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Experiments and modeling of freshwater lenses in layered aquifers: Steady state interface geometry

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SUMMARY

The interface geometry of freshwater lenses in layered aquifers was investigated by physical 2D laboratory experiments. The resulting steady-state geometries of the lenses were compared to existing analytical expressions from Dupuit–Ghyben–Herzberg (DGH) analysis of strip-island lenses for various cases of heterogeneity. Despite the vertical exaggeration of the physical models, which would seem to vitiate the assumption of vertical equipotentials, the fits with the DGH models were generally satisfactory. Observed deviations between the analytical and physical models can be attributed mainly to outflow zones along the shore line, which are not considered in the analytical models. As unconfined natural lenses have small outflow zones compared to their overall dimensions, and flow is mostly horizontal, the DGH analytical models should perform even better at full scale. Numerical models that do consider the outflow face generally gave a good fit to the physical models.

1. Introduction

The oceans of the world contain some 130,000 islands which host around 500 million people (UNEP-WCMC). About half of the worlds population lives within 100 km of the ocean coast, and this percentage can be expected to increase with population growth and migration towards coastal towns. Rising living standards and increasing industrial development combined with effects of droughts will result in additional pressure on the water resources of these regions (e.g., Maas, 2007; Oude Essink et al., 2010). In many cases, groundwater is already the only reliable resource for the freshwater supply of the population. Coastal and island freshwater resources, however, are in dynamic hydraulic equilibrium with underlying saline groundwater. Non-sustainable use of freshwater therefore potentially incurs the intrusion of saltwater with possibly severe consequences.

The interaction of fresh and saline waters in coastal zones and on oceanic islands is reviewed by, e.g., Cooper et al. (1964), Reilly and Goodman (1985), Custodio and Bruggeman (1987), Bear et al. (2010) and Werner et al. (2013). Physical models were amongst the first attempts to study this phenomenon (Pennink, 1915) and are still in use today (e.g. Simmons et al., 2002; Zhang et al., 2002; Oswald and Kinzelbach, 2004; Goswami and Clement, 2007; Werner et al., 2009; Zhao et al., 2009; Abdollahi-Nasab et al., 2010; Jakovovic et al., 2011; Luyun et al., 2011; Shi et al., 2011; Kuan et al., 2012; Stoeckl and Houben, 2012; Chang and Clement, 2012, 2013). They are useful not only to visualize processes but also to test the performance of analytical and numerical models.

Analytical models to calculate the geometry and development of island lenses were developed by, e.g., Fetter (1972), van der Veer (1977), Vacher (1988), Stuyfzand and Bruggeman (1994) and White and Falkland (2010). A variety of numerical studies of variable-density flow on islands has been published (e.g., Oberdorfer et al., 1990; Bailey et al., 2009).

In a previous paper by Stoeckl and Houben (2012), a series of physical model experiments was performed to study the formation and degradation of lenses in homogeneous (single-layer) aquifers. The experiments addressed the steady-state geometry of the lenses, the groundwater flow paths within them, and the spatial distribution of groundwater age. Results were successfully compared to analytical and numerical models. This paper follows a similar outline but considers inhomogeneous, layered systems, that is, lenses occurring in islands that are partitioned into horizontal layers or vertical columns of differing hydraulic conductivities or into areas of differing groundwater recharge. We based our study on the four geometries of infinite-strip islands for which Vacher (1988) developed analytical models (Fig. 1A–D), and we

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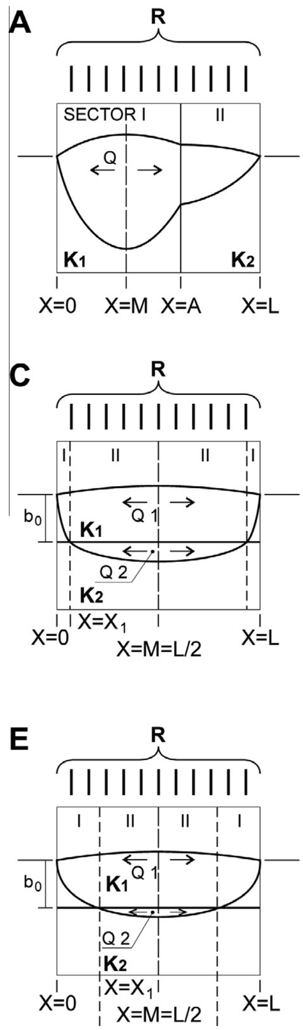

Fig. 1. Investigated cases of inhomogeneous island freshwater lenses: Case A: lateral variation of hydraulic conductivity *K* (K1 > K2), Case B: lateral variation of recharge *R* (R1 > R2), Case C: horizontal layering (K1 < K2), Case D: freshwater lens truncated by impermeable base. Case E: horizontal layering (K1 > K2). *L* = width of island, *x* = distance from shore, x_1 = distance to interface intersection from shore, *A* = distance to vertical sector boundary from shore, *M* = distance to groundwater divide, *K* = hydraulic conductivity of layer, *Q* = flow rate, *R* = recharge of sector. Modified after Vacher (1988).

have added one more scenario from an earlier equation in Fetter (1972) (Fig. 1E).

The main aim of this study was to compare the analytical models developed by Vacher (1988) and Fetter (1972) to our sand tank experiments. The objective was not only to test the analytical models but also to see how the necessary simplifications and geometrical exaggerations of the physical models, e.g. the vertical flow component, affect their performance when compared to analytical models derived for freshwater lenses of natural dimensions with their predominantly horizontal flow. The experiments were also used as a benchmark for the numerical models.

2. Experimental methods and materials

2.1. Physical model

The experimental set-up was based on the one used by Stoeckl and Houben (2012). A cross-section of an infinite strip island was simulated using an acrylic glass box of 2.0 m length, 0.5 m height and 0.05 m width filled with sand. The sand was slightly compacted by palpitation during this process.

Commercially available coarse and medium filter sands, commonly used for gravel packs of wells, were chosen to represent the aquifer material (Table 1). The two sands have a hydraulic conductivity ratio of roughly 10:1. Their grain size distributions were determined optically using a Camsizer (Retsch Technology, Germany), which has a measurement range between 30 μm and 30 mm. Total porosity was calculated using the bulk and mineral densities measured using a helium pycnometer by Micromeritics (USA). Sorting, skewness and sphericity were analysed following the methods of Folk and Ward (1957). As expected for filter sands, both samples are very well sorted and composed of well-rounded grains. The granulometric data were used to calculate the hydraulic conductivity following the empirical methods of Seelheim (1880), Hazen (1911) and Bialas and Kleczkowski (1970).

The saturated hydraulic conductivity according to Darcy's law was measured using a constant-head permeameter by Eijkelkamp Agrisearch (Netherlands). Ten experiments were conducted for each type of sand. The results are shown in Table 2.

The impermeable material used for Case D was pink plasticine (Play-Doh, Hasbro, USA), which proved to be quite effective as no dyed water crossed this barrier.

The density of both fresh and saline water was determined using a density meter DMA 38 by Anton Paar (Austria). Density of freshwater was determined to be 997.4 kg/m^3 and that of saline water to be 1021.2 kg/m^3. Prior to injection, the saltwater was degassed to prevent air entrapment by outgassing. It was injected slowly from the bottom of the model, thereby expelling air and saturating the sand. The temperature of the laboratory was monitored and kept constant throughout the experiment (23 °C).

Recharge was simulated by fifteen freshwater drippers installed above the island surface (0.04 m^2) and supplied by a multi-channel peristaltic pump (Ismatec BVP, Wertheim, Germany). The recharge rate for Cases A, C and D was set to 1.33 m/d, equivalent to 2.46 ml/min per drip. For Case B, the recharge rates were 1.38 and 0.67 m/d for the Sectors I and II, respectively, and for Case B-modified, the two rates were 1.38 and 0.0 m/d, respectively. For Case E, a recharge rate of 1.33 m/d did not result in a penetration of the freshwater-saltwater interface into the second layer. At a rate of 2.66 m/d we did observe a small amount of penetration of the freshwater body into the lower sand layer.

For the visualization of flow paths, the fluorescent dyes uranine (yellow), eosine (red) and indigotine (blue) were added to the freshwater as tracers at a concentration of 0.3 g/l. The effects of the different tracers on density and viscosity of the fluid are negligible.

Freshwater that discharged at the outflow zones was continuously skimmed at both sides of the model by an Ismatec BVP peristaltic pump (Ismatec, Germany) set to a rate equaling total freshwater recharge. The intention of the skimming was to prevent dilution of saltwater and to maintain a constant seawater head.

Table 1
Granulometric properties of sand materials.

Parameter	Unit	Coarse sand	Medium sand
d_{10}	(μm)	1272	440
d_{20}	(μm)	1391	500
d_{60}	(μm)	1802	657
u (=d_{60}/d_{10})	(–)	1.42	1.49
Median	(μm)	1694	618
Sorting	(–)	1.17	1.17
Skewness	(–)	1.00	0.98
Sphericity	(–)	0.82	0.85
Porosity	(–)	0.41	0.45
Hydraulic conductivity *K*			
SEELHEIM	(m/s)	$1.0 \cdot 10^{-2}$	$1.4 \cdot 10^{-3}$
BIALAS/KLECZKOWSKI	(m/s)	$7.7 \cdot 10^{-3}$	$7.3 \cdot 10^{-4}$
HAZEN	(m/s)	$1.9 \cdot 10^{-2}$	$2.3 \cdot 10^{-3}$