Report as of FY2006 for 2006AL47B: "Investigating the Role of Surface-Groundwater Interactions on Surface Water Quality"

Publications

- Conference Proceedings:
  - Hogan, M. B., R. R. Goswami, K. G. Villholth, T. H. Illangasekare, and T. P. Clement, Understanding the Flow and Mixing Dynamics of Saline Water Discharge into Coastal Freshwater Aquifers, Proceedings of the SWIM/SWICA joint meeting, Sardinia, Italy, September 25-29, 2006.
  - Clement, T. P., R. R. Goswami, M. Hogan, Understanding the Dynamics of Freshwater and Saltwater Mixing Processes in Unconfined Aquifers - Laboratory Scale Model Results, Proceedings of the International Conference on MODFLOW and More 2006 Managing Ground Water Systems, Golden, Colorado, May 2006, P. 16-17.
- Articles in Refereed Scientific Journals:
  - Goswami, R. R. and T. P. Clement, Laboratory-scale Investigation of Saltwater Intrusion Dynamics, Water Resources Research, Vol. 43, W04418, doi:10.1029/2006WR005151, 2007.
- Dissertations:
  - Hogan, M. B., Understanding the flow and mixing dynamics of saline water discharge to coastal aquifers, MS Civil Engineering Thesis, Auburn University 2007

Report Follows

INVESTIGATING THE ROLE OF SURFACE-GROUNDWATER INTERACTIONS ON WATER QUALITY

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A. PROBLEM STATEMENT AND OBJECTIVES

In the state of Alabama, most of the population obtain their water supply from a combination of surface water and groundwater sources. Therefore, it is important to understand and solve the problems related to groundwater-surfacewater interactions. In recent years, there has been a growing interest in understanding the mechanisms involved in surfacewater/groundwater interactions since researchers have established that these interactions play a crucial role in controlling the behavior of contaminant transport in both systems. Surface/groundwater interactions can influence the downstream water quality significantly since the concentration distribution in both systems (stream or groundwater) can change due to the biogeochemical reactions that occur between the minerals/nutrients in the subsurface and the stream. In this project, we completed both theoretical and experimental investigations to quantify the contaminant exchange patterns between surfacewater and groundwater. The theoretical analysis was designed to measure the lateral path of a contaminant plume as it interacts between the surfacewater and groundwater along the flow path. Laboratory-scale experiments were completed to demonstrate the existence of a vertical transport pathway for a contaminant plume in the stream as it interacts with the subsurface water beneath it.

Recent natural disasters such as Katrina and the Asian-tsunami have created a need for understanding saline surfacewater transport into unconfined groundwater systems after a large inundation event. Therefore, in addition to studying the traditional stream-groundwater interaction pathways, we also explored the interactions between coastal surfacewater and groundwater during a hurricane-induced flooding event. Hurricane surge waves and tsunamis have the potential to inundate large areas of coastal aquifer region with saline water. Estimating the impacts of these flood waters on groundwater quality is a part of any disaster management program. Our second objective was to conduct multiple experiments to quantify the contaminant transport processes and associated times scales within a coastal unconfined aquifer after an inundation event. Controlled experiments were completed by discharging a surge wave over an unconfined aquifer. Observations were made to study the fate of the dense surfacewater as it migrated across the water table boundary.

B. RESEARCH METHODOLOGY AND RESULTS

B.1. Experimental setup to study groundwater stream interactions

To observe the vertical flow between surface water and hyporheic zone which lies under the streambed, we built a straight stream by using the small-scale plexi-glass model. We filled the plexi-glass model with uniform silica sand to represent the porous media and developed a straight channel cross-section within the material with a constant depth and cross-sectional area to simulate a stream segment shown in the schematic (see Figure 1). In this setup, we first maintained a constant flow rate at upstream and then injected a dye beneath the channel. We observed the vertical path of the dye within the streambed. We observed the path of the tracer as it was transported vertically within the stream bed. All of these conceptual experiments were completed to demonstrate the vertical exchange processes which were hypothesized in our theoretical model.

B.2. Experimental setup to study groundwater and coastal water interactions

Saline surfacewater flooding experiments were conducted in a rectangular flow tank. The tank was constructed using 6 mm thick Plexiglass™. The internal dimensions of the porous media region are: 53 cm (length) × 2.7 cm (width) × 30.5 cm (height). A conceptual diagram of the experimental setup is shown in Figure 2. The flow tank was divided into three distinct chambers: a central flow chamber containing the porous medium, and two constant head chambers containing salt and fresh waters. The constant head chambers are 5 cm long and are separated from the porous media chamber by two fine screens of mesh size US # 16. Uniform silica beads of average diameter 1.1 mm, obtained from Potter Industries Inc., were used as the porous medium. Self-adhesive measurement tapes were pasted on the sides and at the bottom of the tank to allow direct measurements. The experiments were recorded using Nikon Coolpix digital camera in a high resolution mode. The digital data allowed us to zoom and observe small-scale variations occurring at the millimeter scale.

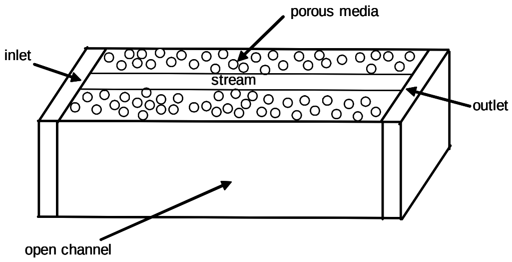

Fig 1. Experimental setup to study stream/GW interactions

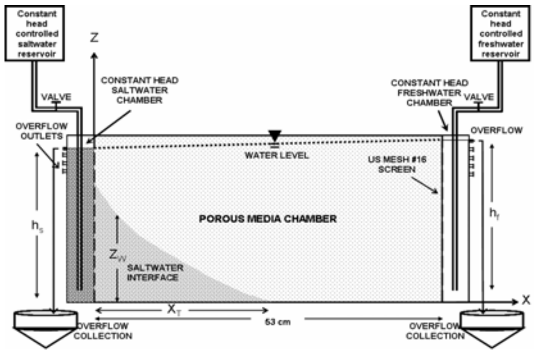

Fig 2. Experimental setup to study coastal-water/GW interactions

B.3. Results of the theoretical investigation

For steady state open channel flow over a permeable bed, there is an open channel – groundwater interaction mechanism for interface flow. This analysis should be considered as an order of magnitude analysis until more complete modeling and experimental verification is completed. For small vertical flow velocities it can be assumed that the variation of y(x) in the surface water defines the head variation in the ground water. Thus, Darcy's law for the groundwater flow and the gradually varied flow equation for open channel flow can be expressed in terms of y(x)

$q = -K\frac{dh}{dx} = -K\frac{dy}{dx}$, Darcy's law.

$\frac{dy}{dx} = \frac{S_0 - S_f}{1 - F^2}$, the gradually varied flow equation for open channel flow.

$F = \frac{v}{\sqrt{gy}}$ = the Froude number.

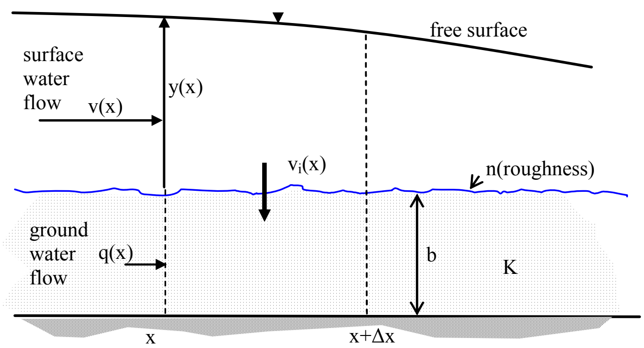

Figure 3. Surface and Ground Water Interaction: y(x) = surface water depth,
b = subsurface aquifer thickness, v(x) = surface water velocity, q(x) = subsurface Darcy veloclity, $v_i(x)$ = surface transfer velocity, K = aquifer hydraulic conductivity,
n = Mannings roughness coefficient for the open channel.

The preliminary laboratory data collected in this study have indicated the type of interface flow hypothesized in our theoretical analysis. This data is shown in Figure 4 below.

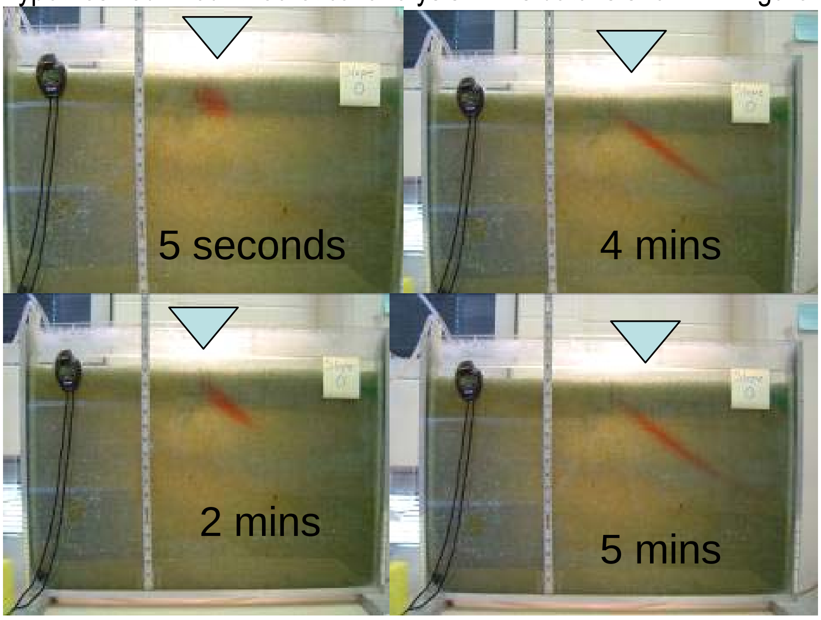

Figure 4. Laboratory data indicating vertical velocities induced by surfacewater flow

For open channel, steady state flow, the depth variation, y = y(x) is nonlinear. Darcy's law for the subsurface flow indicates that q = constant if the y(x) is linear. Thus, q is not constant which implies there must be some interface velocity between the surface water and the groundwater. Preliminary analysis indicates that this interface velocity is small and it can be either positive or negative describing flow from or into the ground water formation. Preliminary laboratory experiments have shown vertical flow velocity in porous media below the free surface flows. Enhanced physical-chemical modeling of contaminant transport between the surface and ground water depends on further quantification of laboratory and analytical descriptions of the scale of this interface transport velocity. For subcritical flow F < 1, and the further constraint that $v \ll (gy)^{0.5}$, then $1-F^2 \rightarrow 1$. This limiting case then can be analyzed to obtain an approximate method to explain a mechanism of surface water (open channel flow) and ground water flow under the channel bed. For these constraints two approximate expressions for interface flow can be derived.
Case 1: For horizontal channel: ($S_0 = 0$)

$$v_i = \frac{\left(bK\alpha^2 \frac{10}{3}\right)}{y^{23/3}}$$

Case 2: For a channel with constant bed slope, $S_o \neq 0$,

$$v_i = -bK\alpha \frac{10}{3} y^{-13/3}\left(S_0 - \alpha\, y^{-10/3}\right).$$

The results show that interface velocity may be positive or negative, that is into the aquifer or from the aquifer. It is true that for typical values of the physical parameters these calculated interface velocities are very small. Acting over large areas and over long time periods, the interface velocity could contribute to surface and ground water quality. Transient effects on the interface velocity can, however, be more significant. Water depths in the channels can change due to changes in hydrologic conditions in the watersheds and can change due to variable downstream depth controls. Downstream control depths change rapidly due to hurricane surge waves and tsunamis. These types of depth changes are also accompanied with the influence of density differences between the fresh water and dense coastal waters, which can augment the interface flow.

B.4. Results of dense coastal water and groundwater exchange experiments

The aim of the first set of experiments was to study the fate and transport of saline plume evolving from a surfacewater pond. The flow tank and the porous medium used in this study were similar to the one described in Figure 2. The saline water was supplied as a source to the surface of the porous media through a continuous volume displacement peristaltic pump at a constant rate. A small amount of red food coloring was added to the saltwater to differentiate the salty surfacewater from the fresh ground water. It is assumed that the contaminant source (i.e., flooded lagoon or the inundated region) is located at a distance inland such that the effects of the ocean water boundary can be ignored. Several experiments under various flow conditions were completed in this study. An example dataset for an unstable plume migrating from a dense surfacewater pond is shown in Figure 5.

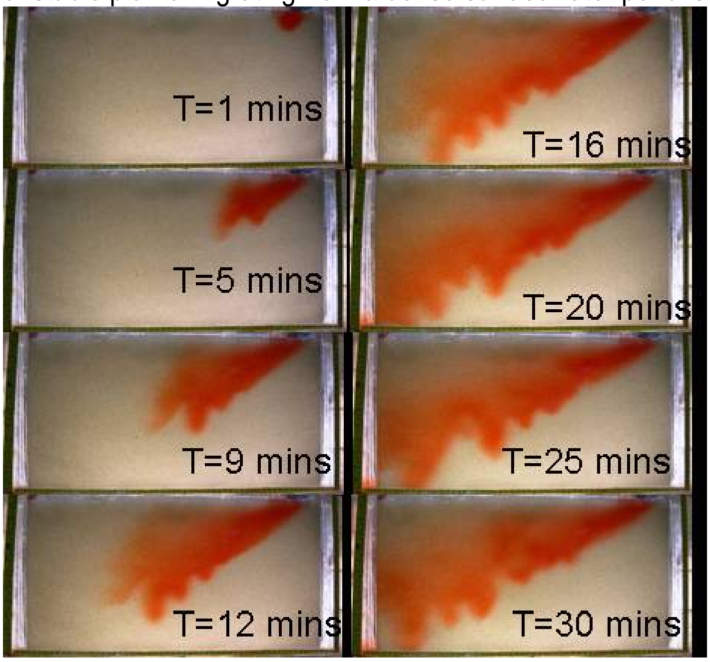

Figure 5: Dataset for an unstable plume

The aim of the second set of coastal water/ groundwater exchange experiments was to study the fate and transport of saline water dumped over a freshwater aquifer after a large-scale inundation event such as a hurricane or a tsunami wave. The flow container described above was also used in this inundation experiment. The surfacewater water flood was simulated by instantaneously distributing a fixed volume of saline water directly over the top boundary of the model. Experiments were performed under high- and low-flow groundwater flow conditions. The data shown in Figure 6 show the transport of this dense saline water over a time period of 11 minutes. Note that under high groundwater flow conditions the contaminant slug was transported quickly through the systems and formed a rather shallow contamination zone. On the other hand, when the ambient flow was low, the saline water migrated downward and contaminated larger volume of aquifer. There was also more intense fingering in the low flow case.

D. RESEARCH FINDINGS AND SIGNIFICANCE

The behavior of contaminant transport in streams is greatly influenced by the processes that exchange fluid between surface and ground waters. We derived an analytical approach to model the vertical exchange between a surfacewater body and the stream bed. The exchange process was also demonstrated through a conceptual experimental study. In the second phase of this work, we studied the interactions between groundwater and coastal waters. The recent natural disasters such as Katrina and the Asian-tsunami have created the need for understanding the saline water transport processes within an unconfined groundwater system, after a large-scale, surfacewater inundation event. We provide several detailed data sets to illustrate the interactions between a dense surfacewater body (e.g., ocean) with a local unconfined aquifer. The first type of experiment involves the study of saline water migration from surfacewater storage ponds located along coastal dunes. The second type of experiment involves simulation of saline water migration patterns into a local unconfined aquifer after a large-scale flooding event.

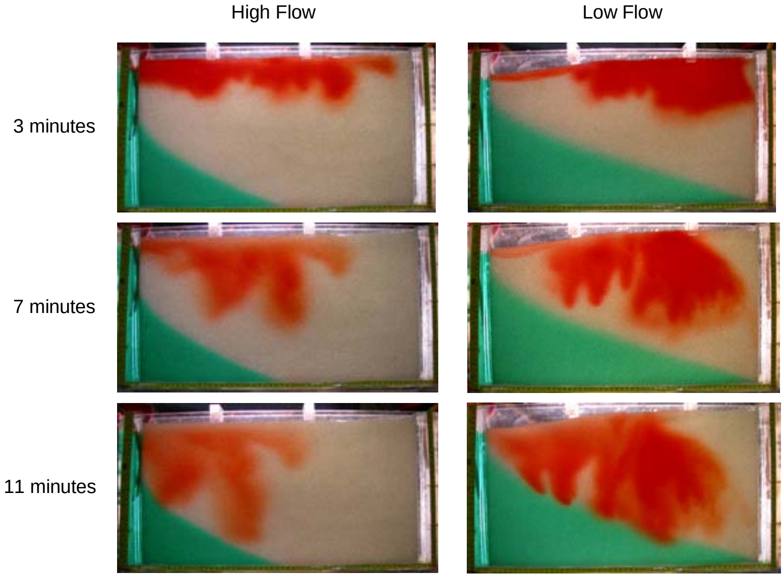

Figure 6: Beach face infiltration in a high GW flow (left photographs) and low GW flow conditions (right photographs)