Extracting Freshwater From Aquifers Underlain By Saltywater

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ABSTRACT

The native groundwater in the central regions of *doabs* of the Indus Basin of Pakistan was deep and saline because of the marine origin of the hydrogeologic formation. Percolation of fresh irrigation waters has formed a fresh groundwater lens above the saline groundwaters. The thickness of this fresh groundwater lens varies from a few meters to 150 meters. The costs involved in the installation of horizontal subsurface drains to extract the water are prohibitive. Alternatively, shallow wells with small discharge rates, commonly known as the skimming wells, can be used to extract the freshwater. Extraction of this water from inappropriate depths and at inappropriate rates will cause 'upconing' of the fresh and saline water interface, and draw marginal quality water to the root zone, resulting in salinity and sodicity.

In this paper, two numerical models, MODFLOW (McDonald and Harbough, 1988) and MT3D (Zheng, 1990) were used to model the movement of the fresh and saline water interface of an unconfined aquifer in Punjab, Pakistan. Data collected by Kemper *et al.*, (1976) was used to calibrate and validate the models. Subsequently, the sensitivity of the depth to watertable, discharge rate, thickness of the fresh groundwater lens, well penetration ratio, and well operating hours per day on the salinity of pumped groundwater was studied. The results show that skimming wells of 10-18 liters per second (lps) discharge rates can be installed and operated successfully with 60-70% well penetration ratio for 8-24 hours per day from an unconfined aquifer with 15-18m thick fresh groundwater lens.

INTRODUCTION

In several unconfined aquifers, the groundwater system consists of a saturated porous medium containing miscible fluids of variable solute concentrations. The saline groundwater tends to remain separated from the overlying fresh groundwater. However, a zone of dispersion, known as the fresh and saline water interface forms between the two fluids. This interface has been found to vary in thickness. This interface is not static but responsive to recharge and discharge mechanisms. Thus, when it is desired to pump fresh groundwater, the well should be installed and operated so that minimum of saline groundwater mixing is occurred either within the well or within the aquifer itself.

When a skimming well (which is partially penetrating fresh groundwater well) starts pumping, it disturbs the equilibrium between the fresh groundwater and saline groundwater in the aquifer. The interface starts moving towards the bottom of the well. This phenomenon is known as saline groundwater upconing. However, when the well is operating at less than or equal to "critical discharge rate", a new equilibrium can be attained in which a stable cone develops at the underlying interface with the apex of the cone some distance below the bottom of the well screen. Therefore, at the critical discharge rate, which is a function of local hydrogeologic conditions, the well pumps essentially fresh groundwater and no flow occurs in the saline groundwater zone. But, when the well discharge rate exceeds the critical discharge rate, it disturbs the interface and induces a greater upconing of saline groundwater. Flow also occurs from the saline groundwater, and the salinity of the pumped water deteriorates to a degree depending on the discharge rate, the duration of pumping, the thickness of fresh groundwater lens, and the local hydrogeologic conditions.

The native groundwater, which existed in the pre-irrigation period in the Indus basin of Pakistan, was saline because of the underlying geologic formation being of marine origin. However, fresh groundwater lenses, now, overlie this native saline groundwater. These fresh groundwater lenses resulted from deep percolation of the extensive water conveyance and distribution system, as well as, from irrigation and rainfall. Thus, a shallow fresh groundwater lens occurs between the native pre-irrigation and the present day watertables. The thickness of the fresh groundwater lens is around 30 meters in the lower or central parts of *doabs* (area between two rivers), 60 meters or more along the margins of *doabs*, and approximately 150 meters near the rivers and canals. It has been estimated that nearly 200 Km^3 of fresh groundwater is lying above the saline groundwater (NESPAK, 1983).

The demand for freshwater within the Indus basin has increased enormously with the increase in population over the past two decades. Consequently, the groundwater withdrawals have increased exponentially both in the private and public sectors. High capacity tubewells are being installed even in the thin fresh groundwater zones. In such zones, these tubewells are likely to draw a substantial portion of their discharge from the saline groundwater. Many high capacity public tubewells are being shutdown at the request of farmers in areas where the pumped water has become saline with time (NESPAK, 1983). The primary reason is that the tubewell discharges are too large for the given physical situation of the aquifer. This is particularly true for the tubewells located in the central regions of *doabs* in Punjab, Pakistan.

One solution in such a condition is the installation of horizontal subsurface drains below the watertable, but its capital and installation costs are very high. Even their operation and maintenance have proven to be difficult in various parts of the Indus basin (Bhutta, et al., 2000). As an alternative method, shallow skimming wells can be installed. Many researchers have determined the performance of various skimming well designs as means of pumping fresh groundwater from an unconfined aquifer. But, proper guidelines regarding (i) the design and installation of a skimming well while considering the aquifer characteristics, and (ii) the operation and management strategies for getting groundwater without compromising the quality, are still lacking for hydrogeologic conditions in Punjab.

Better use of groundwater resources can be ensured if the behavior of fresh and saline groundwater systems is properly understood. Mathematical modeling is commonly used for simulating groundwater systems with complex behaviors, as it permits the predictions of the response of the aquifer to applied stresses and presents alternative suggestions for its use. In this study, PMWIN (Chiang and Kinzelbach, 1996), which is a complete simulation system for modeling groundwater flow (with MODFLOW of McDonald and Harbough, 1988) and solute transport processes (with MT3D of Zheng, 1990), was used to develop guidelines for installation, operation and management of skimming wells in the Indus Basin. Data collected by Kemper *et al.*, (1976) was used to calibrate and validate the models. Subsequently, the sensitivity of the depth to watertable, discharge rate, thickness of the fresh groundwater lens, well penetration ratio, and well operating hours per day is determined.

PHYSICS OF GROUNDWATER FLOW AND TRANSPORT MECHANISMS

The partial differential equation describing three-dimensional movement of groundwater through porous material can be written as:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)-W=S_s \frac{\partial h}{\partial t} \quad (1)$$

where K_x, K_y, K_z are values of hydraulic conductivity along x, y, and z coordinate axes. W is the volumetric flux per unit volume and represents sources and/or sinks of water. S_s is the specific storage of the porous material, h is the piezometric head, and t is the time.

The partial differential equation describing three-dimensional transport of dissolved solutes in the groundwater can be written as follows:

$$\frac{\partial}{\partial x_i}\left(D_i \frac{\partial C}{\partial x_i}\right)-\frac{\partial}{\partial x_i}(v_i C)\pm\frac{q_s}{0}C_s=\frac{\partial C}{\partial t} \quad (2)$$

where x_i and D_i are the distance and hydrodynamic dispersion coefficient along the respective Cartesian coordinate axis, respectively, C is the concentration of dissolved solute in the groundwater, v_i is the seepage or linear pore water velocity, q_s is the volumetric flux of water per unit volume of the aquifer representing source (positive) and sinks (negative), C_s is the concentration of the source or sink, 0 is the porosity of the porous medium, and t is the time.

These differential equations can be solved analytically as well as numerically. Major advances in understanding fresh and saline groundwater systems have occurred through numerical modeling by using both sharp interface (Ledoux *et al.*, 1990; and Holm and Langtangen, 1999) and dispersion zone (Voss, 1984; Zheng, 1990; Chandio and Chandio, 1992; and Chiang and Kinzelbach, 1996) approaches.

The factors affecting successful operation of skimming wells in the Indus basin include the well penetration ratio, the thickness of the fresh groundwater lens, thickness and salinity of the water withdrawal zone, and the location of the transient watertable boundary, etc. Moreover, hydrodynamic-dispersion phenomenon significantly affects the flow towards such wells (Kemper *et al.*, 1976; Mirbahar, *et al.*, 1997; and Sufi *et al.*, 1998). Any model that is based on the sharp interface approach can not correctly include all these factors. Thus, only a dispersion zone approach model can evaluate carefully the effects of various hydrogeological parameters and operating strategies on skimming well performance. Therefore, PMWIN (Chiang and Kinzelbach, 1996) was selected for the study. A brief description of PMWIN is presented below.

PROCESSING MODFLOW FOR WINDOWS-PMWIN

This is a complete simulation system for modeling groundwater flow and transport processes. This software is easy to use and maintain. Any system features that are not relevant for the aquifer under study can be ignored. The PMWIN uses some of the most popular groundwater flow and solute transport models available:

1. The MODFLOW, a modular three-dimensional finite-difference groundwater flow model, can simulate and predict the hydraulic behavior of groundwater systems. This model uses different iterative solutions to solve the finite-difference equation for groundwater flow (i.e., Equation 1). Hydrogeologic layers can be simulated as confined, unconfined, or a combination of confined and unconfined. External stresses such as wells can also be simulated. Boundary conditions include specified head, specific flux, and head-dependent flux.

2. The MT3D, a modular three-dimensional finite-difference groundwater solute transport model based on dispersion approach, can simulate and predict solute transport behavior of groundwater systems. This model uses a mixed Eulerian-Lagrangian approach to the solution of the three-dimensional advection-dispersion transport equation (i.e., Equation 2). MT3D is based on the assumption that changes in the concentration field will not affect the flow field significantly. This allows the user to construct, calibrate and validate a flow model independently. After a flow simulation is complete, MT3D receives the calculated hydraulic heads and various flow terms saved by MODFLOW to set the basis for simulating and predicting the solute transport behavior of groundwater systems. The MT3D transport model can be used to simulate changes in concentration of miscible solutes in groundwater considering advection, and dispersion.

3. Doherty *et al.*, (1994) developed PEST, which is the aquifer hydraulic and salinity parameters estimation and optimization model. The PEST is used to assist in data interpretation and in model calibration. If there are field and/or laboratory measurements, PEST can adjust model parameters in order that the discrepancies between the pertinent model-generated numbers and the corresponding measurements are reduced to a minimum. It does this by taking control of the models (MODFLOW and MT3D) and running them as many times as it is necessary to determine the optimal set of parameters. PMWIN and MT3D help the user to inform PEST of assigning the adjustable parameters.

FIELD EXPERIMENT

A set of field experiments related to skimming wells technology were designed and executed during 1976 at Phullarwan Research Farm of Mona Reclamation and Experimental Project (MREP), Bhalwal, Pakistan (Kemper *et al.*, 1976). Preliminary investigations indicated that the study area has 25-30m thick zone of relatively fresh groundwater above saline groundwater. Groundwater fluctuates between 1 to 2m depths in a yearly hydrological cycle. Total thickness of the aquifer is about 90-100m. The aquifer is unconfined and is mainly composed of sand with sandy loam layer of 3m thickness at the soil surface. Based on these preliminary investigations, this site was considered suitable and was selected for skimming well trials.

Single-strainer skimming well trials were conducted from January 5 to January 20, 1976. Total well depth was 18m with 4 and 14m lengths of blind pipe and well screen, respectively. Centrifugal pump of 14 lps capacity was used to withdraw groundwater by this skimming well. The pump was operated continuously for 15 days. The layout of observation wells and a single-strainer skimming well are shown in Figure 1. The observation wells, T1-1, T1-2, T1-3 and T1-4 were 2.44, 4.88, 9.45 and 21.34m, respectively, away from the center of the well.

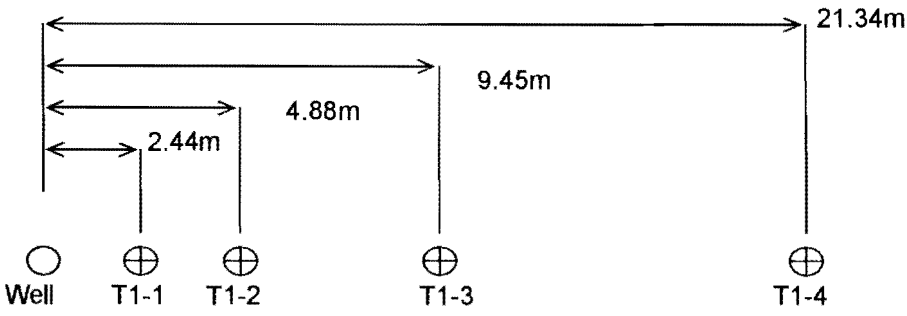

Figure 1. Schematic layout showing single-strainer skimming well and observation wells.

Observations made during the trials, as initial and observed conditions of the groundwater salinity, are presented in Figure 2. The figure shows that irrespective of the distance from the pump, variation in groundwater salinity with depth is similar. During the trials, the drawdown at the well was 0.8m, and the radius of influence was approximately 21m. Change in groundwater salinity with depth was minimal at observation well T1-4 after 15 days of pumping. However, upconing was observed in observation wells T1-1 and T1-3. If the concentration at the fresh and saline groundwater interface is taken equal to 3000 ppm, then the rise of interface as indicated by the successive positions of the 3000 ppm iso-concentration line under single-strainer skimming well operation is shown in Figure 3. Rate of rise of the interface is almost linear function of the time for single-strainer skimming well pumping at 14 lps discharges.

CALIBRATION AND VALIDATION

The simulation domain of 89x89m in areal perspective was divided into 23x23 number of rows and columns, while simulation domain of 100m in the vertical perspective was divided into 9 number of layers (Figure 4). The skimming well is located in the center of the simulation network. Top layer was considered unconfined while other layers were considered convertible between unconfined and confined depending upon the aquifer hydraulic conditions.

To closely evaluate and properly understand the behavior of groundwater system during its exploitation, the groundwater system should be represented as accurately as possible in terms of aquifer parameters, and initial and boundary conditions. Thus, the observed groundwater flow and transport behavior described by Kemper *et al.*, (1976) was used by PEST to estimate hydraulic and solute transport parameters. Then, these estimated parameters were used to validate MODFLOW and MT3D for specific initial and boundary conditions to simulate the behavior of groundwater system during its exploitation with single-strainer skimming well.

Calibration of MODFLOW for hydro-geological conditions

The values of hydraulic parameters, namely hydraulic conductivity (horizontal and vertical) and specific yield of the aquifer, were estimated by using PEST. The observed watertable behavior (spatial) on January 6, 1976, i.e., after one day of pumping, was used during hydraulic parameter estimation process. Horizontal hydraulic conductivity and specific yield are taken as independent parameters, while vertical hydraulic conductivity is taken as tied parameter with the horizontal hydraulic conductivity.

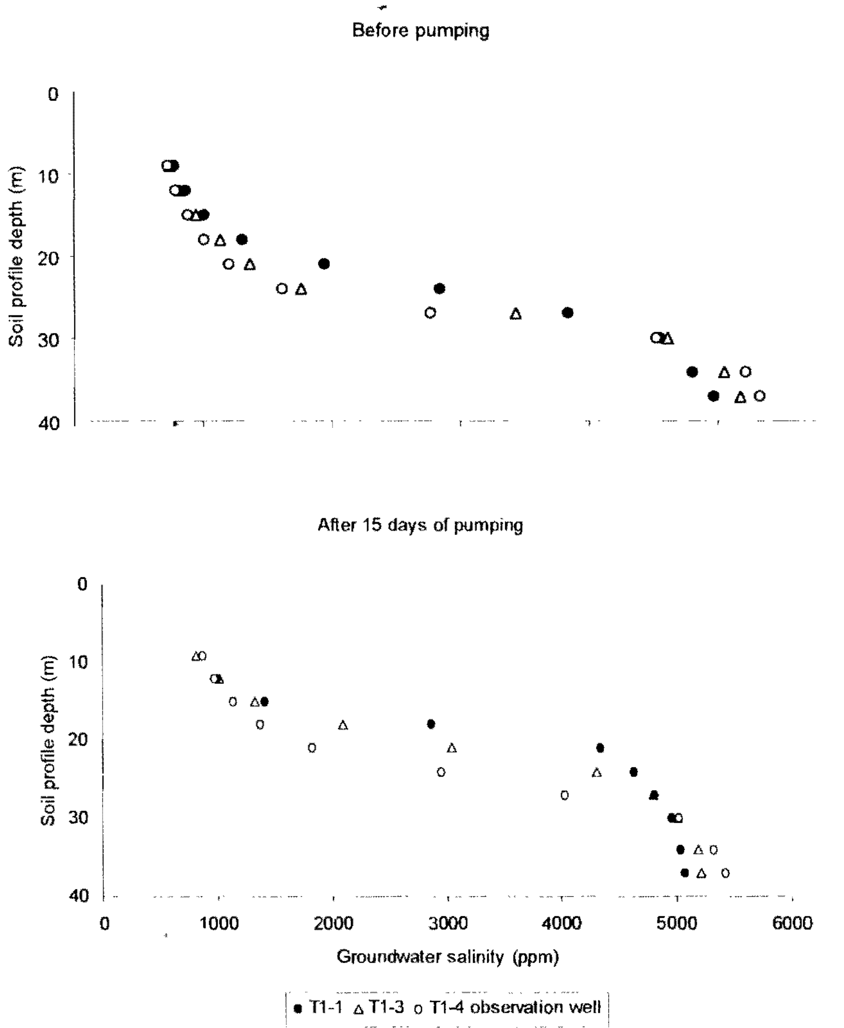

Figure 2. **Initial and observed groundwater salinity profiles.**

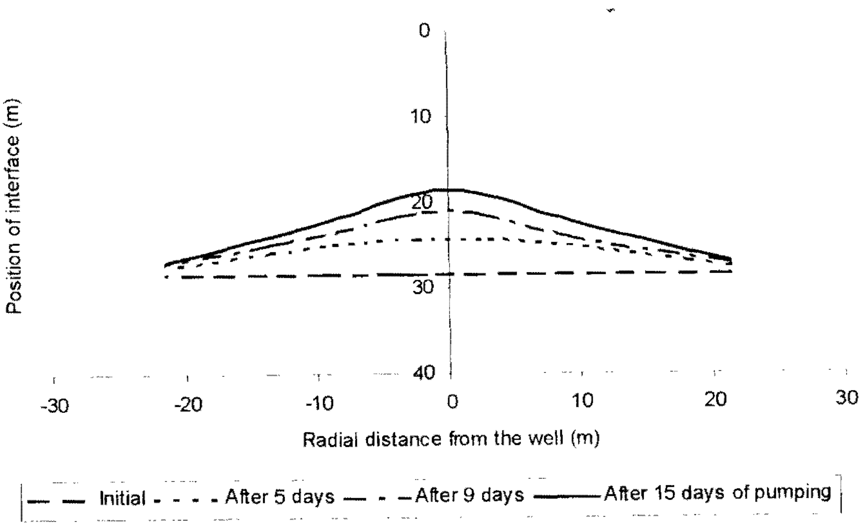

Figure 3. Interface movement during pumping.

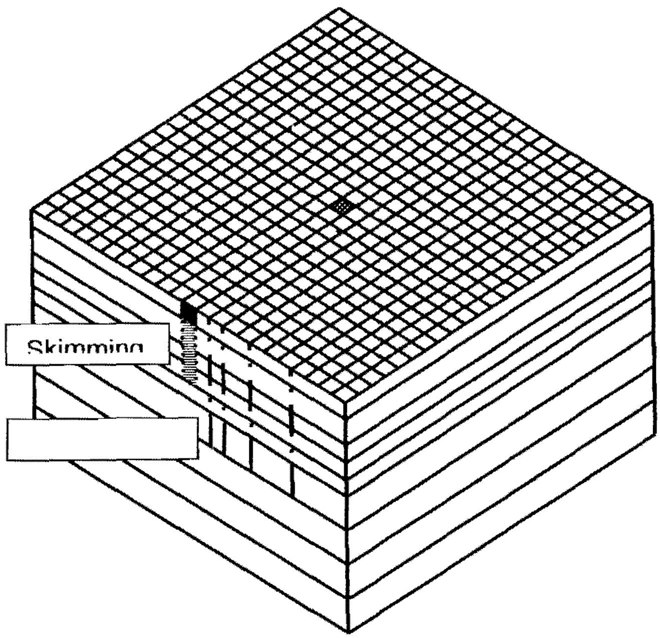

Figure 4. Schematic configuration of simulation set up.

The initial estimates of horizontal hydraulic conductivity are taken equal to 40, 35 and 30 m/day (These estimates are based on the field permeability tests carried out by Bennett *et al.*, 1964 at 36 sites in the study area). The ratios of horizontal hydraulic conductivity to vertical hydraulic conductivity are taken equal to 1, 1.25, 1.5, 5, 10, 20, 50 and 100 to observe the effect of vertical conductivity on the watertable behavior. The PEST compares the observed watertable depths with MODFLOW simulation results, and estimates the best fitted values of the parameters. The estimated values of horizontal hydraulic conductivity, vertical hydraulic conductivity, and specific yield are 30 m/day, 20 m/day, and 0.4 respectively.

Calibration of MT3D for hydro-chemical conditions

The estimation of longitudinal dispersivity, vertical transverse dispersivity and horizontal transverse dispersivity is carried out by matching the observed groundwater salinity behavior with depth (spatial and temporal) with the MT3D-simulated values. The observed groundwater salinity behavior (spatial) with depth on January 10, 1976, i.e., after 5 days of pumping, was used during the estimation process. Before pumping, the groundwater salinity from 3m to 21m depths ranged from 690 to 1400 ppm. At depths below 34m, the groundwater salinity was between 5050 to 5350 ppm.

Longitudinal dispersivity is taken as an independent parameter, while transverse dispersivity is taken as a tied parameter with the longitudinal dispersivity. The effects of horizontal and vertical transverse dispersivity on the solute transport behavior are considered equal. Ahmad (1974) reported that the values of longitudinal dispersivity ranges between 1.89 and 5.0m for the aquifers in the Indus Basin of Pakistan. Therefore, the initial values of longitudinal dispersivity are taken equal to 1.89, 3.5 and 5.0m. The ratios of transverse (vertical and horizontal) to longitudinal dispersivity are set equal to 0.01, 0.1, 0.2, 0.33, 0.5, 0.67. After comparing the observed groundwater salinity behavior (spatial) with MT3D simulation results, the best fitted values of the longitudinal dispersivity, horizontal transverse dispersivity and vertical transverse dispersivity are 1.89, 0.378, 0.378 respectively. Effective porosity is also required by the MT3D to calculate the average velocity of the flow through the porous medium. The value of the effective porosity of the aquifer is set equal to 0.4 after Kemper *et al.*, (1976).

Validation of estimated parameters for hydraulic simulation

After estimating the hydraulic parameters, the hydraulic behavior of the aquifer was reproduced. The observed watertable behaviors (spatial) after 4, 5, 10, 11, and 15 days of pumping were used during the calibration process. The observed watertable behavior (spatial) on January 16, 1976, i.e., after one day of pump closure, was also used during calibration process.

The graphical presentation is made to assess the MODFLOW simulation performance. Figure 5 compares the observed and simulated results after 15 days of pumping. Statistical measures of the goodness-of-fit are also used to assess the MODFLOW simulation performance objectively. The objective functions to measure the goodness-of-fit based on the analysis of residual error are defined as under:

$$\text{The maximum error, } ME = \max\left(\left|O_i - S_i\right|\right)_{i=1}^{n} \qquad (3)$$

$$\text{The modeling efficiency, } EF = 1 - \frac{\sum_{i=1}^{n}\left(O_i - S_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \qquad (4)$$

Where: O_i and S_i represents the observed and simulated values, n represents the number of observed and simulated values used in the comparison, and $\overline{O}$ is observed average ($\overline{O} = \frac{\sum_{i=1}^{n} O_i}{n}$).

The ME is a dimensional quantity and takes the unit of the variable examined, whereas EF is a non-dimensional quantity. The lower limit for the ME is zero, whereas the EF can take negative values. The negative EF is characterized by high variability between simulated and observed values. The zero value of EF shows poor simulation. If the model simulated values exactly match the observed values, then ME = 0, and EF = 1.

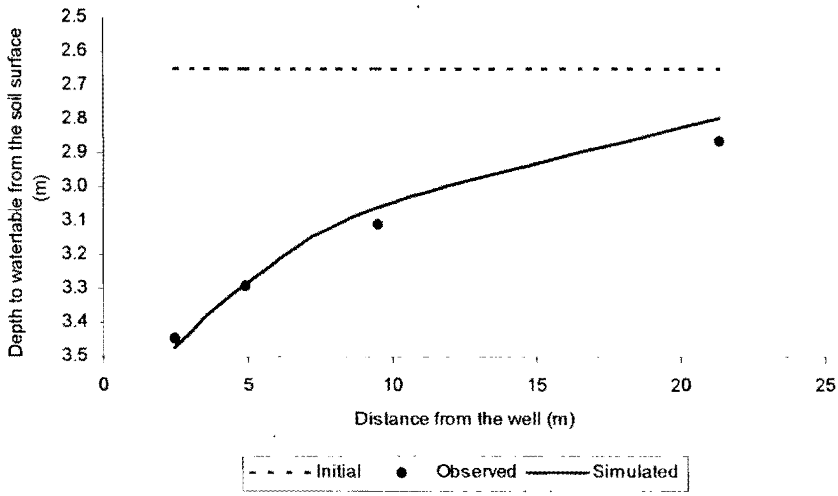

Figure 5. Change in depth to watertable after 15 days of pumping

Table 1 gives the stochastic comparison of the observed and simulated values. The maximum error induced in hydraulic simulation results varies from 2 to 7cm while the modeling efficiency remains between 0.97 and 0.99. The reasons of close fit between observed and simulated results are: (i) the experimental site underlain by the sandy aquifer, (ii) the well pumped water continuously for 15 days, and (iii) even the discharge rate was fixed (i.e., 0.5 cusec).

Table 1. Stochastic analysis of MODFLOW calibration.

Description	Maximum Error, ME (m)	Modeling Efficiency, EF
After 4days of pumping	0.04	0.99
After 5days of pumping	0.04	0.98
After 10days of pumping	0.02	0.99
After 11days of pumping	0.02	0.99
After 15days of pumping	0.07	0.95
After 1day of pump closure	0.04	0.99

These stochastic indices and graphical presentation show that MODFLOW is validated properly for hydraulic simulations of the groundwater system under a single-strainer skimming well for the given hydrogeologic conditions.

Validation of estimated parameters for salinity simulation

After estimating the solute transport parameters, the MT3D was used to reproduce water salinity variations with time and depth. The observed groundwater salinity behaviors with depth (spatial) after 5, 9, and 15 days of pumping were used during the calibration process. Figure 6 compares the observed and simulated results after 15 days of pumping. The groundwater salinity behavior with depth is almost a linear function of time under a single-strainer skimming well pumping at 14 lps. It means that surface recharge, resulting from deep percolation under the irrigated agricultural areas around the well, did not influence the groundwater salinity behavior in the aquifer depths during continuous pumping.

Table 2 gives the stochastic comparison of the observed and simulated values. The maximum error induced in solute transport simulation results varies from 301 to 535 ppm while the modeling efficiency remains between 0.98 and 0.99. The reasons mentioned above for the close fit between observed and simulated results for hydraulic simulations also hold true salinity simulations.

Table 2. Stochastic analysis of MT3D calibration.

Duration of pumping (days)	T1-1		T1-3		T1-4	
	ME (ppm)	EF	ME (ppm)	EF	ME (ppm)	EF
5	461	0.98	367	0.99	176	0.99
9	373	0.99	452	0.98	310	0.99
15	301	0.99	374	0.98	535	0.98

These stochastic indices and graphical presentation show that MT3D is validated properly for solute transport simulations of the groundwater system under a single-strainer skimming well for the given hydrogeologic conditions.

DESCRIPTION OF PMWIN APPLICATION RUNS

Calibrated and validated MODFLOW and MT3D were, then, used to prepare guidelines for designing a single-strainer skimming well along with its operation and management strategies to get the desired amount of pumped water without compromising its salinity while ensuring its sustainability for future use. Essentially, operational parameters include operational hours per day, and discharge rate, while penetration depth defines the well design. In unconfined aquifers that have shallow watertable, this penetration depth is also related to the depth of water table, and the thickness of fresh groundwater lens. Therefore, the sensitivity of the following variables was studied:

I. Depth to watertable below the soil surface.

II. Discharge rate of the well.

III. Thickness of fresh groundwater lens.

IV. Well penetration ratio[1].

V. Operating hours per day.

A total number of 11 runs were executed for simulating different scenarios. Run 1 was executed as the base run. The remaining simulation runs were executed by changing only one parameter in the base run. A summary of runs is given below (Table 3).

The reasons of limiting the duration of application runs to 15 days are: (i) the target area has canal water supplies which operates on 7 days interval *warabandi* system (fixed-turn system of water distribution), and (ii) the skimmed water is only required to supplement irrigation requirements. Therefore, the duration of 15 days is considered suitable for executing PMWIN application runs, as it covers 2 irrigation turns. The ranges of other

[1] Normally, this ratio equals to the depth of well divided by the depth of aquifer. However, for the skimming well it may be appropriate to define this ratio with respect to the depth of interface rather than the depth of aquifer.

parameters (like, depth to watertable and thickness of fresh groundwater lens) were selected while keeping in mind the aquifer characteristics and conditions of the area under study.

Table 3. Summary of model runs.

Run No.	Depth to watertable (m)	Discharge rate (lps)	Thickness of fresh water (m)	Well penetration ratio (%)	Operational hours/day
1	1.5	14	18	60	24
2	**1.0**	14	18	60	24
3	**2.0**	14	18	60	24
4	1.5	**10**	18	60	24
5	1.5	**18**	18	60	24
6	1.5	14	**13**	60	24
7	1.5	14	**15.3**	60	24
8	1.5	14	18	**66.6**	24
9	1.5	14	18	**73.3**	24
10	1.5	14	18	60	**8**
11	1.5	14	18	60	**12**

RESULTS AND DISCUSSION

Figures 7-11 show the effect of depth to watertable, discharge rate, thickness of the fresh groundwater lens, well penetration ratio, and well operating hours per day on the salinity of pumped water. Figure 12 shows the effect of different design, operation, management and aquifer parameters (within the ranges specified during simulation runs) on the changes in salinity of pumped water with quantity. Based on these figures, following inferences can be made.

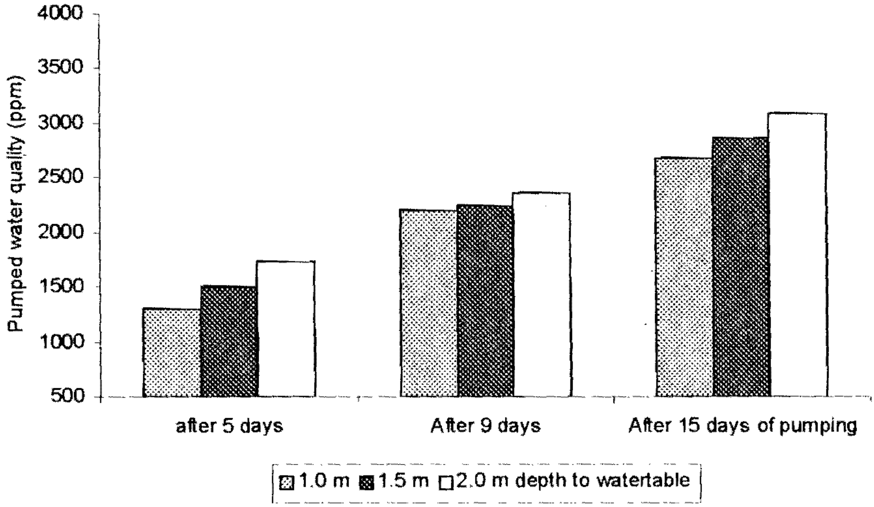

Figure 7. **Effect of depth to watertable on the salinity of pumped water.**

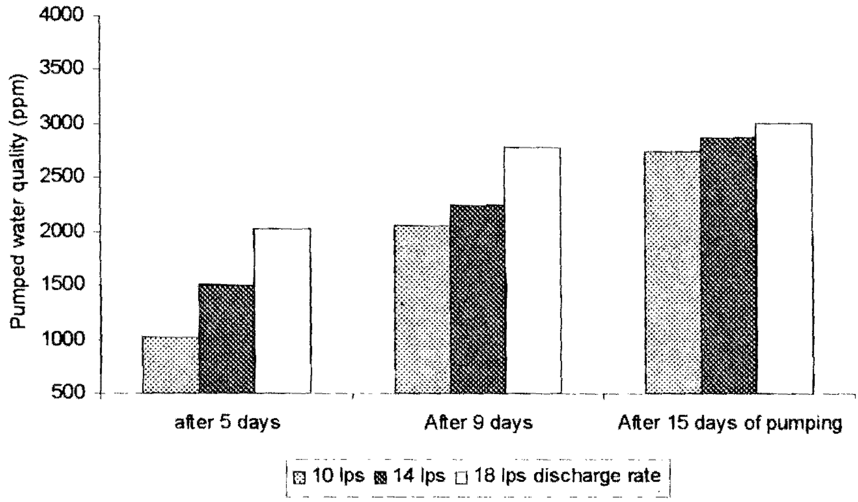

Figure 8. **Effect of discharge rate on the salinity of pumped water.**

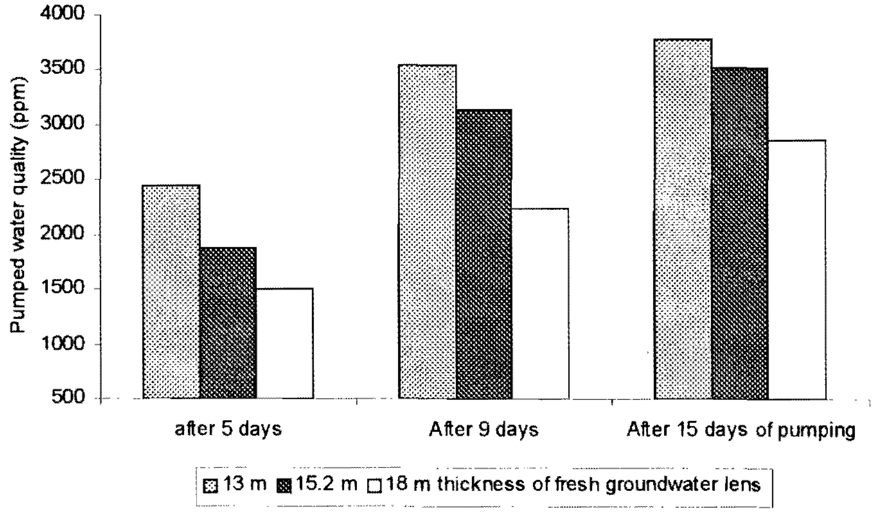

Figure 9. **Effect of thickness of fresh groundwater lens on the salinity of pumped water.**

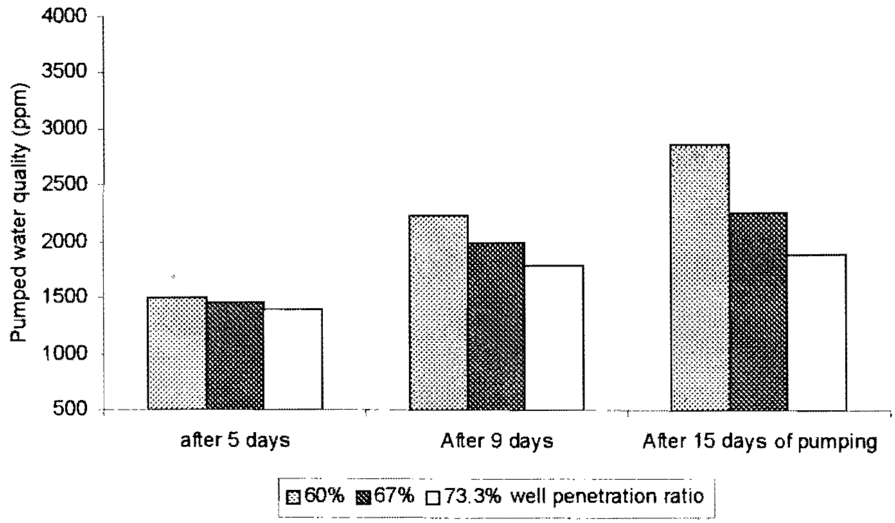

Figure 10. **Effect of well penetration ratio on the salinity of pumped water.**

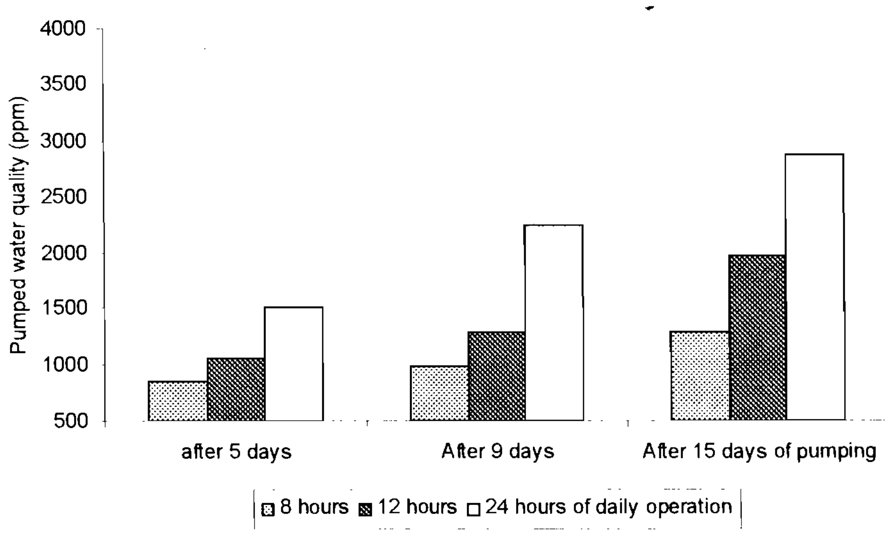

Figure 11. **Effect of operating hours per day on the salinity of pumped water.**

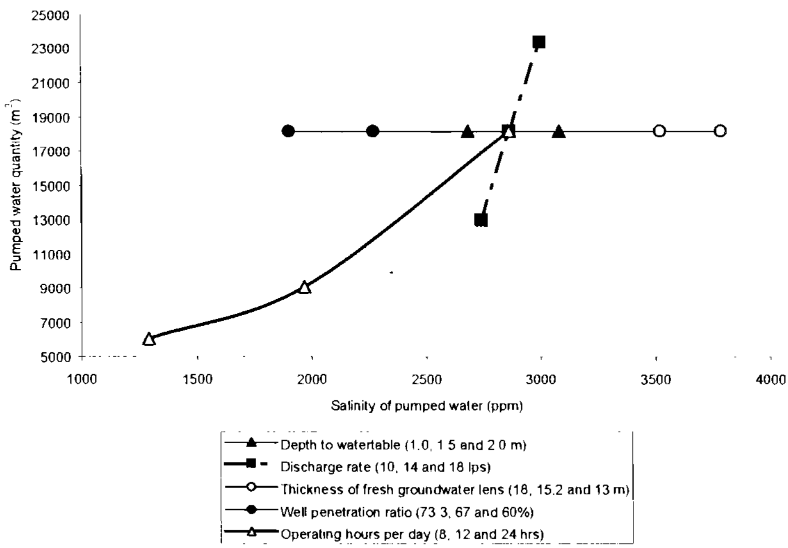

Figure 12. **Changes in salinity of pumped water with quantity.**

Depth to watertable

The discussion is based on Runs 1, 2, and 3. After 5 days of continuous pumping with watertable depths of 1.0, 1.5, and 2.0meters from the soil surface, the salinity of pumped water becomes 2000 ppm while the position of the interface is still below the well bottom. This fresh and saline water interface enters the well screen sometimes between 5 to 9 days of pumping for this particular set up. However, even if the interface enters the well screen, salinity of pumped water does not exceed 3000 ppm during 15 days of continuous pumping with 14 lps discharge rate (Figure 7).

Generally, with the increase in watertable depths from 1.0 to 2.0m, there is increase in the concentration of solutes for the increased amount of pumped water. However, for pumping 18144m^3 of groundwater during 15 days of operation, the salinity does not deteriorate more than 3000 ppm (Figure 12).

These runs show that the depth to watertable has minimal impact on the salinity of pumped water. Variations in salinity of pumped water are attributed to the minor changes to the thickness of the aquifer.

Discharge rate

The discussion is based on Runs 1, 4, and 5. The salinity of pumped water is around 2000 ppm after 5 days of continuous pumping with discharge rates from 10 to 18 lps. The position of the fresh and saline water interface is below the well bottom having 60% well penetration ratio during first 5 days of pumping operation. This interface enters the well screen sometimes between 5 to 9 days of pumping for 14 and 18 lps scenarios. But in case of 10 lps scenario, it enters the well bottom after 9 days of pumping. However, even if the interface enters the well screen, salinity of pumped water does not increase more than 3000 ppm during 15 days of continuous pumping with 10-18 lps discharge rate, 1.5m deep watertable, and 18m thick fresh groundwater lens (Figure 8). The quantity of groundwater discharges in 15 days of operation with 10, 14 and 18 lps are 12960, 18144 and 23328m^3, respectively (Figure 12).

These runs show that despite the variations in salinity of pumped water with discharge rates, the salinity of pumped water is below 3000 ppm for discharge rates as high as 18 lps.

Thickness of fresh groundwater lens

The discussion is based on Runs 1, 6, and 7. After 5 days of continuous pumping at 14 lps discharge rate, the interface does not enter the well screen when the thickness of fresh groundwater lens is 18m and the depth to watertable is 1.5m. The salinity of pumped water is around 1500, 2000, and 3000 ppm in this case, after 5, 9, and 15 days respectively. Although, in case of groundwater system having 15.3m thick fresh groundwater lens, this interface enters the well screen, but the salinity of pumped water is still less than 2000 ppm after 5 days of pumping. This salinity of pumped water remains under 3000 ppm even after 9 days of pumping. But, the salinity of pumped water deteriorates and reaches 3500 ppm on 15^{th} day of pumping. However, with 13m thick fresh groundwater lens, the interface enters the well screen and salinity of pumped water deteriorate to 2500 ppm within 5 days of pumping. In this case, the salinity of pumped water touches 3500 and 3800 ppm marks on 9^{th} and 15^{th} day of pumping (Figure 9).

The salinity for the same quantity ($18144m^3$ in 15 days of operation) of water pumped from aquifers having 18, 15.2 and 13m thickness of fresh groundwater lens, becomes around 3000, 3500, and 3800 ppm (Figure 12). Even within 9 days of well operation, the salinity of pumped water ($10886m^3$) exceeds 3000 ppm mark in case of aquifers with 15.2 and 13m thickness of fresh groundwater lens (Figure 9 and 12).

These runs show that when the thickness of fresh groundwater lens is less than 15m, the salinity of pumped water deteriorate very rapidly with duration and quantity of pumping.

Well penetration ratio

The discussion is based on Runs 1, 8, and 9. For well penetration ratio of 60.0 to 73.3% of the fresh groundwater lens, the salinity of pumped water does not exceed 1500 ppm and the interface remains below the well bottom during first 5 days of pumping with 14 lps discharge rate. During 5 to 9 days of pumping, the salinity of pumped water becomes 2000 ppm, and afterwards, it touches 3000 ppm mark on the 15^{th} day of pumping from an unconfined aquifer having 18m thickness of fresh groundwater lens (Figure 10). For well penetration ratio ranging from 60 to 73.3%, the salinity of pumped water ($18144m^3$ in 15 days of operation) remains under 3000 ppm (Figure 12).

Operating hours per day

The discussion is based on Runs 1, 10, and 11. For 8 hours of daily operation with 14 lps discharge, the salinity of pumped water remains below 1300 ppm and the interface also remains lower than the well bottom even after 15 days of pumping. However, with 12 hours of daily operation, the salinity of pumped water exceeds 1000 ppm after 5 days of pumping with 14 lps discharge rate. But it remains below 2000 ppm after 15 days of pumping and the interface still remains below the well bottom. Whereas, with continuous operation of 14 lps discharge pump, the salinity of pumped water becomes 3000 ppm after 15 days of pumping from an unconfined aquifer with 18m thickness of fresh groundwater lens, and at 1.5m deep watertable (Figure 11). With the increase in operating hours per day, the quantity and salinity of pumped water increases. During 15 days of pumping operation, the salinity becomes 1300, 2000, and 3000 ppm for 6048, 9072, and $18144m^3$ of pumped water quantity (Figure 12).

The salinity of pumped water does not deteriorate more than 3000 ppm during 15 days of pumping operation except for scenarios representing

13 and 15.2m thickness of the fresh groundwater lens. The rate at which the salinity of pumped water deteriorates declines as the interface moves towards the well. However, once the interface enters the well screen, the salinity of pumped water deteriorates with increasing trend with time of pumping operation. Thus, an adequate amount of water (18144m^3) having salinity less than 3000 ppm can be pumped while keeping the design, operation, management and aquifer parameters within the ranges specified during simulation runs except for scenarios representing 13 and 15.2m thickness of the fresh groundwater lens.

CONCLUSIONS

1. For the hydrogeologic conditions studied, a skimming well can be installed and operated successfully with 60-70% well penetration ratio for discharge rates of 10-18 lps operating at 8-24 hours per day from an unconfined aquifer with 15-18m thick fresh groundwater lens.
2. The critical discharge rate is not an appropriate criterion in using skimming wells to pump fresh groundwater. Various factors such as water salinity in the aquifer, the tolerable limits of salinity of pumped water, and economics of the operation must be taken into account while making a decision regarding the design and the operational management strategies of conventional skimming wells. Furthermore, the rate of recharge (due to deep percolation from irrigation application, canal seepage, and rainfall) is also an important parameter that effects the operational management strategies of conventional skimming wells installed in the shallow fresh groundwater aquifers underlain by saline groundwater.
3. Figure 12 may be used to determine the design and operational criteria for pumping a required quantity of water of acceptable salinity. An adequate amount of water (18144m^3) having salinity less than 3000 ppm can be pumped during 15 days of pumping operation while keeping the design, operation, management and aquifer parameters within the ranges specified during simulation runs except for scenarios representing 13 and 15.2m thickness of the fresh groundwater lens.

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