Numerical Experimentation to Develop Design and Operational Parameters for Skimming Wells: A Case Study of the Chaj Doab of Punjab, Pakistan

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ABSTRACT

In the present study, MODFLOW-MT3D groundwater model was employed to perform numerical experimentation to develop design and operational parameters for SW (Skimming Wells) based on hydrogeology and groundwater salinity conditions of Chaj Doab, Punjab, Pakistan.

Numerical experimentation resulted in: (i) a 1-strainer SW with discharge of 14 l/s (litres per second) and penetration of 30% resulted in more saltwater upconing at 8 hours/day well operation compared to that occurred at 4 hours/day operation; (ii) a 1-strainer well with penetration of 30% and operation of 8 hours/day caused higher saltwater upconing at 14 l/s discharge compared to that at 9 l/s discharge; (iii) a 4-strainer well with penetration of 30% and operation of 8 hours/day also caused more saltwater upconing at 14 l/s well discharge compared to that at 9 l/s discharge. Similar trend was found for a 8-strainer well; and (iv) 1- or 4- or 8-strainer well with 30-60% penetration, 9-14 l/s discharge and 4-8 hours/day operation could provide pumped groundwater of salinity less than 1000 ppm.

Considering hydro-chemical performance and costs of wells, a 4-strainer well with 30% penetration, 9-14 l/s discharge and 4-8 hours/day operation is recommended to skim groundwater of salinity less than 1000 ppm in Chaj Doab of Punjab, Pakistan.

Key Words: **Skimming Wells, MODFLOW-MT3D Groundwater Model, Saltwater Upconing, Chaj Doab's Aquifer, Pakistan's Punjab.**

1. INTRODUCTION

SW with discharge rates of less than 28 l/s play an important role in abstracting shallow fresh groundwater overlying deep saline groundwater [1]. However, proper well design and operational strategy are vital to obtain good quality groundwater through skimming wells on long-term sustainable basis [2-4]. A comprehensive insight into saltwater upconing; SWU (the vertical upward movement of saltwater in the form of a cone or mound from the saline water zone into fresh water zone in response to pumping freshwater from the aquifer) provides basis to establish proper well design and operational strategy for SW.

Numerical groundwater models are invaluable simulation and predictive tools to gain deep insight into saltwater upconing [5] thereby to develop well design and operational parameters of skimming wells to pump good quality water on long-term sustainable basis. For the present study, the groundwater modeling system, MODFLOW-MT3D was used for simulation and

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evaluation of SWU and SW design and operational parameters for better performance of SW. The main objectives of the present study were to:

- Conduct numerical experimentation employing the MODFLOW-MT3D groundwater model on SWU and salinity of pumped water by SW under different design and operational parameters.
- Recommend design and operational strategies for SW to abstract good quality groundwater on long-term sustainable basis in the Chaj Doab of Punjab, Pakistan.

2. MATERIALS AND METHODS

In the present study, MODFLOW-MT3D numerical model was employed to simulate and evaluate SWU and different design and operational parameters for SW through numerical experimentation using the hydrogeological and groundwater salinity conditions prevalent in the Chaj Doab of Punjab, Pakistan. The recommendations on skimming well design and operational strategies to obtain better quality groundwater on long-term sustainable basis in the Chaj Doab of Punjab, Pakistan were based on the results of numerical experimentation.

2.1 MODFLOW-MT3D Groundwater Numerical Model

MODFLOW of US Geological Survey [6-9] and solute transport model MT3D [10-12] was used in the present study. The FORTRAN code is structured into a main program and various independent subroutines. The code solves groundwater flow and solute transport equations using finite difference numerical technique.

2.2 Study Area Description

The present groundwater modeling study on skimming wells was carried out in the Chaj Doab of Punjab, Pakistan. The Chaj Doab lying between the Jhelum and Chenab Rivers **(Fig. 1)** has gross command area of 0.89 Mha (Million Hectares) and CCA (Culturable Command Area) of 0.86 Mha. About 4.4 BMC (Billion Cubic Meters) of irrigation water are provided by irrigation canals. Groundwater pumping contributes about 4.9 BCM to irrigation water supplies to the CCA of Chaj Doab [13].

2.2.1 Physical and Hydraulic Characteristics of Chaj Doab Aquifer

The Chaj Doab area is underlain by a highly transmissive unconfined alluvial aquifer having average thickness of 300m. Hydraulic conductivity ranges from 37-121 m/day with average value of 73 m/day. Transmissivity varies from 2411-7380 m^2/day with average value of 3102 m^2/day. Specific yield varies from 4-39% with average value of 20% [13]. In the Chaj Doab area, depth to water table ranges from 0.2 to more than 15m [13].

2.2.2 Chemical Characteristics of Chaj Doab Aquifer

Aquifer salinity increases with depth reflecting a vertical salinity gradient in the aquifer [12]. The salinity of groundwater up to 100m depth across the Chaj Doab is given in Table 1 [14]. In larger area lying near the rivers and irrigation canals, groundwater salinity ranges from 0-1000 ppm. In considerable area lying in the central and lower parts of the Doab, groundwater salinity ranges from 1000-3000 ppm and also is more than 3000 ppm.

FIG. 1. LOCATION MAP OF THE CHAJ DOAB OF PUNJAB, PAKISTAN

3. NUMERICAL EXPERIMENTATION ON SWU AND SW

3.1 Model Development

In the present study, considering the typical hydro-geological and groundwater salinity conditions of the Chaj Doab of Punjab, Pakistan, model input data used is given in Table 2.

The groundwater salinity at different aquifer depths (layers) used to derive initial groundwater salinity for the model is given in Table 3 [15].

The initial groundwater salinity at different aquifer depths (layers) used as input in model is given in Table 4.

The present study is a local scale study for which the model domain consisted of 300x300x61m using the typical hydro-geological and groundwater salinity conditions of the Chaj Doab. 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 30m dimension. The discretized domain had 27 rows and 27 columns for a total of 729 grid cells. The aquifer thickness of 61m 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, 3, 3, 2, 5, 7.5, 8, 6, 8 and 16m, respectively. For the domain, 625 cells were designated as active cells, where heads can vary dynamically (Fig. 2).

3.1.1 Initial and Boundary Conditions

To make simulations, model needs initial hydraulic heads, wells locations and depths with their pumping capacities and recharge flux in addition to physical dimensions of the domain to be modeled (length, width and thickness of the aquifer (Table 2) and hydraulic properties (horizontal and vertical hydraulic conductivities, specific yield, coefficient of storage, specific storage, effective porosity and transmissivity (Table 2). In the present study, considering the aquifer thickness of 61m and depth to water table of 1.5m, 59.5m served as the initial head distribution for the model (Table 2). The cells, surrounding the model domain represented constant head boundary where hydraulic head was constant throughout simulations (Fig. 2). The average groundwater recharge (areal recharge flux) from all sources was considered equal to 0.00111 m/day.

TABLE 2. MODEL INPUT DATA USED FOR CHAJ DOAB.

Model Domain	300x300 m
# rows	27
# columns	27
# layers	10
Aquifer thickness	61m
Horizontal Hydraulic Conductivity	45 m/day
Vertical Hydraulic Conductivity	0.9 m/day
Specific yield	0.20
Effective Porosity	0.20
Specific Storage	0.0000033 m^{-1}
Depth to Water Table	1.5 m
Initial Hydraulic Head	59.5 m
Longitudinal Dispersivity	1.5 m
Transverse Dispersivity	0.45 m
Simulation Period	4 years

TABLE 3. GROUNDWATER SALINITY AT DIFFERENT AQUIFER DEPTHS IN CHAJ DOAB.

Aquifer Layer Thickness (m)	Salinity (ppm)
23 (first layer)	358
8 (second layer)	3320
6 (third layer)	5120
24 (fourth layer)	7680

TABLE 1. GROUNDWATER SALINITY IN TOP 100M DEPTH OF CHAJ DOAB'S AQUIFER.

Groundwater Salinity	0-1000(ppm)	1000-1500(ppm)	1500-3000(ppm)	> 3000(ppm)
Area (%)	63	10	9	18

Initial groundwater salinity values and salinity of recharging water in addition to solute transport parameters (longitudinal dispersivity, and transverse dispersivity given in Table 2, vertical transverse dispersivity and effective molecular diffusion coefficient were also required to run the model. In the present study, groundwater salinity at different aquifer depths (layers) is given in Table 4 served as initial salinity concentration in the model domain layers. The concentration of areal recharge flux was 300 ppm for the present model study.

TABLE 4. INITIAL GW SALINITY AT DIFFERENT AQUIFER DEPTHS (LAYERS) USED AS MODEL INPUT.

Layer Number	Layer Thickness (m)	Salinity (ppm)
1	2.5	358
2	3	358
3	3	358
4	2	358
5	5	358
6	7.5	358
7	8	3320
8	6	5120
9	8	7680
10	16	7680

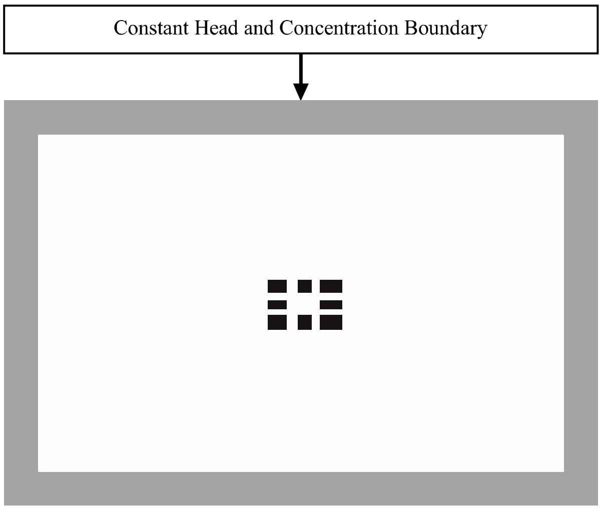

FIG. 2. MODEL GRID LAYOUT FOR THE CHAJ DOAB (WHITE COLOR SHOWS ACTIVE CELLS, LIGHT BLUE COLOR SHOWS INACTIVE CELLS AND BLACK COLOR SHOWS LOCATION OF WELLS

3.1.2 Well Parameters

In the present study, 1-, 4-, and 8-strainer wells were considered for groundwater abstractions. These wells below water table were penetrated to 30 and 60% of fresh water layer thickness of 23m out of total aquifer thickness of 61m and were operated for 4 and 8 hours/day at pumping rates of 9 and 14l/s. To identify the cell location of the well, termed as pumping cell on the model grid, well screens were located in the second and third layers for 30% well penetration and in the second, third, fourth and fifth layers for 60% well penetration of the model grid in accordance with well depth of 7 and 14m, screens spacing of 4.5m for 4-, and 8-strainer wells and well discharge of 9 and 14 l/s.As discharge rate has to be specified for each of layers in which well is penetrated, discharge for each well layer was calculated by dividing the total well discharge in proportion to the thickness of each layer relative to total depth of well penetration.

3.2 Simulation Scenarios

Eight different scenarios (**Table 5**) for each of 1-, 4-, and 8-strainer wells were simulated for the Chaj Doab for evaluation of effect of Pw (Well Penetration Depth), Qw (Well Discharge) and Tw (Well Operational Time) on the saltwater upconing and salinity of pumped water.

TABLE 5. DIFFERENT SIMULATION SCENARIOS FOR SKIMMING WELLS IN CHAJ DOAB

Scenario #	Well Penetration Depth (Pw) (%)	Well Discharge (Qw) (l/s)	Operational Time (Tw) (hours/day)
1	30	14	4
2	30	14	8
3	30	9	4
4	30	9	8
5	60	14	4
6	60	14	8
7	60	9	4
8	60	9	8

Pw = Well Penetration Depth (%) = (Well depth in fresh water layer/total thickness of fresh water layer)x 100; Qw = Well Discharge (litres/second, l/s); Tw = Well Operational Time (hours/day)

3.3 Modeling Saltwater Upconing Phenomenon under a Pumping Well

The comprehension of saltwater upconing, which is the vertical upward movement of salt water in the form of a cone or mound from the saline water zone into fresh water zone in response to pumping fresh water from the aquifer as shown in **Fig. 3** [16] is essential to establish the design and operational criteria for skimming wells. The phenomenon of salt water upconing is studied by two approaches, namely; (i) immiscible fluids (sharp interface between fresh and saline waters) approach and (ii) miscible fluids approach (which assumes a continuous gradation of salinity from the salt water to the fresh water due to hydrodynamic dispersion). Under this approach, fresh water and salt water are miscible fluids and solute dispersion (refers to mixing and spreading of solutes caused partly by molecular diffusion and partly by variation in velocity within the porous medium) causes mixing and a transition zone exists in which salinity concentration changes gradually from salt water to fresh water.

In the present study, miscible fluids approach was used to investigate saltwater upconing beneath a pumping well

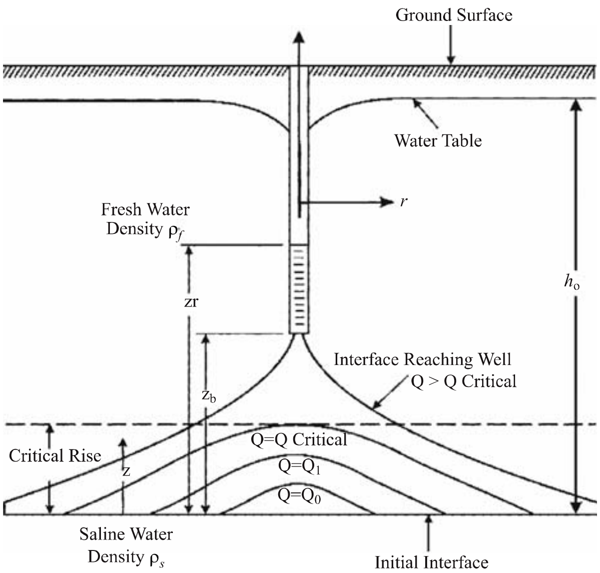

FIG. 3. SALTWATER UPCONING BENEATH A PUMPING WELL [13]

by employing MODFLOW-MT3D groundwater modeling system. In the model based on miscible approach, partial differential equations governing groundwater flow and solute transport through porous media are solved by numerical techniques to analyze saline water upconing.

3.4 Results of Saltwater Upconing Experimentation

Interpretation of Model Simulation Results for Saltwater Upconing Determination: In the present study, the interface was taken as the depth at which groundwater salinity in the aquifer was equal to 3320 ppm (the interface criteria) and all references to the interface in the present study corresponded to groundwater salinity of 3320 ppm. On this basis, the fresh water layer thickness was determined to be 23m out of total aquifer thickness of 61m (Table 4).

The bottom of the aquifer layer (Table 4) containing groundwater salinity of 3320 ppm is taken as datum showing zero elevation of interface thereby showing original (initial) position of interface prior to pumping by well. The model salinity simulated values between the datum and the bottom of the pumping well (bottom of well cell) are interpreted to locate interface (salinity value of 3320 ppm) by plotting these salinity values against their elevations from datum). The elevation of 3320 ppm salinity values after certain period of puming by a well of a certain pumping capacity denotes rise in interface, which in turn represents the salt water upconing beneath the pumping well. The composite salinity of pumping cells is considered as salinity of pumped water by a well.

Fig. 4 shows a comparison of elevation of (rise in) the saline-fresh water interface (salt water upconing) for a single strainer well operated for 4 years at 4 and 8 hours/day at the same Qw of 14 l/s and Pw of 30%. At the end of year 4, interface rose to 13 and 8m from its original position for Tw of 8 and 4 hours/day, respectively. Clearly, higher Tw of 8 hours/day for the same well caused significant salt water upconing.

Keeping the same operational time of 8 hours/day and well penetration of 30% but changing well discharge from 9-14 l/s revealed that 14/l discharge causes considerably more saltwater upconing compared to 9 l/s.

The impact of an increase in the Qw from 9-14 l/s for the same Tw of 8 hours/day and Pw of 30% on the elevation of (rise in) interface (saltwater upconing) for a 4-strainer well operated for 4 years was also simulated. The rise in interface was 7 and 12m for Qw of 9 and 14 l/s, respectively. It indicated that higher discharge (14 l/s) caused higher saltwater upconing compared to lower discharge (9 l/s).

Fig. 5 depicts the impact of an increase in the Qw from 9-14 l/s for the same Tw of 8 hours/day and Pw of 30% on the elevation of (rise in) interface (salt water upconing) for a 8-strainer well operated for 4 years. The rise in interface is 7 and 12m for Qw of 9 and 14 l/s, respectively. This also indicated higher saltwater upconing at 14 l/s compared to 9 l/s well discharge.

3.5 Results of Pumped Water Salinity Experimentation

For Pw of 30%, the operation of single-strainer well with Qw of 9 and 14 l/s for Tw of 4 and 8 hours/day results in pumped water salinity of 441, 472, 461, and 537 ppm., respectively (Fig. 6). Similar to previous numerical studies on pumping-induced upconing and pumped water salinity [2-3,17-18], the numerical results show that with increase in Qw from 9-14 l/s, for the same Tw, say 4 or 8 hours/day, salinity of well water also increases. Similar case is with increase in Tw from 4-8 hours/day. The overall finding is that for the given hydro-geological and groundwater salinity conditions of the study area, a single-strainer well with Pw of 30% of fresh water layer thickness (23m), could be operated safely with Qw of 9 and 14 l/s for Tw of 4-8 hours/day to obtain good quality (salinity less than 1000 ppm) well water on sustainable basis.

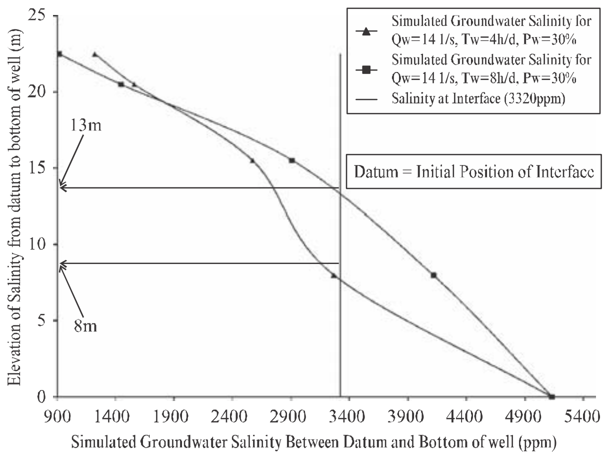

FIG. 4. ELEVATION OF INTERFACE AT THE END OF YEAR 4 FOR A SINGLE STRAINER WELL WITH QW OF 14 L/S, TW OF 4 AND 8 HOURS/DAY AND PW OF 30%

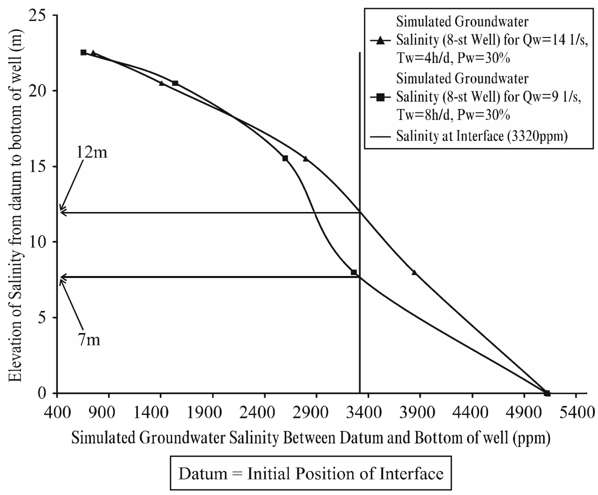

FIG. 5.ELEVATION OF INTERFACE AT THE END OF YEAR 4 FOR AN 8-STRAINER WELL WITH QW OF 14 AND 9 L/S, TW OF 8 HOURS/DAY AND PW OF 30%

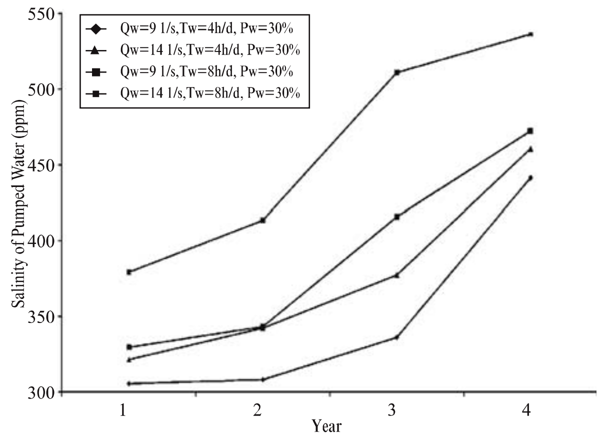

FIG. 6. FOUR- YEAR SIMULATED SALINITY OF PUMPED WATER FOR QW OF 9 AND 14 L/S, TW OF 4 AND 8 HOURS/ DAY AND PW OF 30%

For a single-strainer well with Pw of 60%, at the end of year 4, salinity of well water for Qw of 9 l/s operated for Tw of 4 and 8 hours/day is 727 and 985 ppm, respectively (Fig. 7). The salinity of well water is 845 and 1095 ppm for the same well when operated for Qw 14 l/s at Tw of 4 and 8 hours/day, respectively (Fig. 7). Clearly, at 60% Pw, the salinity of pumped water has increased for the same Qw and Tw, compared to Pw of 30% (Fig. 7) but, still, well is pumping water of reasonable salinity (1095 ppm). It reflects that even at 60% Pw well could be operated safely with Qw of 9 and 14 l/s for 4-8 hours/day.

Fig. 8 reveals the simulated salinity of well water salinity for a 4-strainer well with Pw of 30%, Qw 9 and 14 l/s and Tw of 4 and 8 hours/day. The well water salinity was 419 and 483 ppm for Qw of 9 l/s and Tw of 4 and 8 hours/day, respectively, whereas it was 448 and 536 ppm, when the same well was operated at 14 l/s for 4 and 8 hours/day, respectively. Clearly, higher Qw of 14 l/s and higher Tw of 8 hours/day caused increase in pumped water salinity compared to low Qw of 9 l/s and low Tw of 4 hours/day. The overall finding is that at Pw of 30%, 4-strainer well could be operated safely at 9 and 14 l/s for 4 and 8 hours/day.

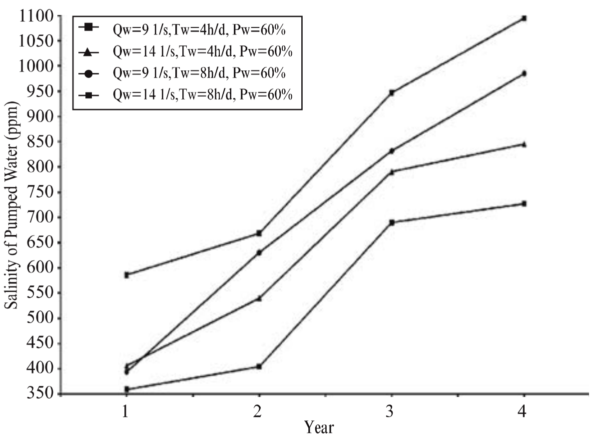

FIG. 7. FOUR-YEAR SIMULATED SALINITY OF PUMPED WATER FOR QW OF 9 AND 14 L/S), TW OF 4 AND 8 HOURS/DAY AND PW 60%

For a 4-strainer well with Pw of 60% and Qw of 9 l/s, well water salinity was 695 and 915 ppm for Tw of 4 and 8 hours/day, respectively (Fig. 9). The well water salinity was 805 and 945ppm when the same well was operated at Qw of 14 l/s for the Tw of 4 and 8 hours/day, respectively (Fig.9). Clearly, these values are higher compared to those obtained at Pw of 30% for the same well for the same Qw and Tw. But still, the 4-strainer well at Pw of 60% pumps water of reasonable salinity (<1000ppm) for Qw of 9 and 14 l/s for 4 and 8 hours per day well operation. It reflects that a 4-strainer well with Pw of 60% and operating at 9 and 14 l/s for 4 and 8 hours/day could pump better quality water.

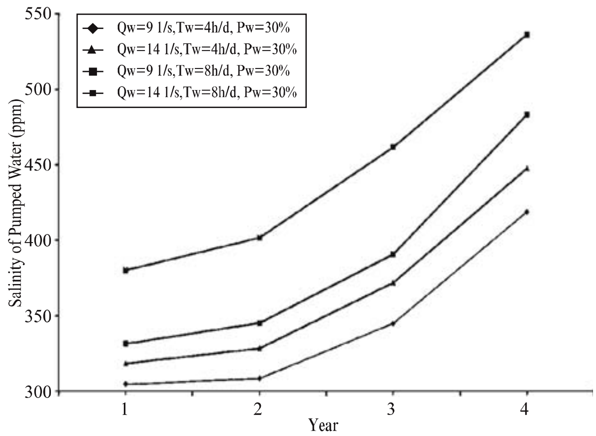

FIG. 8. FOUR-YEAR SIMULATED SALINITY OF PUMPED WATER FOR QW OF 9 AND 14 L/S, TW OF 4 AND 8 HOURS/DAY AND PW OF 30%

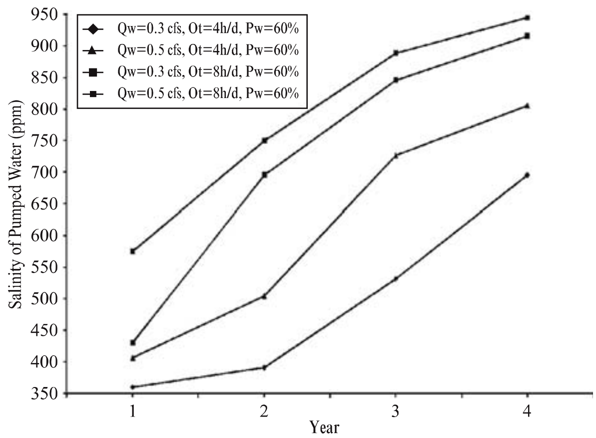

FIG. 9. FOUR-YEAR SIMULATED SALINITY OF PUMPED WATER FOR QW OF 9 AND 14 L/S, TW OF 4 AND 8 HOURS/DAY AND PW OF 60%

Fig. 10 depicts simulated groundwater salinity of an 8-strainer well with Pw of 30% and Qw of 9 and 14 l/s for Tw of 4 and 8 hours/day. The salinity of pumped water was 416 and 470 ppm when well was operated at Qw of 9 l/s for 4 and 8 hours/day, respectively. When the same well was operated at Qw of 14 l/s for Tw of 4 and 8 hours/day, salinity of well water was 445 and 502 ppm, respectively. The overall finding is that 8-strainer well with Pw of 30% and Qw of 9 and 14 l/s for 4 and 8 hours/day could provide good quality water.

For an 8-strainer well with Pw of 60% and Qw of 9 l/s, simulated salinity of well water was 770 and 1010 ppm for Tw of 4 and 8 hours/day, respectively (Fig. 11). The salinity of pumped water was 882 and 1050 ppm when the same well was operated at Qw of 14 l/s for 4 and 8 hours/day, respectively (Fig. 11). Though these salinity values are higher than those obtained at Pw of 30 (Fig. 10) for the same Qw and Tw, still at Pw of 60%, an 8-strainer well could deliver water of reasonable quality on long-term sustainable basis.

4. CONCLUSIONS

In the present study, MODFLOW-MT3D groundwater model was employed to perform numerical experimentation to develop design and operational parameters for skimming wells based on hydrogeology and groundwater salinity conditions of Chaj Doab, Punjab, Pakistan.Numerical experimentation resulted in:

(i) A 1-strainer skimming well with discharge of 14 l/s, penetration of 30% and operation of 4 and 8 hours/day caused 8 and 13m rise in saline-fresh groundwater interface, respectively reflecting more saltwater upconing at 8 hours/day operation.

(ii) A 1-strainer well with penetration of 30%, discharges of 9 and 14 l/s and operation of 8 hours/day caused 8 and 13m rise in interface, respectively indicating higher saltwater upconing at 14 l/s discharge.

(iii) 4- and 8-strainer wells both with discharge of 9 and 14 l/s, operation of 8 hours/day and penetration of 30%, caused 7m interface rise for 9 l/s and 12m for 14 l/s discharge indicating higher saltwater upconing at 14 l/s discharge in both wells.

(iv) 1- or 4- or 8-strainer well with 30-60% penetration and 9-14 l/s discharge could be pumped for 4-8 hours/day to obtain groundwater of salinity less than 1000 ppm.

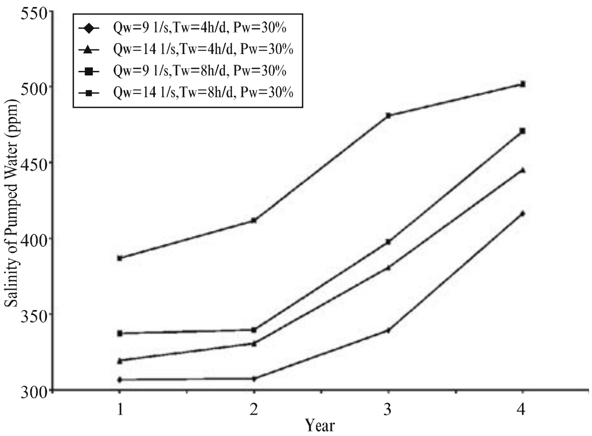

FIG. 10. FOUR-YEAR SIMULATED SALINITY OF PUMPED WATER FOR QW OF 9 AND 14 L/S, TW OF 4 AND 8 HOURS/ DAY AND PW OF 30%

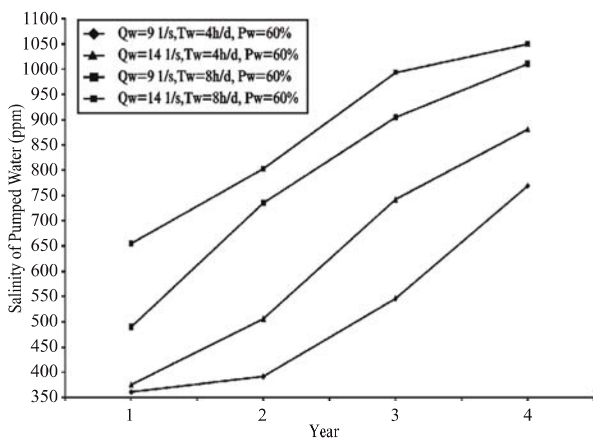

FIG. 11. FOUR-YEAR SIMULATED SALINITY OF PUMPED WATER FOR QW OF 9 AND 14 L/S, TW OF 4 AND 8 HOURS/ DAY AND PW OF 60%

5. RECOMMENDATIONS

(i) For the hydro-geological and groundwater salinity conditions of the Chaj Doab, 1- or 4- or 8-strainer well could be installed in 30-60% depth of the fresh water layer thickness of 20-30m and could be pumped at a well discharge of 9-14 l/s for 4-8 hours/day to obtain usable groundwater of salinity less than 1000 ppm.

(ii) Considering the hydro-chemical performance and cost aspects, a better option will be a 4-strainer well with well penetration of 30%, well discharge of 9-14 l/s and well operational time of 4-8 hours/day to skim the better quality water (salinity <1000 ppm) on long-term sustainable basis under the hydro-geological and groundwater salinity conditions of the Chaj Doab of Punjab, Pakistan.

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