Techniques used in our field study</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conservative tracer tests (chemical)</td>
<td>$10^3 - 10^5$ m</td>
<td>min–mo</td>
</tr>
<tr>
<td>Reactive Raz–Rut tracer system</td>
<td>$10^{-1} - 10^3$ m</td>
<td>min–d</td>
</tr>
<tr>
<td>Mini drive-point (USGS MINIPOINT)</td>
<td>$10^{-1} - 10^9$ m</td>
<td>min–h</td>
</tr>
<tr>
<td>Piezometer (head)</td>
<td>$10^9 - 10^5$ m</td>
<td>h–mo</td>
</tr>
<tr>
<td>Streambed temperature (FO-DTS)</td>
<td>$10^{4} - 10^{6}$ m</td>
<td>s–mo</td>
</tr>
<tr>
<td>Streambed temperature (vertical drive-point)</td>
<td>$10^{-3} - 10^9$ m</td>
<td>s–mo</td>
</tr>
<tr>
<td>Electrical resistivity imaging</td>
<td>$10^{-1} - 10^3$ m</td>
<td>min–h</td>
</tr>
<tr>
<td>Seepage meter</td>
<td>$10^9 - 10^3$ m</td>
<td>h–wk</td>
</tr>
<tr>
<td>Differential discharge gauging (manual or automated)</td>
<td>$10^9 - 10^6$ m</td>
<td>min–y</td>
</tr>
</tbody>
</table>

Here are a few methods that can be used to quantify exchange between groundwater and surface water.

We need to match the scale of the method with the scale of the process or setting that we are interested in quantifying.
References cited


