Modelling sea-water intrusion in the Atlantis aquifer

JL Müller*, JF Botha and GJ van Tonder
Institute for Ground-water Studies, University of the Orange Free State, P.O. Box 339, Bloemfontein 9300, South Africa.

Abstract

In this paper the phenomenon of sea-water intrusion in the Atlantis aquifer is studied by means of a vertical two-dimensional numerical model, based on density-dependent transport in a porous medium. To apply the model it was necessary to assume that the aquifer can be approximated by a hypothetical aquifer of constant depth, taken as the depth to bedrock at the Silwerstroom spring. Such a model is likely to over-estimate the distance of intrusion in the actual aquifer. It is, therefore, encouraging to find that, if the abstraction in the vicinity of the Silwerstroom spring is kept to a rate below 4,12 × 10^6 m^3/a, the possibility of sea-water intrusion is small.

Introduction

The phenomenon of sea-water intrusion, although widely studied in countries abroad, has, until recently, not received much attention in South Africa. This is mainly due to the fact that until the mid 1970's, exploitation of coastal aquifers in South Africa was limited to local abstraction of relatively small quantities of ground water from individual boreholes. It was only in the second half of the 70's that the importance of coastal aquifers, such as the Cape Flats and the Atlantis aquifers, came to light.

There are two theoretical methods that can be utilised to study the phenomenon of sea-water intrusion:

- the analytical method; and
- the numerical method.

The phenomenon of sea-water intrusion is so complicated (Bear, 1979) that a number of simplifying assumptions have to be made in order to derive an analytical approximation. Two of the more serious of these are:

(i) that the ground-water head of the salt/freshwater interface boundary is at a constant potential; and

(ii) there exists an abrupt interface between the sea water and freshwater.

These assumptions clearly exclude some of the most important physical features of the real system. For example, assumption (i) neglects the dynamic nature of the system, while assumption (ii) neglects the transition zone of varying density, separating the two phases. The only alternative available to study the phenomenon in detail is to use a numerical model.

Exploitation of the ground-water resources of the Atlantis coastal aquifer commenced in September 1976, with 16 730 m^3 of water pumped from the Silwerstroom spring. Since then several production boreholes have been drilled and by December 1982, 13 of these were utilised to draw an estimated 2,4 × 10^6 m^3 of water annually from mainly two production fields in the aquifer. Recent investigations (Müller, 1984) have established, however, that the only possibility of sea-water intrusion exists in the Silwerstroom area (Figure 1) and therefore the present discussion will be restricted to this area.

In view of the complexity of the phenomenon and the lack of verified physical data (Müller, 1984), it was decided to restrict the present investigation to a two-dimensional vertical model, based on the alternating direction collocation approximation (ADC) proposed by Botha and Celia (1981). The computer code used, was developed by Michael Celia from Princeton University during a short tenure at the Institute for Ground-water Studies in 1982. A complete description of the model can be found in Celia (1984), and will not be repeated here. A description of the mathematics involved can be found in Van Tonder *et al.* (1986).

Geological considerations

To apply a two-dimensional vertical model, requires that a suitable section should be chosen. The location of the section to

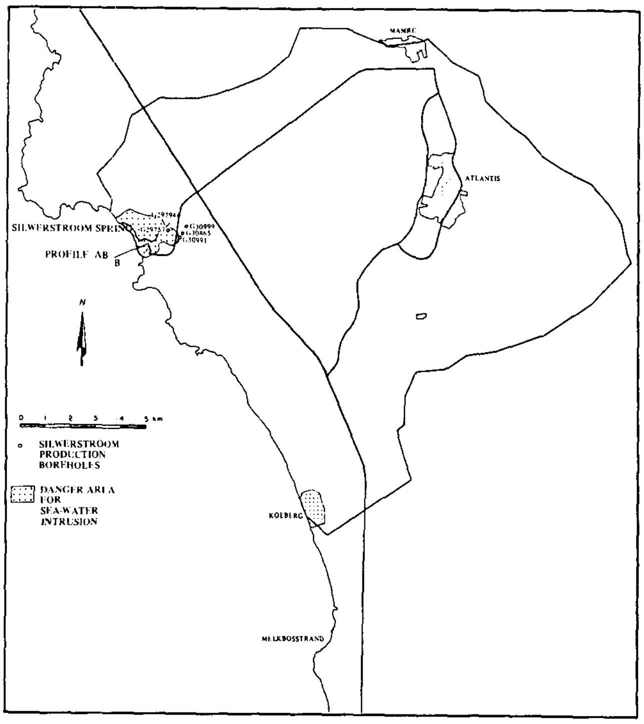

Figure 1
Map showing the danger area for sea-water intrusion, locality of the Silwerstroom production boreholes, the Silwerstroom spring, as well as the profile line along which sea-water intrusion is to be modelled.

---

*Present Address: Terradata, P.O. Box 511, Hartbeespoort 0216, South Africa. To whom all correspondence should be addressed.

Received 12 August 1986.

be modelled was dictated by several physical, hydraulic and even external factors, the single most important one being the geometry of the aquifer itself. To understand this, it will be necessary to briefly discuss the geology of the area concerned.

The main water-bearing units of the Atlantis aquifer comprise Cenozoic sand deposits. The bottom of the flow domain is defined by a clay layer formed by weathering of the underlying metasediments of the Malmesbury Group. Along the coastline unweathered Malmesbury rocks form an impervious groundwater barrier between the sea and the sand of the Altantis aquifer. Müller (1984), however, showed that in the Silwerstroom area the continuation of the sand deposits below sea level is not screened from the sea in any way, thus providing an ideal location for the modelling exercise.

A difficulty frequently encountered in using a two-dimensional vertical model, is the incorporation of production boreholes (Celia, 1984). It was, therefore, decided to try to avoid the necessity of implementing a production borehole by locating a point in the aquifer between the Silwerstroom production field and the coastline, where the pressure of the ground-water system is relatively stable for a given period of time, regardless of the abstraction of ground water from the Silwerstroom production field. As no evidence could be found in the data available that the abstraction of water from the Silwerstroom production field adversely influenced the flow of the Silwerstroom spring, the spring was selected as the landward boundary for the profile to be modelled. This has the advantage that one can use a constant head boundary condition at the Silwerstroom spring. The seaward boundary selected, consists of a point 1 000 m from the coastline, on a line from the spring intersecting the coastline perpendicularly. The location of the Silwerstroom production boreholes, the Silwerstroom spring, as well as the section along which sea-water intrusion is to be modelled, are shown in Figure 1.

The main reason for continuing the section 1 000 m into the sea is to ensure computational stability. The high ground-water gradients prevalent in the area may lead to computational complexity, if the seaward boundary is chosen too close to the coastline.

A major limitation of the present numerical model is the fact that a constant aquifer thickness has to be specified along the entire section. This posed a problem in that the aquifer thickness in the vicinity of the Silwerstroom spring is 18 m and only 5 m at the coastline. However, it is known (Van Tonder and Botha, 1983) that the distance of sea-water intrusion is proportional to the thickness of the aquifer. It was, therefore, assumed that the aquifer has a constant thickness of 18 m. This assumption ensures that the present model is more likely to over-estimate than under-estimate the distance of sea-water intrusion.

The final finite element mesh constructed along the section line AB, as well as the boundary and initial conditions specified, are shown in Figure 2. Since the present position of the salt/freshwater interface is not known, it was decided to represent this as a vertical line at the coast. Although this approach may not be quite correct (Van der Veer, 1977), it is not expected to have any serious effects on the final results, unless the interface already lies inland. This, however, does not seem to be the case in this instance.

The rest of the parameters used in the model, for example the ground-water gradient and the hydraulic parameters, were obtained from a two-dimensional horizontal flow model constructed during an earlier investigation (Müller, 1984). A K-value of 20m/d and a S-value of 0,18 were used at the Silwerstroom spring, with a flow rate of 2 662 m^3/d.

Sea-water intrusion simulations

Three simulations were carried out to investigate the phenomenon of sea-water intrusion in the Atlantis aquifer. In the first simulation the emphasis was more to get a feeling for the behaviour of the system, rather than to see how it would behave under various stresses. This simulation was consequently conducted with the water levels observed for January 1979 as initial conditions. The fact that the Silwerstroom spring was flowing in January 1979, indicating a positive hydraulic head at the spring,

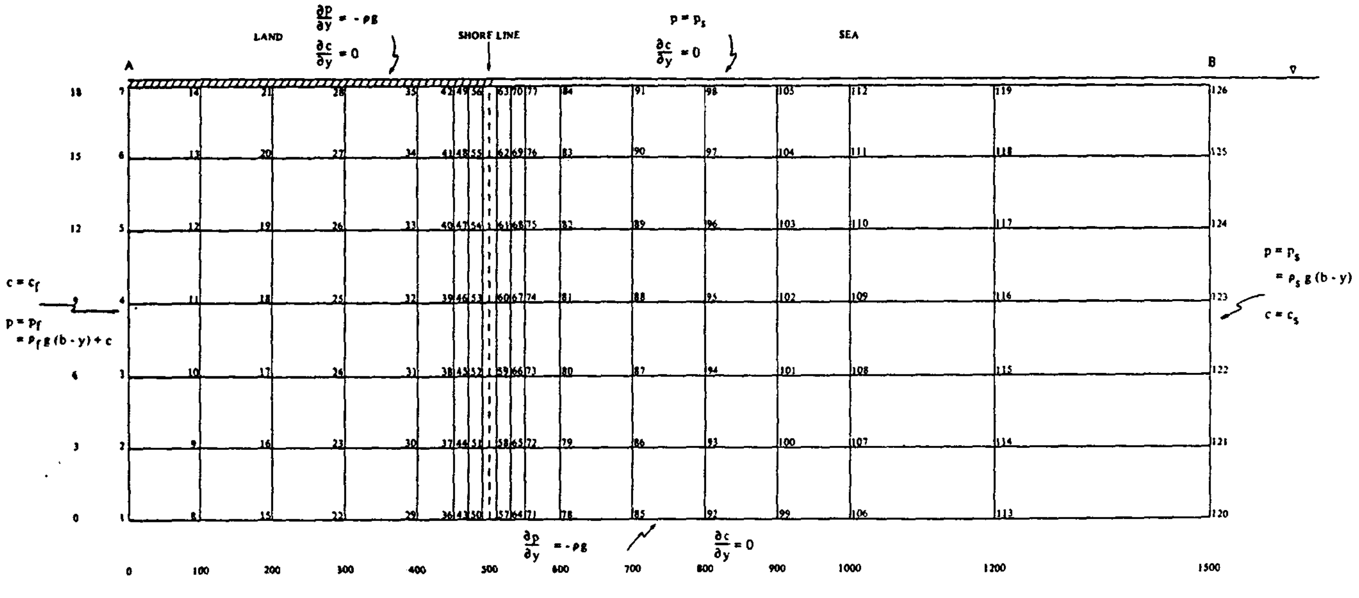

Figure 2
Rectangular finite element mesh used for the simulation of the fresh/sea interface. Boundary and initial conditions are also stated.

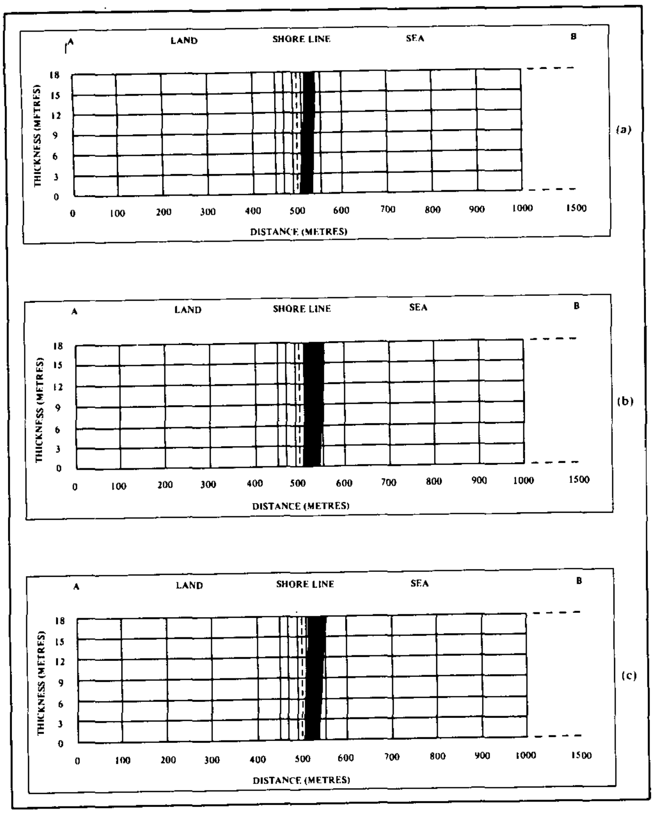

Figure 3
Results for the first simulation indicating the position and physical dimensions of the transition zone, (a) after 90 d, (b) after 360 d and (c) after 720 d.

together with information regarding the topographical elevation of the spring, indicates that a hydraulic head value of 13 m above mean sea level exists at the spring. This value was consequently used as a boundary value on the landward side of the model. On the seaward side a value of zero m at the coast was used and extrapolated linearly seawards.

Since no information is available on the present position of the sea/freshwater interface, it was decided to use an initial salt distribution with a sharp interface at the coast, i.e. freshwater landwards and salt water seawards.

The second simulation was carried out to see what the effect of a 3 m drop in hydraulic head at the spring would be on the distance of intrusion. The same initial and boundary conditions as in the first simulation were consequently used, except that the constant head at the spring was now assumed to be only 10 m above mean sea level. This elevation was shown by an earlier horizontal flow model (Müller, 1984) to be the result of the proposed maximum abstraction rate at the Silwerstroom production field of 4,12 × 10^6 m^3/a (Bredenkamp and Vandoolaeghe, 1982).

The third and final simulation was carried out just to show what can happen if the water level at the Silwerstroom spring is lowered to sea level.

Discussion of the results

The phenomenon of sea-water intrusion in a coastal aquifer can best be illustrated by the movement of the various isochlors, i.e. lines of constant salt concentration expressed in such a way that an isochlor of 1 corresponds with sea water, taken here as water with a total dissolved salt concentration of 35 000 mg/ℓ. In principle, it is thus possible to find isochlors ranging between 0 (freshwater) and 1 in such an aquifer. However, for all practical purposes, the transition zone existing between fresh and salt water is delimitated by the 0,02 and 0,9 isochlors, and for this reason all discussions will be limited to the zone demarcated by these two isochlors. For convenience sake the last 500 m of the finite element mesh on the seaward side is not included in the figures to follow.

The predicted movement of the transition zone as observed over a period of 720 d, can be seen in Figures 3a, b and c, depicting the position and physical dimensions of the transition zone after 90, 360 and 720 d respectively.

It is interesting to note that the transition zone moves rapidly towards the sea during the first 90 d, after which it more or less stabilises. This can solely be attributed to the choice of the initial concentration values used, and must not be seen as a physical reality prevailing in the aquifer. Of more importance, however, is the fact that the zone stabilised on the seaward side of the coastline, after its initial rapid movement. The stabilised position of the transition zone is indicative of the physical realities prevailing in the system, and therefore it can be concluded that given the prevailing physical and hydraulic conditions, sea-water intrusion is not likely to occur.

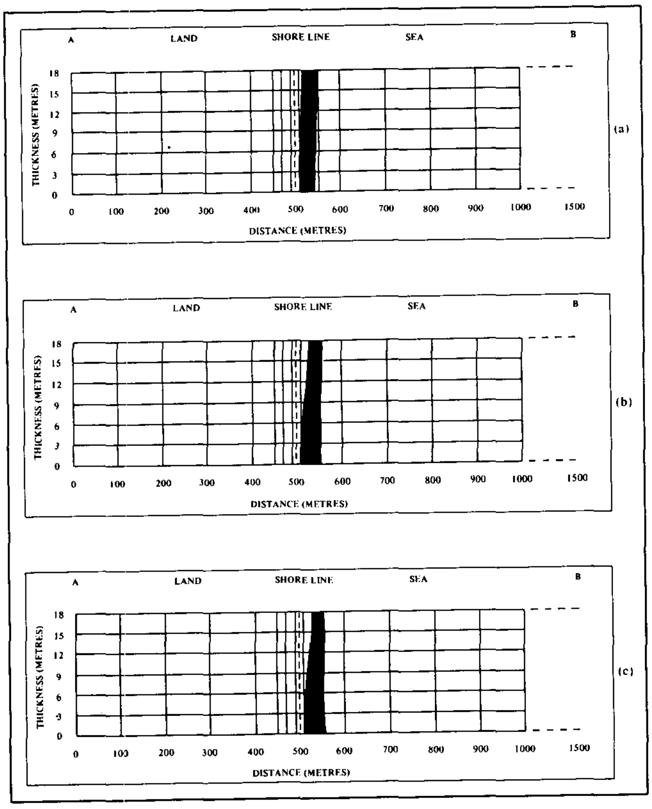

Figure 4
Results for the second simulation indicating the position and physical dimensions of the transition zone, (a) after 90 d, (b) after 360 d and (c) after 720 d.

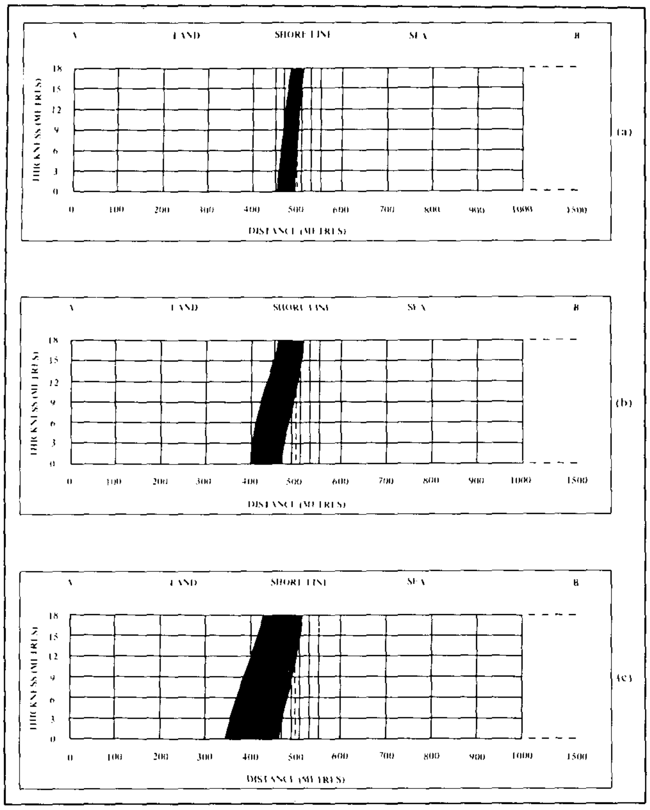

Figure 5
Results for the third simulation indicating the position and physical dimensions of the transition zone, (a) after 90 d, (b) after 360 d and (c) after 720 d.

Another interesting fact to note, is the constant physical dimension attained by the transition zone. After its rapid expansion from 0 to 50 m during the first 90 d, the zone remains more or less constant for the rest of the simulation period, indicating steady state conditions.

The results for the second simulation are shown graphically in Figure 4. It is evident that although the general behaviour of the system is identical to that of the previous simulation, the transition zone lies slightly closer to the coastline. This is, however, to be expected, due to the fact that the driving force of the freshwater has been reduced by the lowering of the hydraulic head at the Silwerstroom spring.

As the total width of the transition zone is still approximately 50 m, it can be concluded that the 3 m drop in hydraulic head at the spring, due to the proposed maximum abstraction rate at the Silwerstroom production field (Bredenkamp and Vandoolaeghe, 1982) will not expedite the intrusion of sea water into the aquifer.

The third and last simulation was included mainly to show what effect extreme conditions of dewatering may have on the system. This is purely a theoretical exercise, but the results are nevertheless spectacular. As can be seen from Figures 5a, b and c, the transition zone moves rapidly inland. Moreover, there is no indication of any stabilisation in its position, not even after 720 d, which indicates that the intrusion process is still continuing. This is quite discomforting if one notices that the 0,02 isochlor already lies 167 m inland after only 720 d (compared to the distance of 500 m that the spring is from the coast). It is also interesting to note that the transition zone has already spread 60 m during the first 90 d, and reaches a total width of 174 m after 720 d.

Conclusions

The results of the present model for Atlantis indicate that sea-water intrusion does not present a serious hazard for the time being. However, as shown by the results of the third simulation, sea-water intrusion may occur if the water level at the Silwerstroom spring is lowered to sea level. In judging these results it must be kept in mind that the aquifer is assumed to be of constant thickness in the present model, and therefore prone to over-estimate the situation. Nevertheless, the lack of more detailed information on the hydraulic parameters and position of the salt/freshwater interface makes it difficult to obtain a better understanding of the behaviour of the aquifer at present. This can only be achieved through a more detailed investigation of these factors and the influence of ground-water abstraction on the spring flow.

Acknowledgements

This paper stems from a project which was financed by the Water Research Commission, Pretoria, South Africa, the Division of Geohydrology of the Department of Environmental Affairs, Pretoria, South Africa, as well as the Institute for Ground-water Studies, UOFS, Bloemfontein, South Africa.

References

BEAR, J. (1979) *Hydraulics of Groundwater.* McCraw-Hill Ltd., New York. 567.

BOTHA, J.F. and CELIA, M.A. (1981) Alternating direction approximations for a parabolic partial differential equation. Water Resources Program, Dept. of Civil Engineering, Princeton Univ., USA.

BREDENKAMP, D.B. and VANDOOLAEGHE, M.A.C. (1982) Die ontginbare grondwaterpotensiaal van die Atlantisgebied. Tech. Report, Gh3227, Dept. of Environmental Affairs, SA.

CELIA, M.A. (1984) Density-dependent transport simulation using alternating direction collocation. *Bulletin Inst. Ground-water Studies*, Bloemfontein 12 1-35.

MÜLLER, J.L. (1984) A preliminary investigation of modelling the Atlantis aquifer. Unpublished M.Sc. thesis, UOFS, Bloemfontein. 174.

VAN DER VEER, P. (1977) Analytical solution for a two-fluid flow in a coastal aquifer envolving a phreatic surface with precipitation. *Journal of Hydrology* 35(3) 271-277.

VAN TONDER, G.J., BOTHA, J.F., MÜLLER, J.L. (1986) The problem of sea-water intrusion near Lake Mzingazi at Richards Bay. *Water SA* 12(2) 83-88.

VAN TONDER, G.J. and BOTHA, J.F. (1983) Modelling water levels and contaminant transport in the Omaruru Delta. Tech. Report, Inst. Ground-water Studies, Bloemfontein. 171.