Assessing the impact of saline intrusion with density dependent flow modelling for the fractured Peninsula Aquifer in Hermanus, South Africa

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ABSTRACT

In the study area of Hermanus, South Africa, the Gateway Wellfield is used to augment municipal water supply. Due to the coastal location, the impact of saline intrusion needs to be considered. The confined Peninsula Aquifer comprises a complex fault system in a fractured rock environment. Analytical equations do not indicate any negative impact of saline intrusion. The impact of different parameters on the interaction between fresh and sea water was tested in a 2D sensitivity analysis. The hydraulic gradient and dispersivity were identified as crucial parameters. In addition, the impact of discrete fractures within a porous medium was tested. Fracture apertures in the likely range of the case study ($b < 1$ mm) showed a negligible effect. The geology of the Peninsula Aquifer was modelled as an Equivalent Porous Medium (EPM) whereby highly fractured zones around the faults were assigned high hydraulic conductivity. A maximum increase in salinity of 30 mg/l was predicted for the first 20 years of groundwater abstraction. An impact of vertical fractures with $b > 1$ mm was detected that is hardly predictable. In order to prove the gained conclusions and completely eliminate a harmful impact, further investigations are recommended.

Key words | coastal aquifer management, density dependent groundwater modelling, fractured rock hydrogeology, saline intrusion

INTRODUCTION

The Gateway Wellfield is used to abstract groundwater from the confined Peninsula Aquifer in the area of Hermanus, South Africa. Since the production boreholes are approximately 1.5 km away from the coast, the boreholes are currently restricted to abstract at a minimum water level of 5 m above sea level to prevent the intrusion of sea water into the aquifer. Testing the appropriateness of this restriction and assessing the actual impact of saline intrusion under various scenarios was the goal of this study.

The geology of the study area is dominated by the Table Mountain Group (TMG). The fractured Peninsula Aquifer was assessed to have the highest potential for groundwater usage. In most of the study area, this unit is confined by the overlying Cedarberg shales. Only in the Fernkloof Mountains to the near north-east of Hermanus has a direct outcrop of the Peninsula Formation been identified as the area of recharge (Umvoto 2007).

Knowledge of the off-shore geology of Hermanus is limited. It is known that the Peninsula Aquifer extends further south from the coastline on the continental shelf. The freshwater discharge is estimated to take place several kilometres off the coast (Umvoto 2007). The form and position of the zone of discharge has not yet been studied in detail but the geology map of Hermanus (Bremner & Malan 1990) indicates an offshore fault about 2.5 km off the coastline. Although there is no scientific evidence, it is reported that submarine fresh water outflow can be found near the Hermanus coast. Due to similarities to other well understood faults in the area, the off-shore fault is interpreted as a barrier to groundwater flow. Since there is evidence of
groundwater flow towards the coast, there must be some submarine discharge between the off-shore fault and the coastline. It is therefore concluded that groundwater discharge takes place through a direct submarine outcrop of the Peninsula Aquifer. The schematic Peninsula Aquifer including recharge and discharge paths is shown in Figure 1.

**ANALYTICAL APPROACHES**

The restriction of a minimum water level of 5 m above sea level was made using the Ghyben-Herzberg principle, which describes the position of a sharp interface between groundwater and sea water. It is based on the assumption that fresh and salt water are two immiscible fluids under hydrostatic equilibrium, i.e. pressure on both sides of the interface is equal. The Ghyben-Herzberg Equation (1) describes the depth of the interface below sea level \( z \) as a function of the fresh water density \( \rho_f \approx 1,000 \text{ kg/m}^3 \), the salt water density \( \rho_s \approx 1,025 \text{ kg/m}^3 \) and the elevation of the water table above sea level \( h \).

\[
z = \frac{\rho_f}{\rho_s - \rho_f} h \approx 40 h
\]  

(1)

Figure 2 portrays the contact between aquifer and sea for unconfined and confined conditions. Under unconfined conditions piezometric surface, sea level and sharp interface intersect at point P. At this point hydraulic head \( h \) and depth of the interface \( z \) are zero (Equation (1)). Under confined conditions the point of contact between aquifer and sea lies below sea level at \( P' \). If the Ghyben-Herzberg principle is applied, due to the higher salt water density and equal pressures on both sides of the interface, at point \( P' \) the hydraulic head \( h \) lies above sea level. Consequently, at a given hydraulic head at some point inland (such as the right boundary of each figure) the piezometric surface and the salt water interface take on a different slope for unconfined and confined conditions, whereas the depth of the interface under this point remains the same.
If groundwater is abstracted above the salt water body, a local rise of the interface may form. In line with the cone of depression around the abstraction well, a rising interface is observed in depth, also known as upconing (Todd & Mays 2009). This rise of the interface is described by Equation (2) whereby Q is the abstraction rate, d the initial depth of the interface below the base of the borehole and K the hydraulic conductivity. The critical rise at which the interface becomes unstable and the borehole will be impacted has been estimated to range from \( z = 0.3d \) to \( z = 0.5d \). Bear et al. (1999) proposes a safety value of \( z = 0.3d \) that results in a maximum permissible abstraction as given by Equation (3).

\[
z = \frac{Q}{2\pi d K (\rho_d/\rho_f)} \quad (2)
\]

\[
Q_{\text{max}} \leq 0.6\pi d^2 K (\rho_s - \rho_f/\rho_f) \quad (3)
\]

Applying Equation (1) to the observed water levels in the main production borehole GWP02, it is shown that the theoretical interface lies in the (almost) impermeable granite basement in non-pumping conditions, and in the Peninsula Aquifer 671 m below the borehole base in pumping conditions. The application of Equation (3) to the planned abstraction rates of the production boreholes clearly shows that the expected abstraction rates are lower than the theoretical maximum pump rate.

**GROUNDWATER FLOW IN FAULTS AND FRACTURES**

Groundwater flow in the study area is largely determined by a number of faults with adjacent zones of intensive fracturing. Faults as hydraulic barriers are particularly observed in unconsolidated materials with clay content or in sedimentary rocks with inter-bedded shales, such as the TMG. Fine material is understood to result in a very low permeability in the fault core whereas a zone of high fracturing is present around it. Groundwater recharge and flow in the TMG is mainly controlled by fractures (secondary porosity and permeability). At different Peninsula outcrops, average fracture apertures ranging from 2.6 to 6 mm are reported. Aperture values at outcrops are generally increased due to weathering and usually decrease with depth. In the TMG, physical apertures below the weathered surface generally range from 0.05 to 0.5 mm. In the study area, the aquifer compartment of interest has never been exposed and fracture apertures are understood to be in this range, but it is not clear to what extent they are increased in the high conductive damage zone around the faults (Moyce 2009; Xu et al. 2009). For the purpose of this study it is initially accepted that fracture openings are smaller than \( b = 1 \) mm.

**NUMERICAL MODELLING**

In contrast with the sharp interface assumption, fresh water and saline water are miscible fluids resulting in gradually increasing salinity and density between fresh and salt water. The mixing process causes a transition zone of variable thickness and shape depending on geology and flow conditions (Bear 1972). Assumptions and simplifications in the analytical equations are large and mixing through hydrodynamic dispersion is not considered. Especially under pumping conditions, the applied equations are questionable because conditions are far from hydrostatic as assumed by Ghyben-Herzberg. In addition, the impact of flow in fractures or contrasts in hydraulic conductivity cannot be taken into account.

Predictions and conclusions about the effect of groundwater abstraction on flow and mass transport, including a gradual transition from salt to fresh water and a fracture network, may be drawn by means of numerical modelling. Some preliminary 2D modelling of a generic aquifer in seeking to understand the impact of various factors influencing saline intrusion was carried out before a 3D model of the Peninsula Aquifer was developed to assess the current state and future impact of saline intrusion into the Gateway Wellfield.

Most groundwater models use a constant fluid density, which is valid for water of constant salt concentration and/or temperature. In order to include density effects in flow and transport models, the hydraulic head \( h \) and conductivity \( K \) must be treated as functions of a variable fluid density (Anderson & Woessner 1992). As variable density problems have become an issue of particular interest, there are numerous numerical codes to simulate density-coupled flow. Details on some of these may be found in Bear et al. (1999) and Guo & Langevin (2002).
The finite-element groundwater modelling software FEFLOW used offers the combination of density coupled flow and the integration of flow in discrete features (such as fractures) within a continuous porous matrix. Density driven flow is incorporated by the presence of the buoyancy term $(\rho' - \rho_0')/\rho_0'$ within Equation (4). Viscosity and temperature dependencies are not considered for the purpose of this study.

\[ \dot{q}_i = -K_{ij} \mu \left( \frac{\partial h}{\partial x_i} + \frac{\rho'}{\rho_0'} \alpha \beta \right) \]  

\[ \rho' = \rho_0' \left[ 1 + \frac{\alpha}{(C_s - C_0)} (C - C_0) - \beta (T - T_0) \right] \]

$q_i$: Darcy velocity (m/s); $K_{ij}$: hydraulic conductivity tensor (m/s); $\mu$: constitutive viscosity function (kg/(m*s)); $\alpha$: gravitational unit vector (–); $\beta$: density difference ratio, $\alpha = [\rho(C_s - C_0)]/\rho_0$; $C_s$: maximum concentration (kg/m³); $C_0$: reference concentration (kg/m³); $\beta$: fluid thermal expansion coefficient (C⁻¹).

Mass transport is implemented using hydrodynamic dispersion (molecular diffusion plus mechanical dispersion) as introduced for instance by Fetter (2001). The complete governing equations of FEFLOW are given in Diersch (2005).

**Modelling of groundwater flow in fractured aquifers**

If fracture openings are small and fracture density is sufficiently high, it is widely accepted that the Equivalent Porous Medium (EPM) approach may reflect the behaviour of a fractured aquifer on a regional scale (Freeze & Cherry 1979). In contrast to the EPM approach, for the modelling of flow in fractured media using a non-continuum approach, the principles of hydromechanics are required. A detailed summary of the principles of linear and non-linear flow in fractures is given by Kolditz (2001).

Within FEFLOW, fractures can be implemented using discrete elements that are assigned an equivalent hydraulic conductivity. The conductivity tensor $K_{ij}$ as used in Equation (4) may correspond either to the classic Darcy law or to one of the alternative flow laws after Hagen-Poiseuille or Manning-Strickler (Diersch 2005). While the Hagen-Poiseuille law is linear, the Manning-Strickler law is non-linear and may account for turbulent flow. Based on the Reynolds number an initial estimation of the likely nature of flow (laminar or turbulent) was made in order to identify the appropriate flow law.

\[ \text{Re} = \frac{\rho v L}{\mu} \]

$r_h$: hydraulic radius (ratio of cross-sectional area to wetted perimeter) (m); $v$: flow velocity (m/s); $\mu$: dynamic viscosity (kg/(m*s)).

Under the likely fracture aperture ($b < 1$ mm) and hydraulic gradient within the study area, the computed flow velocities are all in the laminar range ($\text{Re} < 2,300$) and an equivalent conductivity tensor value after the Hagen-Poiseuille law is henceforth used for the discrete fractures.

\[ K = \frac{b^2 \rho g L}{12 \mu I} \]

$I$: unit tensor (–); $b$: fracture aperture (m).

**Numerical stability**

In order to keep numerical dispersion and oscillations low, Peclet and Courant numbers need to be less than a defined maximum (Kinzelbach & Rausch 1995).

\[ \text{Pe} = \frac{\Delta x}{\beta L} < 2 \]

\[ \text{CO} = \frac{v M}{\Delta x} < 1 \]

$\Delta x$: characteristic flow length: maximum length of finite elements (m); $\beta_L$: longitudinal dispersivity (m); $\Delta t$: maximum time step (d); $v$: Darcy velocity (m/d).

In the 2D parameter studies, the Peclet and Courant criteria are valid for all scenarios tested. In the 3D model, minimum velocities in the order of 1.2E-15 m/d showed that mechanical dispersion is very small and the influence of diffusion becomes relevant. Therefore the Peclet number is written as:

\[ \text{Pe} = \frac{v \Delta x}{\beta_L v + D^*} < 2 \]

$D^*$: coefficient of molecular diffusion (m²/s).
In some simulations the tolerable value of $Pe = 2$ was exceeded. However, the criterion $Pe^*Co < 2$ proposed by Simunek et al. 2007 was satisfied and the results were hence still used for interpretation.

Sensitivity analysis

The impact of various parameters on the shape and position of the transition zone was tested in a 2D vertical sensitivity analysis. The model setup of these parameter studies is illustrated in Figure 3.

The hydraulic gradient $I$ proved to be a sensitive parameter in terms of the final length of intrusion. It was assigned values ranging from 0.5–3.0%. Figure 4 shows the sea water domain (left side of dashed line) and the salt water wedge intruding into the aquifer (right side of dashed line). The distance to which the sea water intrudes into the fresh water domain increases with a decreasing hydraulic gradient. A higher gradient results in a greater slope of the sea water body which then intrudes less far into the aquifer. This observation is in line with the Ghyben-Herzberg principle as discussed above.

The dispersivity proved to be a sensitive parameter in terms of the width of the transition zone. Figure 5 shows the concentration distribution for a longitudinal dispersivity $\beta_L$ of 50–300 m (transversal dispersivity $\beta_T$ at a constant ratio of $\beta_T/\beta_L = 1/10$). It became evident that the transition zone becomes wider with an increasing value of $\beta_L$. The increase in the transition zone is especially significant from $\beta_L = 100$ m to $\beta_L = 200$ m which suggests a non-linear relationship between dispersivity and width of transition zone.

The general effect of a dense fracture network was simulated using a global fracture set that applied 1D discrete elements on each edge of the 2D finite element mesh. A global fracture set with hydraulic apertures of 1 mm was compared to the standard case without any fractures in Figure 6. It became clear that the difference to the standard case is small. The total distance of intrusion at the aquifer bottom appears to be less (by about 50 m at the aquifer bottom and about 10 m in the middle of the aquifer). The transition only widened slightly (by about 40 m) in the middle of the aquifer whereas it became smaller at the top and bottom (about 10 m and 30 m respectively), if fractures were included. Hence, the EPM approach is an acceptable rather conservative scenario and therefore a reasonable assumption for the purpose of this study.

Modelling of the Peninsula Aquifer

Model setup

In the 3D model the Peninsula Aquifer was simulated as an EPM with relatively high hydraulic conductivity assigned to zones of increased fracturing. Due to their annealed largely impermeable core, four different faults were used as model boundaries (no flow boundaries). The damage zone around them was assigned increased hydraulic conductivity (order of $1.0E-04$ m/s) whereas the relatively
Figure 4 | Concentration distribution for hydraulic gradient scenarios.

Figure 5 | Concentration distribution for dispersivity scenarios.
undisturbed protolith was assigned very low conductivity (order of 1.0E-09–1.0E-08 m/s). Conceptual understanding and the calibration of conductivity values were adopted from an earlier wellfield model developed by Umvoto Africa (2011). Since the area of interest is between the Gateway Wellfield (modelled as the main production borehole GWP02) and the coast, recharge in the Fernkloof Mountains was implemented as simplified injection wells. The conceptual model of the aquifer is shown in Figure 7. To incorporate an uncertainty in terms of the understanding of the submarine discharge, two slightly different conceptual models were developed. Discharge into the sea takes place at a submarine Peninsula outcrop of varying size and location (geology scenarios A and B) at the aquifer top. In both cases the area of discharge is limited by an off-shore fault mapped by Bremner & Malan (1990). Parameters and characteristics of the model are given in Table 1.

Figure 6 | Concentration distribution for (a) standard conditions without any discrete fractures and (b) for a global fracture set with a hydraulic aperture of 1 mm.

Figure 7 | Conceptual model of the Peninsula Aquifer with boundary conditions (b.c.), abstraction point (GWP02) and two scenarios of a submarine outcrop (A and B).
The total distance of intrusion at the aquifer bottom under non-pumping conditions varies depending on the geology scenario. If the submarine Peninsula outcrop is located further off the shore, then the less the sea water body intrudes into the aquifer. Figure 8 shows a vertical cross section of the body of intrusion as well as the equipotential lines of geology scenario A (outcrop nearer to coast). The cross section is shown along the highly conductive fault zone along the eastern aquifer boundary (Hermanus Fault), where the wellfield is located. The steep slope of the salt front and the short distance of intrusion go along with a very steep hydraulic gradient (dense spacing of equipotential lines) in the area of discharge. In contrast, in the centre of the model, in the vicinity of the wellfield, the hydraulic gradient is very shallow (wide spacing of equipotential lines). The observation that the slope of the salt front and therefore the total distance of intrusion are mainly determined by the hydraulic gradient confirms the results of the sensitivity analysis. This becomes especially relevant because the pattern of the hydraulic gradient is a direct result of the calibration of hydraulic conductivity. At a constant flow rate throughout the model length, the resulting hydraulic gradient is shallow for a high conductivity and steep for a low conductivity. Therefore, the higher calibrated conductivity around the wellfield directly affects the salt front as computed by the model.

Although the water level at the main production borehole GWP02 drops down to 6.9 m above sea level (compared to a rest water level of 33.4 m above sea level), at the maximum rate of 25 l/s (93% of the conservative recharge estimation) the rise in concentration in the first 20 years is less than 30 mg/l. This does not seem significant compared to the background concentration of 250 mg/l.

A simulation of 40 l/s after 10 years of usual pumping at 20 l/s was tested to assess the impact of increased abstraction rates during peak season. Figure 9 shows that

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<th>Parameters and characteristics of the model of the Peninsula Aquifer</th>
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<td><strong>Density ratio</strong></td>
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the increased drawdown results in a water level of –2.6 m above sea level after 6 months of twice the usual pump rate. The additional rise in concentration during the doubled pumping lies in the order of 1 mg/l. After a return to pumping at 20 l/s, the rise in concentration returns to usual conditions, although the water level only recovers with some delay.

To assess the potential impact of single fractures of hydraulic apertures greater than average, a hypothetical single 2D fracture plane was introduced along the major faults. Figure 10 illustrates the rise in concentration during 10 years of pumping at 20 l/s under fracture planes of 1 and 5 mm hydraulic aperture compared with a scenario of no fracture plane. At a hydraulic aperture of 1 mm there is hardly any difference to the standard case without any discrete fractures. While the no-plane and 1 mm fracture plane scenarios show a gently rising concentration only, the 5 mm fracture plane scenario shows a steep rise after about 1,000 days.
CONCLUSION

Preliminary assessment using analytical approaches indicates no negative impact of saline intrusion under the scheduled abstraction rates and water levels. This was confirmed by the numerical modelling. However, there is some uncertainty with regards to the impact of a complex fracture network. In summary, the modelling results provide response to the main modelling questions.

Does the specific geology favour or prevent the process of saline intrusion? Modelling results suggest that:

- Flow in fractures of very small aperture $b < 1$ mm does not play a significant role.
- Some fractures larger than average may have an impact, which is hard to assess.
- The zonation of hydraulic conductivity causes a steep gradient in close proximity to the discharge, which pushes the interface seawards.
- The confined conditions affect saline intrusion because the outflow takes place off the coast which results in a greater distance from submarine discharge to abstraction.
- The location and area of submarine discharge have significant impact but are only roughly estimated.

What is the impact of likely pumping scenarios? Modelling results suggest that:

- The salt concentration does not rise significantly ($<30$ mg/l) in the first 20 years of pumping up to 25 l/s, if fracture apertures are small ($b < 1$ mm).
- Over-pumping for a short period of time (e.g. 6 months) is not likely to have any harmful impact. The restriction of keeping a minimum water level of 5 m above mean sea level is over-conservative and can be amended during periods of temporary over-abstraction.

The likely fracture apertures within the Peninsula Formation are well below 1 mm. However, this is an average value and there is no reliable information on how large maximum apertures are. It was shown that one simple fracture plane of greater aperture can have a major impact on the rise of salinity in the borehole. The hypothetical scenarios with fracture planes along the faults cannot be taken as a realistic scenario because they simplify the structure of the damage zone around the fault core to a large degree. In reality a dense fracture network with unknown maximum apertures is expected. Hence the used scenarios only imply that single fractures may have significant impact rather than give a concrete prediction. It is also remarked that the fracture planes as applied in the 3D model are different to the fracture system used in the sensitivity analysis. In the 2D studies vertical and horizontal 1D discrete elements were applied. The effect of a network of these proved to be rather conservative in terms of saline intrusion. In the 3D model vertical 2D planes along the
major faults were applied. The effect was equal to a thin horizontal layer of very high hydraulic conductivity.

The following points are recommended to achieve a more profound assessment of the current and future impact of saline intrusion for the Hermanus project area:

- Electrical conductivity data to be taken from boreholes near the coast to confirm the current understanding of the stable sea water body and calibrate the model to salt concentrations.
- A thorough analysis to be made of the piezometric surface between the boreholes and the point of discharge.
- A review to be made of the hydraulic conductivity zonation with currently sharp contrasts.
- Detailed information on the fracture system, especially maximum hydraulic aperture values, to be established.
- Detailed investigation to be made of the off-shore geology and the submarine groundwater discharge.

REFERENCES


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