Fate and Transport of Contaminants in a Stream−Aquifer System

Problem and Research Objectives

Streams and rivers transport sediments, natural organic matter, and, frequently, land-applied chemicals.

Many drinking-water wells located on streambanks and riverbanks induce a portion of the stream or river water to flow through the aquifer to well screens. The pumped well water is then a mixture of groundwater and induced infiltration water and is of a better quality than the stream or river water. This process is known as “riverbank filtration.”

Stream- and river-water contaminants are removed through straining, colloidal filtration, chemical precipitation, sorption, and microbial degradation. Also dilution is possible if the respective contaminants in the surface water are lower in concentration than in the groundwater. Riverbank filtration is a viable and low-cost water-treatment technology for water utilities.

As this natural filtration process works somewhat differently than engineered filtration systems, knowledge of the dynamic behavior of the system for various flow regimes of the stream or river is important for safe and sustainable operation. Advance understanding of the expected changes in water quality generated by scouring or bed clogging enables water utilities to better address filtrate quality during periods of flooding or heavy sedimentation.

Scouring and clogging of the stream or river bottom affect the rate of infiltration and the fate of the soil-resident or percolating contaminants. Scouring during floods can destroy the clogging layer and introduce oxygen-rich water into the aquifer, disturbing the previously established redox conditions. Conversely, a clogged streambed or riverbed would have a slower infiltration rate and a reduced flow compared to a normal streambed or riverbed.

It is not easy to study these processes in field settings because of high velocity in streams or rivers during high-flow events and our inability to accurately measure clogging and redox processes.

The research objectives were as follows:

(a) To retrofit a recirculating flume to serve as a model stream or river channel and attach a column to the channel bottom to simulate conditions in an aquifer under a streambed or riverbed;
(b) To study the impact of velocity profile on the scouring and deposition processes of particles;
(c) To study the redox conditions in the column as a function of stream velocity, particle-deposition rate, natural-organic-matter content of the recirculating water, and the travel distance;
(d) To examine the effect of channel-bed scouring on the change in the redox conditions of the upper portions of the column and its impact on water quality.

Methodology

Retrofitting of flume/column: A small recirculating flume (15-cm wide, 3.5-m long), available in the Hydraulics Laboratory of the University of Hawaiʻi at Mānoa Civil & Environmental Engineering Department, was retrofitted for this research and extended by 2.0 m.

This recirculating flume could be tilted to change the bed slope. A mechanically-controlled flap made it possible to control the water level on the bed. A 10-cm diameter column attached to the bed of the flume channel simulated the porous media typically present between the stream or river and the well screen. A layer of silica sand simulated the streambed or riverbed. A peristaltic pump drew water at a set rate from the bottom of the column.

Piezometers were placed in the sand bed and the column at 2.7 cm, 10.3 cm, and 12.8 cm below the bed to observe the head loss that occurred as water was pumped from the column. Water flowing out of the flume was collected in a tank and recirculated by another pump to provide water at the upstream end of the flume. Clogging of the bed was simulated by adding fine particles, such as streambed sediments and kaolinite, into the flow stream. Scouring was simulated by increasing the flow rate of the water being pumped into the flume to simulate a flood event.

Velocity impact on scour/deposition: The sediment composition and flow velocity in the recirculation system were adjusted to have distinct particle distributions in the flow systems. For each set of experiments, the corresponding heads in piezometers at various depths below the channel were examined. A series of experiments were conducted in which the velocity of flow was varied from 0.18 m/s to 0.27 m/s. These changes resulted in a concurrent rise in water depth in the flume from 13.3 cm to 16.7 cm at a bed slope of 1.15%.

When the flow velocity was increased from 0.18 m/s to 0.27 m/s the hydraulic heads measured at the piezometers rapidly decreased with the flow showing increased head losses in the column. (Figure 1). This is contrary to the general understanding that a higher flow in the channel would decrease head loss in the column packed with the porous media.

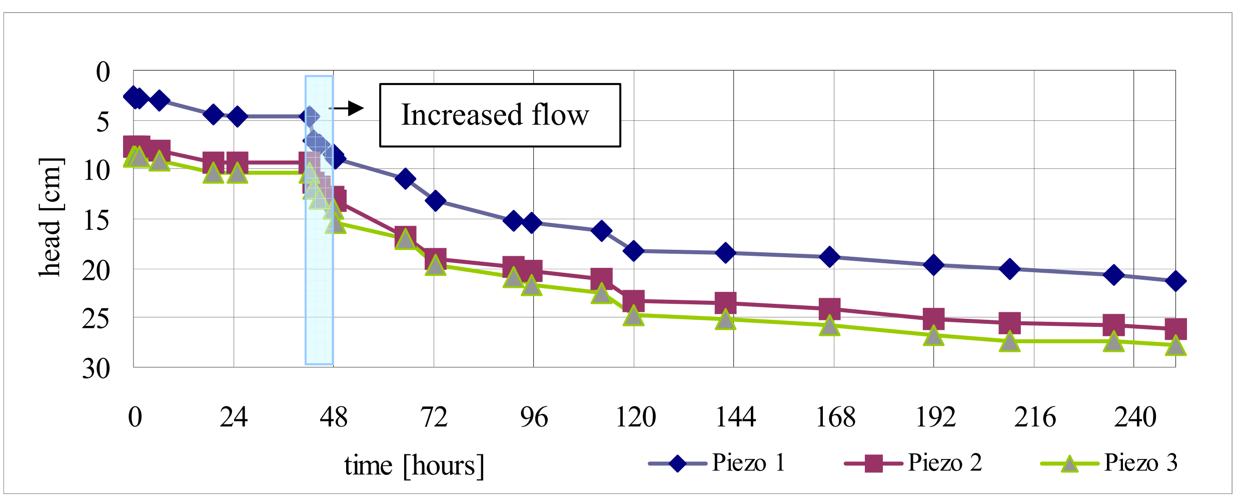

Figure 1: Head loss along the column for a 5-hour increased flow in the flume.
(The blue-shaded segment represents the 5 hours during which the flow was increased.)

Increasing the flow velocity beyond 0.3 m/s resulted in unstable flows and the formation of undulating sand bars on the bed.

It was found that, within the test limits of 0.18 m/s to 0.27 m/s, as the flow was increased the head loss in the top 2.7 cm sand layer above the first piezometer rapidly increased (see the shaded area in Figure 1). The simulated flow was not sufficient to cause scouring of the bed so attrition of the clogging layer was not evident, rather it further increased clogging.

Resumption of the original flow velocity did not reduce the head loss, so the clogging appeared to be nonreversible under the flow conditions prevailing in the flume throughout the observed time. No external sediments were added into the flume. The bed material was made up of well-sorted sand of mean diameter, d_{50} = 0.25 mm, coefficient of uniformity, C_u = 1.8, and particle density of 2.63.

Another run of the experiment was done to investigate the effect of the introduction of suspended sediment in the flowing water. Stream-bed sediment from Honolulu's Mānoa Stream was obtained from under the East Mānoa Road bridge and wet sieved to separate the material passing through 60 mesh sieve (sieve passing 250 µm). This fine sediment was periodically added to the flowing water in the flume to maintain a turbidity of 175 Nephelometric Turbidity Units (NTU). The heads observed in the piezometers are shown in Figure 2.

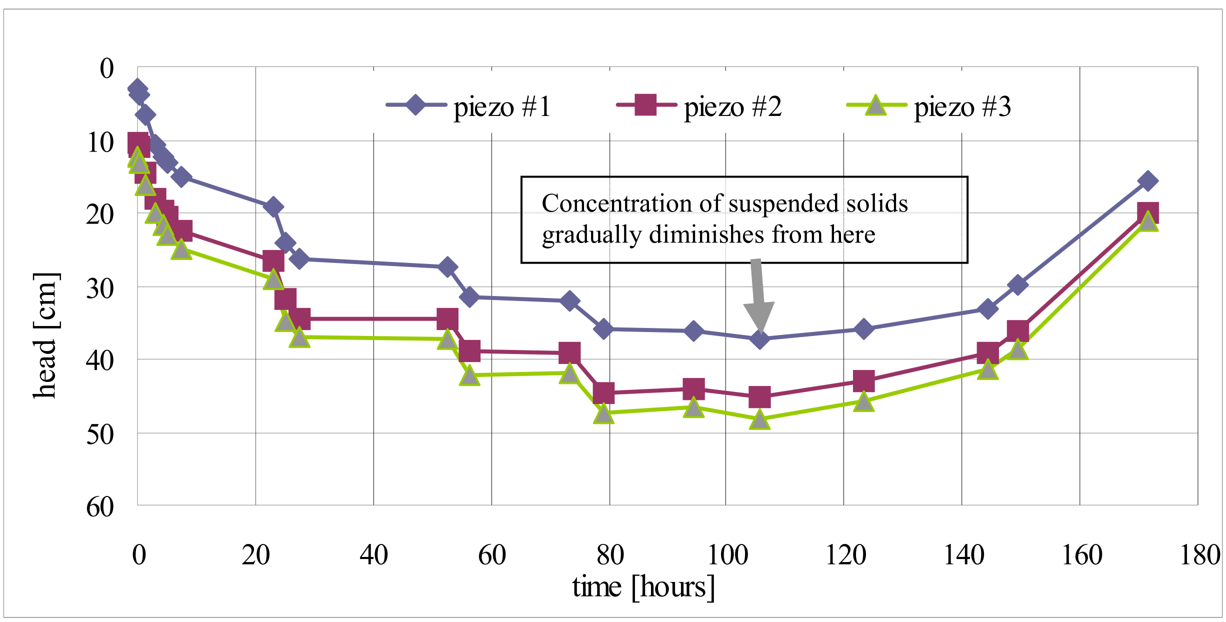

Figure 2: Head loss along the column for channel flow with additional sediments.

Regular additions of the sediments were required to keep the turbidity near a constant value. It was seen that the hydraulic heads in the piezometers dropped sharply every time sediment was added to the flowing water. After about 100 hours of running the experiment no more additional sediments were added and the flowing water gradually cleared up. This also resulted in a gradual recovery of the piezometric heads. So the head losses were seen to be reversible for the case of addition of external sediments.

It was further observed that the addition of sediments expedited the drop in hydraulic heads. It took about 24 hours for the head to drop 5 cm in the first piezometers (Figure 1), shown as Head #1, while it dropped about 20 cm in the first 24 hours with the sediment-laden flow (Figure 2).

The effect of the hydraulic head loss was also used to investigate the distribution of hydraulic conductivity (K) along the depth of the column during the addition of sediments to the flowing water. Three peizomteric measurements were used to divide the column into three layers. The top layer was 2.7 cm thick above the first piezometer, then the second layer was 2.7 cm to 10.3 cm above the second piezometer, and the third layer was 10.3 cm to 12.3 cm above the third piezometer.

It was found, as shown in Figure 3, that the reduction in hydraulic conductivity occurred entirely in the top layer of 2.7 cm, where the hydraulic conductivity reduced by an order of magnitude from 0.03 cm/s to about 0.003 cm/s. The hydraulic conductivities in the subsequent layers remained almost the same at above 0.03 cm/s.

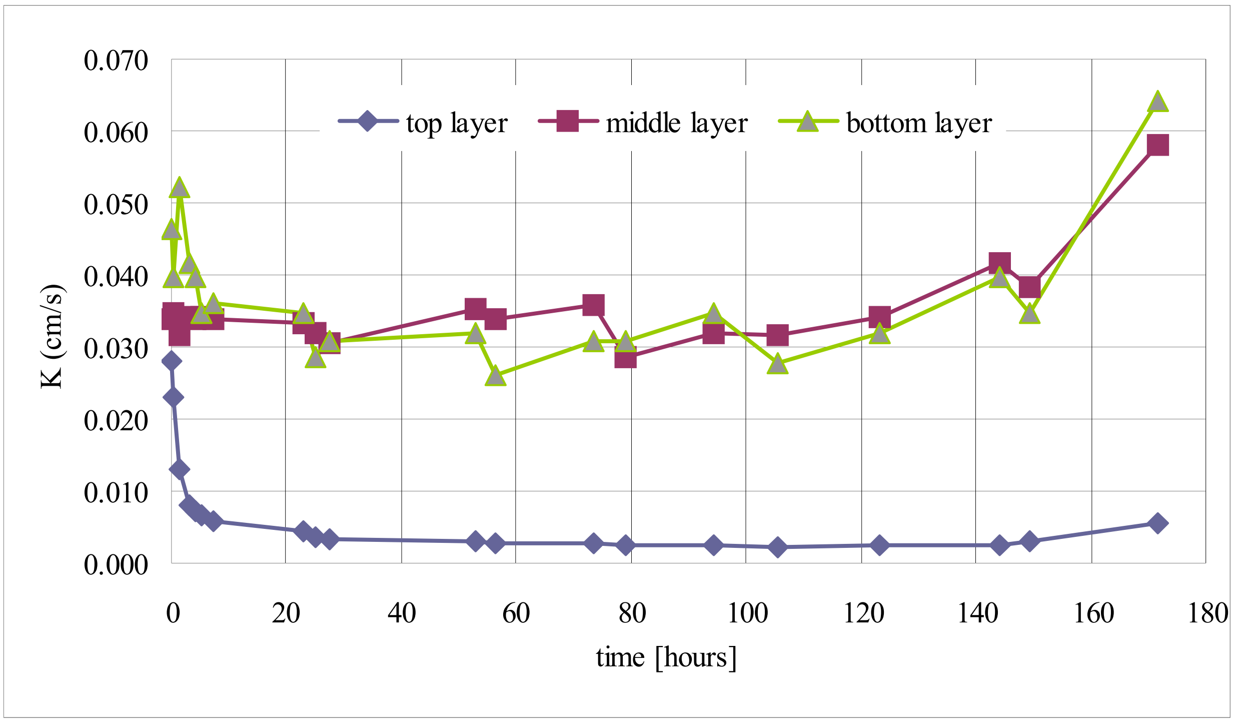

Figure 3: Variation of hydraulic conductivity (K) with time in different layers of the column

Redox dynamics: In further experiments to be conducted next year, redox parameters that will be measured include dissolved oxygen, oxidation-reduction potential, dissolved organic carbon (DOC), and selected redox-sensitive compounds or elements such as nitrates, nitrites, ammonium, iron, and manganese.

Frequent measurements of the velocity profile and the size distribution of the flowing particles should provide a good indication of the small-particle load in the flow stream. Head loss due to particle clogging of the column surface will be correlated with the sizes of the flowing particles. Redox parameters of the flowing water and the sampled water will be correlated with the velocity profile in the channel, particle-size distribution, DOC in the channel water, and water extraction rate through the column.

Scouring effects on redox: In additional further experiments to be conducted next year, once a redox regime (based on a flow regime in the channel, DOC content of the water, and the sediment load in the channel water) in the column is established, conditions in the channels will be changed to that of incipient scour. Head loss in the column will be examined and selected redox parameters in the column will be monitored. Following a given period of disturbance (i.e., simulation of a flood passage), the time needed to re-establish a redox condition that is conducive for denitrification and the degradation of other chemicals will be examined.

Principal Findings and Significance

Retrofitting of the flume/column and studies of velocity impact on scour/deposition are nearly complete. A no-cost extension has been requested to complete the studies of redox dynamics and of scouring effects on redox during the next reporting period.

Findings indicate that the clogging layer is developed in the sand bed in a very thin top layer only. Reduction in the hydraulic conductivity of the top layer of the column by an order of magnitude was observed. Clogging developed with the addition of fine sediments (higher turbidity) was found to be reversible. Head losses decreased as the turbidity was reduced.

Head loss also increased in the top layer when the flow rate in the flume was increased—however these losses were not recovered when the flow reverted to the lesser discharge. This warrants a closer look at the different processes of bed clogging and a more detailed study of the mechanisms of clogging.

Publications Cited in the Synopsis

n/a