Assessment of Skimming Well Performance in Punjab, Pakistan by Groundwater Simulation Modeling

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Synopsis

This paper presents the results of a modeling study on skimming well performances using the MODFLOW-MT3D groundwater model in Rechna Doab of Pakistan' s Punjab. After calibration and validation of the developed model using the field data, a scenario analysis was conducted to identify the best management practice for well operation. The result of the analysis showed that a 4-strainer well with 0.2 to 0.5 cfs (340 to 850 l/min) discharge and well penetration (Pw) of 30 to 40% of the 30 m thick fresh water layer is best recommended to be operated 4 to 8 hours/day to obtain water with a salinity that is less than 1500 ppm without a significant saltwater upconing on long-term basis in Rechna Doab of Pakistan' s Punjab.

Keywords : Skimming well, Groundwater model, Pakistan' s Punjab, Saltwater upconing, Salinity

1. INTRODUON

Irrigated Agriculture and Salinity Perspective

In the Indus Basin Irrigation System (IBIS) of Pakistan, agriculture being one of the biggest economic sectors of the country contributes about 21% to the national Gross Domestic Product (GDP). It supports 60% of the population providing self employment to 40% of rural families. Out of 21 Mha of agricultural land, 16 Mha is irrigated through its large scale irrigation systems, while 5 Mha is rain-fed or flood based. About 65% of the average river inflows are diverted for agriculture and other economic uses through 45 main canals supported by 2 large reservoirs ; Mangla and Tarbela of 19.2 BCM live storage capacity and 14 link canals (Haq et al., 2008).

The Indus Basin Irrigation System (IBIS) of Pakistan serves an area of 16 million hectares (Mha) and distributes 172 billion cubic meters (BCM) of high-quality (150–200 ppm TDS) river water per year. The surface water through canal irrigation network provides about 50% of crop water requirement. Inadequate and unreliable canal water supplies (especially at the tail end of distributaries and water courses) and change in cropping patterns from low-delta-crops to high-delta crops have made farmers' depend on marginal-quality groundwater for irrigation. Depending on the circumstances, groundwater meets 10 to 90 percent (on average 50 percent) of the irrigation requirements.

In Punjab, groundwater supply has increased tremendously over time due to its flexibility in meeting the water demand as and when needed. Consequently, groundwater contributes 40–50% of the crop water requirement. Industrial and domestic water requirements are also met from groundwater in the fresh groundwater areas. Currently, about one million public and private tube wells are pumping groundwater in Pakistan to meet irrigation, domestic and industrial needs. The highest number of wells is in the Punjab Province. The intensive use of groundwater has resulted in an increasing danger of depletion, quality deterioration, and serious environmental consequences. In the Punjab Province, particularly in Rechna Doab' s large tracts of land, groundwater pumping has lowered the water table levels during the late 1970s and early 1980s (Aslam and Prathapar, 2006).

In Punjab of Pakistan, agriculture contributes 20.3% to GDP and provides employment to more than 45% of the labour force. Over 90% of Punjab's agricultural production is derived from about 8. 4 million hectares of irrigated land. Irrigation System is one of the largest contiguous systems in the world. The surface and groundwater constitute vital lifeline of Punjab's agro-based economy. However, currently, Punjab faces several irrigation, drainage and salinity challenges with profound socio-economic and environmental implications. The major water sector challenges include: growing water shortages, over exploitation of groundwater and deterioration of groundwater quality due to saline water intrusion from saline groundwater areas into fresh water areas as a result of excessive pumping by deep and high capacity (1-2 cusecs) tube wells in fresh groundwater areas.

The capillary up-flow from shallow water tables and evapotranspiration concentrate the salt, which salanizes the soil and water. In areas where river water is unavailable and groundwater of marginal quality is used for irrigation, evapotranspiration leads to sodicity. Thus, salinization in IBIS is due to two significantly different processes: (i) by shallow saline water tables; and (ii) due to irrigation with marginal quality groundwater. About 70% of tube wells of the Indus Basin pump sodic and/or saline-sodic water because of which secondary salinization is taking place in irrigated lands of the Indus Basin of Pakistan (Qureshi and Barrett-Lennard, 1998). Estimates of losses due to salinization are 28,000 to 40,000 ha of land abandoned within the Indus basin due to secondary salinization and about US$230 million of revenue per year due to low crop yield because of salinization. An area of about 2 Mha is estimated to be salinized at present (Aslam and Prathapar, 2006).

In Punjab, pumping brackish groundwater at some locations has accelerated the process of secondary salinization. Research in Punjab has revealed that irrigation with groundwater, which is rich in sodium and bicarbonates leads to the sodification of the soil. Farmers indicate that the adverse effects of poor quality irrigation water are felt by them quite rapidly. After two to three irrigations with such water, a surface crust develops. In addition to such a development, there is a likelihood of hard layers occurring in the soil within an irrigation season (Aslam and Prathapar, 2006). A modeling on conjunctive use of canal water and groundwater of relatively high sodium content revealed that a loam soil could become sodic within a short period of 3 years resulting in rapid sodification of soil (Aslam and van Dam, 1998). Salinity management is central to the future of Pakistan's agriculture, hence merits considerable further effort and research now and in the future as well.

Groundwater Development and Use Scenario

Pakistan has a large high-conductivity unconfined groundwater aquifer with an areal extent of 2, 10,000 Km^2 underlying the alluvial Indus plains. The aquifer thickness varies from 60 to 300 m across the Indus Plain of Pakistan. The average specific yield of Pakistan's aquifer varies from 13 to 17%.

An estimated annual average potential of Pakistan's groundwater system is about 65 million acre feet (MAF) and groundwater use through public and private tube-wells is estimated about 45 MAF per year (Associated Consulting Engineers (ACE) Pvt. Ltd and Halcrow, 2003). In Punjab, groundwater potential is 40. 65 MAF/year and groundwater pumpage is about 35 MAF/year. Currently, about 1001434 private tube wells in Pakistan and about 885078 private tube wells in Punjab are pumping groundwater for different uses mainly for irrigation of croplands (Punjab Agriculture Department, 2009).

In the Indus Basin of Pakistan, farmers are meeting about 50% of their crop water requirement through groundwater use. About 70% of the private tube wells are located in the canal commands where groundwater is used in conjunction with canal water; the remaining 30%

are the sole source of irrigation water. The estimated number of users is over 2.5 million farmers, who pump groundwater directly or hire the services of tube wells from their neighbors (Qureshi et al, 2008).

In Punjab, about 32 MAF of groundwater are used to meet crop water requirements and more than 70% of Punjab farmers depend on groundwater. As a result of conjunctive use of surface and groundwater, cropping intensities have increased from 80 to more than 150% and the crop yields are 50-100% higher compared to farmers without tube-wells (Qureshi et al, 2008).

Excessive use of groundwater through unregulated and uncontrolled abstraction is posing several threats to its sustainable use and management. Declining groundwater tables, high pumping costs, deterioration of groundwater quality and the rise of soil salinity are considered to be the major immediate threats to sustainability of groundwater use for irrigation in Pakistan. In fresh groundwater areas of Punjab, groundwater tables have fallen from 5 ft in the areas near the major rivers to more than 60 ft in the central parts of Doabs (Qureshi et al, 2008).

Saline Water Intrusion and Saltwater Upconing

In Punjab of Pakistan, declining groundwater tables due to over-exploitation of groundwater are causing *intrusion (horizontal movement) of saline water* from saline groundwater areas into the over pumped fresh groundwater areas thereby causing deterioration in groundwater quality in fresh groundwater areas.

In Punjab, groundwater aquifers with vertical salinity gradient have shallow freshwater body overlying more saline groundwater at deeper depths. Pumping with high capacity (more than one-cusec) and deep wells from these kinds of aquifers, causes mixing of saline water with the freshwater due to saltwater upconing. *The saltwater upconing is the vertical upward movement of saltwater in the form of a cone or mound from the saline water zone in response to pumping from the aquifer* (Fig. 1). As the pump discharge rate is increased, there is a greater likelihood that will bring the deeper saline groundwater upward into the pumping well and consequence will be the withdrawal of saline groundwater, use of which for irrigation accelerates the process of secondary salinization.

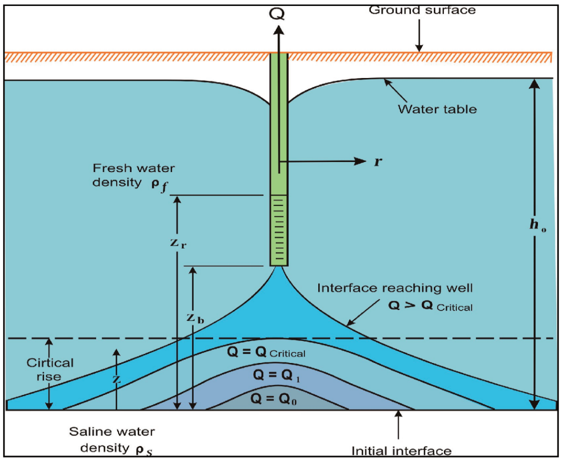

Fig. 1. Saltwater upconing beneath a pumping well (Source: Reilly and Goodman, 1987)

Skimming Wells

In the Indus Basin of Pakistan, the term "skimming well" is used to refer to a *partially penetrating well in shallow freshwater layer having pumping capacity less than one-cusec (30 l/s)*. Skimming wells play an important role in minimizing the mixing of fresh and salt waters in the aquifers with vertical salinity gradient thus expediting pumping of shallow groundwater of reasonable salinity which overlies more saline groundwater at deeper depths, for irrigation purposes. If the pump discharge rate is increased, there is a greater likelihood of the deeper saline groundwater being moved upward into the well. Improved well-design and better operating strategies are vital to ensure that the operation of skimming wells would not cause mining of fresh water layer as well as degradation in quality of fresh water layer.

Rationale of the Present Study

In order to use groundwater on environmentally sustainable long-term basis, it becomes extra-important to manage the freshwater withdrawals from the groundwater aquifers having shallow freshwater layer underlain by deep saline water layer. The Indus Basin of Pakistan (IBP) presents an excellent example of such aquifers in which deep native saline groundwater due to geological formation of marine origin is overlain by fresh groundwater because of seepage from the river and canal system. Thus, IBP groundwater aquifer has vertical salinity gradient characteristic. A recent estimate reveals that approximately 200 billion cubic meters (BCM) of freshwater in the form of shallow thin water bodies are present over the deep saline groundwater in the IBP (NESPAK, 1983). The thickness of the freshwater layer varies from 120 to 150 m within the 24 to 48 m wide belt in the river flood plains and along the irrigation canals. Within doabs (land lying between two rivers), the thickness of freshwater layer varies from about 30 m in the central and lower parts to about 60 m along the periphery of the doabs.

Under the conditions of aquifers having vertical salinity gradients, properly designed and operated skimming wells help managing the freshwater withdrawals by controlling the saltwater upconing. A thorough knowledge of saltwater upconing phenomenon and solute transport processes in the saturated porous medium provides the basis for establishing proper well design and operational strategies. The computer numerical groundwater models are invaluable tools to study the physics of saltwater upconing and solute transport processes taking place in the groundwater aquifers to devise design and operational parameters for the skimming well technology by evaluating its performance under these parameters.

Though computer numerical groundwater models are invaluable tools for simulations and long-term predictions on saltwater upconing (SWU) and skimming well technology (SWT) performance, but a comprehensive database is requisite for reliable and dependable model studies results. Researchers and investigators have developed several groundwater flow and solute transport simulation models. Every model has strengths and weaknesses. The selection of a model depends on the purpose for which that model is being used.

For the present study, the groundwater modeling system, MODFLOW-MT3D (McDonald and Harbugh, 1988; Pollock, 1988, 1989, 1994; Zheng, 1990; Chiang, 1994; and Doherty et al., 1994) was selected and employed for simulation and evaluation of SWU and SWT performance for long-term period. This model has the capabilities to simulate the SWU and SWT through groundwater flow and solute transport processes taking place in the saturated zone (groundwater aquifer) using miscible fluids approach (which assumes a continuous gradation of salinity from the salt water to the fresh water due to hydrodynamic dispersion, and is physically more vigorous and realistic than the immiscible fluids approach, which assumes a sharp interface between fresh and saline waters for analysis of the saltwater upcoming), and also this model has been used widely for different groundwater related studies, thereby establishing its validity for its use for analysis of various groundwater issues. The detailed description of MODFLOW-MT3D model is given in Appendix 1.

In the present study, firstly, MODFLOW-MT3D model was validated by simulating and comparing SWT performance with observed performance using the field data on groundwater aquifer parameters, skimming well parameters, groundwater salinity profile and observed pumped water salinity. This data was collected during a past field study on skimming wells in Mona Reclamation Experimental (MREP) area of the Indus Basin of Pakistan. Then, this model was used to simulate and evaluate the performance of the SWT under different design and operational strategies for obtaining good quality pumped water on long-term sustainable basis. These model simulations were made using typical hydrogeological and groundwater

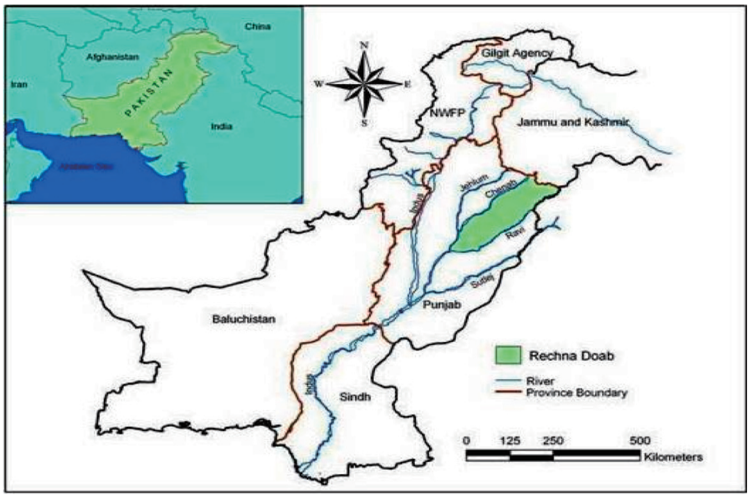

Fig. 2. Map showing the location of Rechna Doab of Punjab, Pakistan

salinity conditions prevailing in the Rechna Doab of the Indus Basin of Pakistan (IBP). The recommendations on skimming well design and operational strategies for obtaining good quality groundwater on long-term basis in the Rechna Doab were based on the modeling simulations. The main objectives of the present study were:

- To simulate and evaluate the performance of SWT under different design and operational management strategies using MODFLOW-MT3D groundwater modeling system; and
- To recommend SWT design and operational strategies for abstraction of good quality groundwater on long-term sustainable basis in the Rechna Doab of Punjab, Pakistan.

2. MATERIALS AND METHODS

Study Area: The Rechna Doab

The Rechna Doab is the land between the Ravi and Chenab rivers (Fig. 2). This Doab has a gross area (GCA) of 2.97 Mha of which about 2 Mha (CCA) is irrigated. The climate shows large seasonal variations in temperature and rainfall. The summer (kharif season) is hot with temperature ranging from 21 to 50 degrees Celsius. In winter (Rabi season) temperature ranges from 15 to 27 degrees Celsius. The mean annual rainfall is 1,080 mm in the upper part of the doab and is 340 mm in the lower part of the doab. About 75% of the rainfall occurs during the monsoon season (mid-July to mid-September). The Rechna doab area falls under the rice-wheat and sugarcane-wheat agro-climatic zones of Punjab of Pakistan. Rice, cotton and forage crops are major summer (kharif) crops and wheat and fodder crops are major winter (rabi) crops.

In the Rechna Doab, two main canals, namely; the Upper Chenab Canal (UCC) and the Lower Chenab Canal (LCC) command the irrigated land (Fig. 3). UCC covers upper Rechna Doab and LCC covers lower Rechna Doab. The total irrigation water supply at the farmgate has increased to about 15.79 million hectare-meters (Mhm), from 7.86 Mhm in 1965. Surface water constituted 86% of the total water supply at farmgate in 1965; however, now it is about 65% assuming a groundwater contribution in 1996 at

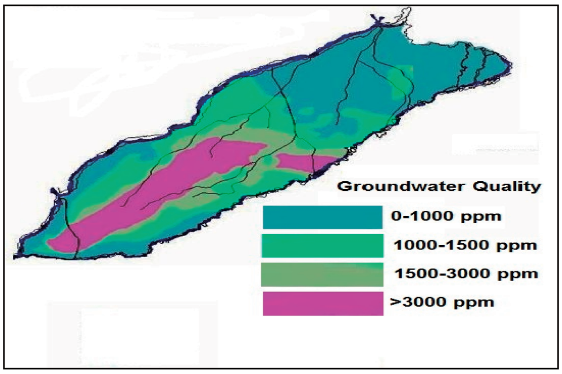

Fig. 3. Groundwater salinity up to 105 m depth across the Rechna Doab

5.6 Mhm. The greatest share in the increased groundwater pumpage comes from the private tube well development.

The alluvial material in the Rechna Doab forms part of the extensive heterogeneous and anisotropic unconfined groundwater reservoir underlying the Indus Plain and is more than 300 m deep. The alluvial consists of silt and fine sand or mixture of both. The aquifer material is highly porous and is capable of storing and transmitting water readily, the horizontal hydraulic conductivity being greater than the vertical hydraulic conductivity. Based on 140 pumping tests performed in Punjab, specific yield of the unconfined aquifer ranges from 1 to 42 percent with an average value of 14 percent. Horizontal hydraulic conductivity (Kh) ranges 26 to 173 m/day with an average value of 100 m/day. The common values of Horizontal hydraulic conductivity are between 66 and 105 m/day. Vertical hydraulic conductivities (Kv) range from 0.26 to 11.1 m/day with average value of 1.26 m/day. Anisotropy ratios (Kh : Kv) range from 3 : 1 to 195 : 1, with an average value of about 55 : 1.

The variation in lithology imparts a wide range of hydraulic and chemical properties to groundwater and consequently, the wells screened opposite the most permeable sand lenses may pump water of different quality from different horizons. The groundwater discharge from each well is a mixture from several water bearing zones and represents the average water quality that has been imposed by local geological conditions, the pumping rate and the hydraulic properties. Based on the Water And Power Development Authority (WAPDA) data, the groundwater salinity of deeper water samples (up to 105 m depth) across the Rechna Doab is shown in Fig. 3. Area with different groundwater salinity is shown in Table 1. Groundwater quality is good (TDS <1,000 ppm, even less than 500 ppm in some cases) generally in the upper parts of the doab and in a 24–48 kilometers (Km) wide belt along the flood plains of the Chenab and Ravi rivers. Highly saline groundwater (TDS > 3,000 ppm) is found in the lower and central part of the doab.

In Rechna Doab, chemical analysis of about 1,500 shallow water samples taken from 6 to 18 m depth, showed that about 49 percent of 1,500 samples contain groundwater salinity of 750 ppm, 39 percent vary in salinity from 751 to 1,500 ppm, 10 percent vary from 1,501 to 3,000 ppm and 2 percent contain salinity above 3,000 ppm (Ahmed, 1995). Generally, within the doab, the thickness of freshwater layer varies from about 30 m in the central and lower parts to about 60 m along the margins of the doab. Under these shallow freshwater lenses, skimming wells offer great potential for providing good quality pumped water on long-term sustainable basis. That is why in the present study SWT was modeled for its performance to determine optimum design and operational parameters.

Model Validation

To establish the validity of the groundwater flow and solute transport model, MODFLOW-MT3D for simulations of SWT, drawdown and salinity of the pumped water from a 2-strainer well were reproduced and compared with the field observed values of the abovementioned parameters from the same well. This well was located in the Mona Reclamation Experimental Project (MREP) area (Salinity Control and Reclamation Project, SCARP II) of the Indus Basin. The model input data (Table 2) was derived mainly from the secondary source and well data from report (Hafeez et al. 1986). The model development for validation purpose is explained below.

Table 1. Areas (Mha) with different groundwater salinity range up to 105 m depth

Gross area	0–1,000 ppm	1,000–1,500 ppm	1,500–3,000 ppm	>3,000 ppm
2.319	1.449 (62.5%)	0.334 (14.4%)	0.357 (15.4%)	0.179 (7.7%)

Table 2. Input data used for model validation.

Aquifer Physical, Hydraulic and Solute Transport Properties	
Aquifer Thickness	36 m
Depth to Water Table	2 m
Hydraulic Conductivity (Kh)	45 m/day
Hydraulic Conductivity (Kv)	30 m/day
Specific Storage (Ss)	0.0000033 m^{-1}
Specific Yield (Sy)	0.3
Effective porosity (Ep)	0.3
Longitudinal Dispersivity (αL)	1.5 m
Transverse Dispersivity (αT)	0.15 m
Molecular diffusion coefficient (Dm)	1.5 E-11 m^2/day
Groundwater Salinity at depths (m): 9, 12, 15, 18, 21, 24, 27, 30, 33 and 36	TDS (ppm): 750, 976, 1,014, 1,182, 1,386, 1,800, 3,240, 4,940, 5,260 and 5,270
Well Information	
2-strainer well depth	9 m
Strainers spacing	30 m
Well Discharge	1,223 m^3/day (14 l/s)
Pumping Period (continuously)	32 days

Model Domain and Grid Layout

The present study is a local scale study for which the model domain consisted of 300×300×36 m. The selected model domain was replaced by a discretized domain, which consists of a grid of block-centered finite difference cells of 30, 27, 15, 15, 12, 12, 9, 9, 6, 6, 3, 3, 2, 2, 2, 3, 3, 6, 6, 9, 9, 12, 12, 15, 15, 27 and 30 m dimension, for numerical modeling purposes. The discretized domain has 27 rows numbered from top to bottom and 27 columns numbered from left to right, for a total of 729 grid cells. The aquifer thickness of 36 m was divided into 10 layers. The thickness of layer1, layer 2, layer 3, layer 4, layer 5, layer 6, layer 7, layer 8, layer 9 and layer 10 was 3, 7.5, 3, 3, 3, 3, 3, 3, 3 and 4.5 m, respectively. The location of a cell was represented in terms of the column (j), row (i), and layer (k). A no-flow boundary is constituted automatically around the model domain, within which cells are designated as active and inactive. An inactive cell is impermeable or constant head (where the head is not computed or fixed during simulation). For the selected domain, 625 cells were designated as active cells, where heads can vary dynamically.

Aquifer Hydraulic and Solute transport Parameters

The horizontal and vertical hydraulic conductivity, specific storage, effective porosity and specific yield values given in Table 2 were specified for each of 10 layers. Also values of longitudinal dispersivity, transverse dispersivity and molecular diffusion coefficient (Table 2) were also specified for all layers of the model grid.

Initial and Boundary Conditions

Considering the depth to water table of 2 m, 34 m served as the initial head distribution for the model under consideration. The cells, surrounding the model domain represented constant head boundary where hydraulic head was constant throughout simulations. The groundwater salinity profile given in Table 2 served as initial salinity concentration in the model domain layers.

Well Parameters

In the present study, a 2-strainer well was considered for groundwater abstractions. This well was 9 m deep with strainers spacing of 30 m. This well was operated continuously for 32 days at pumping rate of 1,223 m^3 per day. To identify the cell location of the well, termed as pumping cell on the model grid, well screens were located in the second layer of the model grid in accordance with well depth of 9 m, screens spacing of 30 m and well discharge of 1,223 m^3 per day.

Model Validation Simulations

A validated groundwater model demonstrates the model's ability to reproduce the hydrologic conditions of the natural system in terms of field-measured heads/ drawdowns and groundwater salinity (an acceptable match between the simulated and measured field values). In the present study, after developing model for the 2-strainer well, it was run for 32 days (well was operated continuously for 32 days). The drawdown recorded at the end of 32 days was 1.1 m. The observed salinity of the pumped groundwater at different times of pumping is given in Table 3 (Hafeez et al. 1986).

Table 3. Areas (Mha) with different groundwater salinity range up to 105 m depth

Time (days)	Salinity (ppm)
1	750
5	760
10	780
15	832
20	900
32	1,200

Table 4. Measured and simulated drawdown after 32 days of pumping

Category	Value
Measured drawdown	1.1 m
Simulated drawdown	1.0 m

The simulated drawdown after 32 days of pumping and salinity of the pumped water at different times of pumping period were compared with the measured values of drawdown and pumped water salinity. The measured and simulated groundwater table drawdown (Table 4) and salinity of pumped water (Table 5) matched closely and showed similar groundwater flow and solute transport trends in the model domain, and the absolute difference remained within a minimal range of 1 to 6 percent, which is acceptable.

These simulations results indicate clearly that the model successfully simulates the groundwater flow (heads/drawdowns) and the solute transport (salinity of groundwater) thereby establishing its validity for use for SWU and SWT simulations.

Model Development for the Rechna Doab

In the present study, the typical hydrogeological and groundwater salinity conditions prevailing in the Rechna Doab were considered for modeling purposes. The hydrogeological and solute transport parameters used for model development for the Rechna Doab are provided in Table 6.

The groundwater salinity concentration profile used in the model as the initial groundwater salinity profile is given in Table 7.

The model domain consisted of 300 × 300 × 60 m. The domain was replaced by a discritized model grid with finite difference cells of 30, 27, 15, 15, 12, 12, 9, 9, 6, 6, 3, 3, 2, 2, 2, 3, 3, 6, 6, 9, 9, 12, 12, 15, 15, 27 and 30 m dimension. The discretized domain has 27 rows and 27 columns for a total of

Table 5. Measured and simulated salinity of pumped water

Time (days)	Measured Salinity (ppm)	Simulated Salinity (ppm)	Difference (% of measured salinity)
1	750	735	−2
5	760	772	+2
10	780	830	+6
15	832	867	+4
20	900	906	+1
32	1,200	1,160	−3

− *means simulated value is less than observed one and* + *means simulated value is greater than observed one.*

Table 6. Input parameters used for the development of Rechna Doab model

Model Domain	300 × 300 m
# rows	27
# columns	27
# layers	10
Aquifer thickness	60 m
Horizontal Hydraulic Conductivity	40 m/day
Vertical Hydraulic Conductivity	10 m/day
Specific yield	0.25
Effective Porosity	0.25
Specific Storage	$0.0000033\ \mathrm{m}^{-1}$
Hydraulic Head	58.5 m
Longitudinal Dispersivity	2 m
Transverse Dispersivity	0.4 m
Simulation Period	4 years

Table 7. Groundwater salinity profile used in groundwater model of the Rechna Doab

Layer Number	Layer Thickness (m)	Salinity (ppm)
1	2.5	750
2	4	750
3	4	750
4	3	750
5	3	850
6	3	850
7	4.5	900
8	6	1,000
9	15	2,500
10	15	3,500

729 grid cells. The aquifer thickness of 60 m was divided into 10 layers. The thickness of layer 1, layer 2, layer 3, layer 4, layer 5, layer 6, layer 7, layer 8, layer 9 and layer 10 was 2.5, 4, 4, 3, 3, 3, 4.5, 6, 15 and 15 m, respectively. For the domain, 625 cells were designated as active cells, where heads can vary dynamically.

For the single and multi-strainer well (4-strainers well) with horizontal distance of 4.5 m, 12 different scenarios (Table 8) for each type of well (1- and 4-strainer well) are developed for the Rechna Doab for evaluation of effect of well depth, well discharge and well operational factor on the salinity of pumped groundwater (evaluation of skimming well performance under different combination of well depth, discharge and operational factor).

3. SIMULATIONS RESULTS FOR THE RECHNA DOAB

Saltwater Upconing Simulations

The rise in interface at the end of year 4 of pumping for a single well for two well discharges of 0.5 and 0.2 cfs (340 to 850 l/min), operational time of 8 hours per day for Pw of 30, 40 and 60% are shown in Figures 4, 5 and 6, respectively. For Pw of 30% case, the Qw of 0.5 cfs has shown about 27.2 m rise in interface compared to about 27 m in case of Qw of 0.2 m. So rise in interface in Qw of 0.5 cfs is higher compared to that caused by Qw of 0.2 cfs and consequently, salinity of pumped water would be less due to less salt water

Table 8. Different simulation scenarios for SWT for the Rechna Doab

Scenario No.	Well Penetration, PW (%)	Well Discharge, Qw (cusec)	Operational Time, Ot (hrs/day)
Single Strainer Well			
1	30	0.5	8
2	40	0.5	8
3	60	0.5	8
4	30	0.2	8
5	40	0.2	8
6	60	0.2	8
4-Strainer Well			
7	30	0.5	8
8	40	0.5	8
9	60	0.5	8
10	30	0.2	8
11	40	0.2	8
12	60	0.2	8

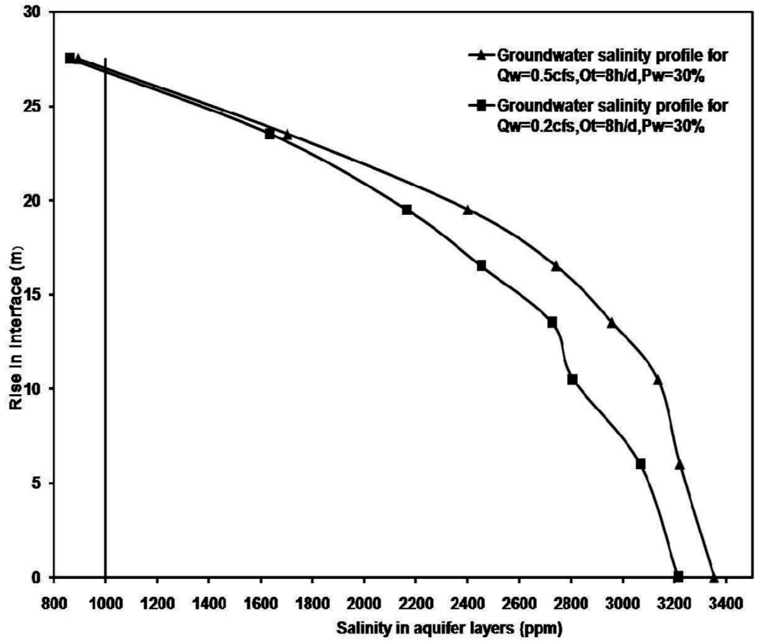

Fig. 4. Rise in interface at the end of year 4 for a single strainer well discharge (Qw) of 0.5 cfs, and 0.2 cfs, operating time (Ot) of 8 hours/day, and well penetration (Pw) of 30%.

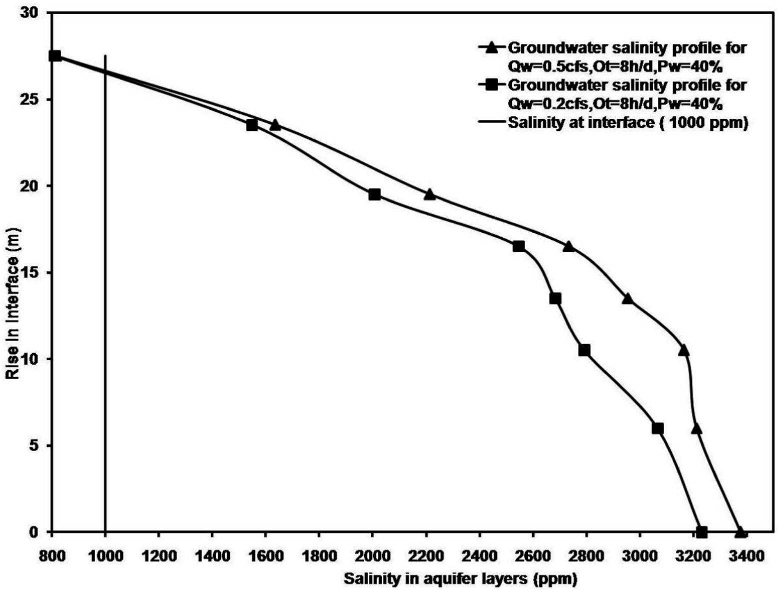

Fig. 5. Rise in interface at the end of year 4 for a single strainer well discharge (Qw) of 0.5 cfs, and 0.2 cfs, operating time (Ot) of 8 hours/day, and well penetration (Pw) of 40%

upconing in case of 0.2 cfs discharge compared to Qw of 0.5 cfs. The same trend has been seen in case of Pw of 40% (Fig. 5). In case of Pw of 60%, Qw of 0.5 cfs has caused about 27.5 m, rise in interface whereas Qw of 0.2 cfs has caused about 27 m rise (Fig. 6). Clearly, Qw of 0.5 cfs has caused more saltwater upconing compared to 0.2 cfs. Consequently, salinity of pumped water would be less for Qw of 0.2 cfs compared to 0.5 cfs.

A comparison of rise in interface due to a single strainer and a 4-strainer well with well discharge of 0.5 cfs, operational time of 8 hours per day and

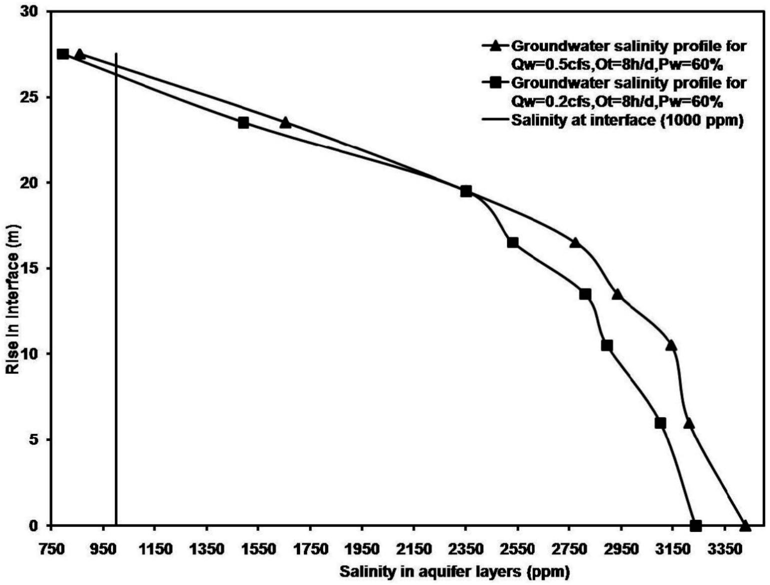

Fig. 6. Rise in interface at the end of year 4 for a single strainer well discharge (Qw) of 0.5 cfs, and 0.2 cfs, operating time (Ot) of 8 hours/day, and well penetration (Pw) of 60%.

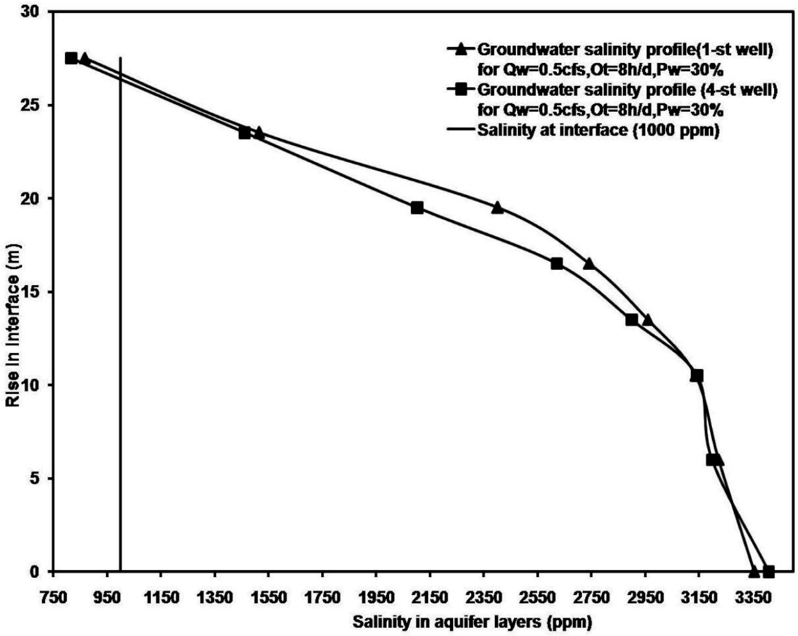

Fig. 7. Rise in interface at the end of year 4 for a single and 4-strainer well, for well discharge (Qw) of 0.5 cfs, operating time (Ot) of 8 hours/day, and well penetration (Pw) of 30%

well penetration of 30%, is presented in Fig. 7. The single strainer well causes about 27.2 m rise in interface whereas 4-strainer well causes about 27 m rise. Though there is a small difference between the rise in interface for a single strainer well and that caused by the 4-strainer well, but it shows that a multi-strainer well (4-strainer) causes less salt water upconing compared to a single-strainer well and consequently, the salinity of the pumped water by a multi-strainer will be less compared to that in case of a single-strainer well for the same Qw of 0.5 cfs, Ot of 8 hours per

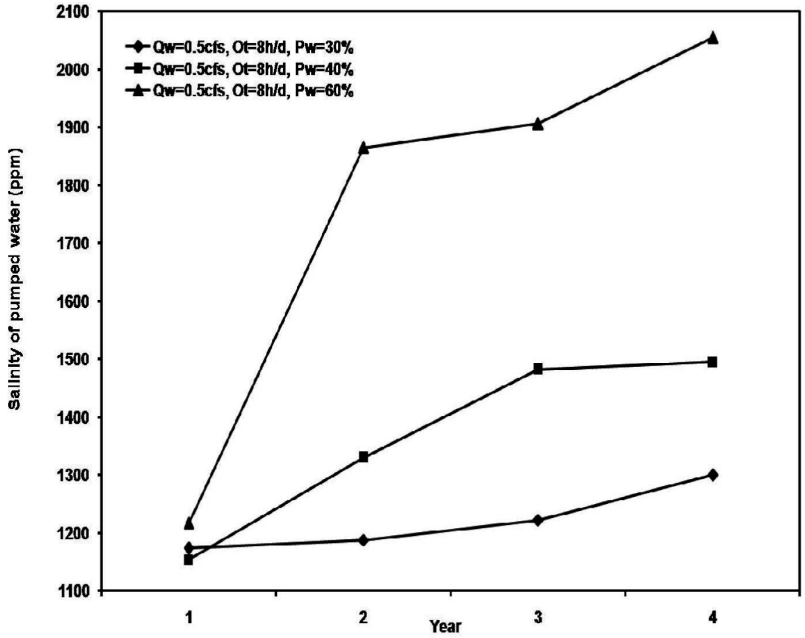

Fig. 8. Four-year simulated salinity of pumped water for Qw of 0.5 cfs, Ot of 8 hours/day, and well penetration of 30, 40 and 60% for a single strainer well

day and well penetration of 30%.

Pumped Water Salinity Analysis

Fig. 8 presents simulation results for four years on salinity of pumped water for a single-strainer well for Qw of 0.5 cfs, Ot of 8 hours per day for Pw of 30, 40 and 60%. The pumped water salinity after 4 years of pumping is 1,300, 1,495 and 2,055 ppm for Pw of 30, 40 and 60%, respectively. Clearly, if the single-strainer well with 30 and 40% Pw and discharge rate of 0.5 cfs would be operated for 8 hours per day, it could deliver pumped water of relatively reasonable quality (< 1,500 ppm). If the same well with the same discharge rate of 0.5 cfs, the same Ot of 8 hours per day, but with 60% Pw, it will not pump water of acceptable quality (> 1,500 ppm) on sustainable long-term basis. The overall finding is that a single-strainer well with 30 and 40% Pw and discharge rate of 0.5 cfs and operational time of 8 hours per day, could be operated safely to get pumped water of reasonable quality on long-term basis.

Fig. 9 presents simulation results for four years on salinity of pumped water for a single-strainer well for Qw of 0.2 cfs, Ot of 8 hours per day for Pw of 30, 40 and 60%. The pumped water salinity after 4 years of pumping is 1,250, 1,391 and 1,933 ppm for Pw of 30, 40 and 60%, respectively. Clearly, these salinity values are less compared to those obtained for well discharge rate of 0.5 cfs for Pw of 30, 40 and 60% and Ot of 8 hours/day. Also, if the single-strainer well with 30 and 40% Pw and discharge rate of 0.2 cfs would be operated for 8 hours per day, it could deliver pumped water of relatively reasonable quality (< 1,500 ppm). If the same well with the same discharge rate of 0.2 cfs and the same Ot of 8 hours per day, but with Pw of 60% it will not pump water of acceptable quality (>1,500 ppm) on sustainable long-term basis. The overall finding is that a single-strainer well with 30 and 40% Pw and discharge rate of 0.2 cfs and operational time of 8 hours per day, could be operated safely to get pumped water of reasonable quality on long-term basis.

Fig. 10 presents simulation results for four years on salinity of pumped water for a 4-strainer well for Qw of 0.5 cfs, Ot of 8 hours per day for Pw of 30, 40 and 60%. The pumped water salinity after 4 years of pumping is 1,170, 1,538 and 1,968 ppm for Pw of 30, 40 and 60%, respectively.

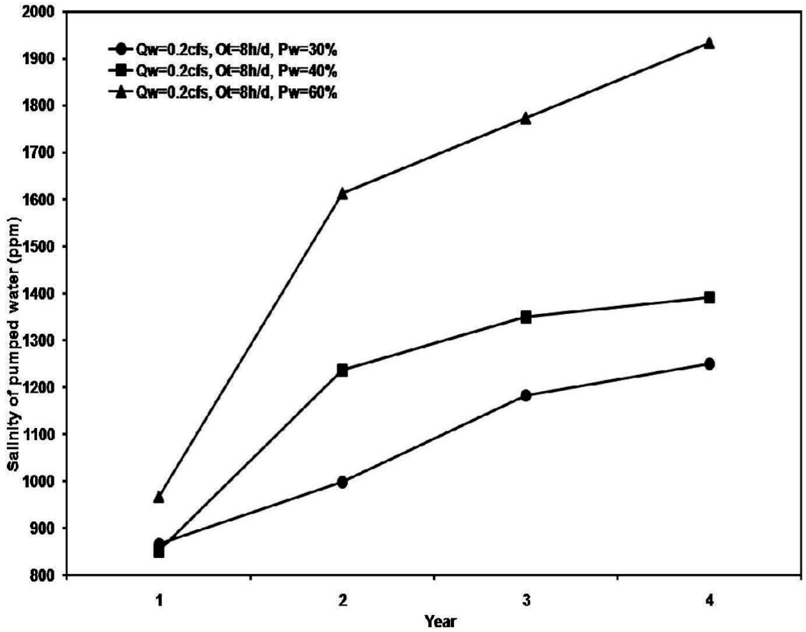

Fig. 9. Four-year simulated salinity of pumped water for Qw of 0.2 cfs, Ot of 8 hours/day, and well penetration of 30, 40 and 60% for a single strainer well

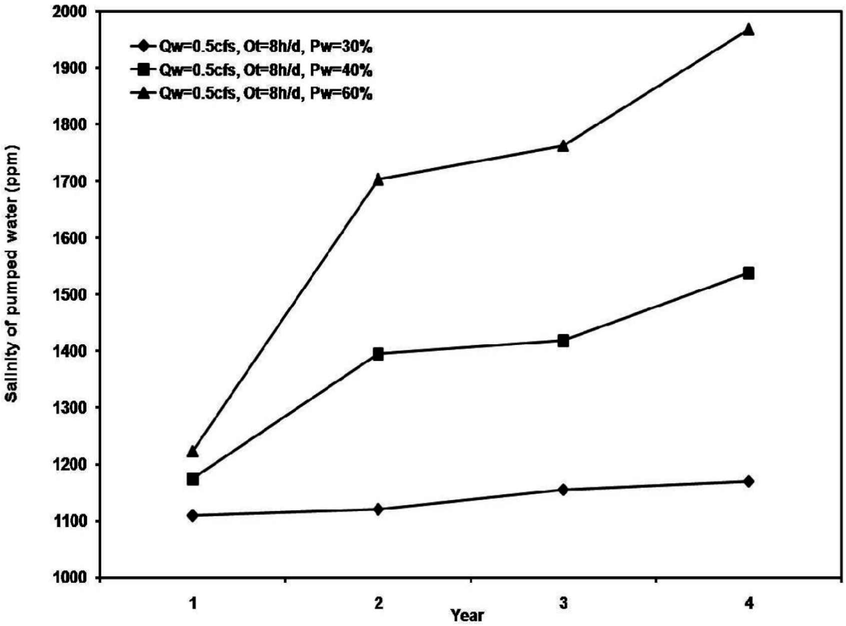

Fig. 10. Four-year simulated salinity of pumped water for Qw of 0.5 cfs, Ot of 8 hours/day, and well penetration of 30, 40 and 60% for a four-strainer well

Clearly, if the 4-strainer well with 30 and 40% Pw and discharge rate of 0.5 cfs would be operated for 8 hours per day, it could deliver pumped water of reasonable quality (1,170 ppm for Pw of 30% and 1,538 ppm for Pw of 40%). If the same well with the same discharge rate of 0.5 cfs and the same Ot of 8 hours per day, it will not pump water of acceptable quality (1, 968 ppm) on sustainable long-term basis. The overall finding is that a 4-strainer well with 30 and 40% Pw and discharge rate of 0.5 cfs and operational time of 8 hours per day, could pump water of reasonable quality on long-term basis.

Fig. 11 presents simulation results for four

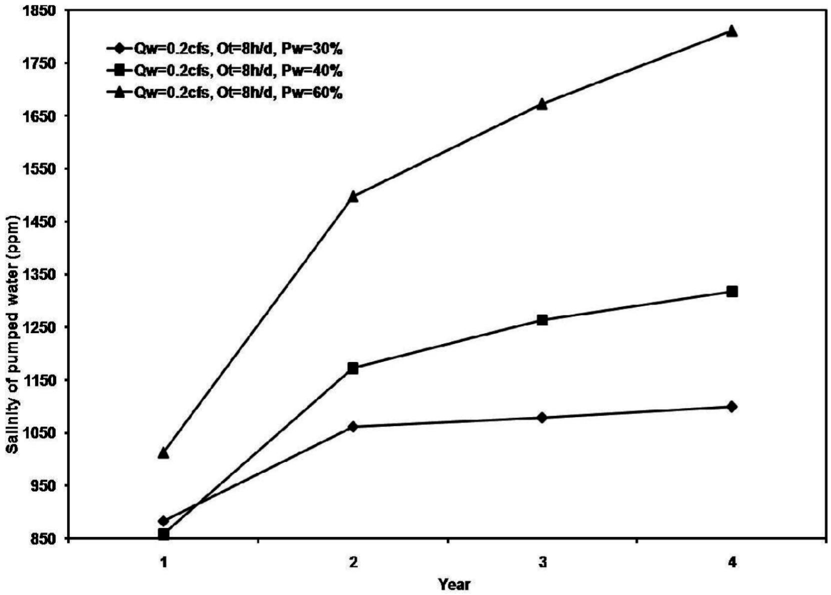

Fig. 11. Four-year simulated salinity of pumped water for Qw of 0.2 cfs, Ot of 8 hours/day, and well penetration of 30, 40 and 60% for a four-strainer well

years on salinity of pumped water for a 4-strainer well for Qw of 0.2 cfs, Ot of 8 hours per day for Pw of 30, 40 and 60%. The pumped water salinity after 4 years of pumping is 1,099, 1,318 and 1,811 ppm for Pw of 30, 40 and 60%, respectively. Clearly, these salinity values are less compared to those obtained for well discharge rate of 0.5 cfs for Pw of 30, 40 and 60% and Ot of 8 hours/day. Also, if the 4-strainer well with 30 and 40% Pw and discharge rate of 0.2 cfs would be operated for 8 hours per day, it could deliver pumped water of reasonable quality (1,099 ppm for Pw of 30% and 1,318 ppm for Pw of 40%). If the same well with the same discharge rate of 0.2 cfs and the same Ot of 8 hours per day, but with Pw of 60%, it will not pump water of acceptable quality (1,811 ppm) on sustainable long-term basis. The overall finding is that a 4-strainer well with 30 and 40% Pw and discharge rate of 0.2 cfs and operational time of 8 hours per day, could pump water of reasonable quality on long-term basis.

4. CONCLUSIONS AND RECOMMENDATIONS

- A single-strainer well with well penetrations of 30, 40 and 60% and operational time of 8 hours per day, when operated at well discharge of 0.5 caused about 27.2, 27.2 and 27.5 m rise in interface at end of year 4, respectively for well penetration of 30, 40 and 60%. The well discharge of 0.2 cfs caused 27 m rise in interface for 30, 40 and 60% well penetration, respectively. It shows an increase in well discharge from 0.2 to 0.5 cfs has significant impact on saltwater upconing because well discharge of 0.5 cfs causes 27.5 m rise in interface and 0.2 cfs causes 27 m rise in interface. Consequently, lower discharge (0.2 cfs) would cause less saltwater upconing compared to higher well discharge of 0.5 cfs; and
- For the well discharge of 0.5 cfs, operational time of 8 hours per day and well penetration of 30%, a single strainer well caused about 27.2 m rise in interface whereas a 4-strainer well caused 27 m rise in interface. It reflects that the multi-strainer well causes less saltwater upcoming compared to the single strainer well.
- A single-strainer well with Qw of 0.5 cfs and Ot of 8 hours per day pumped water of salinity of 1,300, 1,495 and 2,055 ppm for Pw of 30, 40 and 60%, respectively, at the end of year 4 of pumping. Clearly, if the single-strainer well with 30 and 40% Pw and discharge rate of 0.5

cfs would be operated for 8 hours per day, it could deliver pumped water of relatively reasonable quality (<1,500 ppm). If the same well with the same discharge rate of 0.5 cfs, the same Ot of 8 hours per day, but with 60% Pw, it will not pump water of acceptable quality (> 1,500 ppm) on sustainable long-term basis. It reflects that a single-strainer well with 30 and 40% Pw and discharge rate of 0.5 cfs and operational time of 8 hours per day, could be operated safely to get pumped water of reasonable quality on long-term basis;

- For a single-strainer well with Qw of 0.2 cfs and Ot of 8 hours per day the pumped water salinity after 4 years of pumping was 1,250, 1,391 and 1,933 ppm for Pw of 30, 40 and 60%, respectively. Clearly, these salinity values are less compared to those obtained for well discharge rate of 0.5 cfs for Pw of 30, 40 and 60% and Ot of 8 hours/day (1,300, 1,495 and 2,055 ppm). Also, if the single-strainer well with 30 and 40% Pw and discharge rate of 0.2 cfs would be operated for 8 hours per day, it could deliver pumped water of relatively reasonable quality (<1,500 ppm). If the same well with the same discharge rate of 0.2 cfs and the same Ot of 8 hours per day, but with Pw of 60% it will not pump water of acceptable quality (>1,500 ppm) on sustainable long-term basis. It implies that a single-strainer well with 30 and 40% Pw and discharge rate of 0.2 cfs and operational time of 8 hours per day, could be operated safely to get pumped water of reasonable quality on long-term basis;
- A 4-strainer well with Qw of 0.5 cfs and Ot of 8 hours per day delivered water of salinity of 1,170, 1,538 and 1,968 ppm for Pw of 30, 40 and 60%, respectively, at the end of year 4 of pumping. Clearly, if the 4-strainer well with 30 and 40% Pw and discharge rate of 0.5 cfs would be operated for 8 hours per day, it could deliver water of reasonable quality (1,170 ppm for Pw of 30% and 1,538 ppm for Pw of 40%). If the same well with the same discharge rate of 0.5 cfs and the same Ot of 8 hours per day, it will not pump water of acceptable quality (1,968 ppm) on sustainable long-term basis. It implies that a 4-strainer well with 30 and 40% Pw and discharge rate of 0.5 cfs and operational time of 8 hours per day, could pump water of reasonable quality on long-term basis;
- For a 4-strainer well having Qw of 0.2 cfs and Ot of 8 hours per day the pumped water salinity after 4 years of pumping was 1,099, 1,318 and 1,811 ppm for Pw of 30, 40 and 60%, respectively. Clearly, these salinity values are less compared to those obtained for well discharge rate of 0.5 cfs for Pw of 30, 40 and 60% and Ot of 8 hours/day (1,170, 1,538, and 1,968 ppm). Also, if the 4-strainer well with 30 and 40% Pw and discharge rate of 0.2 cfs would be operated for 8 hours per day, it could deliver pumped water of reasonable quality (1,099 ppm for Pw of 30% and 1,318 ppm for Pw of 40%). If the same well with the same discharge rate of 0.2 cfs and the same Ot of 8 hours per day, but with Pw of 60%, it will not pump water of acceptable quality (1,811 ppm) on sustainable long-term basis. It means that a 4-strainer well with 30 and 40% Pw and discharge rate of 0.2 cfs and operational time of 8 hours per day, could pump water of reasonable quality on long-term basis; and
- Considering the hydrogeology and groundwater salinity characteristics of the Rechna doab, a 4-strainer well with well discharge of 0.2 to 0.5 cfs (6 to 15 l/s), well depth of 30 to 40% of fresh water layer thickness of 30 m is recommended to be operated at 4 to 8 hours per day to obtain better quality skimmed water of salinity less than 1,500 ppm on long-term basis.

REFERENCES

ACE (Associated Consulting Engineers (Pvt) Ltd) and Halcrow (Group Ltd), 2003, Exploitation and Regulation of Fresh Groundwater. Final Report, April 2003. Volume I, Main Report. 22/A-E/II, Gulberg-III, Lahore, Pakistan.

Ahmad, N. 1995. Groundwater Resources of

Pakistan (Revised). Published by Shahzad Nazir, 16 B/2 Gulberg-III, Lahore, Pakistan.

Aslam, M. and S.A. Prathapar, 2006. Strategies to mitigate secondary salinization in the Indus Basin of Pakistan: A selective review. Research Report 97. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Aslam, M.; van Dam, J. C. 1998. Modeling soil salinity and sodicity processes in an unsaturated zone using LEACHM: A case study from the Chistian Irrigation Sub-Division. IWMI Pakistan, Report No. 50. Lahore, Pakistan: International Water Management Institute (IWMI).

Chiang, W.H. 1994. PMPATH for windows. User's manual. Scientific Software Group. Washington.

Doherty, J.L. Brebber and P. Whyte. 1994. Pest-Model-independent parameter estimation. User's manual. Watermark Computing. Australia.

Hafeez, A., Piracha, Z. A., and Ahmed N. 1986. Multi-strainer Tube wells, for Skimming Top Layer of Fresh Water Underlain by Saline Water in the Aquifer, Mona Reclamation Experimental Project, WAPDA Publication No. 152.

Haq A.U., Khan, M.H. and Khan, M.A. 2008. Water Management Framework in Pakistan's Indus River Basin: Historical Perspective and Emerging Challenges. Paper presented at ICID Congress held at Wapda House, Lahore, Pakistan. 13-18 October, 2008.

McDonald, M. C. and A. W. Harbaugh, 1988. MODFLOW, A modular three-dimensional finite difference ground-water flow model, U.S. Geological Survey, open-file report 83-875, Chapter A1.

NESPAK. 1983. Drainage and irrigation in shallow sweet water areas overlying saline water using radial collector wells. Technical Appraisal, NESPAK, limited, Lahore, Pakistan: 7-35.

Pollock, D.W. 1988. Semianalytical computation of path lines for finite difference models. Ground Water (26) 6, 743-750.

Pollock, D. W. 1989. MODPATH (version 1. x) - Documentation of computer programs to compute and display path lines using results from the U.S. Geological survey modular three-dimensional finite-difference ground-water model. U.S. Geological Survey Open-file report 89-381.

Pollock, D. W. 1994. User's guide for MODPATH/MODPATH-PLOT, version 3: A Particle tracking post-processing package for MODFLOW the U. S. Geological Survey finite-difference ground-water flow model. Reston, VA. U.S.Geo. Survey.

Punjab Agriculture Department, 2009, Directorate of Agriculture Crop Reporting Service. Lahore, Pakistan.

Qureshi, A. S., McCornick, P. G., Qadir, M., and Aslam, Z. 2008. Managing salinity and water logging in the Indus Basin of Pakistan. Journal of Agricultural Water Management 95 (2008) 1-10.

Qureshi, R. H., and Barrett-Lennard, E. G. 1998. Saline Agriculture for Irrigated Land in Pakistan: A handbook. Australian Center for International Agricultural Research, ACIAR, Canberra, Australia.

Reilly, T.E. and A.S. Goodman. 1987. Analysis of saltwater upconing beneath a pumping well. Journal of Hydrology 89: 169-204.

Zheng, C. 1990. MT3D, a modular three-dimensional transport model, S.S. Papadopoulos and Associates, Inc., Rockville, Maryland.

APPENDIX 1

Modflow-Mt3d Groundwater Modeling System

One of the recommended modeling protocols is the selection of a computer program that contains the verified governing equations representing the physical processes occurring in porous media and the verified code generating the solution for the mathematical model comprised of governing equations. Processing MODFLOW for Windows (PMWIN) provides a complete simulation system for modeling groundwater flow, solute transport, particle tracking, and parameter estimation processes using the following codes:

- A Modular Three-Dimensional Finite-Difference Groundwater Flow Model MODFLOW of the United States Geological Survey;
- A Modular Three-Dimensional Transport Model-MT3D;
- Particle Tracking with PMPATH for Windows

or MODPATH ; and

- Parameter Estimation Program-PEST.

Only MODFLOW and MT3D capabilities of PMWIN were used in the present study. MODFLOW-MT3D is the most popular and widely used public-domain groundwater flow and solute transport simulation modeling system. The code is written in FORTRAN language and structured into a main program and a series of independent subroutines grouped as a module/package to deal with specific features of the hydrologic system. The code solves the block-centered finite difference approximation of the partial differential equations (PDE) combined with specified initial and boundary conditions.

PMWIN is a simulation system for modeling groundwater flow with the modular three dimensional finite-difference groundwater model MODFLOW of the U. S. Geological Survey (McDonald and Harbugh, 1988), the particle tracking model PMPATH for Windows (Chiang, 1994) or MODPATH (Pollock, 1988, 1989, 1994), the solute transport model MT3D (Zheng, 1990) and the parameter estimation programme PEST (Doherty et al., 1994). The capabilities of MODFLOW include simulation processes representing types of layers as confined, unconfined, and/or a combination of the two; external stresses, such as wells (Well Package), streams (River Packages), drains (Drain Package), areal recharge (Recharge Package), and areal loss from the water table (Evapotranspiration Package) ; and boundary conditions of specified head, specified flux, and head dependent flux (General Head Boundary Package). The finite difference solution methods provided are iterative Strongly Implicit Procedure (SIP) and Slice-Successive Over Relaxation (SOR). The flexibility and modularity of the MODFLOW program encouraged adding relevant new packages. PMWIN includes some new stress and solver packages such as stream flow routing, reservoir, preconditioned conjugate gradient 2 (PCG2) solver, etc. The processes are represented in the form of independent packages allowing the examination of the effects of various stresses, one by one. For the present study, stress packages used are Well and Recharge while newly added PCG2 solver package is utilized for numerical solutions.

Governing Equations

The groundwater numerical model is based on two partial differential equations, which govern three dimensional flow and solute transport due to advection and dispersion phenomena.

Flow Equation

The three-dimensional movement of groundwater of constant density through the porous media may be described by the following partial-differential equation (McDonald and Harbugh, 1988) :

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

Where K is the hydraulic conductivity (L/T) ; h is the potentiometric head (L) ; W is the volumetric flux per unit volume and represents sources or sinks of water (1/T) ; S_S is the specific storage of the porous material (1/L) ; t is the time (T) ; and x, y, z are the Cartesian coordinates aligned along the major axes of hydraulic conductivity K_{xx}, K_{yy}, K_{zz}, respectively.

Solute Transport Equation

The partial differential equation describing the three-dimensional transport of contaminants in groundwater can be written as follows (Zheng, 1990):

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(v_iC)+\frac{q_s}{\theta}C_s+\sum_{k=1}^{N}R_k$$

Where C is the concentration of contaminants dissolved in groundwater, M/L^3 ; t is the time, T ; xi is the distance along the respective Cartesian coordinate axis, L ; D_{ij} is the hydrodynamic dispersion coefficient, L^2/T ; n_i is the seepage or linear pore water velocity, L/T ; q_s is the volumetric flux of water per unit volume of aquifer sources (+) and sinks (−), 1/T ; Cs is the concentration of the sources or sinks, M/L^3 ; q is the porosity of the porous medium dimensionless; and Rk is the chemical reaction term, M/L^3T^{-1}.

Model Input Data Requirements

Physical and Hydraulic Parameters

In order to make simulations, model needs physical dimensions of the domain to be modeled (length, width and thickness of the aquifer). The required hydraulic properties include horizontal and vertical hydraulic conductivities, specific yield, and coefficient of storage, specific storage, effective porosity and transmissivity. Initial hydraulic heads, wells locations and depths with their pumping capacities and recharge flux are also needed to run the model.

Solute Transport Parameters

The required input data on solute transport include Advective and Dispersive solute transport parameters. Mainly these parameters are longitudinal dispersivity, horizontal transverse dispersivity, vertical transverse dispersivity and effective molecular diffusion coefficient.

Model Input Data File Preparation

The model needs a properly developed input data file for making simulations. The steps involved in the preparation of input data file are discussed below.

Creation of Grid

The model does not handle whole aquifer system as a single unit. Therefore, in the model, a discretized domain consisting of an array of nodes and associated finite difference cells replaces an aquifer system. Fig. 1 shows a spatial discretization of an aquifer system with a mesh of cells and nodes at which concentration and hydraulic heads are calculated. The number of rows, columns and layers are given to the model. The thickness of each model layer and the width of each column and row may be variable. The location of cells is described in terms of columns, row and layers. The notation used for rows, columns, and layers are i, j and k, respectively.

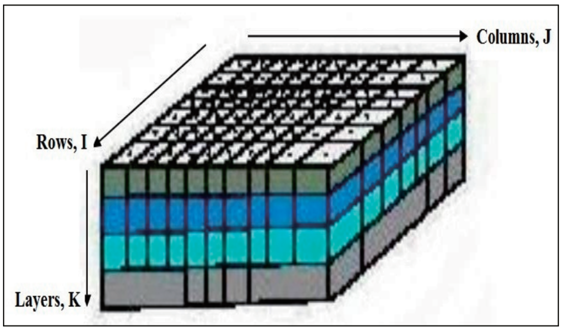

Fig. 1. Three-Dimensional View of a discritized schematic aquifer system.

Defining Layer Type

The type of layer, confined or unconfined is selected. There are different types of layers for which a code (0, 1, 2, and 3) is chosen depending on the field situation. The description of codes is given below:

- "0" means the layer is strictly confined. For transient simulations, the confined storage coefficient (specific storage x layer thickness) is used to calculate the rate of change in storage. Tranmissivity of each cell is constant throughout the simulations;
- "1" means that the layer is strictly unconfined. The option is valid for the first layer only. Specific yield is used to calculate the rate of change in storage for this layer type. During a flow simulation, transmissivity of each cell varies with the saturated thickness of the aquifer;
- "2" means that the layer is partially convertible between confined and unconfined. Confined storage coefficient is used to calculate the rate of change in storage, if the layer is initially fully saturated. Otherwise, specific yield will be used to calculate the rate of change in storage. Transmissivity of each cell is constant throughout the simulation. Leakance from the above layer is limited if the layer de-saturates; and
- "3" means that the layer is fully convertible between confined and unconfined. Confined storage coefficient is used to calculate the rate

of change in storage, if the layer is initially fully saturated. Otherwise, specific yield will be used to calculate the rate of change in storage. During a flow simulation, transmissivity of each cell varies with the saturated thickness of the aquifer. Leakance from the above layer is limited if the layer de-saturates.

Elevation of Top and Bottom Layers

The elevation of the top and bottom of the layers is provided to the model. These elevations are used to calculate the transmissivity.

Boundary Conditions

The domain is defined by external boundaries and the condition of these boundaries is specified to obtain unique solution for the problem under consideration. There are two types of boundary arrays given to the model:

(1) An IBOUND array is required by MODFLOW (flow model). This array contains a code for each cell that indicates:

- Hydraulic head is computed (active cell or variable head cell) : code = 1 ; or
- Hydraulic head is kept fixed at a given value (constant head cell or time variant specified head cell) : code = −1 ; or
- No flow takes place within the cell (inactive cell) : code = 0.

(2) An ICBUND array is required by MT3D (solute transport model). This array uses the same codes as IBOUND array, for concentration at boundary cells.

- Concentration is calculated (active concentration cell or variable concentration cell) : code = 1 ; or
- Concentration is kept fixed at a given value (constant concentration cell or time variant specified concentration cell) : code = −1 ; or
- No transport simulation takes place within the cell (inactive concentration cell) : code = 0.

Initial Conditions

The values of variables, usually taken at $t = 0$, at all points within the domain are known as initial values. The conditions that describe these values are called initial conditions. In the steady state simulation, the initial values are starting values for the iterative equation solver. Hydraulic heads and concentrations at $t = 0$ are given to the model which are required to start the simulation.

Horizontal and Vertical Hydraulic Conductivity

Horizontal and Vertical hydraulic conductivity is assigned to all the layers of model domain. Transmissivity of the layer is calculated by using hydraulic conductivity and layer thickness by model itself. The units used in the model are m/day.

Storage coefficient

In a confined layer, the storage term is given by storativity or confined storage coefficient (= specific storage [1/L] × layer thickness [L]). The storativity is a function of the compressibility of the water and the elastic property of the soil matrix. Layers of type 0, 2 and 3 require the confined storage coefficient. PMWIN uses specific storage and the layer thickness to calculate the confined storage coefficient, if the corresponding Storage Coefficient flag in the Layer Options dialog is calculated. By setting the Storage Coefficient flag to User Specified and choosing Storage Coefficient from the Parameters menu, confined storage coefficient can be directly specified.

Specific storage

The specific storage or specific storativity is defined as the volume of water that a unit column of aquifer releases from storage under a unit decline in hydraulic head. The values of specific storage are needed for all layers to simulate water flow by MODFLOW.

Specific yield

In a phreatic (an unconfined) layer, the storage term is given by specific yield or drainable porosity. Specific yield is defined as the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table. Specific yield is a function of porosity (and is not necessarily equal to porosity), because a certain amount of water is held in the solid matrix and cannot be removed by gravity drainage. Specific yield is required for layers of type 1, 2 and 3.

Effective Porosity

Effective porosity provided to the all layers is used to calculate the average velocity of the flow through porous medium.

Transmissivity

The model needs the tranmissivity value. The transmissivity is set to be calculated while defining the layer type. The model calculates transmissivity value for each layer by using specified horizontal hydraulic conductivity and the top and bottom of each layer.

Capacity and Depth of Well

In the model, water well is represented under the Well package in the Packages menu. Data Editor is used to specify the discharge (m^3/day) by assigning the negative cell value. The discharge rate of a well is constant during a given stress period and the discharge rate for each layer has to be specified. As the discharge rate for each layer is approximately calculated by dividing the total discharge rate in proportion to the transmissivity values of each layer.

Advective Solute Transport Parameter

The solute movement due to advection for a given time step is simulated by the MT3D using the corresponding velocity computed by the MODFLOW (flow model).

Dispersive Solute Transport Parameters

The following values are specified for each layer in the Dispersion Package (MT3D).

- The ratio of horizontal transverse dispersivity to the longitudinal dispersivity;
- The ratio of vertical transverse dispersivity to the longitudinal dispersivity; and
- The effective molecular diffusion coefficient.

Simulation Time

The simulation time is divided into one Stress Period, which is further divided into different time steps for different scenarios. The length of a time step used for a head solution is usually large. Therefore, in the MT3D, each time step is further divided into smaller time increments, called Transport Steps by an automatic time step size control procedure in MT3D. The steady state flow type is also assigned to model for simulation.

Model Output

MODFLOW Output

The output data obtained by running MODFLOW for the present study are described below.

Hydraulic Heads

The hydraulic heads are the primary result of a MODFLOW simulation. Hydraulic heads in each finite-difference cell are saved in the unformatted (binary) file HEADS.DAT.

Drawdowns

Drawdowns are the differences between the initial hydraulic heads and the calculated hydraulic heads. Drawdowns in each cell are saved in the unformatted (binary) file DDOWN. DAT.

Interface file to MT3D

This is an unformatted (binary) file containing the computed heads, fluxes across cell interfaces in all directions and locations and flow rates of the various sinks/sources. The interface file is created by the LKMT package provided by MT3D. There are three versions of the LKMT package, which are incorporated in the versions of MODFLOW contained in the PMWIN.

To check the simulation results, MODFLOW calculates a volumetric water budget for the entire model at the end of each time step, and saves the results in the simulation record file OUTPUT. DAT. A water budget provides an indication of the overall acceptability of the numerical solution. In numerical solution techniques, the system of equations solved by a model actually consists of a flow continuity statement for each model cell. Continuity should therefore also exist for the total flows into and out of the entire model or a sub-region. This means that the difference between total inflow and total outflow should equal the total change in storage.

MT3D Output

The MT3D transport model calculates *salinity concentration of groundwater and pumped water*. The calculated concentration values are saved in the unformatted binary file MT3D. UCN. In addition, the mass contained in each cell is saved in the unformatted binary file MT3D.CBM. All output files are located in the same folder containing the model.

地下水シミュレーションモデルによるパキスタン・パンジャブ地方におけるスキミング井戸有効性の検証

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要　約

本研究では、パキスタンパンジャブ州レチナドアブ地域を対象として、スキミング井戸の有効性をMODFLOW-MT3D 地下水モデルを用いたシュミレーションにより検証した。現地データを用いてモデルのキャリブレーションと再現性の検証を行った後、シナリオ分析を行い最適な井戸管理方法の摘出を試みた。結果として、対象地域で地下水を使用するには4-ストレイナー井戸を淡水層30メートルに対する井戸侵入率（Pw）を30-40%の深さで設置し、揚水量を毎分340-850リットルで一日４－８時間稼働させることを提案した。この条件下においては、地下塩水の上昇を抑えるとともに揚水の塩分濃度を1,500 ppm以下に制御できることが明らかとなった。

キーワード：スキミング井戸、地下水モデル、パキスタン　パンジャブ州、塩水上昇、塩害