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Dynamic Salt-Fresh Interface in an Unconfined Aquifer: Bribie Island Groundwater Study

L. T. ISAACS

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Department of Civil Engineering,
University of Queensland,
St Lucia, Q 4067, Australia,
[Tel:(07) 377-3342, Telex:UNIVQLD AA40315]

DYNAMIC SALT-FRESH INTERFACE IN AN UNCONFINED AQUIFER: BRIBIE ISLAND GROUNDWATER STUDY

by

L. T. Isaacs, BE, MEngSc, PhD, MIEAust.
Senior Lecturer in Civil Engineering

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Synopsis

Potential dangers of serious saltwater intrusion exist for any unconfined, coastal aquifer from which significant volumes of water are extracted. Under quasi-steady conditions, the extent of saltwater intrusion can be estimated satisfactorily from regular field measurements of water table levels and the Ghyben-Herzberg approximation.

If water table levels fall temporarily, e.g. during a drought, this approach yields an overestimate of the extent of saltwater intrusion and an improved method is needed if realistic estimates are to be made. Such conditions occured in the Bribie Island aquifer in the summer of 1983. This report describes a subsequent study into the dynamic response of the salt-fresh interface for that aquifer.

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1. INTRODUCTION

Bribie Island's water supply is obtained from the unconfined aquifer in the southern part of the island. Water is collected in a long trench in the water reserve and pumped from one end of the trench to the water treatment plant.* Rainfall was unusually low during the 1983 summer and there was a consequent increased demand for water from the trench during the period of decreased rainfall recharge to the aquifer. As a result, groundwater levels fell. The aquifer extends to approximately 16 m below sea level in the south-east corner of the island. If the Ghyben-Herzberg approximation is used (see Todd (1980)), the estimated position of the toe of the salt water wedge is below the 0.4 m groundwater level. During the summer of 1983, water levels in the trench fell below mean sea level and the maximum groundwater level between the trench and the sea came uncomfortably close to the 0.4 m value. Water restrictions were imposed and the aquifer was recharged between the trench and the sea to prevent further declines in groundwater levels in the critical region.

The Ghyben-Herzberg approximation gives $\zeta = \beta s$ (see Appendix A for definition of terms) but assumes steady state conditions. However, the conditions at Bribie Island during the summer of 1983 were far from steady and questions that arose from this experience were

(a) how does the salt-fresh interface respond to unsteady conditions? and

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* A detailed description of the Bribie Island aquifer is given in Walker (1983) and Isaacs and Walker (1983).

(b) how accurately can the position of the salt-fresh interface be predicted using the Ghyben-Herzberg approximation in conjuntion with the field measurements of the groundwater levels?

The report describes the development and application of mathematical models used to investigate these questions.

2. PROBLEM DEFINITION

2.1 Description of Problem

The mathematical problem for which a solution is sought is that of one-directional groundwater flow as shown in Figure 1. It is assumed that the Dupuit approximation applies and that there is a well defined interface between the salt and fresh water zones. The aquifer geometry and properties, $q^f(L,t)$ and $R(x,t)$ are assumed to be known. The unknowns for which a solution is sought are $s(x,t)$ and $\zeta(x,t)$.

2.2 Governing Equations

The governing equations (Shamir and Dagan (1971), Bear (1972)) are

for $x \leq x_t$

in freshwater zone

$$n^f \frac{\partial s}{\partial t} + n^s \frac{\partial \zeta}{\partial t} - \frac{\partial}{\partial x}\left[K^f(\zeta + s)\frac{\partial s}{\partial x}\right] = R \qquad (1)$$

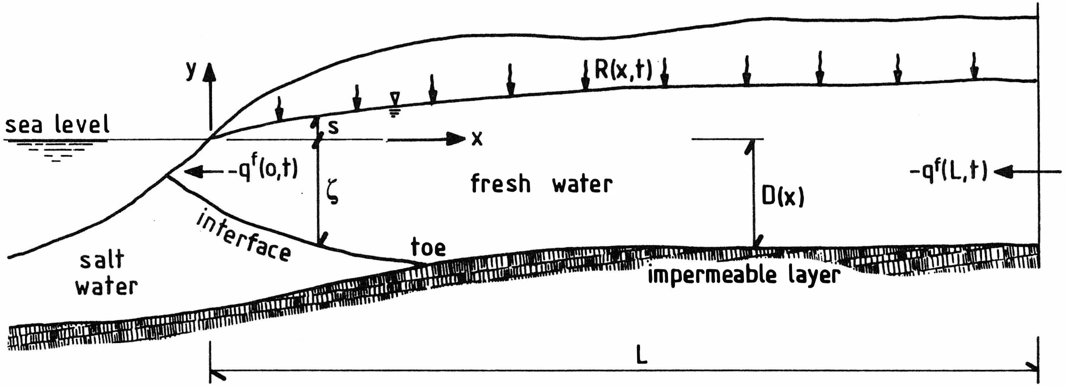

FIGURE 1: Vertical Section Through an Unconfined Coastal Aquifer

in saltwater zone

$$n^s \frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}\left[K^s(D - \zeta)\frac{\partial}{\partial x}\left(\frac{\gamma^f}{\gamma^s} s - \frac{\Delta\gamma}{\gamma^s}\zeta\right)\right] = 0 \qquad (2)$$

for $x \geq x_t$

$$n^f \frac{\partial s}{\partial t} - \frac{\partial}{\partial x}\left[K^f(D + s)\frac{\partial s}{\partial x}\right] = R \qquad (3)$$

2.3 Boundary Conditions

The boundary conditions (assumed known) are $s(0,t)$ and $\zeta(0,t)$ at $x = 0$ and either $q^f(L,t)$ or $s(L,t)$ at $x = L$. Since $D/L << 1$ in the aquifer to be studied the conditions adopted at $x = 0$ are

$$s(0,t) = 0 \qquad \text{and} \qquad \zeta(0,t) = 0 \qquad (4)$$

The use of this boundary condition will not make any significant difference to the results in this study. Should a better estimate be required for $\zeta(0,t)$ a method is presented in Shamir and Dagan.

Another required boundary condition is that $s(x,0)$ and $\zeta(x,0)$ be known. In this study the assumption has been made that steady state conditions prevail for $t \leq 0$.

3. STEADY STATE CONDITIONS

Under steady state conditions $\zeta = \beta s$ and the governing equations become

$$-\frac{\partial}{\partial x}\left[K^f \alpha s \frac{\partial s}{\partial x}\right] = R, \quad 0 \leq x \leq x_t \qquad (5)$$

and

$$-\frac{\partial}{\partial x}\left[K^f(D+s)\frac{\partial s}{\partial x}\right]=R, \quad x_t \leq x \leq L \tag{6}$$

If K and R are constants, the solution for $0 \leq x \leq x_t$ is,

$$s^2 = -\frac{Rx^2}{\alpha K} - \frac{2q_o x}{\alpha K} + s_o{}^2 \tag{7}$$

in which

$$q_o = -K\left(\frac{\partial s}{\partial x}\right)_o \alpha s_o = q^f(L,0) - RL \tag{8}$$

The toe is located at the position where $s = D/\beta$ and for $s_o = 0$, $R \neq 0$

$$x_t = -\frac{q_o}{R} - \left\{\left(\frac{q_o}{R}\right)^2 - \left(\frac{D}{\beta}\right)^2 \frac{\alpha K}{R}\right\}^{\frac{1}{2}} \tag{9}$$

If D is also constant, the solution for $x_t \leq x \leq L$ is

$$(D+s)^2 = -\frac{Rx^2}{K} + \frac{2}{K}\left(RL - q^f(L,0)\right) x + C \tag{10}$$

The value for C is determined from the condition that $s = D/\beta$ at x_t.

Table 1: Typical values for Bribie Island Aquifer

L	=	1000 m
D	=	16 m
K	=	25 m/day
R	=	8.22×10^{-4} m/day
β	=	40
L/D	=	62.5
R/K	=	3.288×10^{-5}

4. PRELIMINARY EVALUATION

4.1 Objectives

The purposes of the preliminary evaluation included

(i) the development of a general understanding of the dynamic behaviour of the interface

(ii) the indentification of the parameters that determine the position of the interface and its dynamic response to changes in these parameters

(iii) an assessment of the need for a numerical model for further evaluation and of the type of model that should be used.

The work described in the preliminary evaluation is also useful in the verification of any numerical model. Should a numerical model give results inconsistent with the conclusions of the preliminary evaluation, the numerical model would be suspect.

4.2 Dimensional Analysis

Dimensional analysis may be used to obtain functional relationships between the parameters of the problem. If it is assumed that $K^f = K^s = K$ and $n^f = n^s = n$, the position of the toe, x_t, depends on D, L, t, K, R, q_L, n and β. q_L is the flow across the boundary at $x = L$. $(-q_L)$ is the flow into the aquifer across the boundary. Dimensional analysis yields

$$\frac{x_t}{D} = f\left(\frac{L}{D}, \frac{tK}{D}, \frac{R}{K}, \frac{(-q_L)}{DK}, \beta, n\right) \tag{11}$$

Under steady conditions, x_t/D is independent of tK/D and n,

$$\frac{x_t}{D} = f\left(\frac{L}{D}, \frac{R}{K}, \frac{(-q_L)}{DK}, \beta\right) \tag{12}$$

Equation 9 can be rearranged to give the explicit form of Equation 12,

$$\frac{x_t}{D} = \frac{(-q_L)}{DK}\,\frac{K}{R} + \frac{L}{D} - \left\{\left[\frac{(-q_L)}{DK}\,\frac{K}{R} + \frac{L}{D}\right]^2 - \frac{\beta + 1}{\beta^2}\,\frac{K}{R}\right\}^{\frac{1}{2}} \tag{13}$$

Typical values for the Bribie Island aquifer are given in Table 1 (Walker (1983)). For the purposes of this preliminary assessment $(-q_L)$ was assumed to range from zero to RL. Table 2 shows how the non-dimensional toe position, x_t/D, is affected by small changes in parameters under steady conditions. Increases in L, R or $(-q_L)$ cause a decrease in x_t/D while increases in D or K cause an increase in x_t/D. These trends will also be true in the unsteady case but the important questions relate to the rate at which x_t moves.

Equation 11 shows that, under unsteady conditions, x_t will be a function of R(t) and $-q_L(t)$ but it is not possible to make any deductions about the effects of R and $-q_L$ on the rate of response of the interface. The terms tK/D and n become significant in unsteady cases. The first of these suggests that the response of the interface will be faster in shallow aquifers or in aquifers of high hydraulic conductivity. Since n forms a product with the time derivatives in Equations 1, 2 and 3, an increase in n will lead to a reduction in these derivatives and, therefore, to a slower rate of response. Further information on the rate of response can be obtained from another line of reasoning as follows.

Table 2: Effects of changes in aquifer parameters on x_t/D (steady conditions)

Value Changed by + 1%	Percentage change in x_t/D		
	$-\frac{q_L}{KD} = 0$	$-\frac{q_L}{KD} = 1.0275*10^{-3}$	$-\frac{q_L}{KD} = 2.055*10^{-3}$
L/D	- 1.105	- 0.693	- 0.510
R/K	- 1.108	- 0.670	- 0.497
$- q_L/KD$	0	- 0.348	- 0.510
β	- 1.073	- 1.038	- 1.027
D	1.105	1.037	1.015
K	1.059	1.024	1.013

4.3 Mathematical Deductions

Because the mathematical model assumes that the Dupuit approximation is valid and that p takes the same value either side of the interface

$$h^s = \frac{\gamma^f}{\gamma^s}(s + \zeta) - \zeta \qquad (14)$$

Under steady conditions $h^s = 0$ throughout the salt water zone and there is no flow in the salt water zone (although there is flow in the fresh water above the interface). If some change is made, the rate at which the interface will move will depend on the velocities in the salt water zone (to satisfy continuity). If the interface is to respond quickly to changes, these velocities (and therefore $|\partial h^s/\partial x|$) must be relatively large.

Consider a case in which $R = R_1$ for $t < t_o$ and $R = R_2$ for $t > t_o$ and steady conditions occur for $t < t_o$. After the change the interface will move until the new steady state position has been achieved. Note that $h^s = 0$ for $t < t_o$ and $h_s = 0$ when the new steady state is achieved. Therefore the velocities in the salt water wedge will be zero prior to and at the end of this change in conditions. Therefore, the interface will move relatively quickly only if relatively large gradients $|\partial h^s/\partial x|$ are generated during the period of the change.

It might be expected that, if there is a sudden change to s, this sudden change from an equilibrium to a non-equilibrium state would produce a large response at the interface.

If $\gamma^s = 1.025\ \gamma^f = 1.025$ (typical values) Equation 14 becomes

$$h^s = \frac{40}{41} s - \frac{1}{41} \zeta \tag{15}$$

For small changes in s and ζ

$$\delta h^s = \frac{40}{41} \delta s - \frac{1}{41} \delta\zeta \tag{16}$$

Note that, if δs and $\delta\zeta$ are changes from one steady state to another, $\delta\zeta = 40\ \delta s$ and $\delta h^s = 0$.

Now assume that an instantaneous δs is applied to s with the interface in the previous equilibrium position (so that $\delta\zeta = 0$). Under such a change $h^s = \frac{40}{41} \delta s$. Consider two locations x_1 and x_2 with $\Delta x = x_2 - x_1$. The gradient produced in the salt water zone by this change to s is given by

$$\frac{\partial h^s}{\partial s} \simeq \frac{\Delta h^s}{\Delta x} = \frac{40}{41\Delta x}\left(\delta s_2 - \delta s_1\right) \tag{17}$$

Since, in typical situations, $\delta s_2 \simeq \delta s_1$, the head gradients and, therefore, the velocities produced in the salt water region will be very small. Therefore the initial response of the interface to the new, non-equilibrium condition will be slow. Since the interface has to move until $\delta\zeta = 40\ \delta s$, it will take a relatively long time to shift to the new equilibrium position.

This analysis indicates that the interface is relatively slow to respond to changes. It follows that, under unsteady conditions, the position of the toe cannot be predicted from the Ghyben-Herzberg approximation.

Although the preliminary evaluation has yielded only qualitative results, these results are useful. They indicate that, under dynamic conditions, the extent of salt water intrusion cannot be ascertained from field records of water table levels in the fresh water zone. This means that, where observation bores are used to monitor coastal aquifers and management decisions are based on the records from these bores, consideration should be given to the possibility of locating some observation bores in the salt water zone so that the variations in h^s are monitored. If s and h^s are known, an estimate of the position of the interface can be made using Equation 14.

4.4 Conclusions

The possibility of using a mathematical model based on Equations 1 and 3 with $\zeta = \beta s$ in Equation 1 was considered. However, the results from the preliminary evaluation indicate that any simplification based on an assumption of quasi-steady conditions (e.g. $\zeta = \beta s$) could be seriously in error in predicting the location of the interface. Where the location of the interface is not the main objective of the analysis, this simplified model might be worth considering. It is easier to program than the complete model and could give acceptable results for s(t). It would certainly give better results for s(t) than an unsteady analysis that ignores the salt water zone completely. However, when an accurate prediction of the interface location under dynamic conditions is required, the preliminary evaluation shows that the mathematical model should be based on Equations 1, 2 and 3. (The applicability of quasi-steady models to dynamic analyses of the salt-fresh interface is treated in more detail in another report - see Isaacs (1983)).

The understanding gained from the preliminary evaluation is also of value when decisions are made about the number of numerical analyses to be done and which parameters should be altered from one run to the next. In some cases it may be possible to use results from previous analyses to assess the consequences of changes without further analysis. For example, if an analysis has shown that salt water intrusion is not a problem but later data indicate that the value of K used in the analysis was too high, the effect of a reduction in K will be a reduction in x_t and a slower response to changes. A new analysis is not required to show that salt water intrusion will not be a problem if K is reduced.

Despite the usefulness of the results from the preliminary evaluation, they cannot yield specific answers to questions about the extent of salt water intrusion and the dynamic response of the interface. These answers can come only from the solution of Equations 1, 2 and 3.

5. METHOD OF SOLUTION

At present, general, analytic solutions of Equations 1, 2 and 3 are not available. For this study the numerical, finite-difference scheme described by Shamir and Dagan (1971) has been adopted. Although there are some minor differences between the techniques used by Shamir and Dagan and those used by the author, these are relatively unimportant and will not be discussed. The reader is referred to the paper by Shamir and Dagan for details of the solution method. The Pseudo-Code for the program is:-

```
Calculate initial steady state solution (including s, $\zeta$, $x_t$)
Set up grid for t = 0
Set values for s and $\zeta$ at grid points for t = 0
REPEAT
    REPEAT
        Calculate equation coefficients from s, $\zeta$ values at
        start of time step
        Solve equations for s, $\zeta$ at end of time step
        Calculate $x_t$ at end of time step
        IF change in $x_t$ too large THEN
            Reduce time step
        ENDIF
    UNTIL a satisfactory time step is completed
    Update time and toe position
    Generate new grid and calculate s, $\zeta$ values at new
    grid positions for start of next time step from s, $\zeta$
    values at old grid positions at end of previous time step
    IF change in $x_t$ too small then
        Increase time step
    ENDIF
UNTIL total time of simulation is reached.
```

The method has been implemented via a FORTRAN program on the PDP 11/34 computer in the Department of Civil Engineering.

6. PROGRAM VERIFICATION

Some checks were performed to verify the program. The equation coefficients in the numerical solution for s and ζ at time $t + \Delta t$ are such that if $\Delta t = 1$ and $n = 0$ the equations reduce to the finite difference equations for steady conditions. In one check the program was run with $\Delta t = 1$ and $n = 0$ and the results obtained agreed with the analytical solution, Equations 9 and 10. The effect of $n = 0$ is to remove the unsteady terms $\partial s/\partial t$ and $\partial \zeta/\partial t$ from the finite difference equations. However, if $n \neq 0$ while $R(t)$ is kept constant at the value of $R(t = 0)$, the unsteady terms are retained in the finite difference equations but the computed changes during a time step should be zero. This was confirmed in a second check. A small perturbation is possible because of discretization and roundoff. Manual checks were performed to confirm that any differences between the numerical and analytical results were caused by these effects. Other checks were done by independent, manual calculations of some of the equation coefficients computed in the program. A further check is provided by a comparison of the results obtained from the program with the trends predicted by the preliminary evaluation. These checks all indicate that the program is free of errors and accurately performs the computations required for the numerical solution of Equations 1, 2 and 3.

7. NUMERICAL RESULTS

The values of the parameters used in the numerical analyses are shown in Table 3. These values are judged to be typical of the field values for southern Bribie Island (Walker 1983). Since the major objective of the study is an assessment of the rate of response of the interface, a step function for R(t) was adopted in Runs 1,2,3,4. Runs 3,4 were done to demonstrate the effects of changes in n and D on the rate of response. Finally, Run 5 was performed to investigate the response of the interface to a complex pattern of R(t). In all runs $K^s = K^f = K$, $n^s = n^f = n$, $q_L = 0$, $\beta = 40$, R and D were independent of x. Results from these runs are presented in Figures 2 to 8.

The results show that the response of the interface to a change in recharge is indeed very slow. In Run 1, the initial toe position was $x_t = 576$ m. 1800 days after the increase in R the toe was located at $x_t = 408$ m whereas the steady state location for the increased value of R is 108 m. The overall rate of response to a decrease in R (Run 2) was comparable to the overall rate in Run 1 but slightly slower. In Run 1, x_t changed by 168 m in 1800 days and in, Run 2, x_t changed by 151 m in the same period.

The results also demonstrate that an estimate of the toe position from the Ghyben-Herzberg approximation would be seriously in error. The plots of (x at $s = D/\beta$) vs time show the toe position from the Ghyben-Herzberg approximation using the computed values for s(t). In Run 1, for example, the use of this method for locating the toe would lead to the conslusion that the new steady state position ($x_t = 108$ m) had been effectively achieved 800 days after the change in R whereas the computed value for x_t at this time is 541 m.

Table 3: Parameter values used in numerical analyses

Run No.	L m	D m	K m/day	n	R m/day
1	1 000	16	25	0.2	$0.2*10^{-4}$, $t < 200$ hrs $0.8*10^{-4}$, $t > 200$ hrs
2	1 000	16	25	0.2	$0.8*10^{-4}$, $t < 200$ hrs $0.2*10^{-4}$, $t > 200$ hrs
3	1 000	26	25	0.15	$0.2*10^{-4}$, $t < 200$ hrs $0.8*10^{-4}$, $t > 200$ hrs
4	1 000	12	25	0.2	$0.2*10^{-4}$, $t < 200$ hrs $0.8*10^{-4}$, $t > 200$ hrs
5	1 000	16	25	0.2	Complex pattern

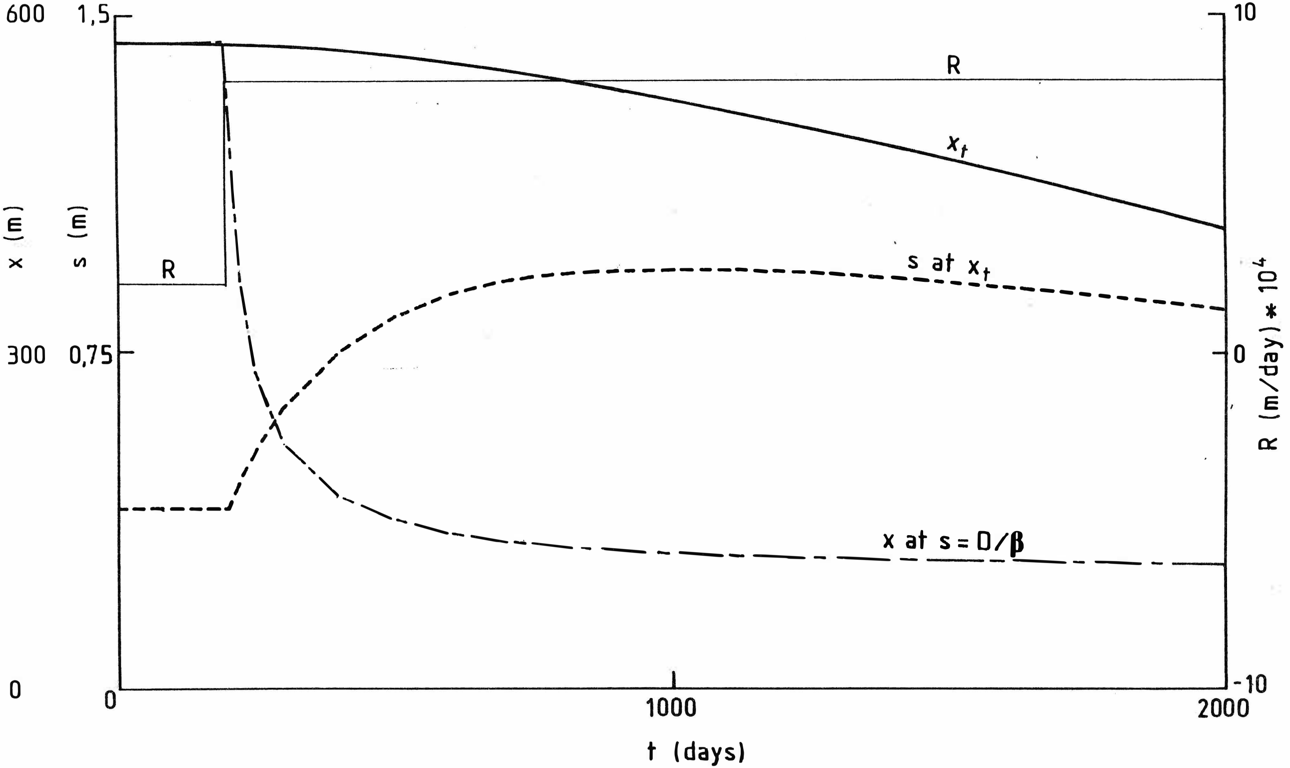

FIGURE 2: Results from Run No. 1

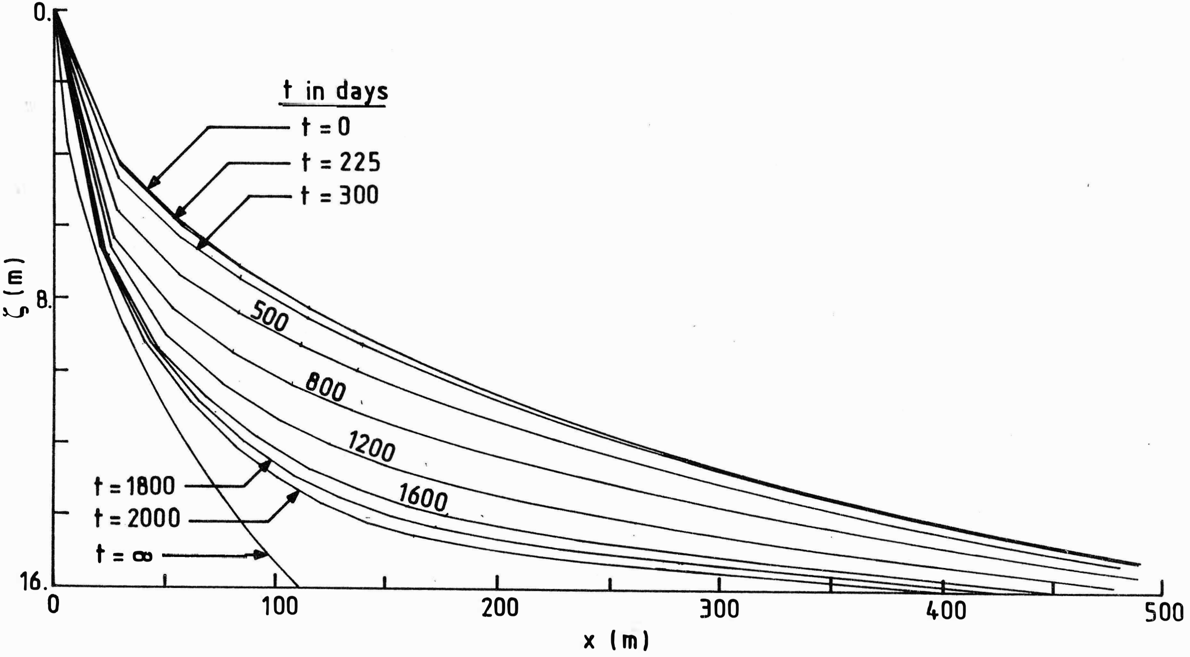

FIGURE 3: Interface Profiles from Run 1

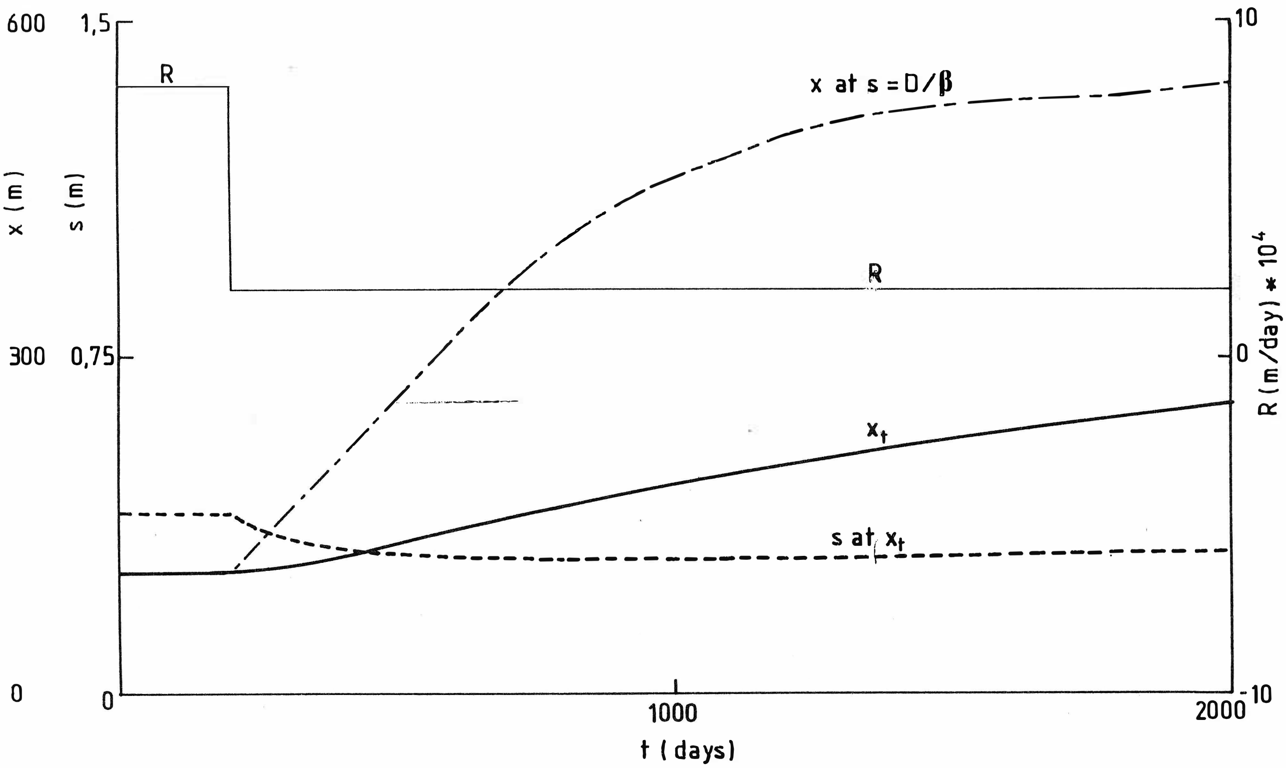

FIGURE 4: Results from Run No. 2

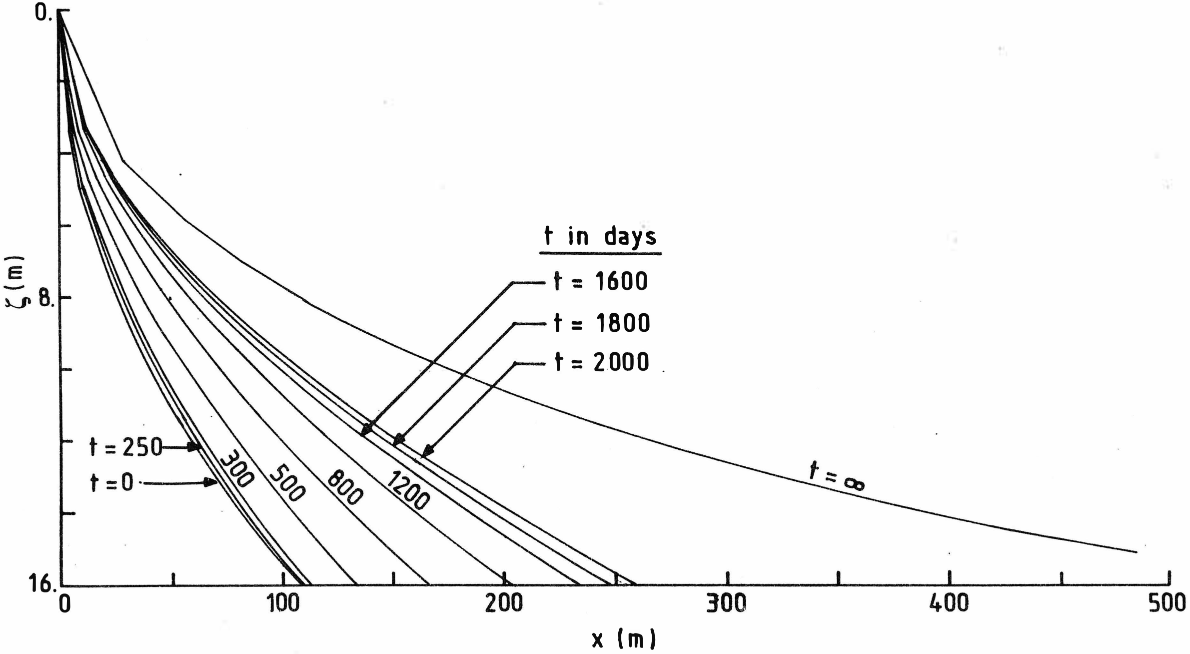

FIGURE 5: Interface Profiles from Run 2

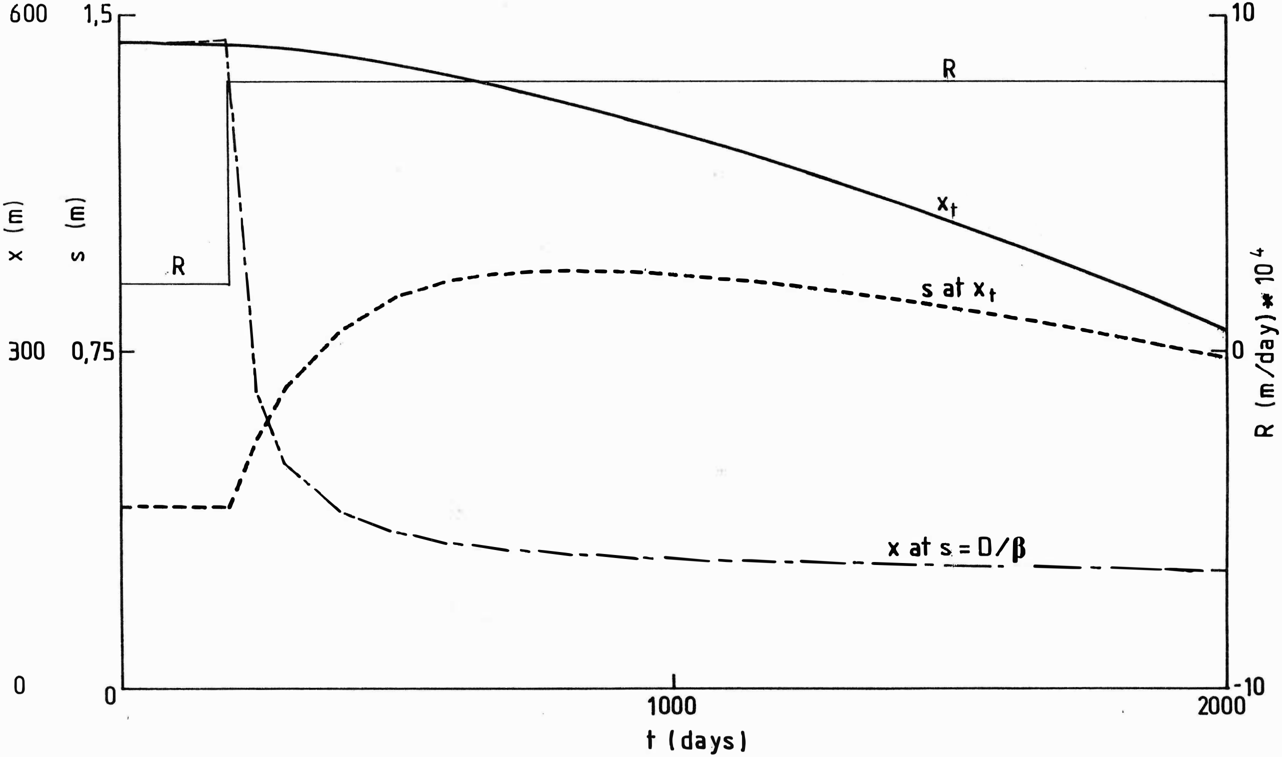

FIGURE 6: Results from Run No. 3

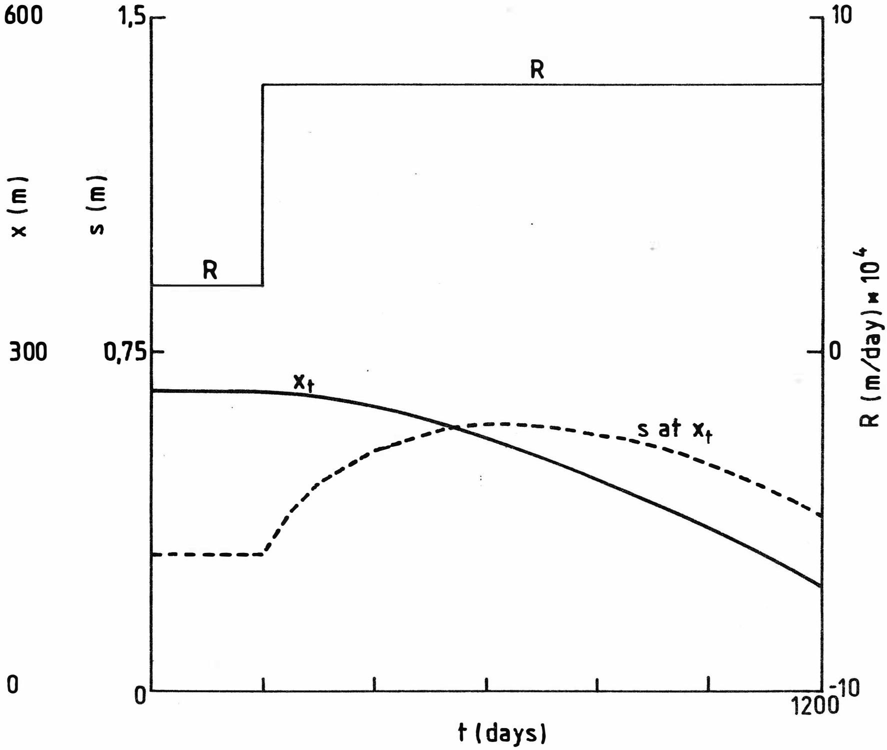

FIGURE 7: Results from Run No. 4

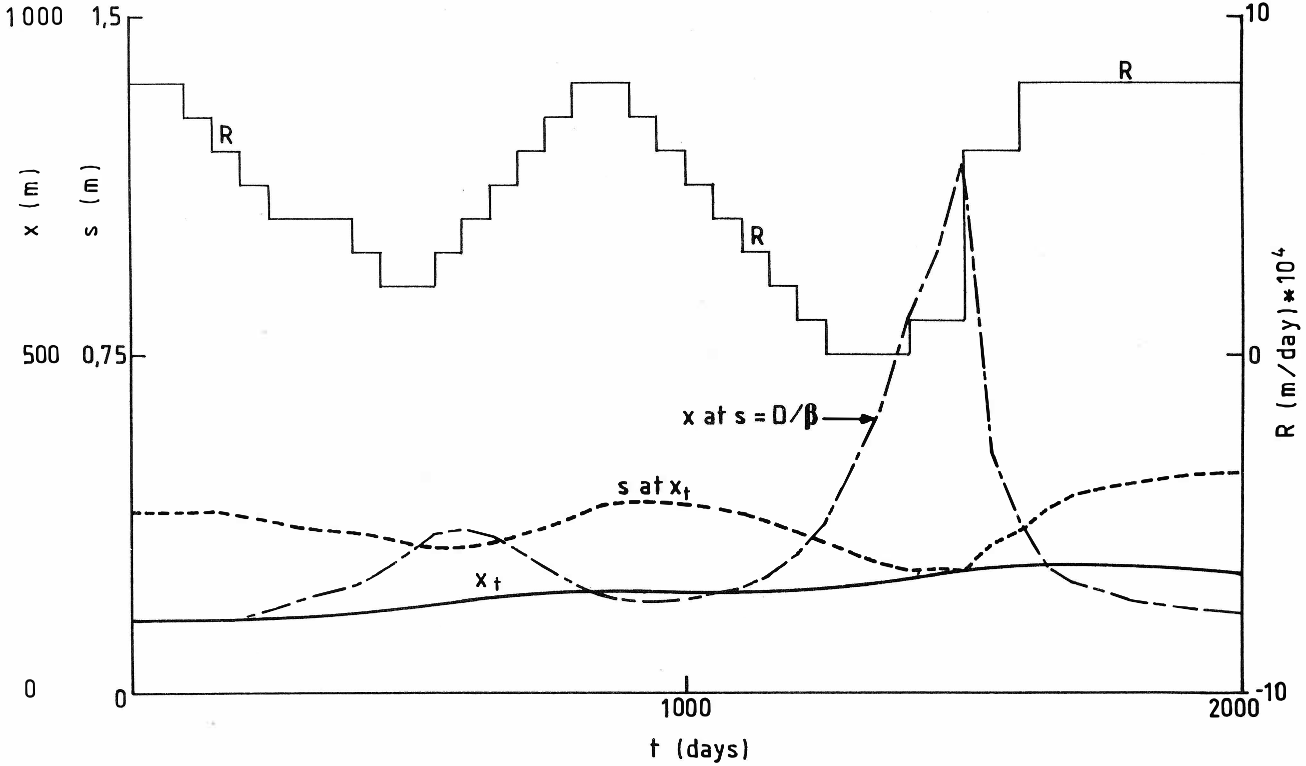

FIGURE 8: Results from Run No. 5

The values for s at x_t have also been plotted. The values for t < 200 days in Runs 1,2,3,4 are for steady conditions and satisfy the relationship $s = D/\beta$. Following an increase in recharge, the value of s above the toe location can be significantly greater than this value (more than twice D/β) - see Figures 2,6,7. Following a decrease in recharge, the value of s falls below D/β - see Figure 4.

A comparison of the results from Runs 3 and 4 (Figures 6 and 7) with the results from Run 1 (Figure 2) shows how the rate of response is affected by changes in n or D. A decrease in n or D produces a faster response. These results confirm the predictions made in the preliminary evaluation.

Run 5 (Figure 8) was performed to investigate the response of the interface to a complex pattern of R(t). Steady state conditions with $R = 8 \times 10^{-4}$ m/day and $x_t = 108$ m exist for t < 100 days. Thereafter R varies between 8×10^{-4} m/day and zero as shown in Figure 8. The computed variation in x_t is also plotted and this plot shows that the variations in x_t are relatively small. The maximum value computed for x_t was 190 m. Furthermore, because of the slow rate of response of the interface, it is possible for the toe to continue to move inland during a period in which the recharge increases and vice-versa. The results further demonstrate the serious errors that can arise in predictions of x_t from measured values of s and the Ghyben-Herzberg approximation. In Run 5 this method predicts a maximum value for x_t of 784 m - four times the computed maximum.

8. CONCLUSIONS

(i) The salt-fresh interface in an unconfined coastal aquifer (comparable with the Bribie Island aquifer) will respond slowly to changes in recharge rates.

(ii) Under unsteady conditions, the location of the interface cannot be determined from water table measurements.

(iii) The location and direction of movement of the interface depends on the previous history of recharge, not only on the conditions at the time.

(iv) Provided recharge and other conditions remain constant in the long term, relatively short periods (e.g. a few months) of low or zero recharge should not produce serious salt water intrusion problems.

(v) On the other hand, the effects of major changes in recharge or extraction will not become evident in the short term and short term data cannot be used to assess the final consequences of changes.

(vi) Field monitoring of coastal aquifers should include measurements of the piezometric head in the salt water zone if an estimate of the extent of salt water intrusion is required.

(vii) Numerical models based on any assumptions of quasi-steady relationships may give serious errors in the prediction of the extent of salt water intrusion. Any useful model for this purpose should be based on the unsteady equations (Equations 1,2 and 3 of this report).

APPENDIX A - NOMENCLATURE

Symbol	Meaning
$D = D(x)$	thickness of aquifer from sea level down to impervious layer
f	(as superscript) refers to fresh zone
g	acceleration due to gravity
$h = \frac{p}{\rho g} + y$	piezometric head
K	hydraulic conductivity
L	length of aquifer
n^f	effective porosity for movement of the phreatic surface
n^s	effective porosity for movement of the interface
p	pore water pressure
$q = q(x,t)$	two-dimensional seepage discharge, $q_0 = q(0,t)$
$R = R(x,t)$	nett discharge into aquifer from above
$s = s(x,t)$	elevation of phreatic surface above sea level, $s_0 = s(0,t)$
s	(as superscript) refers to salt zone
t	time
$T = T(x,t)$	transmissivity
v	Darcy velocity
x	horizontal distance measured from origin at intersection of sea level and land surface
$x_t = x_t(t)$	distance to toe of interface
y	vertical distance measured from origin
$\alpha =$	$1 + \beta$
$\beta =$	$(\gamma^s - \gamma^f)/\gamma^f$
ρ	density
γ	specific weight of water
$\Delta\gamma =$	$\gamma^s - \gamma^f$
$\zeta = \zeta(x,t)$	distance from sea level to the interface

APPENDIX B - REFERENCES

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