The Delayed Effects of Variable Density Flow on Flow and Heads in Fresh Groundwater

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ABSTRACT
Variable density flow may often be neglected in groundwater calculations, unless there is a special interest in the movement of brackish or salt water, for example when there is an environmental risk of salinization of wells or discharge areas. The presence of salt or brackish groundwater has a major impact on the flow and heads in the fresh part of the aquifer, and sometimes in a surprising fashion. We will show that extraction of brackish water below a discharge area may eventually result in an increase of total freshwater discharge. The underlying principles are demonstrated by conceptual models. Through the use of transient numerical calculations using MODFLOW-SWI (Bakker et al. 2005) we will show how the effects of short-term changes in the freshwater regime may be magnified or reduced by the long-term movement of an interface. Results for the island of Terschelling in The Netherlands are presented at the end of the paper.

CONCEPT
Suppose we have an aquifer with fresh groundwater, overlying stagnant salt or brackish groundwater. The interface is at rest and there is a steady state flowfield in the fresh groundwater zone. In this case the interface may be seen as an impermeable boundary, and the transmissivity is determined by the thickness and conductivity of the fresh groundwaterzone only. A change in the hydrology will cause the interface to move towards a new equilibrium position. While the interface is not at equilibrium, the heads and flows are dependent on the transmissivity of the entire aquifer.

In the new equilibrium position, the effective transmissivity has decreased again to the fresh groundwater zone only. This time-dependent transmissivity may lead to an unexpected transition between the two steady-state situations, as will be shown in the following two cases.

Case 1.
Figure 1 shows the developement of a phreatic freshwater zone in a cross-sectional model of an elongated island. The simulation starts with a completely salt aquifer. When the equilibrium is reached after 27 years the recharge is suddenly increased by 50 percent. As a result, the head jumps approximately 10 cm, as shown in Fig. 2. After this initial jump, the head rises an additional 5 cm. This secondary rise is caused by the slow movement of the interface towards a new equilibrium; the secondary effect may be responsible for a significant portion of the total increase in head.

Case 2.
Polders are areas where the water level is fixed by drains and ditches, and they are generally discharge areas of groundwater. In this case we have a crossection through an elongated polder with a drainage level that is one meter below the surrounding polders. In the equilibrium situation there is significant upconing in the center of the polder area (dashed line in figure 3).

Next, we will evaluate what happens when we pump salt groundwater, using a series of wells along the center line of the polder. We are especially interested in the evolution of the discharge. We know that the aquifer will freshen, and eventually the discharge to the polder will increase due to the increased fresh transmissivity. However, the salt water extraction initially results in a decrease of freshwater discharge into the polder. While the interface continues to move the freshwater discharge will increase to a level that is higher than the initial value (Fig. 3, lower right graph).

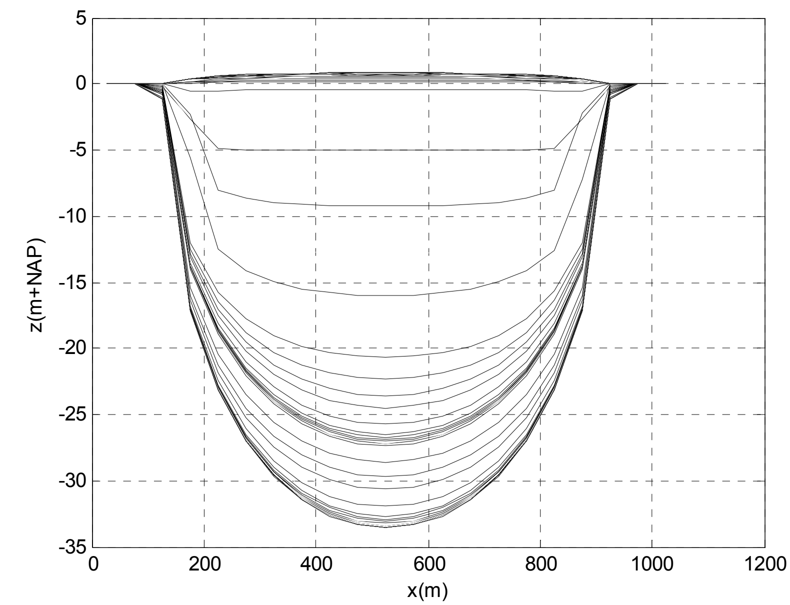

Figure 1. Phreatic groundwaterlevel and position of the interface.

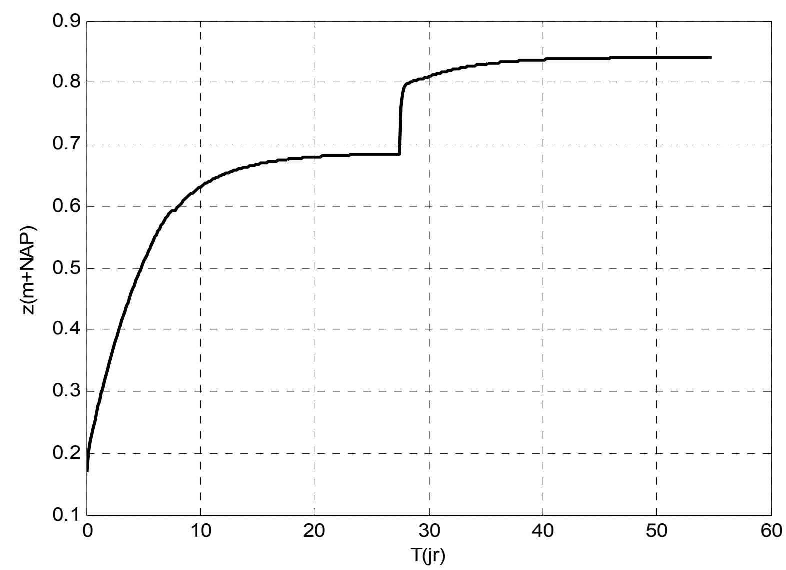

Figure 2. Development of the phreatic groundwaterlevel in the center of the cross-section.

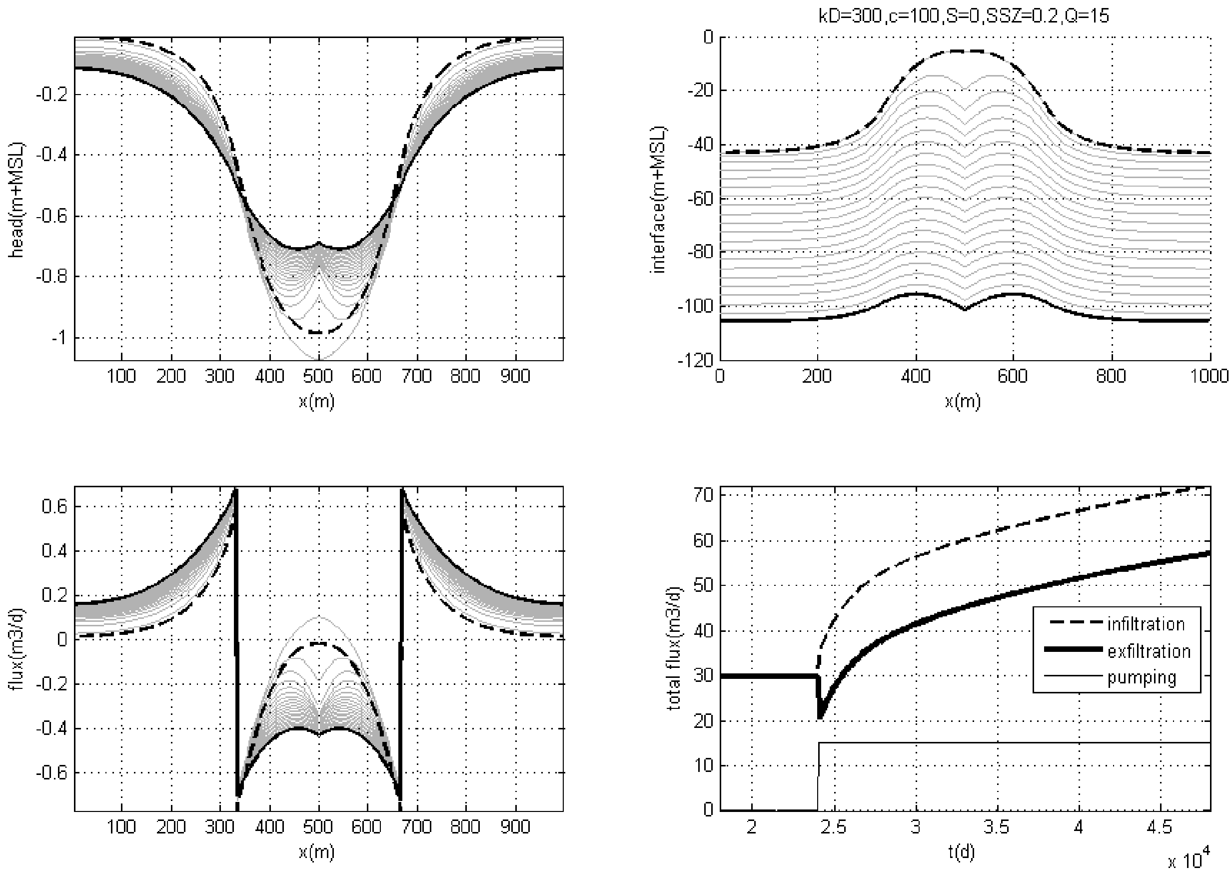

Figure 3. Effect of salt groundwater pumping under a discharge area. Cross-section for head (upper left), interface position (upper right), flux (lower left), and total flux vs. time (lower right).

CASE TERSCHELLING ISLAND

The island of Terschelling is situated in the northern part of The Netherlands. It is divided in a dune area in the North and an agricultural (polder) area in the South. In 2006 the Vitens water supply company started a pilot study to investigate if a self-supporting and sustainable water supply on the island is possible (Kok et al. 2008). One of the options is a salt groundwater extraction in the center of the polder area. In figure 4 the results are shown for three different extraction rates after twenty years. In the dunes the dashed contours represent the 5 centimeter drawdown area. As expected the drawdown area is larger for higher extraction rates. However, in the polder the extraction leads to an increase in head (5 cm head increase, solid contours) close to the pumping well. These increased heads are caused by the increased fresh transmissivity as a result of the lowering of the interface.

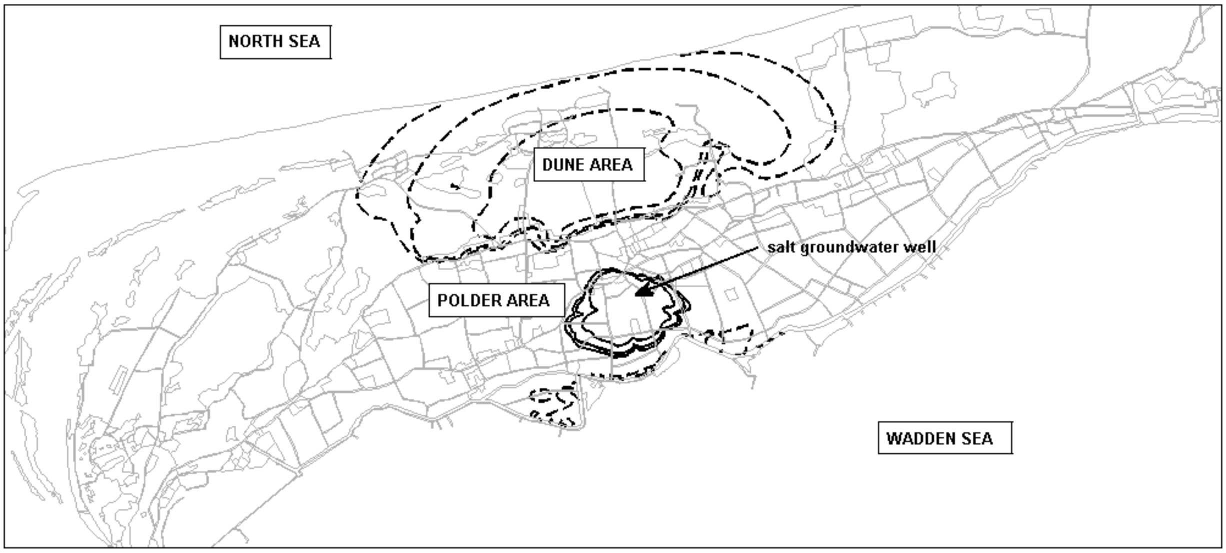

Figure 4. 5 cm contours for different extraction rates at the island of Terschelling.

CONCLUSIONS

The movement of brackish or salt water can have a considerable impact on the flow and heads in the fresh groundwater zone. The magnitude and direction of the effect is time-dependent. For predictions the transmissivity should be adapted to the considered timescale.

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