EFFECT OF AQUIFER BOTTOM MORPHOLOGY ON SEAWATER INTRUSION

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ABSTRACT

In a coastal aquifer with a valley-shaped impermeable bottom, the seawater convection cell is essentially horizontal rather than vertical as is usually assumed, with seawater entering inland across the whole thickness of the aquifer in the central (deepest) portion. This causes a marked increase in the saltwater intrusion along such a section and a much more marked response to pumping. A "lateral buoyancy" dimensionless number can quantify this effect. In many deltaic areas, the aquifer bottom is an erosive surface characterized by the presence of paleochannels that are the deepest and often the most permeable zones of the aquifer.

A study of the effect of aquifer bottom topography on seawater intrusion requires 3D numerical modelling because lateral variations in elevation have to be coupled to variations in density along the vertical coordinate. A synthetic sedimentary medium representative of paleochannels is studied. The effect of bottom topography is assessed in three cases: (1) a horizontal aquifer, (2) an aquifer with constant seawards slope, and (3) a non-planar aquifer with a deep central section and a shallow lateral section. Results suggest that cases 1 and 2 display qualitatively similar behaviours, with the typical vertical convection cell in the seaward side of the interface, while case 3 displays a lateral convection cell.

INTRODUCTION

Three-dimensional (3D) geometry of aquifers is an important factor in understanding groundwater flow and especially, contaminant transport. Three-dimensionality in a simulation may be a critical element for studying saltwater intrusion problems because it may allow enhanced buoyancy effects to occur.

Most seawater intrusion models are based on two-dimensional (2D) groundwater flow and transport, or on 2D and 3D sharp interface approximations. The former suffer two constraints: first, only a vertical cross section can be modelled and, second flow is assumed parallel to the section. Neither is true in most cases, for example in polder areas, where geohydrologic geometries are complex, or in the vicinity of extraction or recharge wells (Oude Essink & Boekelman, 1996). 3D sharp interface models, based in the Badon Ghyben-Herzberg principle, also present some limitations. First, the mixing zone between fresh water and seawater can be simplified to a sharp interface only when the thickness of the brackish zone does not exceed a few meters. This is not typical of real cases where the interface frequently changes position due to natural hydro-geological stresses such as tides or because of changes in the recharge/pumping rate in the aquifer. Second, it assumes hydrostatic equilibrium whereas real aquifers deviate frequently from this equilibrium. This discussion indicates that 3D flow and transport seawater intrusion models are needed in many cases.
It may be surmised that variability in the topography of the aquifer bottom may indeed be one case where 3D analysis is necessary. This may be seen based on an inspection of Darcy’s law. Let $h_f$ be the equivalent freshwater head; $\rho_f$ and $\rho$ be the fresh water and true water densities respectively, and $z$ the vertical coordinate. Then, flux $q$ is given by:

$$ q = K(\nabla h_f + \frac{\rho - \rho_f}{\rho_f} \nabla z) $$

The first term is essentially directed towards the sea in unpumped aquifers. However, in aquifers with irregular bottoms, the second term may not. In fact, if the aquifer slope is large, this term may become prevalent. For example, if $(\rho_s - \rho_f)/\rho_f = 1/40$ ($\rho_s$ being seawater density) and the aquifer slope, $\delta z/\delta y = 4\%$ ($y$ being the coordinate parallel to the coast), then the second term becomes 0.1%, which is a sizable value in comparison with $\nabla h$. In such a case, buoyancy would cause a lateral flux, leading to the development of a lateral convection cell. This phenomenon can only be simulated with a 3D model. Up to few years ago, 3D models were not practical due to high computer time requirements. However, improvements in computer speed are making it increasingly feasible to build grids sufficiently refined to reduce problems of numerical dispersion caused by the use of coarse elements. Moreover, many codes are available: FEFLOW (Diersch, 1998), ROCKFLOW (Kolditz, 1998), HST3D (Kipp, 1986), TVDT3D (Ackerer et al., 1999), METROPOL (Sauter et al., 1993), MVAEM (Strack, 1995), MOCDENSE3D (Essink, 1998), SWICHA (Huyakorn et al., 1987), SWIFT (Ward, 1991), CODESA (Gambolati et al., 1999), and SUTRA (Voss and Provost, written communication, 2001). As a result, variable density 3D models of real cases are becoming increasingly frequent (Oude Essink, 2001, Xue et al., 1995, Barrocu et al., 1994).

One of the difficulties in obtaining reliable 3D models is the lack of good geologic or geophysical information to characterize the aquifer geometry. In fact, 3D models can represent the shape of the aquifer bottom more or less faithfully, depending on the information available. However, no reference to the effect of this shape is made in the analysis of the results, either because it is not remarkable or because it has not been considered at all. Flores-Márquez et al. (1998) obtained the basement of the Costa de Hermosillo aquifer (Mexico) by means of inversion of gravity data. The depth of this basement ranges from 300 to 3500m and is rather complex. They compared this information with the pattern of the dissolved solids in groundwater, finding a good agreement between the deepest areas and the highest concentrations of salt. However, only 2D density dependent flow cross sections of the aquifer were modelled. Thus, the three dimensionality of the flux due to the irregularity of aquifer bottom was not considered. Bachu et al. (1995, 2002) studied density driven flow in sloping aquifers, applying it to two sedimentary basins, Alberta (Canada) and Los Llanos (Colombia). Malkovsky (2002) showed the importance of natural convection in a heat-generating liquid waste plume in a sloping aquifer, which could cause acceleration as well as slowing down of the plume depending on the system parameters. However, they did not examine the effect of lateral variations in aquifer depth. In summary, in the knowledge of the authors, there is no case in the literature where emphasis has been placed on analysing the effect of aquifer topography on seawater intrusion. The objective of this paper is precisely to fill this void and test the conjecture that aquifer bottom topography indeed may significantly affect seawater intrusion patterns in coastal aquifers.

**METHODOLOGY**

**Problem definition**

This work is inspired by the deep aquifer of the Llobregat Delta (northeast of Spain), wherein seawater intrusion problems have been widely studied (Custodio et al., 1982 and 1987; Iribar et al., 1992 and 1997; Manzano et al., 1992). Chloride distributions display some fingers that can be attributed to heterogeneity. Increasing geological information suggests that one possible cause of fingers is the presence of deep and permeable paleochannels.
Model description

A 3D model of half of the aquifer (Figure 1) is used to evaluate the extent to which the variation in the depth of the aquifer base can contribute to irregularities in saltwater intrusion. Model dimensions are 5000 x 5000 x 50 m.

Figure 1 Symmetric aquifer modelled and model domain (grey area), including model boundary conditions: freshwater inflow inland and specified pressure in the seaside boundary.

The results of the simulated cases are considered first for a natural steady state, and second, after 30 years of pumping 4 hm³/year in a fully penetrating well, located 2950 m away from the coast directly over the aquifer symmetry axis. Three cases are simulated (Figure 2):

1. a horizontal aquifer
2. a sloping aquifer (1, 3 or 10% of slope, that is lowering 50, 150 and 500 m the seaside)
3. a “curved” or “non-planar” aquifer (obtained by lowering point A in Figure 1 by 50, 150 or 500 m in 3 sub-cases).

CASE 1: HORIZONTAL AQUIFER

CASE 2: SLOPING AQUIFER

CASE 3: NON-PLANAR AQUIFER

Figure 2 Schematic description and model domain (grey area) of the three simulated cases: (1) horizontal aquifer, (2) sloping aquifer, and (3) non-planar aquifer. Freshwater flow takes place from the background towards the foreground, where the aquifer intersects the ocean.
Boundary conditions used are: (1) constant inflow from inland (1.8 hm\(^3\)/year across the whole boundary) with constant fresh water concentration and (2) specified pressure along the seaside boundary ($p_i = \rho_i g z_i$) with an entering solute concentration equal to seawater concentration. Both sea level and the horizontal plane (ABCD in Figure 1) are set at $z = 0$. Flow and transport parameters used for the simulation are specified in Table 1. The remaining boundaries are closed to flow and solute transport.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>$\phi$</td>
<td>0.25</td>
<td>Porosity</td>
</tr>
<tr>
<td>$K$</td>
<td>$1.25 \times 10^{-11}$ m(^2)/s</td>
<td>Permeability (isotropic)</td>
</tr>
<tr>
<td>$\alpha_{L_{\text{max}}} = \alpha_{L_{\text{med}}}$</td>
<td>20 m</td>
<td>Max. and med. longitudinal dispersivity</td>
</tr>
<tr>
<td>$\alpha_{L_{\text{min}}}$</td>
<td>2 m</td>
<td>Min. longitudinal dispersivity (for vertical flows)</td>
</tr>
<tr>
<td>$\alpha_T$</td>
<td>2 m</td>
<td>Transverse dispersivity</td>
</tr>
<tr>
<td>$D_m$</td>
<td>$1.0 \times 10^{-9}$ m(^2)/s</td>
<td>Molecular diffusion coefficient</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$1.0 \times 10^{-8}$ (kg/m(^2)/s(^{-1}))</td>
<td>Matrix compressibility</td>
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<td>Fluid compressibility</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.001 kg/m/s</td>
<td>Fluid viscosity</td>
</tr>
</tbody>
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**Table 1** Parameters used in the simulations.

**Numerical methods**

Computer simulations were carried out with the 3D version (Voss and Provost, written communication, 2001) of SUTRA (Voss, 1984), being finalized for public release by the U.S. Geological Survey. The numerical technique used by SUTRA is the Galerkin finite element method with hexahedral elements. Implicit finite differences are used for time integration. The iterative methods chosen to solve the linear system of equations are the conjugated gradient method for the flow equation and GMRES for the transport equation. The Picard method is used to solve the non-linear system problem.

The mesh consists of 36 x 73 x 11 nodes and 25200 hexahedral elements. A fine discretization in the vertical direction is needed to get good resolution of the interface shape as well as to avoid numerical dispersion in the vertical direction. Horizontal discretization is finer near the seaside boundary as well as in the boundary representing the symmetry axis of the aquifer (Figure 1).

**Analysis**

In order to analyse the effect of aquifer bottom topography a dimensionless number ($N_b$) is defined, comparing the two terms in equation (1). The first one, freshwater head driven flow ($K \nabla h_f$), is approximated by the boundary freshwater influx ($q_b$). In the second one (buoyancy term), the gradient of altitude is approximated by the maximum slope of the aquifer bottom ($m$), which is valid if the aquifer thickness is small compared to horizontal extent. Therefore, an “aquifer bottom buoyancy” dimensionless number may be defined:

$$N_b = \frac{\rho - \rho_f}{\rho_f} \frac{K \nabla z}{K \nabla h_f} \approx \frac{\rho - \rho_f}{\rho_f} \frac{K m}{q_b}$$

(2)

However, for the purposes of this work it is more appropriate to consider a “lateral buoyancy” dimensionless number, comparing the seawards driving force with the lateral component of buoyancy ($y$ coordinate, parallel to coast):

$$N_{by} = \frac{\rho - \rho_f}{\rho_f} \frac{K \partial^2 z}{q_b}$$

(3)
This number resembles the Driving Forces Ratio (DFR) proposed by Bachu (1995) and Bear (1972) to define free and forced convection in vertical flow.

\[
DFR = \frac{\rho - \rho_f}{\nabla h_f} = \frac{\rho_f}{\nabla h_f}
\]  

(4)

The numbers defined here, \(N_b\) and \(N_{by}\), are preferable because the fresh water flux is a concept better defined than \(\nabla h_f\). Moreover, these numbers explicitly take into account the aquifer slope, which is an important driving force. This has been recognised by Dorgarten and Tsang (1991) who proposed an expression for DFR essentially identical to (2), although motivated by heat transport. However, the number \(N_{by}\) (3) is preferred because the lateral slope \((\partial z/\partial y)\) causes flow to depart from the vertical plane. As will be shown, when the slope is directed towards the sea, intrusion patterns are very similar to those of horizontal aquifers. The slopes chosen for the test cases are 1%, 3% and 10%. Therefore, there are three simulations with \(N_{by} = 0.25, 0.6, 2.5\), respectively.

**RESULTS**

**Natural flow (unpumped aquifer)**

The simulations presented are the result of a transient run of thirty years, starting from the initial concentration and pressure conditions that describe a completely fresh-water aquifer. The steady-state position of the saltwater-freshwater interface is reached in all cases.

The interface positions (50% mixing line) for the horizontal (case 1) and sloping (case 2) aquifers with 1, 3 and 10% slope are shown in Figure 3. As the slope increases, the interface is displaced seaward. This can be simply due to the geometry change that leads to a different intersection point between the aquifer bottom and the interface. In other words, the interface geometry is not significantly affected by the slope. The toe is somewhat displaced seawards both because of the no flow (nor transport) bottom boundary condition and because the intersection of the interface with the aquifer bottom occurs nearer the seaside boundary as the slope increases.

![Figure 3](image)

*Figure 3 The interface position in case 1 (horizontal) and 2 (sloping) in the central cross section (BA in Figure 1). The horizontal axis is the distance to the sea boundary (in meters); the vertical axis shows the depth (meters).*

The results of the non-planar aquifer are presented by comparison to the sloping aquifer. These are comparable because the depth of the deepest point of the aquifer is equal in both cases. Extreme cases are compared first.

The analysis of the non-planar aquifer results is more complex than that in Figure 3. Velocity fields and interface for case 2 (10% slope) and 3 (\(N_{by}=2.5\)) are shown in Figure 4. Observe that vectors in (a) show the expected directions in the sloping aquifer. Freshwater discharges to the sea, and a vertical convective cell is formed by the saltwater entering from the seaside. However, the interface is far from...
the sea boundary in the non-planar aquifer. There is no discharge of fresh water and a careful look at the velocity vectors would suggest that seawater flows inland to disappear, together with the freshwater along the interface area. Figure 5 shows the vector field on the aquifer bottom. It is clear that the lateral slope causes the convection cell in the saltwater wedge to develop sideways. This explains why seawater entering the deepest portion of the aquifer penetrates so far inland. It also explains why seawater velocities are reduced near the interface, seawater is actually deflected sideways and upslope. The same happens to the fresh water, which only discharges in the upper side portions of the shore.

**Figure 4** Some details of the velocity vectors in a transversal cross section over the symmetry axis (AB vertical section in Figure 1). (a) Cross-section of a sloping aquifer with a 10% slope. Notice the typical vertical cell, water entering in the lower part of the aquifer and exiting in the upper part. (b) Cross section of a non-planar aquifer with \( N_{by} = 2.5 \). Notice that in this section, water enters through the whole aquifer thickness. Vector bases are indicated by a small square. Vector lengths indicate the magnitude of the velocity in each element.

**Figure 5** XY view of the bottom velocity vectors in (a) 10% of sloping and (b) a non-planar aquifer with \( N_{by} = 2.5 \). Notice that water entering the aquifer through its lowest point tends to exit at the much higher right hand corner, thus leading to an essentially convention cell. The vector base is indicated by a small square. Thick dashed lines show the general direction of fresh and saltwater flow.
Both freshwater-saltwater interface penetration and shape are conditioned by the flow field, thereby, a different behaviour between AB and CD cross sections (Figure 2) may be expected. Two cross sections in the AB and CD directions are presented in Figure 6. Only the 1000 m closest to the sea boundary is plotted in both sections. As expected, the interface position is not the same along both edges for each of the different non-planar cases presented. The continuous black line corresponds to the horizontal aquifer interface. Taking this first case as a reference, the interface penetration of non-planar aquifers increases in the AB section (corresponding to the deepest sea boundary point) and decreases in the CD section (horizontal). When \( N_{by} \) is higher, the difference between the toe positions in the two edges is greater.

![Figure 6 Interface position in horizontal and non-planar aquifers in two aquifer cross-sections (a) along direction BA and (b) along direction DC (Figure 1). The horizontal axis is the distance to the sea boundary (in meters), the vertical axis shows depth (meters), below the upper edge of the aquifer. Notice that non-planar aquifers have been tilted upwards to overlay the cross section of the horizontal aquifers.](image)

**Results for the 30 years pumping simulation**

A continuous pumping rate of 4 hm\(^3\)/year in a totally penetrating well located 2950 m away from the seaside boundary and located over the AB line (Figure 1) (2 hm\(^3\)/y pumped from the model domain). The starting point is the final steady state presented in the previous section.

The horizontal case simulation is shown in Figure 7. The same evolution is observed for all the sloping aquifer simulations (Figure 8). The only small difference arises in different initial interface positions among all the cases (discussed in section 3.1.). The retardation observed in the interface is slightly accelerated as the slope of the aquifer increases. Once again, the least penetrating wedge corresponds to the 10% sloping aquifer.

The velocity flow field at the bottom of the aquifer for the 10% slope case is shown in Figure 9(a). Two capture zones are marked, one coming from the inland inflow, the other one formed by a mixture between saltwater entering from the seaside and freshwater. The corresponding vector fields correspond to a transient state after 30 years of pumping. The interface position (Figure 8) for the sloping aquifer (10% slope) has a toe about 800 m from the seaside. This is due to the transient state of the result. Because pumping is twice the freshwater inflow rate from inland, salt water will reach the pumping well if pumping is continued.
Figure 7 Saltwater- freshwater interface evolution for a thirty years pumping in a horizontal aquifer. The first picture (a) corresponds to a plan view of the toe position evolution. The second one (b) is the interface evolution in a BA direction cross section (A is seaward and B is landward).

Figure 8 Toe evolution (distance from coast) as the pumping time increases for the horizontal, sloping and non-planar aquifer in a section along the aquifer symmetry axis (AB line in Figure 1).

The results of the non-planar aquifer are qualitatively different from those of the previous cases. Figure 9 (right) represents the velocity field at the aquifer bottom in non-planar (N_{by}=2.5) and, as in the stationary case, four cells are formed in the plan view. Comparison of the pictures in Figure 9 leads to a first conclusion that, in case on the right, the seawater capture zone is only half that in case on the left. The expected penetration of the saltwater wedge in the left hand side of the picture (deeper part) should be greater than on the right. However, flow at the right hand side of each is not affected by the pumping, thus, the wedge does not advance along this edge. The most critical case is that with N_{by}=2.5 in which the saltwater interface almost reaches the well in the thirty-year pumping simulation. The same behaviour is observed in the other simulations of the non-planar aquifer that were carried out. The different toe evolution for the non-planar aquifer simulations is plotted in Figure 8b. The greater N_{by}, the further is the advance of the saltwater front. The acceleration shown as the pumping time increases is due not to the base slope, but to the increasing velocity towards the well.
**CONCLUSIONS**

These results point out that the behaviour of seawater intrusion and ground-water flow in aquifers with non-planar bottoms is qualitatively different from that of aquifers with planar bottoms. The main differences stem from a lateral, essentially horizontal convection cell develops along the ocean side of the aquifer in aquifers with valley-shaped bottoms. This is due to the slope in the impermeable aquifer bottom in the direction parallel to the coast. This causes the seawater wedge to penetrate much further inland in the deepest portion of the aquifer. Consequently, the seawater response to pumping is much faster and seawater intrusion is accelerated in such aquifers. These effects can be quantified by means of a lateral buoyancy dimensionless number. Modelling such effects requires a 3D density-dependent groundwater flow and transport model.

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