Exploitation of Groundwater from Fresh Water Lenses in Saline Aquifers

by
Amjad S. Aliewi[1]
Rae Mackay[1]
Jan Van Wonderen[2]
[1]Water Resource Systems Research Unit, Civil Engineering Department,
University of Newcastle upon Tyne, U.K.
[2]Groundwater Development Consultants (Mott MacDonald), Cambridge, U.K

ABSTRACT

The existence of fresh water overlying saline water in groundwater systems is widespread in many inland aquifers as well as in most coastal aquifers. These fresh groundwaters can be a vital water resource where other surface and subsurface water resources are insufficient to supply the needs of a region. Therefore, it is important to understand how to extract economically the maximum amount of the fresh water from the aquifer whilst preventing the mixing of the fresh and the saline waters. The concept of scavenger pumping (pumping both the fresh and saline waters simultaneously but through separate outlets) has been suggested in the literature to be technically and economically feasible. However, there has been a need to gain further insight into the movement of the fresh/saline groundwater transition zone around scavenger wells in order to derive suitable design criteria: recently, a research study has been undertaken to fill this need.

Using data from experimental scavenger wells in Pakistan and a numerical model for density dependent flow and solute transport in groundwater detailed sensitivity studies of the movement of the fresh/saline water transition zone have been carried out. Three empirical equations have been derived from the results of the sensitivity analyses. These express the fresh/saline water recovery ratio at the well as well as the width and the position of the fresh/saline water transition zone in the well when pumping has reached equilibrium. These equations have been developed for general application to fresh/saline groundwater environments to develop the optimal fresh water recovery from any new scavenger well.

INTRODUCTION

The existence of fresh water overlying saline water in groundwater systems is widespread in many inland aquifers as well as in most coastal aquifers. These fresh groundwater lenses can be a vital water resource where other surface and subsurface water supplies are inadequate for the needs in a region. A movement of saline groundwater into zones of fresh groundwater can degrade both the water and land resources of an area. In shallow groundwater systems, it may exacerbate the waterlogging of cropped areas and cause salinisation of uncropped land. In deep groundwater systems, problems arise from the mixing of the fresh and saline groundwater in the vicinity of abstraction wells leading to a reduction in the quality of the well water and possible abandonment of the well.

The groundwater systems found along the coastal aquifer of the Gaza Strip provide a typical example of potential problems. In Bruins et al. (1991) it is shown that the over exploitation of the fresh groundwater in this area has resulted in declining groundwater levels and a severe increase in the salinity of the abstracted water. To avoid the degradation of these water resources, it has become important to understand how to extract economically the maximum amount of fresh water from the aquifer while preventing the mixing of both the fresh and saline waters. This has required the development of an understanding of the complex dynamic relationship between the different waters in the vicinity of pumped well systems.

Different methods have been used in many countries for the exploitation of fresh water overlying saline groundwater. These include limited lifetime wells (GDC and BGS, 1990), horizontal interceptor drains (McWhorter, 1972), and skimming wells (Reilly et. al., 1987). The application of each of these methods depends on the particular hydrogeological conditions encountered, the purpose for which the water is being extracted and the value of the water recovered. Limited lifetime and skimming wells use standard tubewell technologies in their design and construction. Limited lifetime wells are pumped at a rate which will eventually cause the saline water beneath the well to rise up and contaminate the well discharge. Skimming wells rely on pumping the fresh water at a rate which is insufficient to draw the saline water into the well. In this case, the saline water forms a stable cone beneath the well when the weight forces in the saline water mound are in equilibrium with the pressure gradients towards the well. Interceptor drains use tile or open drainage principles to produce water from shallow lenses of fresh groundwater. As for skimming wells, this approach relies on a balance between the upward and downward forces in the body of saline water beneath the tiles/drains.

In addition to the traditional methods, more recent interest has focused on the use of scavenger pumping (Zack, 1988). In this method both the fresh and the saline waters are pumped simultaneously but through different outlets. Although the concept of scavenger wells has been understood for many years, it is only recently that its use has been considered seriously for thin fresh groundwater lens recovery. Recent discussions in the literature (Birch and Van Wonderen, 1990) have indicated that this method is technically and economically feasible. Modelling studies have been undertaken by Groundwater Development Consultants and the British Geological Survey (GDC and

BGS, 1989b) to demonstrate the behaviour of the groundwater around scavenger wells positioned alongside a seeping canal. However, there was further need to enhance the understanding of the movement of the transition zone between the underlying saline and overlying fresh groundwater in the vicinity of a scavenger well in order to validate and improve scavenger well designs.

In this paper, the results of recent research into the movement and spread of the fresh/saline transition zone in the vicinity of pumping systems are presented. The aims of the research were two-fold:

1) to determine through simulation, the physical controls governing the behaviour of the transition zone under pumped conditions and the sensitivity of the transition zone to each of the properties of the physical system;

2) to establish criteria for the optimal design of scavenger wells.

The results of this research have provided further evidence of the viability of this method of groundwater exploitation.

SCAVENGER WELLS

The Concept

Scavenger well systems (Figure 1) are methods to extract finite thickness lenses of fresh groundwater overlying saline groundwater. To maximise the recovery of fresh water, these systems also extract saline water from the aquifer. Two configurations are adopted in scavenger well system design. In the first configuration (Figure 1A), a single well, screened over both the fresh and saline zones, is used. Two pumps are installed in the well, the lower pump extracts the saline water, the upper pump extracts the fresh water. The discharge rates of both pumps determine the position of the transition zone between the fresh and saline waters and the quality of the water discharged from each outlet. In the second configuration (Figure 1B) two wells are installed side by side: one well is screened in the interval occupied by the fresh water, the other well is screened in the saline water interval. The concept of a scavenger well relies on the fact that transition zone 'upconing' due to pumping the overlying freshwater is balanced by 'downconing' due to pumping the saline water. The two processes can be balanced by varying the pumping rates from the two zones.

It is important to note that in this study the term 'scavenger well' is used solely for the single well configuration (Figure 1A). Various authors (e.g., Fader, 1957; Long, 1965 and Zack, 1988) use the term 'scavenger well' to refer to the well located in the saline water zone of a two well configuration: the other well in the configuration being termed the 'production' or 'supply' well.

A Brief History of Scavenger Wells Applications

The method of pumping both fresh and saline waters using separate pumps or wells (scavenger pumping) was first shown by Pennink (1904,1905). It is interesting to note that Pennink used scavenger pumping to detect the existence of saline water in the aquifer of the dune area of Amsterdam, the Netherlands and not for exploitation. Fifty years later Fader (1957) was one of the first to suggest using a two-well scavenger system to recover fresh water overlying saline water in the Chicot aquifer of southwestern Louisiana (USA). Subsequently, Long (1965) reports further field tests of the feasibility of the two-well scavenging system suggested by Fader (1957). From his tests, he concluded that scavenger well systems are effective for the recovery of fresh groundwater overlying saline water under controlled conditions.

In a study of salinity control in the 1960's, Hunting's Technical Services Ltd (HTS) and Sir Murdoch Macdonald and Partners (MMP), proposed the use of scavenger wells to recover thin lenses of fresh groundwater in the Sind Province of Pakistan (HTS and MMP, 1965). However, this proposal was not taken up until recently. Under a project carried out jointly by Groundwater Development Consultants (Int) Ltd and the British Geological Survey an intensive field testing programme has been carried out (GDC and BGS, 1988, 1989a,b,c,d,e and 1990). Recently, five papers have been published describing the results of this programme: Birch and Van Wonderen (1990), Beeson et al. (1992), Shearer and Van Wonderen (1992), Stoner and Bakiewicz (1992) and Van Wonderen and Jones (1992). In Birch and Van Wonderen (1990), the authors conclude that scavenger wells are the most flexible and economic method for optimising the freshwater recovery in the saline aquifers of the Sind Province, Pakistan.

Zack (1988) describes field studies to demonstrate that screening a pumping well in both the fresh and saline waters provides an effective method for extracting potable water from a thin fresh water layer in the coastal aquifer of Puerto Rico. Stoner and Bakiewicz (1992) also reports that the principle of scavenger wells has been considered in earlier work on the coastal areas of Libya.

Although, several applications of scavenger wells have been reported, most of these applications, other than the field trials in Pakistan, have been for the control of the saline water only. Consequently, scavenger wells are still not conventional methods for the purpose of recovering fresh water. This has arisen predominantly from a lack of a clear understanding of the mechanisms of groundwater flow in the vicinity of scavenger wells and, therefore, their influence on the operational characteristics of scavenger wells. In particular, there has been a lack of research to understand the behaviour of the fresh/saline transition zone around a scavenger well. To fill this gap, a simulation study using data from Pakistan has been undertaken. In this paper, some results arising from this study are reported.

To support the development of the study, use has been made of data from the field trials carried out by GDC and BGS in Pakistan. The area of the field trials is located in the Sind Province of Pakistan (Figure 2). The main water supply to the cultivated land of the project area is the Indus river. Before 1932 the agricultural land in the project area was irrigated with the summer floods of the river Indus. Subsequently, irrigation canals have been used to divert water from the river to the agricultural area. Over the years, the deep percolation of water from the fields and canals to groundwater has meant that the groundwater table has risen dramatically causing widespread waterlogging of cropped areas in addition to severe salinisation of uncropped land and an increase in storm water flooding. The irrigation losses, in particular the seepage losses from the main canals, have formed lenses of fresh water floating on the existing saline water. Thus, the problem since 1960 has been how to lower the groundwater table economically and solve the waterlogging and salinity problems of the region. As a byproduct of this requirement, the reuse of groundwater for irrigation was considered to improve the economics of groundwater drainage. The exploitation of the thin fresh groundwater lenses beneath the canals was explored to provide part of the solution to the rising groundwater level problem. The seepage from the canals represents a permanent contribution of fresh water to the lenses. Therefore, it is potentially possible to use these lenses as a long term source of fresh water.

A field programme of drilling and testing of four pilot scavenger well sites, PSW1A, PSW2, PSW3 and PSW4C (Figure 2) was initiated in 1986. GDC and BGS (1990) proposed the use of scavenger wells to exploit lenses of less than 90m thickness neighbouring the canals from which most of the major seepage is occurring. They demonstrate that whilst interceptor drains are able to intercept only 20% of the seeping water, scavenger wells can be designed, in principal, to develop most of the canal seepage loss to groundwater.

SIMULATION STUDIES

Analysing the Behaviour of Scavenger Wells

Data for the study were taken from the field trials carried out at the site PSW4C (see Figure 2). The research programme comprised two components:

- the development of a finite difference simulation model (Aliewi, 1993) that couples density dependent fluid flow and solute transport in a multi-layer confined/phreatic aquifer system with isotropic/anisotropic hydraulic properties in axi-symmetrical cylindrical coordinates and its calibration using the field data from site PSW4C;

- the performance using the simulation model of sensitivity analyses to determine the behaviour of a scavenger well under different physical, hydrological and operational conditions. The objectives of the sensitivity analyses were the identification of the most sensitive parameters that control fresh water recovery and the identification of design criteria for the construction and economic evaluation of scavenger well systems.

In this paper, the main results of the sensitivity analyses and their interpretation are reported. The response of the transition zone around a scavenger well has been examined through the analysis of the behaviour of the following parameters:

1) 'totz', the depth to the top of the transition zone;

   Since there is no clearly defined line dividing the water in the transition zone and the overlying fresh water, a reference salinity of 600 mg/l has been used to define its position. This reference salinity has been normalised to a value of 0.0 for the presentation of the salt distributions as isochlors. Correspondingly, a normalised value of 1.0 equates to a salinity of 29250 mg/l, the salinity of the underlying saline groundwater.

2) 'wotz', the width of transition zone at well;

   The width of the transition zone is the vertical distance between the 0.0 and the 1.0 isochlors.

3) 'rou', the rate of upconing;

   The rate of upconing is defined by the time taken for the transition zone to reach a new equilibrium after pumping starts.

4) 'RR', the recovery ratio;

   The fresh water recovery ratio is defined as the fresh water abstraction rate divided by the total abstraction rate of the scavenger well. It is hereafter expressed as a percentage.

Simulation and Sensitivity Analysis Results

Sensitivity tests were conducted to establish those parameters that affect most the movement of the transition zone around a scavenger well. In all of the sensitivity tests, ranges were chosen for each variable that were likely to be found in the project area. For most of the analyses, long term steady pumping was assumed in the simulations.

Several variables were found to have a significant effect on parameters 'RR', 'totz' and 'wotz'. Of the physical properties of the aquifer, the transverse dispersivity has the largest effect (Figure 3) on the output parameters studied. However, strong relationships are also apparent between the initial position of the 0.5 isochlor and 'RR', 'totz' and 'wotz' (Figure 4). The ratio of horizontal permeability to vertical permeability also acts as a controlling factor on these parameters (Figure 5).

In addition to the physical variables, the well design variables (and in particular, the size and settings of the well screen) also influence strongly the value of each of the output parameters. To simplify the presentation of the results the following variable is used to represent the screen settings relative to aquifer top, aquifer thickness, screen length, total pumping rate and initial position of the 0.5 isochlor:

$$SIV = \frac{(IDI - SRP)}{\sqrt{\dfrac{LS \times Q_{TOT}}{4155 \times 24.6}}} \qquad (1)$$

$$SRP = STOP + \frac{IDI \times LS}{AQTH}$$

where :

SIV	is the screen interaction variable.
SRP	is distance of screen reference point from saturated aquifer top [L].
STOP	is depth to top of screen from top of saturated aquifer [L].
IDI	is initial depth to the 0.5 isochlor from top of saturated aquifer [L].
LS	is length of well screen [L].
AQTH	is effective aquifer thickness [L].
Q_{TOT}	is the total pumping rate [m^3/day]

Figure 6 a,b and c show the response of each output parameter to variation in SIV. In each case a linear response is found between SIV and 'RR', 'totz' and 'wotz'. An increase in the depth of penetration of the screen reduces the magnitude of the recovery ratio 'RR' unless the well capacity is reduced.

In addition to examining the long term steady behaviour of a scavenger well, the influence of short term dynamic pumping on the position of the interface was also explored. It was shown that, both long and short duration intermittent pumping had negligible influence on the magnitudes of 'RR', 'totz', and 'wotz'.

SCAVENGER WELL DESIGN CRITERIA

Using the results of the sensitivity analyses, design equations for scavenger wells have been established. These equations permit the direct calculation of each of the parameters 'RR', 'totz' and 'wotz' and were derived from a full regression analysis of the results of the sensitivity tests.

a) Empirical Formula for 'RR':

$$\frac{RR}{100} = -1.869\,\alpha_{Tmax} + 0.0175\,IDI + 0.694\left(\frac{K_h}{K_v}\right)^{0.093} + \left(0.0146 - \frac{0.643}{\sqrt{Q_{TOT} \times LS}}\right)(IDI - SRP) + (0.00021\,AQTH - 0.03)\,AQTH \qquad \ldots\ldots(2)$$

where:

α_{Tmax} : transverse dispersivity in the direction of maximum permeability [L].
K_h/K_v : permeability anisotropy ratio.
K_h : horizontal permeability [L/T]
K_v : vertical permeability [L/T].

b) Empirical Formula for 'totz':

$$totz = -51.7\,\alpha_{Tmax} + 0.91\,IDI + 34.24\left(\frac{K_h}{K_v}\right)^{0.053} - \left(0.041 + \frac{118.17}{\sqrt{Q_{TOT} \times LS}}\right)(IDI - SRP) + (0.0118\,AQTH - 1.294)\,AQTH \qquad \ldots(3)$$

c) Empirical Formula for 'wotz'

$$wotz = 71.598\,\alpha_{Tmax} + (0.339 - 0.0065\,IDI)\,IDI - 2.475\left(\frac{K_h}{K_v}\right)^{0.176} + \frac{(0.0174\,Q_{TOT} \times LS + 0.781\,(IDI - SRP))}{\sqrt{Q_{TOT} \times LS}} \qquad \ldots(4)$$

The selection of the design parameters values, STOP, LS and Q_{TOT}, depends on the physical properties of the aquifer system and on the required value of 'RR'. Equation (2) defines the recovery ratio 'RR' as a non linear function of aquifer properties and well screen settings. In order to illustrate the influence of the primary design parameters on the recovery ratio, an example based on the aquifer conditions found at PSW4C is presented in Table 1. In this table the parameters, α_{Tmax}, K_h/K_v and AQTH observed at the site are shown. Using equation (2) 'RR' is calculated for a range of Q_{TOT}, LS and STOP. From this table it can be seen that for an optimal value of 'RR' for STOP=8 of 76%, LS must be 12 m and Q_{TOT} 2025 m^3/day.

Clearly, it is not possible to change the aquifer characteristics in order to derive an optimal recovery ratio for a particular site, but different sites will have different characteristics. To illustrate the influence of the physical conditions on recovery, Table 2 is presented. In Table 2 the parameters, K_h/K_v and STOP, are kept constant and values of 'RR' are calculated for a range of values of Q_{TOT}, LS, α_{Tmax}, IDI and AQTH.

Each of the equations presented in this paper can be used in conjunction with standard well design criteria and cost functions, as well as cost functions for the disposal of the saline water to develop a full economic scavenger well design.

SUMMARY AND CONCLUSIONS

Recovery of thin fresh groundwater lenses overlying saline water is important in many parts of the world. A prime example is the Lower Indus irrigation area in Pakistan. Scavenger wells have been proposed as the most cost effective and practical methods of recovering the fresh water derived from seepage from canals in the Sind region of Pakistan. Four test sites have been used to establish the viability of the scavenger well systems under field conditions. Using the data obtained from one of these test sites, a simulation study has been undertaken to gain a better understanding of the movement of the fresh/saline water transition zone around a scavenger well and its influence on the design of scavenger well systems. A model was developed to simulate the movement of saline and fresh water under constant and variable pumping conditions. The model was calibrated using the available field data. The model was then subsequently used to carry out an extensive sensitivity analysis to determine the influence of each of the physical and major well design variables influencing the recovery of fresh water from the aquifer.

The sensitivity analysis has been achieved by analysing the behaviour of the parameters: recovery ratio, 'RR', rate of upconing, 'rou', depth to top of transition zone, 'totz' and the thickness of the transition zone 'wotz' under different physical, hydrogeological and operational conditions.

The results of the sensitivity analysis were used to identify the parameters which strongly affect the values of 'RR', 'totz' and 'wotz'.

Based on the results of the sensitivity analysis empirical formulae for 'RR', 'totz' and 'wotz' have been established. These formulae can be used to assist in the optimal design of scavenger wells.

The results of the study further confirm the potential for using scavenger wells to exploit shallow fresh water lenses in otherwise saline aquifers.

REFERENCES

Aliewi, A.S. (1993). Numerical Simulation of the Behaviour of the Fresh/Saline Water Transition Zone Around a Scavenger Well. A PhD thesis, University of Newcastle upon Tyne, United Kingdom, 250pp.

Beeson, S., Carruthers R. and Wyness A. J. (1992). Scavenger Wells: 2 - Field investigations and monitoring, in Study and Modelling of Salt Water Intrusion into Aquifers, Proceedings of the 12th Salt Water Intrusion Meeting, 1-6, November, 1992, Barcelona, Spain.

Birch, R.P. and Van Wonderen, J. (1990). Exploitation of freshwater lenses in Sind Province, Pakistan. Intn. Comm. Irrig. Drainage 14th Congress - Rio de Janeiro, Q42-R30, 445-460.

Bruins, H.J., Tuinhof, A. and Keller, R. (1991). Water in the Gaza Strip. Hydrology study by the Ministry of Foreign Affairs of the government of the Netherlands. Final report.

Fader, S.W. (1957). An analysis of contour maps of 1955 water levels with a discussion of salt-water problems in southwestern Louisiana. Wat. Resour. Pamp., (4), 16-27. Published by the Department of Conservation, Louisiana Geological Survey and Louisiana Department of Public Works, Baton Rouge, USA.

GDC and BGS (1988). Scavenger wells and pilot studies: Surface geophysics. Report to UK Overseas Development Administration, London.

GDC and BGS (1989a). Scavenger wells and pilot studies: Hydrogeology. Report to UK Overseas Development Administration, London.

GDC and BGS (1989b). Scavenger wells and pilot studies: Computer model studies. Report to UK Overseas Development Administration, London.

GDC and BGS (1989c). Scavenger wells and pilot studies: Pumping plant study. Report to UK Overseas Development Administration, London.

GDC and BGS (1989d). Scavenger wells and pilot studies: Scavenger well operation and maintenance. Report to UK Overseas Development Administration, London.

GDC and BGS (1989e). Scavenger wells and pilot studies: Monitoring (1989). Report to UK Overseas Development Administration, London.

GDC and BGS (1990). Scavenger wells and pilot studies: Summary. Report to UK Overseas Development Administration, London.

HTS and MMP (1965). Lower Indus Report, WAPDA, Lahore.

Long, R.A. (1965). Feasibility of a scavenger-well system as a solution to the problem of vertical salt-water encroachment. State of Louisiana Department of Conservation, Geological Survey and Department of Public Works in Cooperation with USGS Wat. Resour. Pamp. No. 15.

McWhorter, D.B. (1972). Steady and unsteady flow of fresh water in saline aquifers. Wat. Management Technical Report No. 20, Colorado State University, Fort Collins, Colorado, USA, 49 pp.

Pennink, J.M.K. (1904). The water-supply system of Amsterdam in the dunes. Koninski Inst. Ing. Tidjschr. 1903-1904, The Hague, 183-238.

Pennink, J.M.K. (1905). Investigations for ground-water supplies. Trans. Amer. Soc. Civ. Engrs., Intnl. Engrg. Congress, **54**, Section D, Paper No. 50, 169-181.

Reilly, T.E., Frimpter, M.H., LeBlanc, D.R. and Goodman, A.S. (1987). Analysis of steady-state saltwater upconing with application at Truro Well Field, Cape Cod, Massachusetts. Ground Water, **25**(2).

Shearer, T. R. and Van Wonderen J. (1992). Scavenger Wells:4 - Simulation Modelling. in Study and Modelling of Salt Water Intrusion into Aquifers, Proceedings of the 12th Salt Water Intrusion Meeting, 1-6, November, 1992, Barcelona, Spain.

Stoner, R.F. and Bakiewicz, W. (1992). Scavenger wells 1- Historical development. in Study and Modelling of Salt Water Intrusion into Aquifers, Proc. 12th Salt Water Intrusion Meeting (SWIM), Barcelona, Spain.

Van Wonderen J. and Jones C. R. C. (1992). Scavenger Wells: 5 - Design Criteria and implementation in Sindh. in Study and Modelling of Salt Water Intrusion into Aquifers, Proceedings of the 12th Salt Water Intrusion Meeting, 1-6, November, 1992, Barcelona, Spain.

Zack, A. (1988). A well system to recover water from a freshwater-saltwater aquifer in Puerto Rico. USGS. Water Supply No. 2328

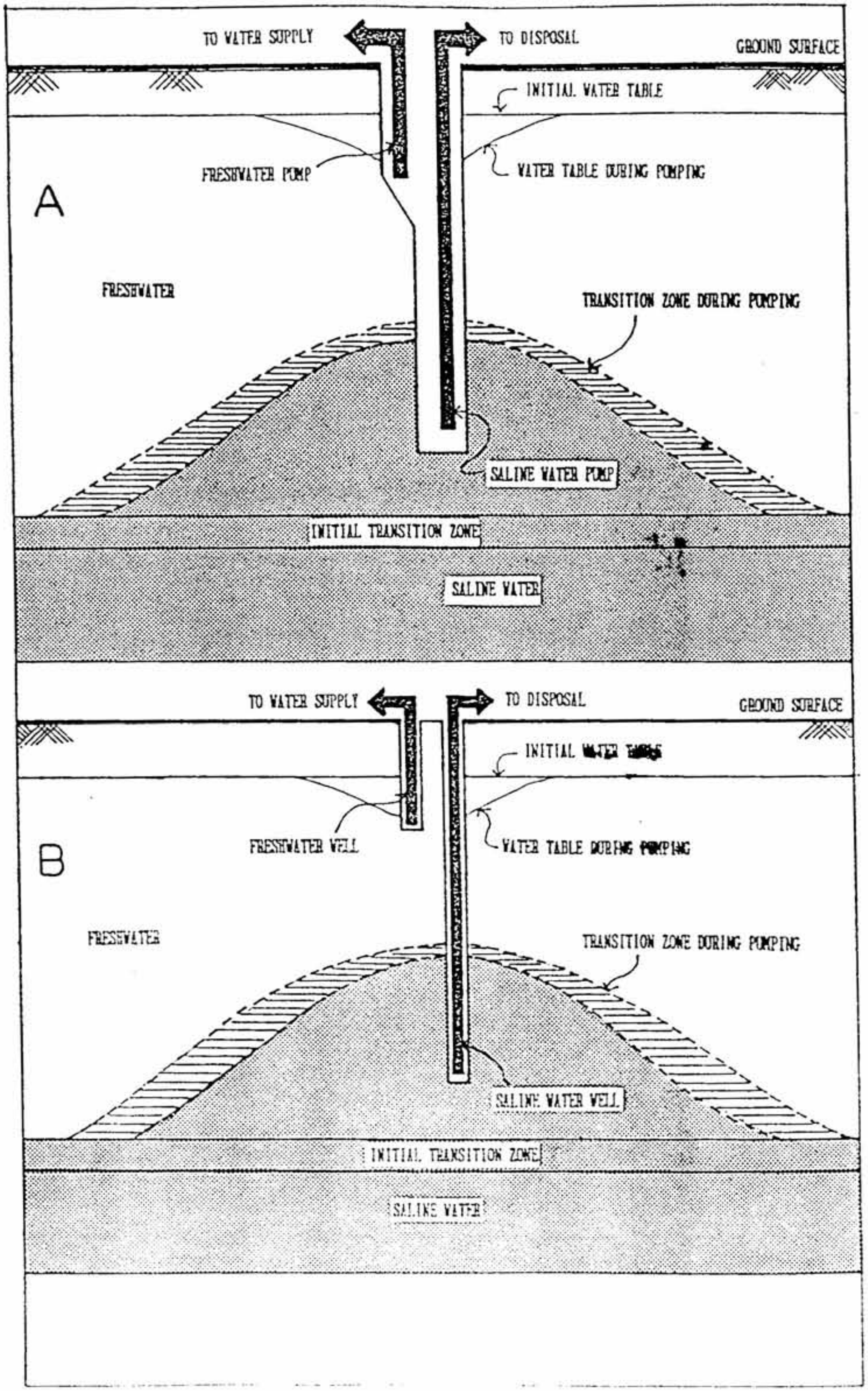
Table 1: Simulation of 'RR' for Standard Aquifer Properties and different values of STOP

α_{Tmax} = 0.02 , K_h/K_v = 20 , AQTH = 55				
Q_{TOT}	LS	RR		
		STOP=0	STOP=8	STOP=15
675	4	61	59	57
1350	8	81	74	68
2025	12	84	76	68
2700	16	84	75	67
3380	20	82	73	64
4050	24	80	70	61
4730	28	77	67	58
5405	32	74	63	54
6080	36	70	60	51
6755	40	67	56	47

Table 2: Simulation of 'RR' for Low and High Levels of α_{Tmax}, IDI and AQTH

K_h/K_v = 20 , STOP = 0							
Q_{TOT}	LS	α_{Tmax}		IDI		AQTH	
		0.01	0.05	33	43	45	55
675	4	63	55	51	71	70	56
1350	8	82	75	68	93	88	76
2025	12	86	78	71	97	91	81
2700	16	86	78	71	97	90	81
3380	20	84	77	70	95	88	80
4050	24	82	74	68	92	84	78
4730	28	79	71	65	89	80	76
5405	32	76	68	62	85	76	73
6080	36	72	65	59	81	72	71
6755	40	69	61	56	77	68	68

FIGURE 1 : SCAVENGER WELL CONFIGURATIONS
A) SINGLE WELL
B) TWINNED WELLS



GURE 2: LOCATION MAP OF PROJECT AREA After GDC & BGS (Volume 1,1990)

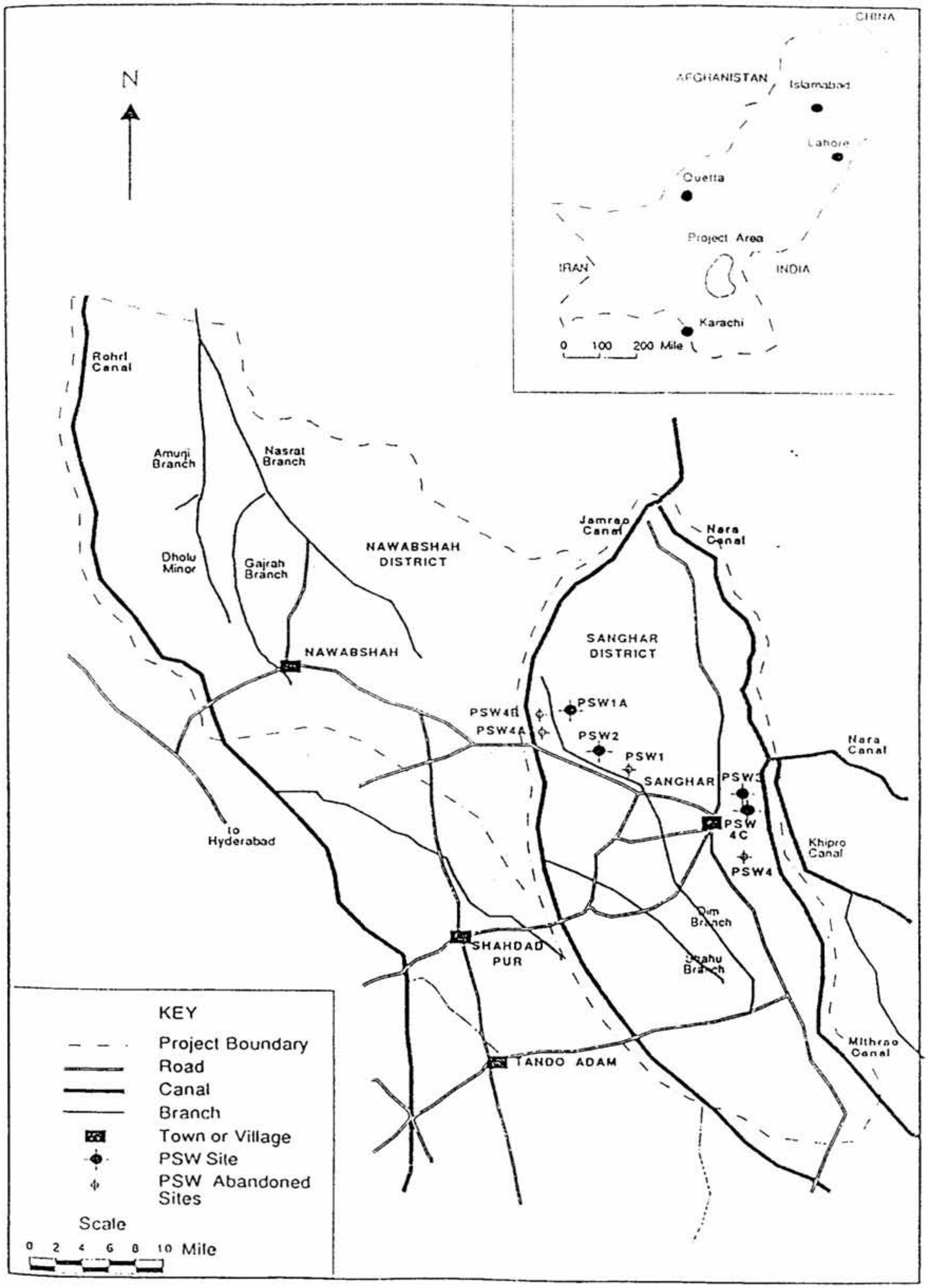
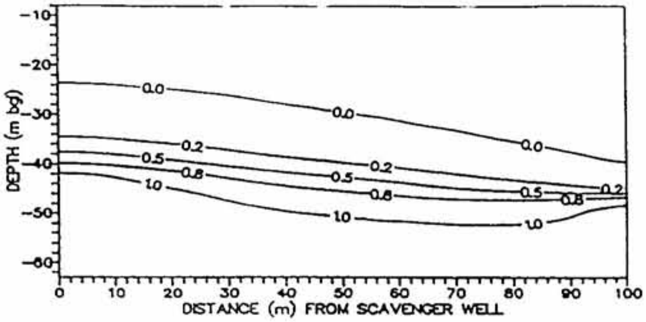
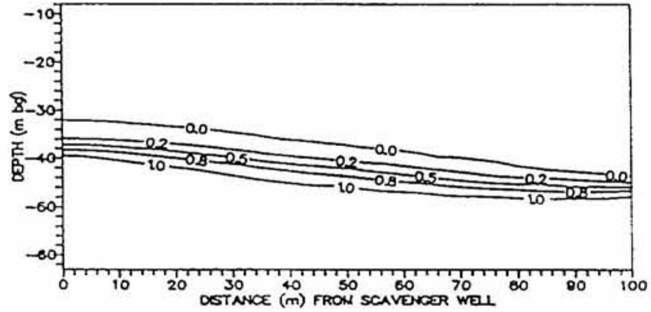


FIGURE 3: SENSITIVITY OF THE TRANSITION ZONE
TO TRANSVERSE DISPERSIVITY

A) 0.2m



B) 0.02m



C) 0.01m

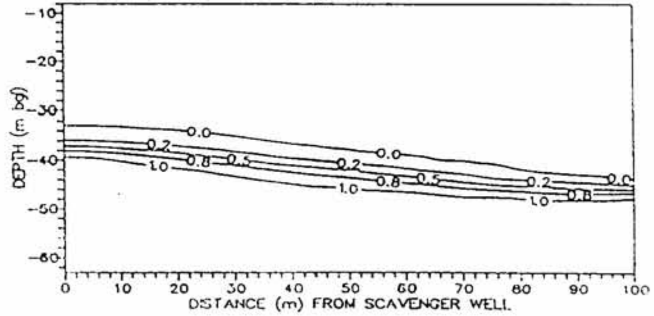
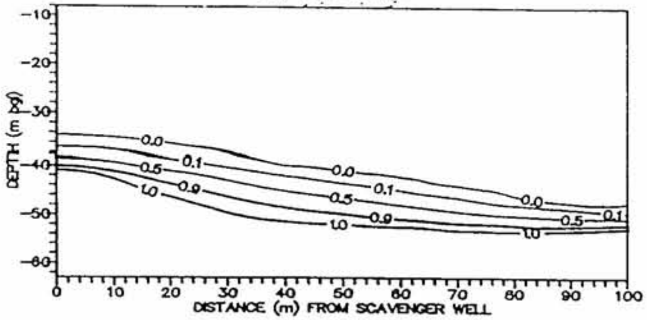
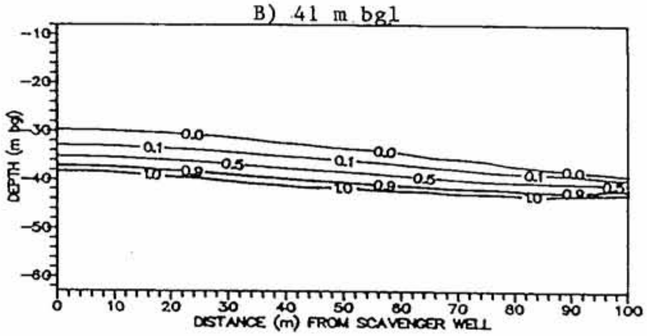


FIGURE 4: SENSITIVITY OF THE TRANSITION ZONE TO THE INITIAL POSITION OF 0.5 ISOCHLOR

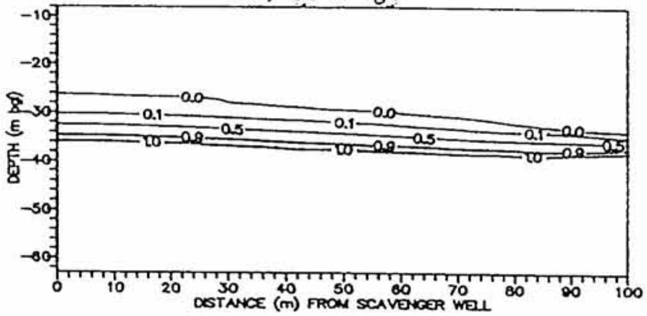
A) 51 m bgl



B) 41 m bgl



C) 36 m bgl



D) 0.0 Isochlor for A, B and C

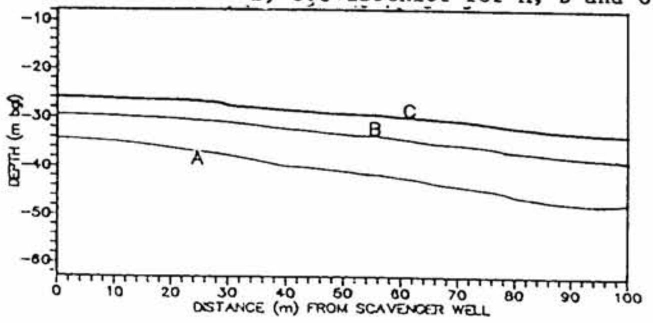


FIGURE 5: SENSITIVITY OF THE TRANSITION ZONE TO PERMEABILITY ANISOTROPY RATIO

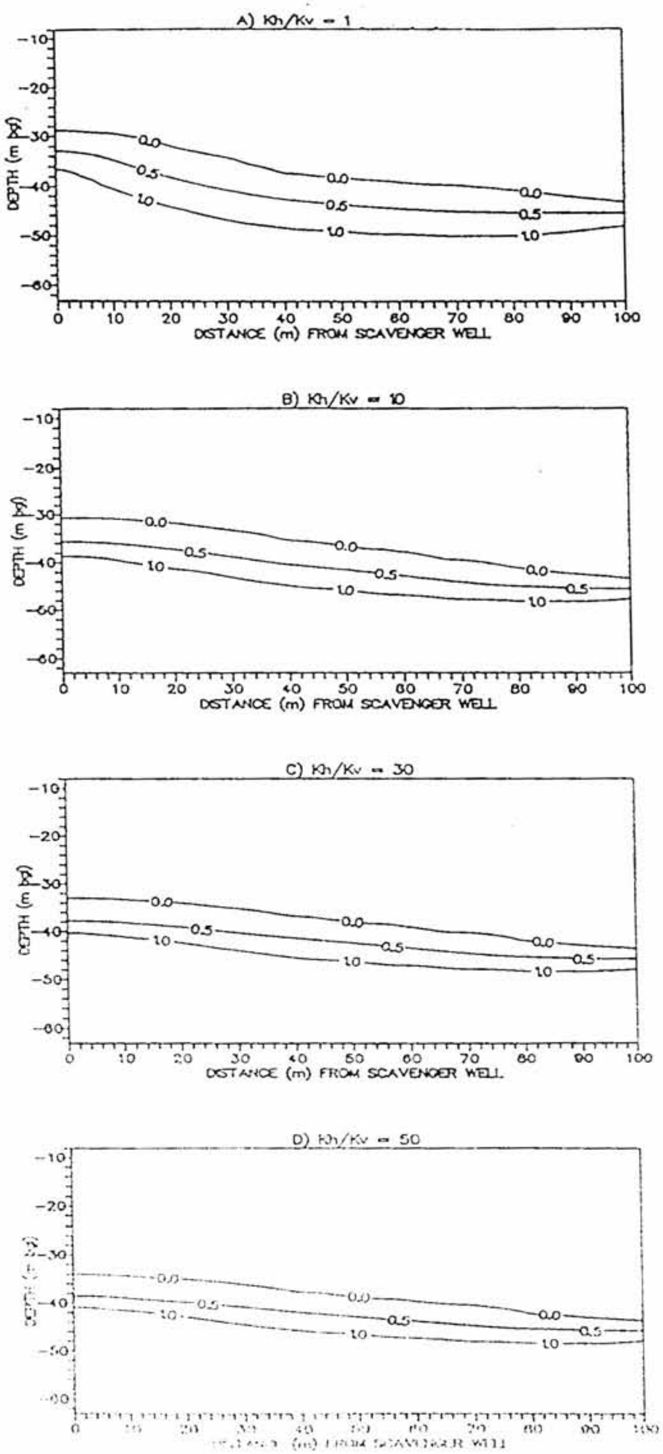


FIGURE 6: SENSITIVITY TO SIV

FIGURE 6a: RR VERSUS SIV

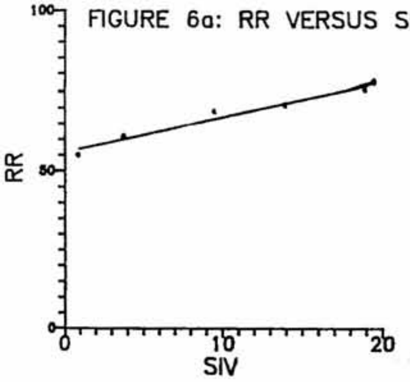


FIGURE 6b: totz VERSUS SIV

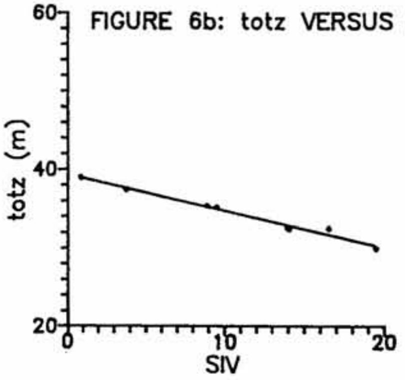


FIGURE 6c: wotz VERSUS SIV