Influence of geological heterogeneity on the saltwater freshwater interface position in coastal aquifers – physical experiments and numerical modeling

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ABSTRACT

Three realizations of a heterogeneous coastal aquifer were simulated by sand tank experiments, using three types of sands with different hydraulic properties. For each of the three experiments, the horizontal dimension (length) of the sand compartments was varied (9 cm, 18 cm, and 27 cm). It was observed that an increase in the lateral dimension of the sand compartments caused the salt water wedge to intrude further inland. For each set-up, five sea level heights were applied and the resulting wedge geometry monitored until steady-state was reached. As expected, an increase of the sea level led to a farther inland saltwater propagation. The results obtained from the physical model were successfully compared to numerical simulations. The numerical results for a homogeneous case with averaged hydraulic properties show an overall farther saltwater intrusion than for the heterogeneous cases.

INTRODUCTION

The influence of different length scales in geological heterogeneity on the salt- and freshwater interface (SFI) position was studied. Regarding the interface and the wedge toe position, as a measure of the saltwater intrusion length, aquifers with larger hydraulic conductivities are clearly more prone to saltwater intrusion than aquifers with lower conductivity. Considering geological heterogeneities of an aquifer, the research question we address here is how the lateral extent of sedimentary compartments with different hydraulic conductivities affects the intrusion of saltwater. This is especially interesting for deltaic coastal zones, e.g. the Ganges Delta, Bangladesh, with its strongly heterogeneous sedimentation patterns.

METHODS

The experimental set-up was based on Stoeckl and Houben (2012). An acrylic tank with a width of 5 cm was filled with three types of sand of different hydraulic conductivity, which were determined by granulometric analysis in the lab: fine sand ($K = 165\ m{\cdot}d^{-1}$), medium sand ($K = 355\ m{\cdot}d^{-1}$), and coarse sand ($K = 1229\ m{\cdot}d^{-1}$). The sands were separately backfilled into the tank, forming a trapezoidal shaped aquifer with a top-length of 1.18 m, a bottom-length of 0.62 and a height of 0.35 m. An angle of 32° was measured for the sloping beach face at the left side of the aquifer, where the ocean was simulated by colored (red) saltwater with a density of $1025\ kg{\cdot}m^{-3}$. Freshwater recharge (yellow, blue) with a density of $1000\ kg{\cdot}m^{-3}$ was applied to the top of the aquifer, using a peristaltic pump (Ismatec BVP, Germany). A constant pumping rate of 1.8 liter/hour was used. Four different saltwater-levels were applied in each experiment (0.210 m, 0.245 m and 0.280 m and 0.315 m above model bottom).

Three different experiments were conducted, varying the horizontal length of the rectangular sand compartments of the aquifer. Keeping the height of 3.5 cm constant for all compartments, a length of 9 cm, 18 cm and 27 cm was chosen for the first, second and third experiment, respectively. This, in turn, increased the anisotropy of the system. Care was taken, that compartments of the same type of sand did not overlay each other.

A numerical model was set up in FEFLOW 6.1 (Diersch, 2005). The finite element mesh with 10,000 elements was generated using the triangular grid builder. The initial time step length was 1 s and the maximum time step length was 3 s. A constant fluid flux boundary condition was assigned to the top of the trapezoidal polygon. The recharge rate was assigned to -1.73 m d^{-1}. The saltwater heads assigned to the left boundary were 0.210 m, 0.245 m, 0.280 m and 0.315 m. For modeling flow in the unsaturated zone, van Genuchten parameters of α = 20, 25 and 30 and n = 2, 2.5 and 3 were assigned for the fine, medium and coarse sand, respectively (van Genuchten, 1980). Coordinates of the SFI geometry were read off manually.

RESULTS

Figure 1 shows a relationship between the length of the sand compartments and the extent of saltwater intrusion: Increasing the compartment length resulted in a movement of the interface (and the wedge toe position) farther into the aquifer, reducing the volume of freshwater.

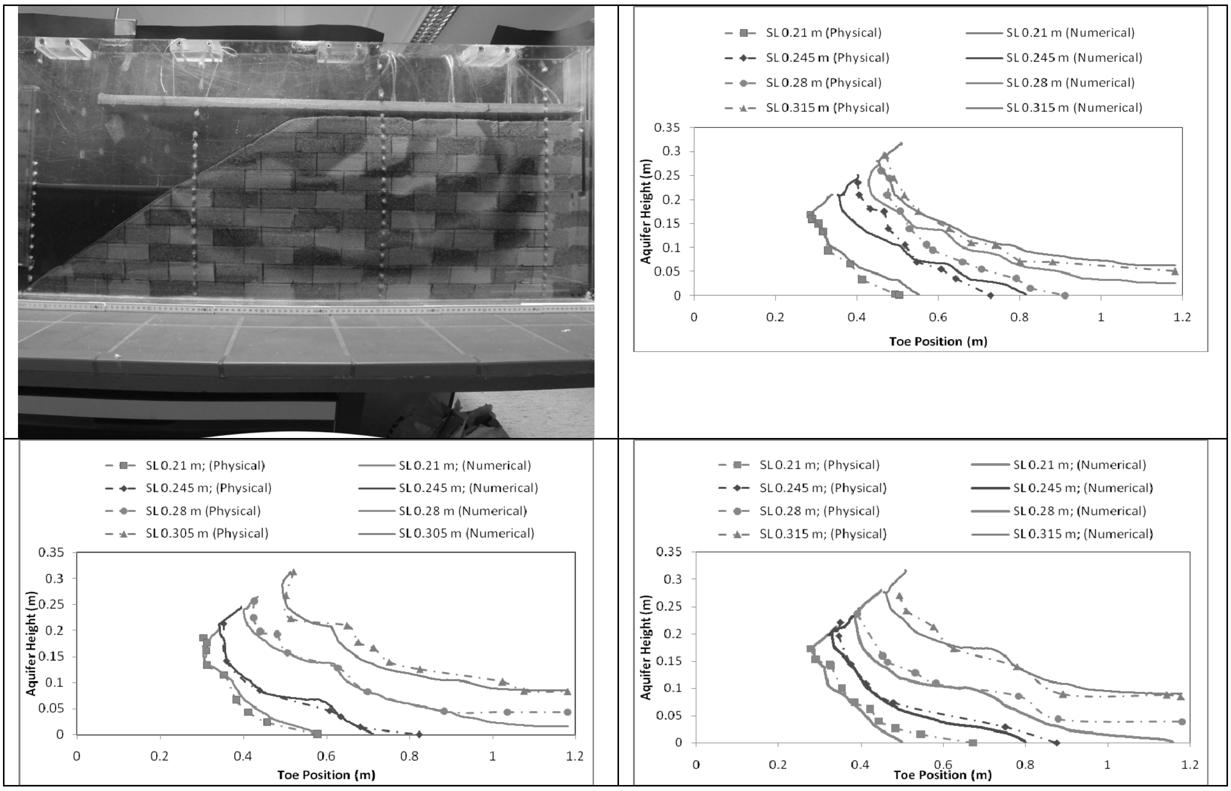

Figure 1: SFI geometry as a function of compartment length and for different sea levels in a) physical model with a compartment length of 9 cm (Experiment 1); results: b) Experiment 1 (compartment length 9 cm); c) Experiment 2 (18 cm); d) Experiment 3 (27 cm).

Further, it was found that by increasing the saltwater-level the interface became less steep, finally leading to its detachment from the impermeable bottom. The interface also became smoother indicating the influence of the length scale of the anisotropy (longer compartments, less bending of the SFI).

Figure 2 shows the SFI for experiments 1, 2 and 3, separated by the applied sea levels (a to d). In addition, the SFI geometry derived from a numerical model of a homogeneous aquifer, having an average hydraulic conductivity of the fine, medium and coarse sand is shown (Fig. 2). The results show, that a) with increasing sea level, the differences between the simulated homogeneous and observed heterogeneous intrusion length were reduced. Interestingly the interface position of the homogeneous aquifer always showed farther saltwater intrusion than for the heterogeneous cases.

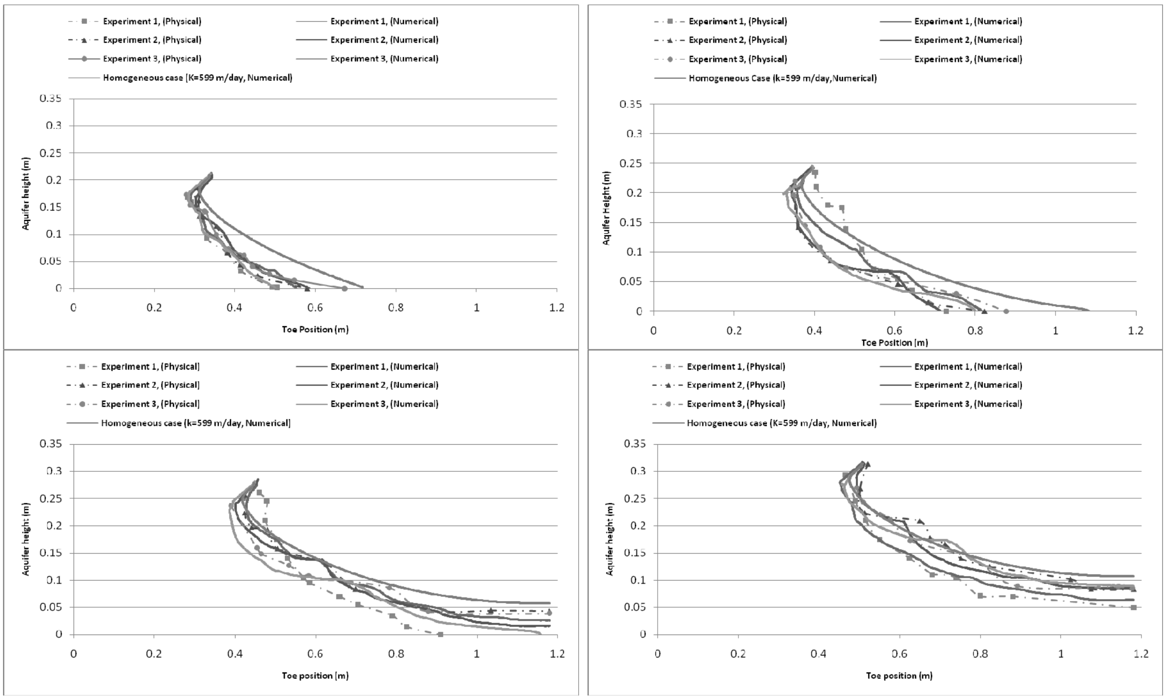

Figure 2: SFI positions in physical and numerical models as a function of sea level a) sea level 0.210 m, b) 0.245 m, c) 0.280 m, and d) 0.315 m with a constant recharge of 1.73 m/day (a simulated interface geometry of a homogeneous case is also included, orange curve)

DISCUSSION AND CONCLUSIONS

Results of sea level rise scenarios showed that with a higher sea level, the saltwater intrusion reached further inland. A good agreement between the physical and numerical model results was observed.

Results for the three different experiments with different compartment lengths (9 cm, 18 cm and 27 cm) showed that the saltwater intrusion reached farther inland with longer compartment sizes. This on the other hand means that aquifers with smaller heterogeneities (short horizontal compartment length) are less vulnerable to saltwater intrusion.

The numerical model results, however, revealed that for a homogeneous aquifer with average aquifer properties, sea water intrusion reached even farther than for all heterogeneous cases. This lead to the assumption that a “tipping point” separating homogeneous and heterogeneous aquifers should exist: when compartments fall below a certain length scale and the representative elementary volume is small enough, the system becomes a “homogeneous” aquifer. Therefore it is assumed that the wedge toe length increases again when compartment sizes are further shortened. This, however, could not be resolved with our limited set of experiments.

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