Hydrogeological features of freshwater lenses on volcanic islands - physical and numerical modeling

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ABSTRACT

We conducted sandtank experiments and numerical model simulations of three typical hydrogeological features of freshwater lenses found on volcanic islands of the Hawaiian type. We investigated the effects of impermeable sheet intrusions (dikes), fringing reefs, and saltwater overwash during storms. The sandtank experiments of the first two cases could be modeled successfully using a 2D numerical model. Although our sandtank is only 5 cm wide, the overwash case showed strong 3D effects, which could not be recreated by the 2D model.

INTRODUCTION

The hydrogeology of volcanic islands is strongly influenced by the presence of lava tubes, volcanic layers of strongly variable hydraulic conductivity (e.g. porous cinder layers vs. fractured Aa lava flows), fringing reefs, and dikes.

We conducted sandtank experiments, followed by numerical models, of three typical hydrogeological features of freshwater lenses, oriented on the Island of Savaií, Samoa:

(A) Impermeable volcanic dike: secondary sheeted vertical intrusions (dikes) may separate the aquifer into several compartments. Head differences across dikes can be large.
(B) Fringing reef: coral reefs often rim volcanic islands. While the reef material can be quite permeable, the hydraulic conductivity of the basalt may be even larger. The fringing reef may therefore act as a local confining layer.
(C) Saltwater overwash: during storm events, seawater may be infiltrated through the soil to the top of freshwater aquifers.

METHODS

The set-up of the sandtank experiments is based on Stoeckl and Houben (2012). Experiments were carried out using an acrylic glass box (2.0 m length, 0.5 m height and 0.05 m width). The freshwater and saltwater densities were 1.000 and 1.025 g/cm³. To visualize the interaction of saltwater and freshwater, tracer colorants were added at a concentration of 0.3 g tracer per liter. For Cases A and B, the aquifer was initially saturated with saltwater (red) and freshwater recharge was applied from the top of the model by drippers (yellow and blue). Several recharge rates were applied consecutively.

For numerical modeling, the finite element model FEFLOW 6.1 (Diersch 2005) was used for Cases A and B, and the simulation model Crunch for Case C.

Case A: The impermeable dyke feature was constructed with plasticine and was installed into the model prior to infilling the model with medium sand, the latter representing the basaltic aquifer (Fig. 1).

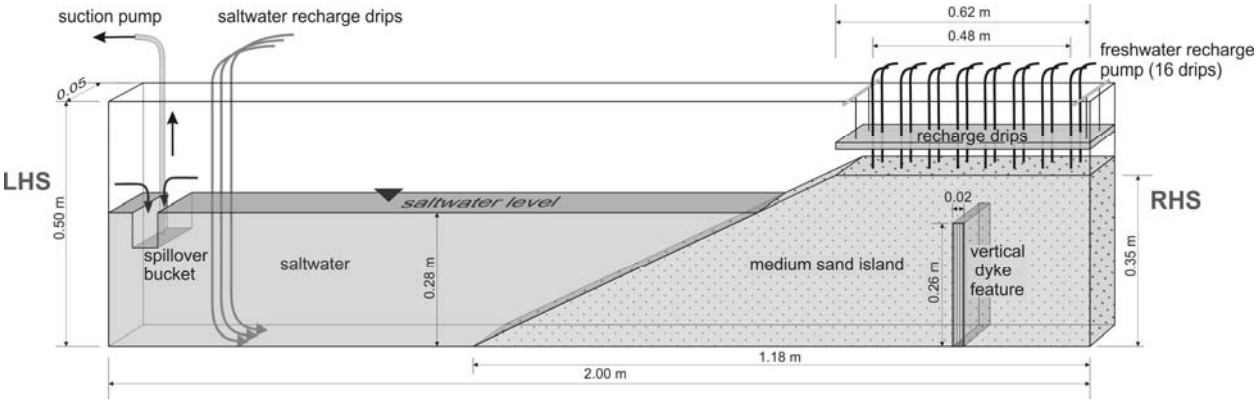

Figure 1. Physical model setup for Case A.

Case B: For the fringing reef case, the sandbox was filled with coarse sand, representing the basaltic aquifer. Fine sand, representing the fringing reef, was added at the coast (Fig. 2).

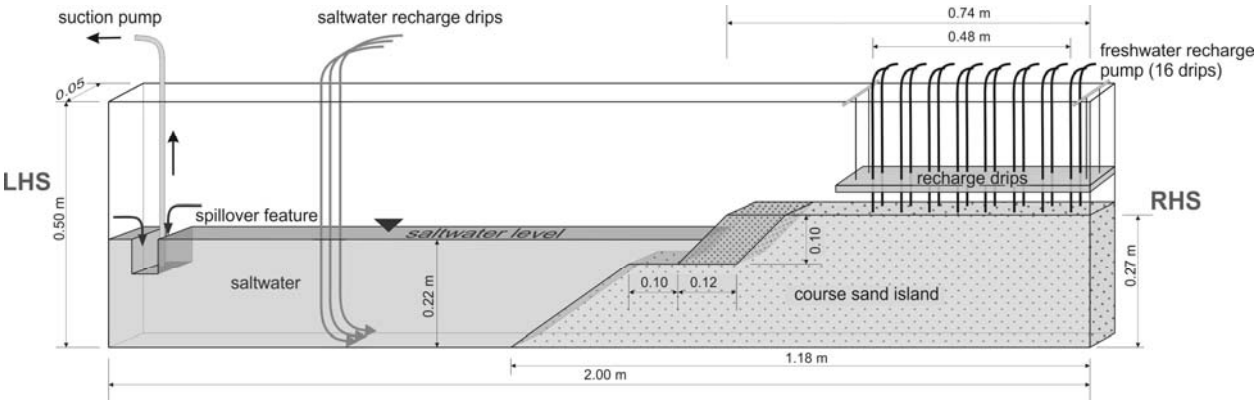

Figure 2. Physical model setup for Case B.

Case C: The tank was completely filled with sand and initially saturated with freshwater. Recharge was applied from the right side to create horizontal flow. Overwash was simulated by injecting saltwater into the upper half of the recharge valves (Fig. 3).

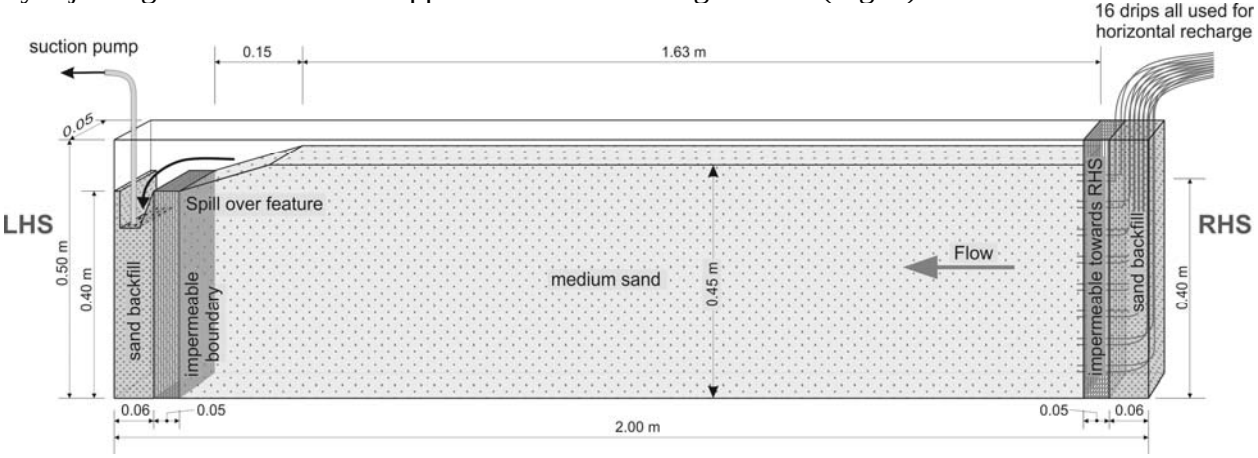

Figure 3. Physical model setup for Case C.

RESULTS

Case A. Impermeable vertical dike

The effects of an impermeable dikes became clearly visible, especially the vertical flow components. The resulting interface geometry, for a set of four recharge rates, was successfully recreated with a 2D numerical model (Fig. 4). The slight differences between the physical and numerical results can be attributed to limited observational accuracy.

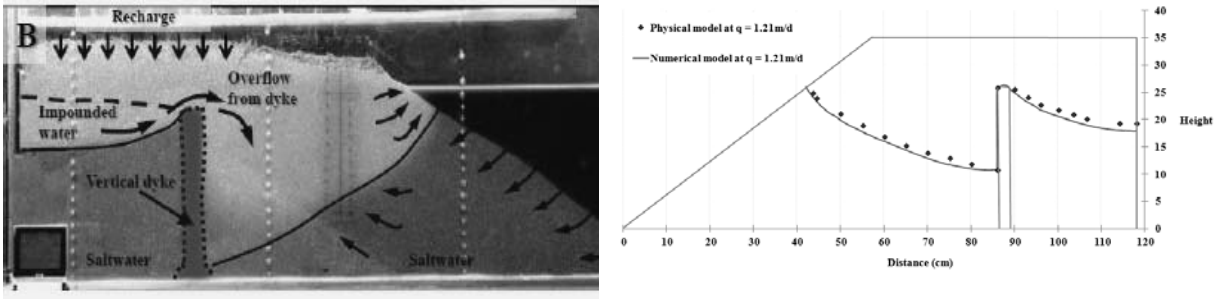

Figure 4. Left: Interface geometry at equilibrium (recharge rate: 1.21 m/d). Right: Comparison of experimental results and numerical model (flipped).

Case B. Fringing reef

A large proportion of the outflowing freshwater passes underneath the less permeable reef and forms submarine springs, a feature also common in Samoa. The comparison between numerical and physical models yielded a good fit for all recharge rates studied (Fig 5).

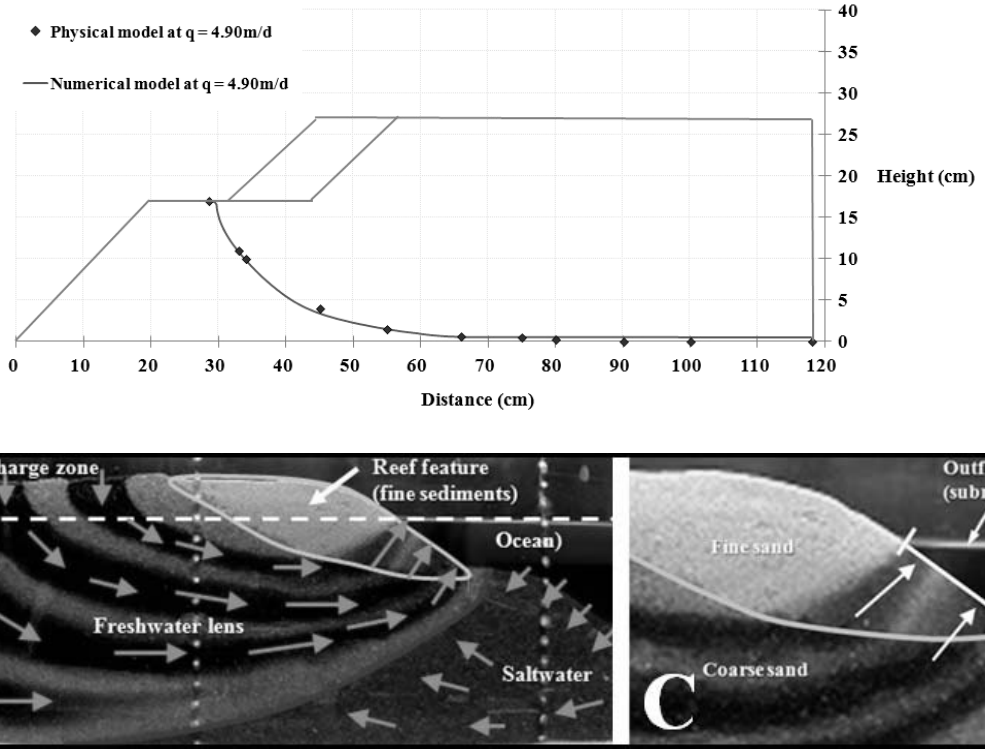

Figure 5. Top: Comparison of experimental results and numerical model (flipped). Below: flow paths at equilibrium (recharge rate: 4.90 m/d).

Case C. Saltwater overwash onto horizontally flowing freshwater

Although the sandtank is only five centimeters wide, strong 3D effects occurred. Saline water flowed downwards on one side of the model, while freshwater rose on the opposite side (Fig. 6). This phenomenon occurred in several experimental runs, using different flow rates and salinity contrasts. Transient fingering was also visible. A 2D numerical model was therefore not able to simulate the outcome of the experiments. Clearly, a 3D approach would be needed.

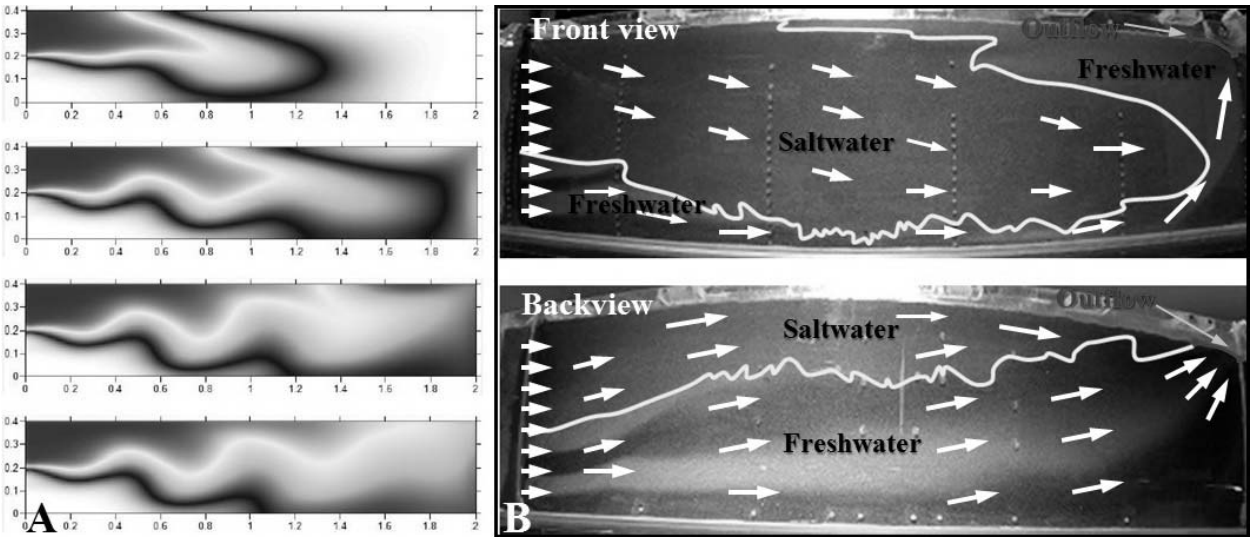

Figure 6. (A) Numerical 2D model, (B) front view, and (C) back view of sandtank experiment. Total recharge: 1.94 m/d.

DISCUSSION AND CONCLUSIONS

Sandtank experiments and numerical models of three typical hydrogeological features of freshwater lenses on volcanic islands were compared. While the results of the sandtank experiments on impermeable sheet intrusions (dikes) and fringing reefs could be modeled successfully using a 2D FEFLOW model, the saltwater overwash case showed strong 3D effects, even in our sandtank of only 5 cm width, and the numerical 2D model was unable to recreate the experimental results.

REFERENCES

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