Sandtank experiments and numerical modeling of coastal aquifer heterogeneity: fringing reefs, vertical flow barriers and structured conductivity fields

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ABSTRACT
The geological heterogeneity of coastal aquifers can strongly affect the flow patterns of groundwater. It can be related to discrete features such as faults and fractures but also to a more or less statistical distribution of the hydraulic conductivity field, e.g. caused by the sedimentation patterns of rivers and deltas. The shape and the position of the interface between saltwater and freshwater, as well as the location and flux rate of freshwater discharge to the ocean can be affected by heterogeneity.

Fringing reefs, a common feature of volcanic islands, can act as caprock for the underlying main aquifers. This can lead to freshwater discharging both at the beach face and through submarine springs. That, in turn, influences the distribution and transport of nutrients in coastal environments. Vertical impermeable barriers such as faults, dykes or underground cut-off walls cause an impoundment of fresh groundwater and a compartmentalization of the aquifer, evidenced by significant jumps in water level over short distances, but also to a delayed expulsion of saline water from the landward side. Compared to homogeneous aquifers, spatially distributed conductivity fields not only alter the shape of the interface but also the wedge toe length of the saltwater wedge. Higher effective transmissivities, resulting from longer compartment lengths cause further landward intrusion of the wedge toe.

INTRODUCTION
Many models of coastal groundwater flow, especially analytical equations, assume a homogeneous aquifer. Field evidence, however, clearly shows that this if often not a valid assumption. Discrete features such as faults, fractures, dykes and artificial cut-off walls can dramatically alter flow patterns on a local scale. Low-permeability coastal deposits, such as fringing reefs or detrital material, can act as cap rocks for coastal aquifers. Fluvial and deltaic sedimentation patterns can lead to a strong compartmentalization of hydraulic conductivity. All these heterogeneities have in common that, at the field scale, their influence is difficult to quantify from the usually small numbers of drillings, hydraulic tests and geophysical surveys. Numerical models could overcome these limitations but often the available geological model is not sufficiently detailed enough to fully describe the hydraulic conductivity field. Therefore, as an intermediate step, we devised a set of physical sandtank experiments that reveal the general effects of three typical geological heterogeneity features (Chowdury et al. 2014; Mariner et al. 2014; Houben et al. 2018):

(a) Fringing reefs: coral reefs and detrital deposits often occur around the coastline of (volcanic) islands. While the material can be quite permeable, it may be significantly less
permeable than the underlying main aquifer, e.g. basalt. The fringing reef may therefore act as a local cap rock.

(b) Impermeable vertical barrier: vertical sheeted intrusions (dykes) are common in volcanic islands of the Hawaiian type but can also occur in sedimentary host rocks. Underground cut-off walls have a similar effect.

(c) Structured conductivity fields as a simplified emulation of the heterogeneous hydraulic conductivity fields commonly found in fluvial and deltaic deposits.

METHODS

The general experimental set-up is based on the sandtank experiments presented by Stoeckl and Houben (2012), using an acrylic glass box of 2.0 m length, 0.5 m height and 0.05 m width. The aquifer is initially saturated with saline water. Freshwater recharge is applied to the top of the aquifer by drippers, using a peristaltic pump. The numerical models were set up using FEFLOW 6.1 (Diersch, 2005).

![Set-up of the sandtank experiments for the three scenarios: a) fringing reef, b) vertical barrier, c) structured conductivity field (modified after Houben et al. 2018).](image)

For the fringing reef, the sandtank was filled with homogeneous medium sand, representing the main island aquifer. A fine sand body, representing the fringing reef, was placed at the
coast (Fig. 1a). Four freshwater recharge rates were applied: 1.21, 2.69, 3.70 and 4.90 m/d, while the sea level was kept constant (details see Mariner et al. 2014; Houben et al. 2018).

The vertical impermeable flow barrier was constructed using plasticine and installed into an otherwise homogeneous medium sand aquifer (Fig. 1b). The same four recharge rates as described above and a constant sea level were applied (details see Mariner et al. 2014; Houben et al. 2018).

For the structured hydraulic conductivity field, three types of sand (fine, medium, coarse) with different hydraulic conductivities were used (Fig. 1c). Three experiments, varying the horizontal length of the individual sand compartments (9, 18 and 27 cm), were conducted, while keeping a constant compartment height of 3.5 cm. Four different saltwater levels were applied (0.210, 0.245, 0.280 and 0.315 m above base) for each experiment. The recharge rate was set to 1.73 m/d, although an additional experiment with a rate of 3.36 m/d was performed for sea level of 0.315 m (details see Chowdury et al. 2014; Houben et al. 2018).

RESULTS

Fringing reef

The fringing reef redistributes groundwater flow at the discharge zone. Despite being comprised of permeable fine sand, it is significantly less permeable than the main aquifer. Therefore, a large proportion of freshwater transiting through the main aquifer passes underneath the reef and discharges offshore into the ocean. Therefore, submarine springs are likely to be found at the outer rim of such reef. Field observations from various coastal zones worldwide confirm this (references see Houben et al. 2018). With increasing groundwater recharge, the ratio of discharge through and below the reef changes. Except for the lowest recharge rate, where reef flow dominates, discharge rates through and below the reef are roughly similar. If one only compares the flow through the node at the beach face to the strongest submarine outflow node of the numerical model, the latter yields almost twice as much freshwater, except for the lowest recharge rate. This confirms field data of strong offshore springs in fringing reef situations (references see Houben et al. 2018). The location and flow rate of freshwater discharging at reefs and lagoons are important factors for their ecology, since nutrient input can disrupt coral growth, e.g. through algal blooms.

Vertical flow barriers

Vertical flow barriers lead to a compartmentalization of coastal aquifers and can cause strong local gradient jumps.

The initially present saltwater is replaced much more slowly on the landward side of the barrier than on the seaward side. Therefore, it may become entrapped there at depth for extended periods of time. The depth to the interface can thus differ significantly on both sides of the barrier. However, continuous but slow dispersive entrainment of saltwater from the volume stored on the landward side will occur. This leads to a local widening of the mixing zone on the seaward side of the barrier.

Structured conductivity fields

Structured variations of the hydraulic conductivity field induce a stepped interface. Increased compartment lengths induce a more pronounced deflection of the interface into the
horizontal direction. Therefore, the wedge geometry deviates from that of a homogeneous aquifer, although for short compartment lengths this deviation is rather small.

The sandtank and numerical models of this study show a landward propagation of the saline wedge with increasing compartment length. Longer compartment lengths induce higher transmissivities and thus a decrease of freshwater heads. Following the Ghijsen-Herzberg principle, lower freshwater heads induce a rise of the interface, leading to a landward migration of the saltwater wedge. Higher sea levels lead to a proportional increase of the wedge toe length. Our experiments confirm qualitatively an analytical model by Strack (1976) for a homogeneous aquifer and field-scale numerical models of heterogeneous aquifers (e.g. Pool et al. 2015).

DISCUSSION AND CONCLUSIONS
Our generalized models of natural heterogeneities are useful for developing conceptual models of actual coastal aquifers, e.g. for situations resembling the Hawaiian Islands or deltaic-fluvial coastal sediments. The deviation of flow patterns caused by geological heterogeneities should be taken into account when planning groundwater extraction, delineating protection zones and assessing contaminant transport to coastal ecosystems.

REFERENCES


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