HYDRO-SALINITY BEHAVIOR OF SHALLOW GROUNDWATER AQUIFER UNDERLAIN BY SALTY GROUNDWATER IN SINDH PAKISTAN

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ABSTRACT

In Pakistan, groundwater is the second largest source of irrigated agriculture. In Sindh province of Pakistan, fresh groundwater lenses are overlying saline groundwater. In order to pump fresh water, shallow skimming tubewells are being used in Sindh. Due to little awareness, the farmers are installing more traditional tubewells that penetrate into higher depths to extract more water without considering the upconning of saline water which deteriorates the quality of pumping groundwater.

This paper discusses the hydro-salinity behavior by applying a three-dimensional mass transfer MT3D model of MPWIN (Processing MODFLOW for Windows) which calibrates and validates the observed data and develops the operational strategies by testing various scenarios using simulated model by increasing duration and discharge of the tubewell pumpage.

Using the experimental setup at selected skimmimg tubewell in the command area of Kunner-II distributary, the spatial and temporal hydro-salinity data was observed. MT3D model was calibrated for simulated salinity profiles with the observed ones for the stress period of 4 hours; both values were achieved much closer to each other. The calibrated ratio of horizontal transverse dispersivity to longitudinal dispersivity, ratio of vertical transverse dispersivity to longitudinal dispersivity and effective molecular diffusion coefficient were found 0.009, 0.0003 and 0.1 respectively. The model was also validated which confirm that the simulated electrical conductivity (EC) values are in good agreement with the observed values having an average percentage error of less than 2.1%.

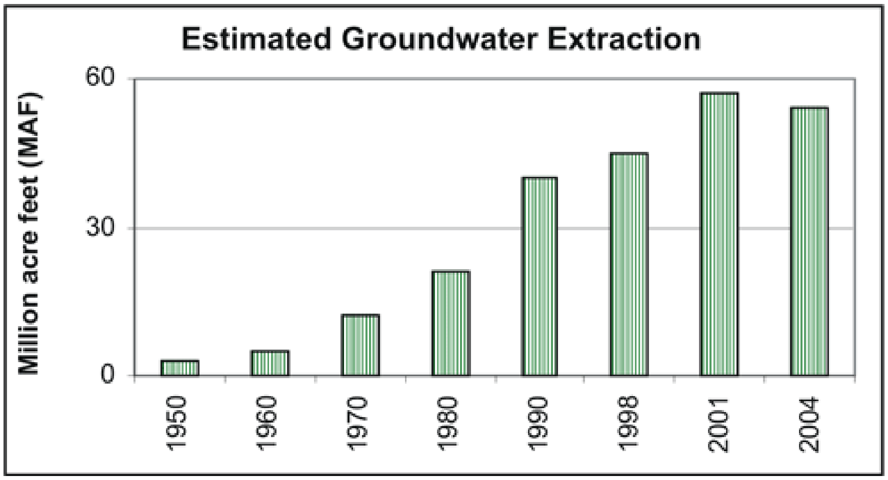
To establish operational management strategy, the calibrated model was tested to simulate salt contaminated groundwater values at different depths for increased discharge and durations. The results indicated that the quality of groundwater is deteriorating at different depths at the bottom of tubewell strainer (24.38 m depth) due to the continuous pumping. Thus, the study concluded that the tubewells should not run more than 12 hours on continuous basis.

Keywords: Hydro-salinity, MT3D Model, Skimming Wells, Upconing

1. INTRODUCTION

In most arid and semi arid irrigated areas of Pakistan, the increasing demand for food and fiber has resulted in increased cropping intensities and a change of cropping patterns. This change has tremendously increased water consumption by irrigated agriculture. This increased demand for water poses many challenges in the vast and developing region of the Indus basin in Pakistan, where the unconfined aquifer underlying the irrigated lands consists of a thin layer of freshwater overlying saline water. The change in cropping pattern and cropping intensity resulted in a gap between demand and supply of canal water. As a result, farmers started extracting groundwater for irrigation.

According to Wilkie and Fortuna [1], renewable water resources of Pakistan are 172 million acre-ft (MAF), whereas 145 MAF is the average inflow of all rivers below RIM (River Inflow Monitoring) stations and 114.4 MAF is allocated for the annual canal diversions to the four Provinces (WAA [2]). However, according to study conducted by Habib [3] on analysis of water demand and supply, the water shortage in agriculture varies from 10 MAF in wet years to 25 MAF in a dry year. After 1970s, groundwater extraction has played an important role in agriculture sustainability in the fresh groundwater zone. The temporal variation of estimated groundwater extraction is described in Fig. 1.



Source: Habib [3]

Fig. 1 Groundwater Extraction in the Indus Basin

In Sindh, Pakistan, farmers are mostly installing skimming wells that are partially penetrating in relatively-fresh groundwater aquifer which are overlying on highly saline groundwater aquifer lenses. The well discharge rate exceeds the critical discharge rate, it disturbs the interface (i.e. the equilibrium between fresh and salty groundwater) and induces an upconing of salty groundwater; hence the quality of tubewell water is deteriorated. The deterioration of the pumped water is not only depending on the discharge rate but also on the pumping duration, thickness of the fresh groundwater lens and local hydro-geologic conditions.

However, the native groundwater, which existed in the pre-irrigation period in the Indus basin of Pakistan, was salty because the underlying geologic formation is of marine origin. The thickness of relatively-fresh groundwater lenses are around 30m in the lower Indus command area. According to NESPAK [4], the estimated volume of water exits in these fresh groundwater layers is about 200 billion cubic meters (BCM).

It is well known that in many areas of Sindh these tubewells have been ceased due to pumping of quite saline water. Under such conditions it is impossible that the agricultural benefits that initially resulted from tubewell installation can be sustained, and there is real risk that agricultural lands will be damaged. The main objectives of this study are to develop an experimental setup for installing the piezometers at various depths, collect the hydro-salinity data during pumping of the selected skimming well, simulate MT3D model for calibration and validation using the above data and to develop operational strategies through testing suitable scenarios**.**

2. METHODOLOGY

2.1 Site Selection and Experimental Setup

To achieve above objectives, a skimming tubewell from the command area of watercourse number 5AR of Kunner-II distributary was selected for the study; the salient features of the tubewell are described in Table 1

Table 1 Salient features of a selected skimming tubewell

S. No.	Description	Value
1	Capacity (m^3/hr)	60 to 100
2	Watercourse	5AR
3	Distributary / Minor	Kunner-II
4	Main Canal	Rohri
5	Village	Chukhi
6	Main Road	Sheikh Bhirkio
7	District	Hyderabad
8	Distance from Rohri canal (m)	1,500
9	Total depth of tubewell below ground surface (m)	24.38
10	Depth of open pit/well (m)	2.8
11	Length of strainer (m)	12.13
12	Diameter of strainer pipe (m)	0.1524
13	Length of delivery pipe (m)	3.8
14	Diameter of delivery pipe (m)	0.127
15	Motor horse power (H.P)	16

For the evaluation of hydro-salinity behavior, four individual piezometers at distance of about 1.83, 15.24, 38.1 and 73.152 m around the selected tubewell were installed. In addition to above, the nested piezometers having eight small sizes (i.e. 0.635cm dia) PVC pipes were installed at different depths viz. 24.384, 27.432, 30.48, 33.528, 36.576, 39.624, 42.672 and 45.72 m below ground level at the distance of about 1.83m away from the centre of tubewell.

Through these piezometers, the groundwater samples were collected before, during and after pumping of the tubewell for the analysis of electrical conductivity (EC), and pH values. The tubewell water samples were also analyzed during the pumping.

2.2 MT3D Model and the Governing Equation

PMWIN, Processing MODFLOW for Windows, (Chiang and Kinzelbach, [5]) has been selected as a complete simulation system. Using the MODFLOW model (McDonald and Harbuaugh, [6]), the hydrodynamic behavior of scavenger tubewells was made by Kori et al. [7] and for the selected tubewell, refer Qureshi et al. [8].

In this paper, MT3D, a modular three-dimensional finite-difference groundwater solute transport model based on dispersion approach, was used to simulate and predict solute transport behavior of groundwater systems. This model uses a mixed Eulerian-Langragian approach for the solution of 3-D advection-dispersion transport equation described as under:

$$\frac{\partial}{\partial x_i}\left(D_i \frac{\partial C}{\partial x_i}\right) - \frac{\partial}{\partial x_i}\left(v_i C\right) \pm \frac{q_s}{\theta} C_s = \frac{\partial C}{\partial t} \qquad (1)$$

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

The MT3D (Zheng [9]) 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 MODFLOW model independently. After completing a flow simulation, 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 was used to simulate changes in concentration of miscible solutes in groundwater considering advection and dispersion. The quality of groundwater will be predicted through model by pumping out the skimming well continuously, especially at the interface due to upconing of highly saline water (shown in Fig. 2)

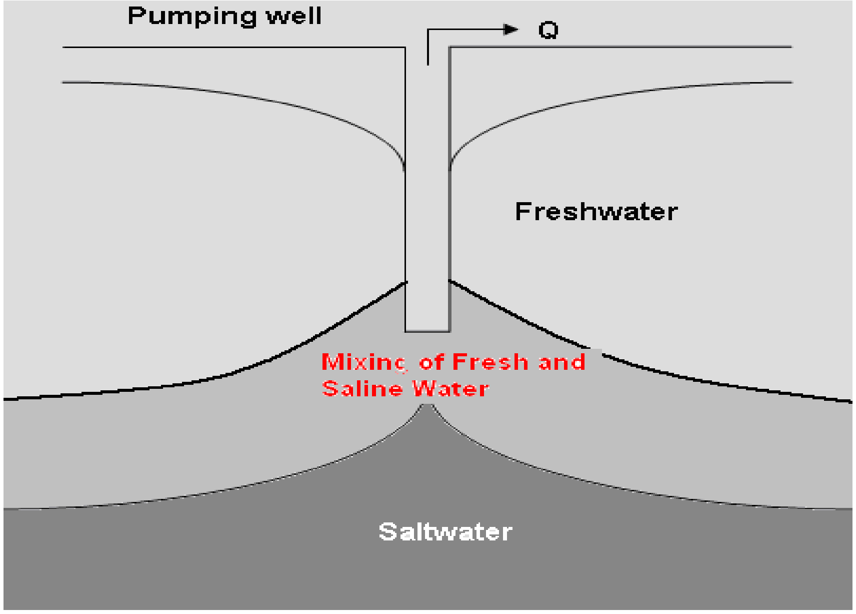


Fig. 2 Upconing of salt water caused by continuous pumping of a tubewell

2.3 Development of Input Data Files for MT3D Model

The models (MT3D and MODFLOW) need properly prepared input data files for their simulation. In this connection, following steps were taken into consideration:

2.3.1 Spatial Discretization of Grid

The block-centered mesh was used to discretize the aquifer at tubewell along KunnerII distributary. In order to get more accurate solution, the mesh was developed in a non-uniform manner with very small elements near the tubewell. The spatial discretized model domain with the size of columns and rows is prepared. The central portion of the discretized mesh showing tubewell (red) and piezometers is shown in Fig. 3.

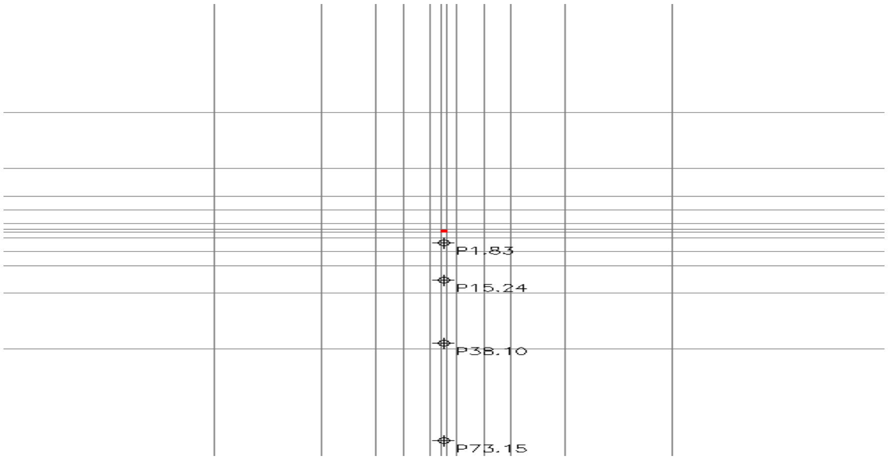


Fig. 3: Generated model grid showing tubewell (red) & observation wells/ piezometers

2.3.2 Layer Types, Pumping Discharge and Strainer Length

The aquifer is divided into 17 layers. The top layer was considered as unconfined while the remaining 16 layers were considered convertible between unconfined and confined depending upon the geological conditions. The elevation of top and bottom layers, thickness and depth of each layer including type of pipe (blind or strainer) is described in Table 2.

Table 2 Vertical discretization of model domain for tubewell of KunnerII Distry

Layer No.	Thickness of Layer (m)	Depth of Layer (m)	Top Layer Elevation (m)	Bottom Layer Elevation (m)	Well Discharge (m^3/hr)	Type of Pipe (Blind or Strainer)
1	3.05	3.05	24.38	21.34	--	Blind pipe/ semi-confined layer
2	9.14	12.19	21.34	12.19	--	
3	12.19	24.38	12.19	0	**74.152**	length of well strainer
4	2.296	26.676	0	-2.296	--	Depth of aquifer below strainer bottom
5	1.514	28.19	-2.296	-3.81	--	
6	1.524	29.704	-3.81	-5.334	--	
7	1.524	31.218	-5.334	-6.858	--	
8	1.524	32.732	-6.858	-8.382	--	
9	1.524	34.246	-8.382	-9.906	--	
10	1.524	35.76	-9.906	-11.43	--	
11	1.524	37.274	-11.43	-12.954	--	
12	1.524	38.788	-12.954	-14.476	--	
13	1.524	40.302	-14.476	-16.002	--	
14	1.524	41.816	-16.002	-17.526	--	
15	1.524	43.33	-17.526	-19.05	--	
16	1.524	44.844	-19.05	-20.574	--	
17	1.524	46.358	-20.574	-28.194	--	

A constant discharge of 74.152 m^3/hr was observed during the pumping test. The above discharge measured during pumping test was assigned to the third layer that was continued through out the entire simulation/computation period. It should be noted that the selected tubewell having a strainer length of 12.19 m, which is also described in 3^{rd} layer.

2.3.3 Initial and Boundary Conditions

The average value of hydraulic heads (20.275m), observed from four piezometers installed around the tubewell along Kunner-II distributary, was used as initial/starting hydraulic head to the cells of the entire model grid. These heads were observed just before pumping test conducted. It should be noted that the tubewell did not run for about 72 hours before pumping test.

The Rohri canal, situated on the north of the tubewell, is far away from the considered domain, there is no need to provide liquid boundary effect. Hence, all sided boundaries along Kunner-II distributary were considered as no flow boundaries.

2.3.4 Temporal Discretization of the Model and Aquifer Hydraulic Parameters

The model is simulated for different time periods. The simulated values of hydraulic heads have been compared with the observed hydraulic head. During model simulation runs, the transient type flow was assigned to the model.

The ranges of aquifer parameters available in literature cited were used for the MODFLOW model simulation. Using MODFLOW model, the calibrated aquifer parameters, described by Qureshi et al. [8], are summarized below (see Table 3).

Table 3 Calibrated hydraulic parameters

Parameters	Values
Aquifer	
Horizontal Permeability	1.38744 m/hr
Vertical Permeability	0.015 m/hr
Effective Porosity	0.2
Specific Storage	0.00041 1/m
Semi-confining layer	
Horizontal Permeability	0.0833333 m/hr
Vertical Permeability	0.09 m/hr
Porosity	0.3
Specific yield	0.2

2.3.5 Advective and Dispersive Solute Transport Parameters

The solute movement due to advection for was simulated by MT3D using corresponding parameters computed by MODFLOW. The parameters used for advective solute transport for MT3D model are described in Table 4.

The ranges for the parameters of adopted from Left Bank Outfall Drain Project 1 and graphs developed by Gelhar and Rehfeldt [10], applied by Ali et al. [11] for scavenger tubewell studies, were used for the calibration of dispersive solute transport parameters through trial and error method as shown in Table 5.

Table 4 Advective Solute Transport Parameters

Parameters	Value
Maximum No: of moving particles, MXPART	1300000
Courant No: (PERCELL)	1
Concentration weighting factor (WD)	0.5
Negligible relative concentration gradient , DCEPS	0.00001
Pattern for initial placement of particles , NPLANE	2
No: of particles per cell in case of DCELL < DCEPS (NPl)	0
No: of particles per cell in case of DCELL > DCEPS (NPH)	18
Minimum No: of particles allowed per cell (NPMIN)	3
Max: No: of particles allowed per cell (NPMAX)	36
Multiplier for the particle No: at source cell (SRMULT)	1
Pattern for placement of particles for sink cells (NLSINK)	0
for placement of Pattern particles for sink cells (NLSINK)	10
Critical relative concentration gradient (DCHMOC)	0.01

Table 5 Dispersive Solute Transport Parameters

Parameters	Ranges	Source
Horizontal Transverse Dispersivity (m)	0.018-0.097	Gelhar and Rehfeldt [10] Ali et al. [11]
Vertical Transverse Dispersivity (m)	0.00076-0.00289	
Longitudinal Dispersivity (m)	3- 15.24	
Porosity (fraction)	0.18-0.35	Ali et al. [11] Leap [12]

3. RESULTS AND DISCUSSIONS

3.1 Observed Hydro-Salinity Data

During pumping test, Electrical Conductivity (EC) and pH were observed for the water samples collected from individual and nested piezometers. The quality of tubewell water was also observed. The quality of water samples collected from all the individual piezometers was slightly improving with time during pumping test (Table 6). This improvement in water quality may be due to recharge from main Rohri canal and seepage from watercourse and other field channels/ irrigated water.

On the contrary, it was noted that the quality of tubewell water was continuously deteriorating (see Fig. 4). This deterioration indicates that there might be any upconing of saline water, which has also been observed from the increasing of salinity of the collected water samples from nested piezometers at different depths (see Table 7). This saline water upconing was observed at the bottom and below the tubewell strainer. The MT3D model was calibrated and validated for these observed salinity reading in the following sub-section.

Table 6 Quality of water samples collected from individual piezometers

S. No.	**Location Point**	**Distance from tubewell (m)**	**Depth below ground surface (m)**	**EC (dS/m) at time**		
				2 hrs	**4 hrs**	**8 hrs**
1	P 1.83/18.3	1.83	18.3	0.896	0.866	0.786
2	P 15.24/18.3	15.24	18.3	0.854	0.784	0.678
3	P 38.1/18.3	38.10	18.3	0.810	0.774	0.746
4	P 73.15/18.3	73.15	18.3	0.665	0.643	0.632

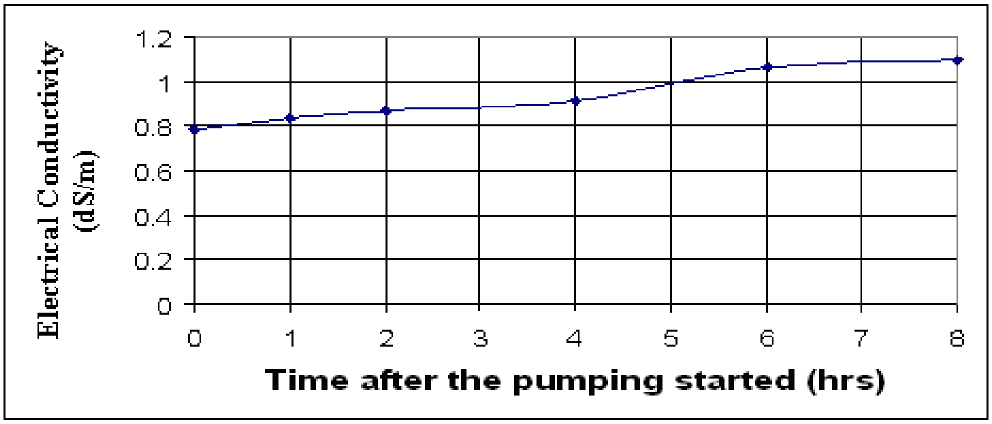


Fig. 4 Temporal variation of tubewell water quality (EC) during pumping

Table 7 EC observed at different depths from ground surface during pumpage

Distance from ground surface	**EC (dS/m) at time**		
(m)	**t = 0**	**t = 4 hrs**	**t = 8 hrs**
24.38	0.958	0.968	0.981
27.43	1.063	1.076	1.087
30.48	1.71	1.723	1.736
33.53	2.473	2.485	2.5
36.58	3.124	3.14	3.16
39.62	4.42	4.56	4.785
42.67	11.04	11.215	11.52
45.72	22.44	22.51	22.64

3.2 Calibration and Validation of MT3D Model

3.2.1 Calibration of the Model

The calibrated MODFLOW model for the hydrodynamic behavior of the selected tubewell of Kunner-II distributary described by Qureshi et al. [8]] was linked with the solute transport MT3D model and using the input data files mentioned in section 2.2 above; the MT3D model was calibrated for the stress period of 4 hours. During calibration process, various diffusion coefficient values were also tested. The simulated Electrical conductivity values are very close to the observed values and show a good agreement between them. The maximum relative error observed was about 4.1%, however, the average absolute percentage error comes out to be be1.015 (Table 8).

Table 8 Observed and Simulated EC values after calibration at stress period of 4 hrs

S. No.	Layer No.	Distance from ground surface	Electrical Conductivity (ppm)		Absolute Relative %age error
		(m)	Observed	Calculated	
1	3	18.3	573.44	573.6809	0.0420
2	4	25.527	619.52	623.129	0.5825
3	5	27.447	688.64	699.7719	1.6165
4	7	30.48	1102.72	1105.356	0.2390
5	9	33.528	1590.4	1587.966	0.1530
6	11	36.576	2009.6	2027.22	0.8768
7	13	39.624	2918.4	3037.905	4.0949
8	15	42.672	7177.6	7277.82	1.3963
9	17	45.72	14406.4	14387.59	0.1306
Average value of absolute % error					**1.0146**

During calibration process, the transport parameters i.e. longitudinal dispersivity, horizontal dispersivity and vertical dispersivity were also calibrated through trial and error method for the selected tubewell command area of Kunner-II distributary. The calibrated parameters such as DRPT, TRPV and the effective molecular diffusion coefficient (DMCOEF) are found as under (Table 9).

Table 9 Calibrated Values of DRPT, TRPV and DMCOEFF Parameters

Parameter	Calibrated Value
Ratio of horizontal transverse dispersivity to longitudinal dispersivity (TRPT)	0.009
Ratio of vertical transverse dispersivity to longitudinal dispersivity (TRPV)	0.0003
Effective molecular diffusion coefficient (DMCOEF)	0.1

3.2.2 Validation of the Model

The model was validated for the data observed for the stress period of 8 hours. The computed/simulated values by the model were compared with the observed values of electrical conductivity (described in Table 10) along with absolute relative percentage error. The observed EC values are matching with the simulated ones; the maximum relative error observed is 7.7% which is also less than 10%. However, the average absolute relative error is about 2.1%, which is very small that shows a good conformity.

Table 10 Observed and Simulated EC values for validation at 8 hrs stress period

S. No.	Distance from ground surface	Electrical Conductivity (ppm)		Absolute relative %age error
	(m)	Observed	Computed	
1	18.3	573.44	573.7781	0.0589
2	25.527	619.52	627.0677	1.2183
3	27.447	688.64	709.7319	3.0628
4	30.48	1102.72	1107.677	0.4495
5	33.528	1590.4	1585.953	0.2796
6	36.576	2009.6	2043.032	1.6636
7	39.624	2918.4	3142.05	7.6634
8	42.672	7177.6	7353.226	2.4468
9	45.72	14406.4	14368.04	2.4468
Average value of relative % error				**2.0812**

3.3 Development of Operational Strategies

After above successful calibration of the model, the model was run for development of operational management strategies. In this connection, two scenarios increasing pumpage durations and increased discharge were tested.

3.3.1 Scenario-I: Increasing Operational duration

The model was run for more for 12, 24, 36, 48 and 60 hours continuously. The simulated EC values show an increase in salinity due to this continuous pumpage (see Fig. 5). It is quite clear from Fig. 5, 6 and 7 that salinity is relatively increased more at bottom of the tubewell i.e. from 23m (75.46ft) to 28.5m (93.5 ft), which shows a clear upconing of saline water.

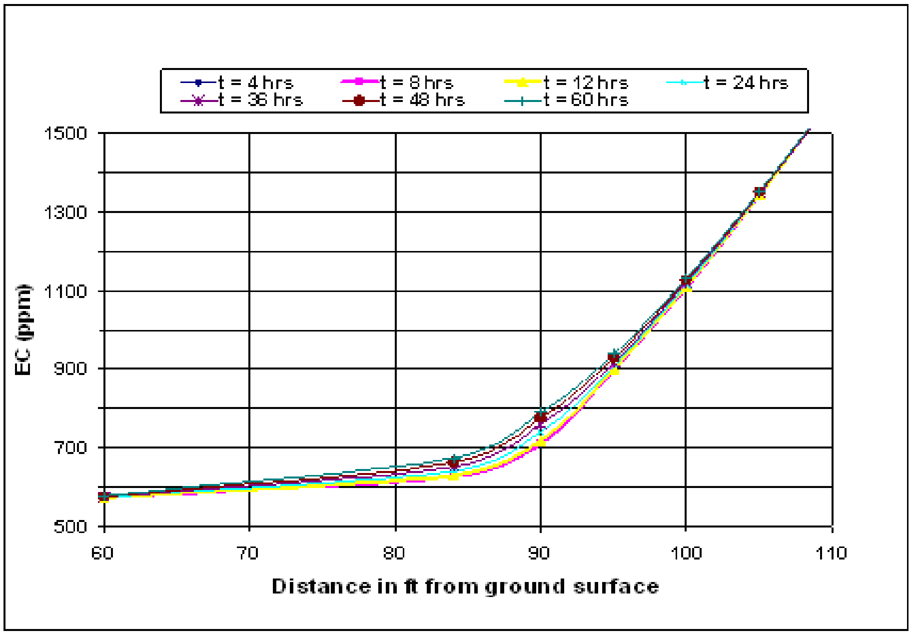


Fig. 5 Increase in EC values with the higher pumpage hours at the tubewell bottom

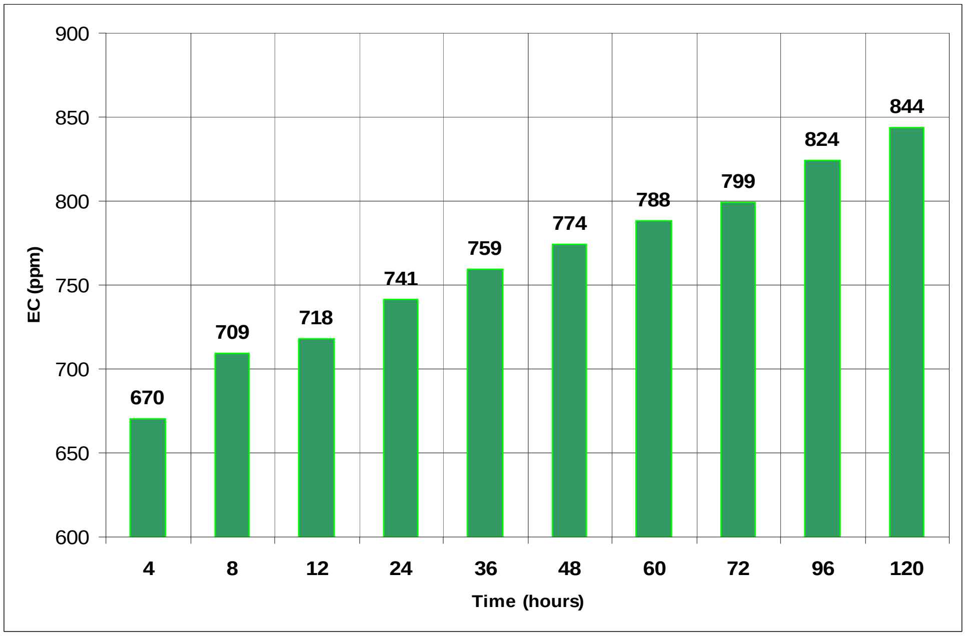


Fig. 6 Variation in EC values at 27.43 m below ground surface

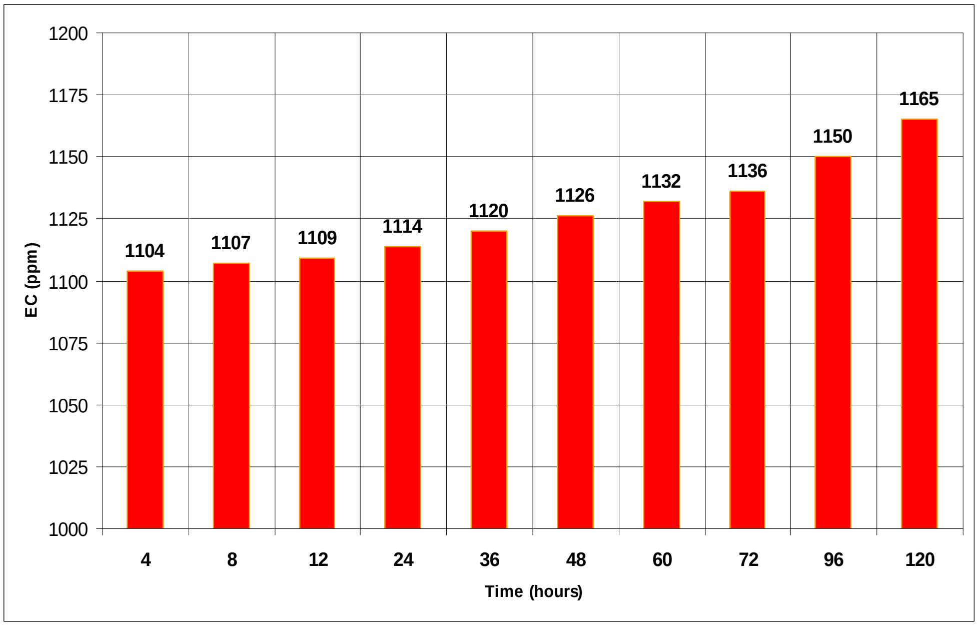


Fig. 7 Variation in EC value at 30.48 m below ground surface

3.3.2 Scenario-II: Increasing tubewell discharge

The calibrated model was run for 33.33% more discharge (i.e. increased up to 98.87 m^3/hr) to simulate the salinity in the aquifer at the bottom of the tubewell for the same higher durations. Figure 8 clearly show the increase in salinity even at the pumpage of only 4 hours at 27.43 m below the ground surface (G. S.) that is about 3 m below the tubewell strainer. With the increase of tubewell discharge, the salinity is increased for all the higher durations. Hence, it is concluded here that the tubewell should run at the normal discharge instead of accelerated discharge.

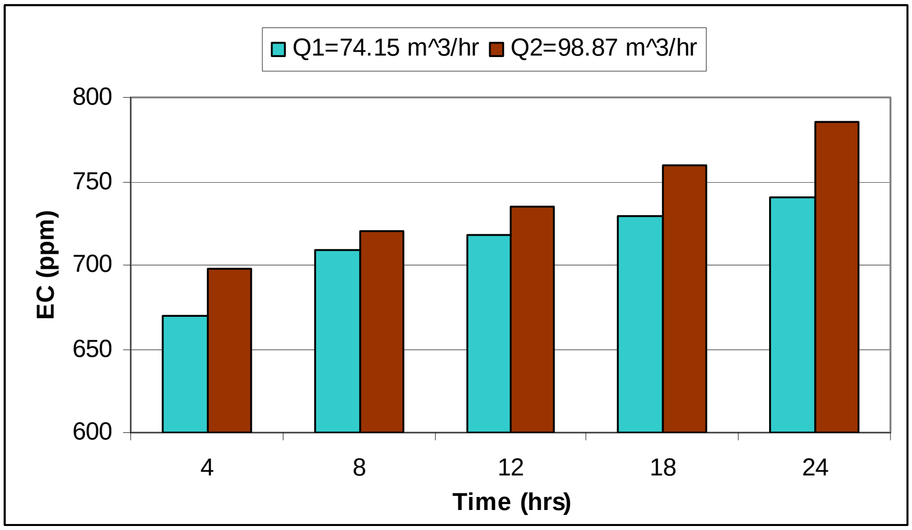


Fig. 8 Variation in EC at 27.43 m below G. S. for normal and accelerated discharge

4. CONCLUSIONS

Based on the observed spatial and temporal hydro-salinity data, the MT3D model was calibrated. During calibration process, ratio of horizontal transverse dispersivity to longitudinal dispersivity, ratio of vertical transverse dispersivity to longitudinal dispersivity and effective molecular diffusion coefficient were found 0.009, 0.0003 and 0.1 respectively.

The model results calibrated at the stress period of 4 hours and validated at 8 hours; show that the simulated electrical conductivity (EC) values are in good agreement with the observed values having an average absolute percentage error of 1.01 and 2.08 respectively.

For establishing operational management strategy, the model was tested to simulate salt contaminated groundwater values at different depths for increased discharge and durations. The results indicated that the quality of groundwater is deteriorating at different depths not only at the tubewell strainer (up to 24.38 m depth) but also below the strainer with the continuous pumping and with accelerated discharge. It has also been observed that the quality of tubewell water is deteriorating with time. Hence, this study concluded that the tubewells should not run more than 12 hours on continuous basis.

ACKNOWLEDGMENTS

Authors are thankful to the Higher Education Commission of Pakistan for the financial support under the National Research Program for Universities for the Project No. 20-769 titled “Sustainable Management of Fresh Groundwater for Irrigated Agriculture and Livelihood of Rural Areas of Sindh”.

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