Investigation of Operational Efficiency and Up-coning Problem of Scavenger Wells in Lower Indus Basin of Pakistan

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Abstract
Groundwater in lower Indus Basin of Pakistan is available in thin aquifers. If groundwater is exploited to unsustainable level, up-coning problem can occur. Up-coning is the saline water intrusion in the fresh water aquifer. Once quality of fresh water is deteriorated because of up-coning of saline water, it is very hard to make it again fit for irrigation usage. Thus, it is always advised to abstract groundwater without bringing saline water into the fresh water aquifer. In this study, we have investigated the operational efficiency of 79 scavenger wells installed at right side of Jamrao canal, lower Indus Basin Pakistan to check whether these wells were performing with the design operational efficiency. We found that majority of scavenger wells were running quite below the design operational efficiency. We also performed a constant rate pumping test on one of the scavenger wells to check whether any chances of up-coning were happening if the both pumps (fresh water and saline water) of the selected scavenger wells were operational. The pumping test results reveal that chances of up-coning were negligible if the pumps are run within the design operational hours (14.4 hrs per day).

Keywords
Lower Indus Basin; scavenger well; groundwater; operational efficiency; up-coning; water quality

INTRODUCTION

In lower Indus Basin of Pakistan, seepage from the irrigation delivery system and deep percolation from agricultural fields have formed thin fresh water layers floating over deep saline groundwater (Kori et al., 2013). The thickness of fresh groundwater is more near to the canals (recharging sources) and decreases linearly as move farther from the centre of the canals (Saeed and Ashraf 2005). Pumping of fresh groundwater from the thin fresh water layer (say between 30-90 m depth of aquifer) may cause up-coning of saline groundwater and may deteriorate quality of pumped water (Jones and van Wonderen 1994; Asghar et al. 2002; Saravanan et al. 2014). The sustainable use of fresh groundwater from thin fresh water layer (aquifer) needs careful thinking in selection, design and operation of tube wells. The type of well that pumps water from thin fresh groundwater layers without or with minimum disturbance to the underlying saline groundwater is called skimming well. The discharge of skimming well is generally less than 102 m^3/hr. The skimming wells can be used by small farmers to supplement canal water supplies for boosting crop production. In order to get more fresh water from thin fresh water layers of fresh groundwater, scavenger wells are proposed (Long 1965; Ali et al. 2004).

Rise in groundwater level in the lower Indus Basin is attributed to extensive irrigation application to agricultural farms and seepage from three irrigation distribution systems under the operation of Sukkur Barrage in1932, Kotri Barrage (1955), and Guddu Barrage (1962). The rise in groundwater level has caused waterlogging problem in some areas of the lower Indus Basin. Pakistan government initiated few projects to combat waterlogging and salinity by constructing a network of tube wells and drainage systems. Farmers also installed private tube wells to supplement canal water supplies for growing crops. SCARP (Salinity Control and Reclamation Project) was started in 1960 in Sindh Province where about 10,000 tube wells were installed for lowering water table and providing fresh water for irrigation purposes. The SCARP project does not cover all the waterlogged areas, but it mostly covers both sides of main canals where seepage from canal was significantly contributing to the rise in groundwater level.

LBOD-1 Project and Scavenger Wells

The second program for combating waterlogging and salinity problems is the Left Bank Outfall Drain Stage 1 (LBOD-1). The LBOD-1 project became operational in 1985 (Ali et al. 2004). The major activities of LBOD-1 project include the remodelling of main canals, construction of surface drains, installation of drainage tube wells, subsurface tile drainage and interceptor drains, and construction of scavenger wells. The project covers some areas of Shaheed Benazir Abad (old name Nawabshah), Sanghar and Mirpurkhas districts of Sindh Province, Pakistan. The LBOD-1 project and its components are shown in Fig. 1.

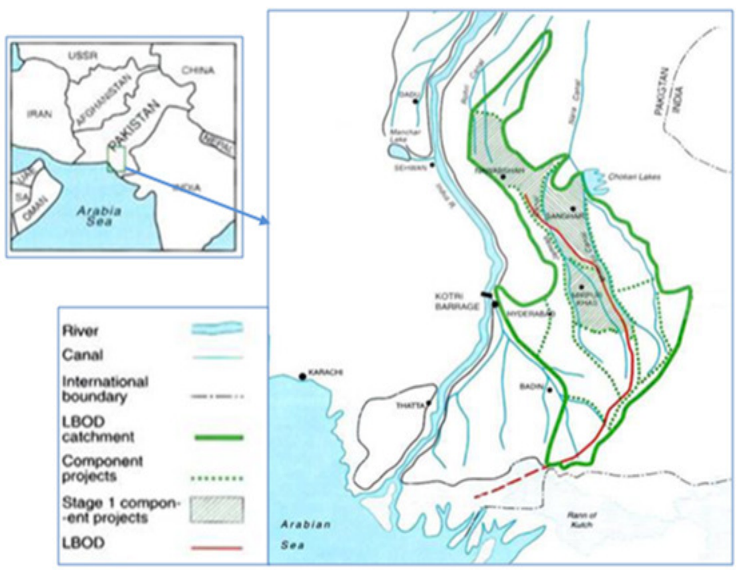

Figure 1. Map of LBOD and its components (Source: Kori et al. 2013)

In the LBOD-1, a total of 378 scavenger wells were installed and most of them (361) in Shaheed Benazir Abad and Sanghar districts (189 in Shaheed Benazir Abad sub-component of LBOD-1 and 172 in Sanghar sub-component) (Kumbhar and Ansari 2002). Out of 361 scavenger wells, 79 are installed on the right side of Jamrao canal. These tube wells are labelled as JRS (Jamrao Right Scavengers). Nominal yields of scavenger wells installed in LBOD-1 project are 34, 42 or 68 l/s. Fig. 2 shows the scavenger wells at the right side of Jamrao canal.

Before the LBOD project, 91% of irrigated agricultural land had a severe water logging situation and 9% of the area was moderately water logged. The recorded average water table depth was <0.15 m. The cropping intensity was recorded at <30% and the maximum yield of major crops such as cotton, wheat and rice was respectively 1080, 1400 and 1400 kg/acre. Maximum land value was less than Rs. 40000 per acre (about 700 US dollar) (Kumbhar and Ansari, 2002; Lashari and Kori, 2011).

Since the installation of 361 scavenger wells in 1994-1995, the operational efficiency of these wells has not been determined. In this study, we have conducted a constant rate pumping test on one of the scavenger wells installed at the right side of Jamrao canal to determine if any up-coning occurs if the selected scavenger well was run for more than the design hours (14.4 hours per day). We also determined the operational efficiency of 79 scavenger wells on the right side of Jamrao canal to see whether the design objectives of the scavenger wells were being achieved.

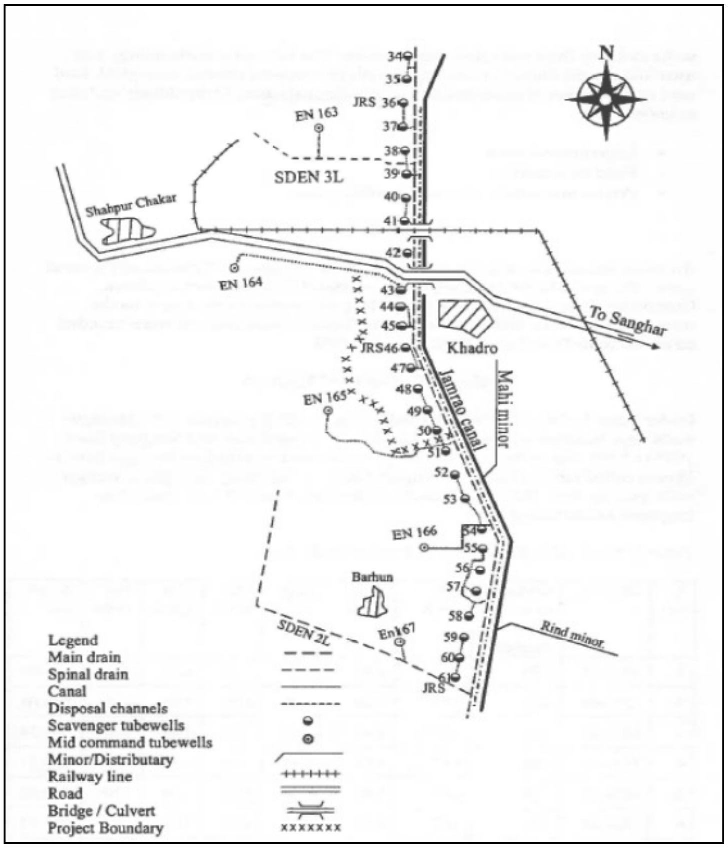

Figure 2. Scavenger wells on right side of Jamrao canal

The scavenger well concept

Scavenger wells provide a means of recovery of fresh groundwater occurring in lenses too thin for conventional skimming wells to be economic. As shown in Fig. 3, scavenger wells pump both the fresh and the saline groundwater but through separate outlets.

Groundwater quality stratification with fresh water floating on a saline layer is common in many areas of the world, particularly in coastal regions and arid climate zones including the Indus Plains in Pakistan. The recovery or skimming of fresh groundwater has been the subject of much work over the last 50 years.

Three different skimming concepts have been studied in relation to the Lower Indus groundwater basin in Sindh.

1. Equilibrium skimming, where the upward potential due to the pumping of a partially penetrating well is balanced by the gravity potential due to the up-coning of denser saline water.
2. 'Limited lifetime' concept where the rise of water is not prevented but takes sufficiently long for the well installation and operation to be economically advantageous. Once invaded by saline water the well is abandoned or converted to a scavenger or compound well.
3. 'Scavenger wells' are designed to pump both the fresh and underlying saline ground water but through separate outlets; provided that the fresh/saline interface or transition zone is confined by streamlines. No mixing takes place and the fresh water can be used, whilst the saline effluent is disposed to waste.

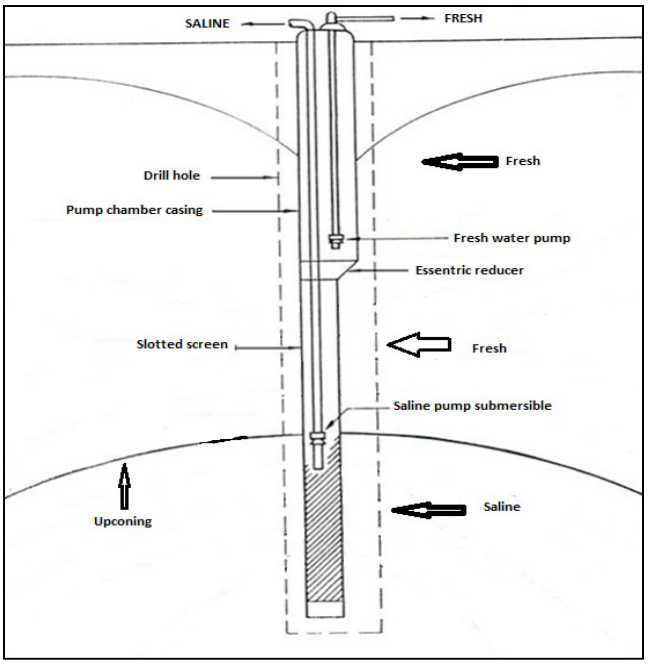

Figure 3. Schematic diagram of scavenger well

If the fresh groundwater layer is thin, scavenger wells may be the best (or even the only economically viable) method of skimming (de Louw et al., 2013). By maintaining a limiting flow line or flow divide above the fresh/saline interface and associated transition or dispersion zone, mixing is prevented and the fresh discharge can be kept at a quality suitable for domestic supply or irrigation.

Governing equation for scavenger well design

When water is being pumped out through Scavenger well, the fresh water and the saline water layers behave as (Van Wonderen and Jones, 1992):

1. Scavenger well induces the canal seepage more than the other drainage options (conventional seepage wells, mid-command drainage wells, interceptor drain and combinations of these).
2. Spacing between wells and distance from canal also affects the design of scavenger wells and have also good impact on the formation of freshwater lens.

An increase in canal seepage occurs under all scavenger well operation conditions (between 12% and 29%) (IIMI, 1998). This increase is highly sensitive to the distance of the well from the canal. However, mid-command wells, seepage wells and interceptor drains also show the same feature as shown in Table 1.

Table 1. Effect of drainage option on induced canal seepage

Option No.	Drainage Option	Canal Seepage (m^3/day/m)	Percentage Increase Relative To	
			Option 2	Option 3
1.	Present condition	1.77	-4	-14
2.	Mid-command wells only	1.84	0	-11
3.	Seepage and mid-command wells	2.07	12	0
4.	Seepage and mid-command wells and interceptor drain	2.16	17	4
5.	Scavenger and mid-command well	2.16	17	4
6.	Scavenger and mid-command well and interceptor drain	2.21	20	7

Note: Scavenger well set at 300m (or 1000 ft.) from canal, seepage well at 800m (or 2600 ft.). Recharge rate taken as 1.45 mm/day.

Fresh water recovery

The fresh water recovery is dependent only upon a limited number of key parameters. These include:

1. The initial depth from the top of the aquifer to the fresh/saline water interface, which is defined as the mid-point of the transition zone between the fresh and saline water bodies.
2. The effective thickness of the aquifer, which was mainly controlled by the occurrence of low permeable layers at a depth of about 200 to 230 ft (61m to 70m). Modeling showed that a contrast in vertical permeability of 10 to 1 was sufficient for the top of the low permeability layer to form an effective aquifer base.
3. The length of well screen, which is related to the discharge capacity of the well.
4. The depth of the top of the well screen measured from the top of the aquifer.
5. The anisotropy ratio of the aquifer thought to be between 5 and 30 in the LBOD area.
6. The thickness of the transition zone at the well screen during scavenger well operation. This thickness is mainly controlled by the transverse dispersivity of the aquifer medium, and was found, from both field monitoring and model simulation, to range from about 14 to 20 ft (4.25m to 6.1m).

Maximum Fresh Water Recovery Ratio

The maximum fresh water recovery ratio, defined as the ratio of fresh water discharge to total well discharge, could be expressed in an empirical form as follows:

$$Q_{um} / Q_c(\max) = [(RATIO + c*(DINT - SRP)] - 0.5*DZ/LS \qquad (1)$$

where,

$$RATIO = 0.01*(a*AQTHI + b)*DINT \qquad (2)$$

$$SRP = WTOP + DINT*LS/AQTHI \qquad (3)$$

$$c = (1 - RATIO)/[67*\{Kh/Kv\}^{-0.42}] \qquad (4)$$

where, Q_{um}/Q_c(max) is maximum ratio of fresh water abstraction to total abstraction from the scavenger well (i.e. maximum recovery ratio), AQTHI is effective aquifer thickness, DINT is depth to the midpoint of the transition zone, which separates the fresh and saline water bodies, WTOP is depth to the top of the well screen from the top of the saturated aquifer, DZ is thickness of transition zone between fresh and saline water, LS is length of the well screen, a and b are empirical constants derived from model simulations, - for 1.0 cusec (ft^3/s) well: a=-0.032, b=3.8, for 1.5 cusecs well: a=-0.038, b=4.0, for 2.0 cusecs well: a=-0.031, b=3.5, SRP is defined in equation (3) as the distance of a so-called screen reference point from the top of the saturated aquifer. The position of the screen reference point on the well screen is independent of the screen setting within the aquifer, C is correction factor, which is a function of initial fresh water lens thickness, effective aquifer thickness and anisotropy ratio, derived from model simulations, and Kh/Kv is anisotropy ratio (Van Wonderen and Jones, 1992).

Well Capacity

The well capacity thus easily follows from:

$$Q_w = WS * Q_{cs} / F \qquad (5)$$

where Q_w is well capacity (cusec), WS is well spacing (ft), Q_{cs} is rate of canal seepage (cusec/ft), and F is operating factors of the ratio or number of daily pumping hours and number of hours in a day (i.e. 24 hours)

Scavenger wells were then targeted at those canal reaches with a drainage requirement exceeding 2.2 cusec (63.5 l/sec)/3200 ft (or 1000 m).

Well Spacing

The basic requirement for scavenger wells in the LBOD project is to maximize the recovery of canal seepage. Therefore, the interval between adjacent wells can be calculated using the equation:

$$WS = Q_w * F / Q_{cs} \qquad (6)$$

All the parameters are defined earlier.

Equation for Drawdown

Drawdown is calculated from the equation:

$$S_w = 1.32 * Q / K * L \qquad (7)$$

Where S_w is well drawdown, m, Q is discharge rate, m^3/day, K is permeability, m/day, and L is length of well screen, m.

Note: K=32 m/day, for Shaheed Benazir Abad, K=26 m/day, for Sanghar, and K=30 m/day, for Shahpur Chakar (research command area).

Optimization of Fresh Water Recovery

The geometry of the fresh water lens, which attains its greatest thickness towards the centreline of the canal, favours a well location as near to the canal as possible. The two parameters that control the screen setting within the aquifer are the top of the well screen relative to the top of the aquifer, and the length of the well screen. The screen reference point combines the two parameters, and optimization of fresh water recovery favours the maximizing of the distance between the screen reference point and the position of the interface particularly for anisotropy conditions. This, in turn favours short screen lengths. In contrast, the rate of fresh water recovery is constrained by the thickness of the transition zone at the well screen during well operation. The optimization of fresh water recovery obviously minimizes the effect of the transition zone if the screen length is at a maximum Beeson et al. (1992). The optimization well screen is related to the controlling parameters as follows:

$$LS_{opc} = \sqrt{\frac{0.5 * A * DZ * AQTHI}{(1 - RATIO) * DINT}} \qquad (8)$$

where additionally, LS_{opc} is optimum screen length for maximum fresh water recovery; and

$A=67*\{Kh/Kv\}^{-0.42}$

Since the design discharge capacity of the well is closely related to the screen length, with 50-56 ft (15m to 20m) per cusec being the norm in the LBOD Project Area. And taking into consideration the requirements to satisfy the first objective of the well, a compromise well design is required.

METHODOLOGY

Constant rate pumping test

Constant Rate Pumping Test was conducted on JRS-36 tube well on the right side of Jamrao canal. Salient features of JRS-36 tube well are given in Table 2. Aquifer thickness was 60m (190 ft) and high abstraction rate i.e. 1.25 fresh water discharge (good conditions for up-coning). Four piezometers were installed to monitor the performance of the tube well. Water quality from the upper pump remained below 900 us/cm throughout the pumping period, the lower pump water quality was "steady state" where the EC of the discharge water is relatively constant. Drawdown at well was found as 15 ft (4.58m) within the time of four hours since the test started. After that it remained constant throughout the test. The piezometers and observation wells in the vicinity of the scavenger well were also monitored during the test at the interval of two hours. Location map of piezometers is shown in Fig. 4. Operational efficiency of scavenger wells was determined from the operational hours recorded on digital board for each scavenger well and using following equations:

$$E_{fwp} = \left(\frac{H_{fwp} \ per \ day}{14.4}\right) * 100 \qquad (9)$$

$$E_{swp} = \left(\frac{H_{swp} \ per \ day}{14.4}\right) * 100 \qquad (10)$$

where

$$H_{fwp} \ per \ day = \frac{Total \ Fresh \ Water \ Pumping \ Hours}{365.25 * 18}$$

$$H_{swp} \ per \ day = \frac{Total \ Saline \ Water \ Pumping \ Hours}{365.25 * 18}$$

where E_{fwp}, H_{fwp} and E_{swp}, H_{swp} are operational efficiency and operational hours of fresh and saline water pumps respectively.

Table 2. Salient features of JRS-36 scavenger well (modified after SMO, 1996)

Sr. No.	Parameter	Value
1	Drilling depth	43.6 m
2	Distance form canal	460.0 m
3	Design discharge	3.4 m^3/min
4	Fresh design discharge	2.13 m^3/min
5	Saline design discharge	1.28 m^3/min
6	Fresh/Saline Ratio	60/40
7	Depth of interface	41.2 m
8	Thickness of transition zone between fresh and saline water	7.6 m
9	Screen length	27.5 m
10	Saline pump depth (cased)	43.5 m
11	Static water level below ground surface	1.75 m
12	Depth of interface below ground surface	40.25 m
13	Slotted casing length (Fresh)	3.05 m
14	Slotted casing length (Saline)	24.4 m
15	Electrical conductivity (EC) of fresh water	900 μS/cm

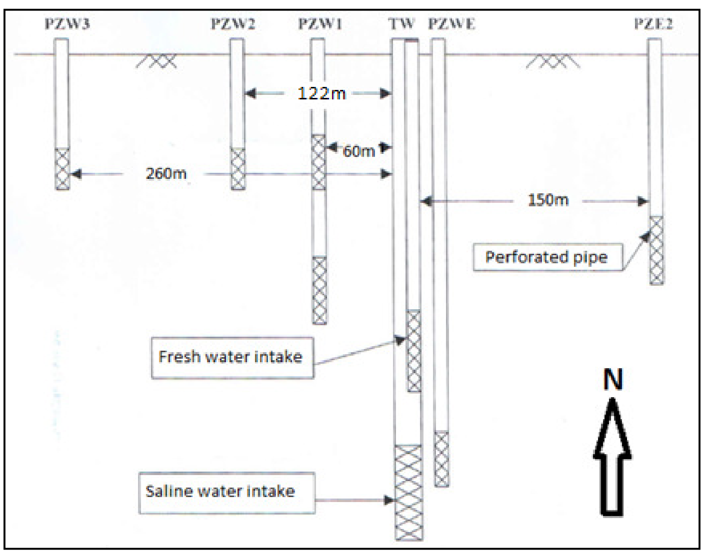

Figure 4. Location of piezometers around the JRS-36 tube well

RESULTS AND DISCUSSION

Constant rate pumping test

Table 3 presents some of the pumping test results including drawdown in each piezometer. PZE2 shows rapid drawdown at the start of the test and gradual and slow increase after ten hours of the test (Fig. 5). The final drawdown measured at PZE2 was found as 22.8 cm. Drawdown witnessed at PZW1 remained in fluctuation during the whole period of the

Constant Rate Pumping Test. Some sudden increase in the level of water table was due to the irrigation water application to the nearby agricultural land or because of induced canal water seepage (Fig. 6). If the reduction in drawdown is because of the induced canal seepage, it could be uneconomical to run tube well for 26 hours continuously.

Table 3. Piezometers and tube well data

Piezometer	Parameters				
	Distance from JRS-36 tube well (m)	Total drawdown in 26-hour pumping test (cm)	Rate of drawdown (cm/hr)	EC (µS/cm)	TDS (mg/l)
PZWE (JRS-36)	0.0	435	16.73	190	84
PZE2	150	22.8	0.87	190	111
PZW1	60	29.4	1.13	575	292
PZW2	122	33.6	1.29	450	221
PZW3	260	32.4	1.24	370	265

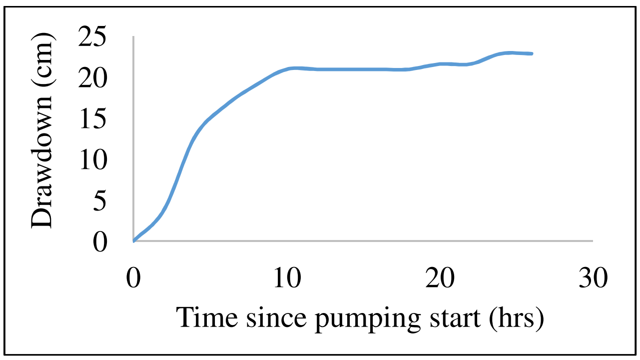

Figure 5. Drawdown at PZE2 during constant rate pumping test

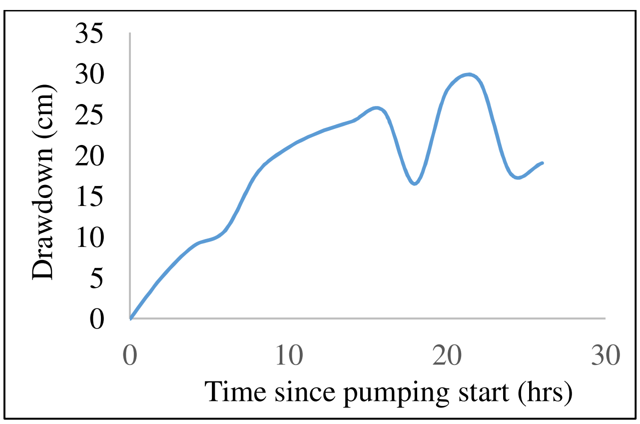

Figure 6. Drawdown at PZW1 during constant rate pumping test

Results obtained at PZW2 show a gradual increase in the drawdown and that was due to the Position of piezometer in barren land. Total drawdown measured at PZW2 was found as 33.6 cm (Fig. 7). This piezometer was installed far away from the well but the drawdown result shows good effect on the water table level. The drawdown measured at PZW3 (Fig. 8) has shown the same trend as of the PZW1.

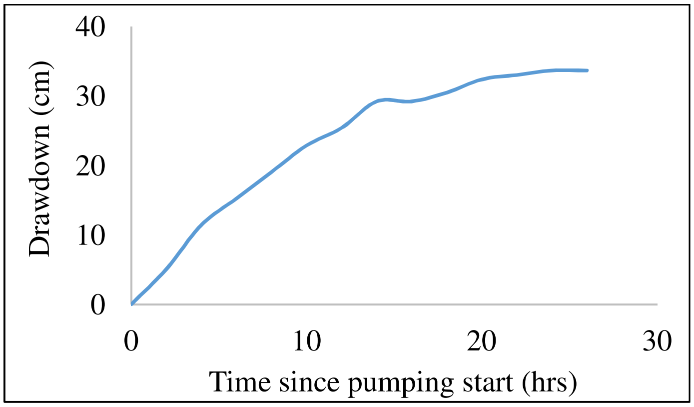

Figure7. Drawdown at PZW2 during constant rate pumping test

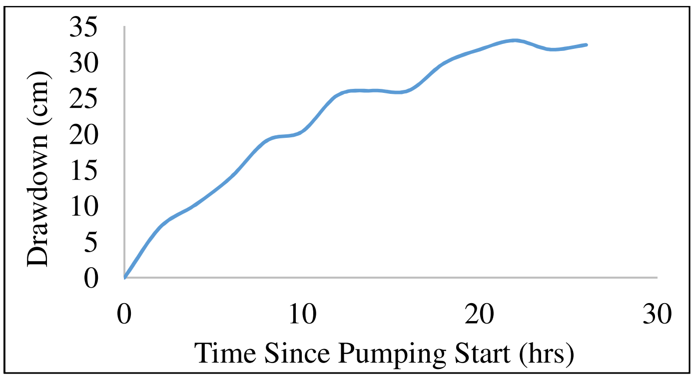

Figure 8. Drawdown at PZW3 during constant rate pumping test

Water quality measurements of the JRS-36 tube well shows improvement after the test start. The water quality of JRS-36 tube well remained below 1300 us/cm Electrical Conductivity (EC) value and that is suitable for irrigation usage (Figs. 9). The discharge of the saline water pump shows gradual increase in the EC values. After some time this water will come to the fresh water pump discharge and will affect the quality of it (Fig. 10).

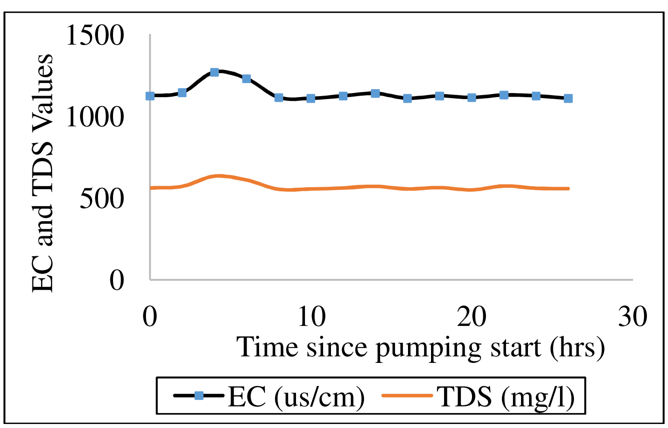

Figure 9. Water quality measurements at JRS-36 tube well

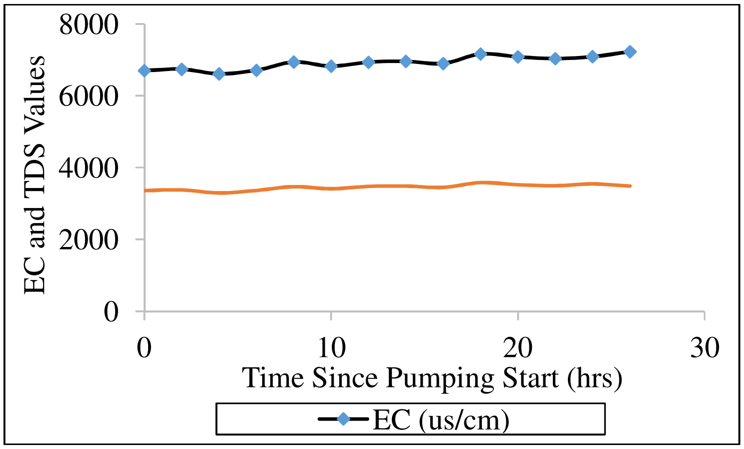

Figure 10. Water quality measurements of saline pump

Operational efficiency of scavenger wells

Operational hours of scavenger wells are automatically updated on digital board installed separately for each tube well. Each scavenger well is designed to run for 14.4 hours every day for controlling up-coning of saline water and recovering fresh groundwater for irrigation, drinking and other uses. The design operational efficiency of each tube well is presumed to be 100% if both objectives of scavenger wells are achieved. In order to check whether the scavenger wells were operating with the design operational efficiency, it was important to analyze the operational hours readings. For that, readings from digital boards of the scavenger wells were taken and analyzed by using Eqs. 9 & 10. The analysis of the operational hours data of all 79 scavenger wells reveals some interesting results. Three locations were indentified where at least three consecutive scavenger wells were running below 30% of the pump efficiency. If this low operational efficiency persists for some long period, it may cause at least two problems: 1) rise in water table in the vicinity of these scavenger wells; 2) not much fresh water is abstracted for meeting irrigation and other demands for fresh water.

The analysis of operational hours data for the selected 79 scavenger wells shows that none of the fresh water pumps of 79 scavenger wells had current operational efficiency above 50% of the design operational efficiency (Fig. 11). Thirty-five fresh water pumps which make 44% of 79 scavenger wells were operating less than 30% of the design operational efficiency. This clearly shows that fresh water recovery from the scavenger wells was very small. We also identified that at least three locations (marked with red colour in Fig. 11) where more 3 or more adjacent scavenger wells had operational efficiency below 30% of the design operational efficiency. These areas can get waterlogged if these wells were not immediately repaired and brought back into function.

The average operational efficiency of 79 fresh water pumps was merely 30.7%, which means that each fresh water pump of the scavenger wells on average was running 4.4 hours per day. However, these pumps were designed to run for 14.4 hours per day to control up-coning problem and abstract fresh water for irrigation and other purposes. The low average operational efficiency of fresh water pumps indicates that the farmers were deprived of fresh water for irrigating their agricultural farms and this in turn can significantly affect their farm income.

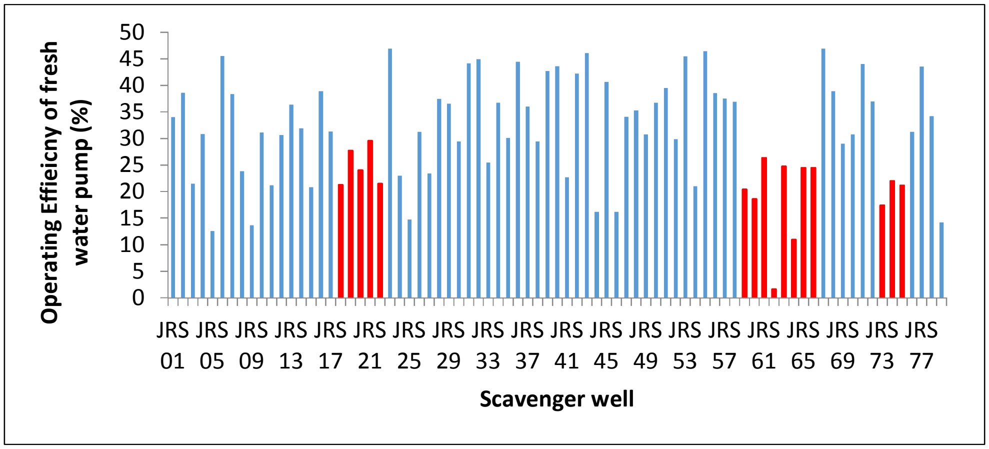

Figure 11. Operational efficiency of fresh water pump of scavenger wells

A similar pattern for operational efficiency of saline water pumps was observed. The average operational efficiency of 79 saline water pumps was 37.7% (slightly higher than the operational efficiency of fresh water pumps). On average, each saline water pump was running for just 5.4 hours per day. The data analysis further reveals that 92.5% of saline water pumps were operating below 50% of the design operational efficiency, which can be attributed as poor performance of the saline water pumps (Fig. 12).

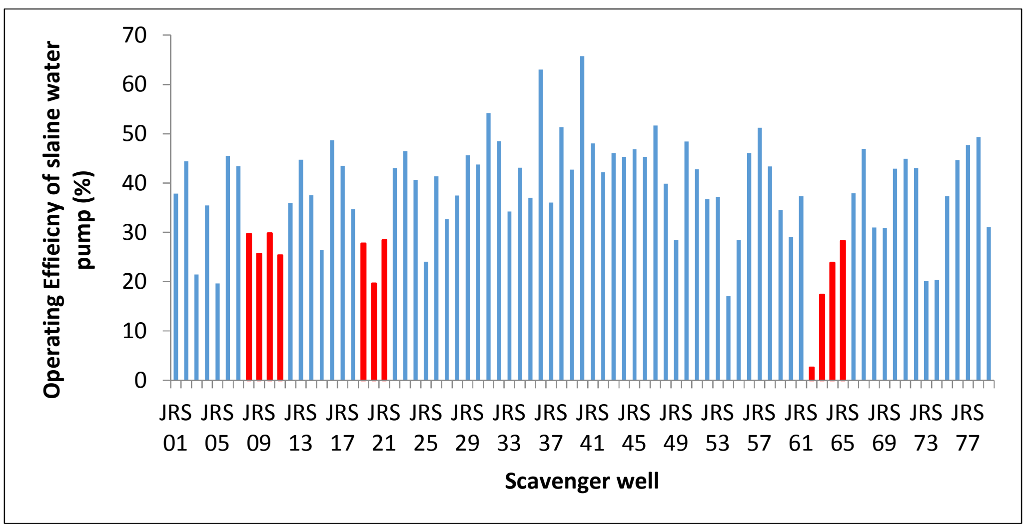

Figure 12. Operational efficiency of saline water pump of scavenger wells

Twenty-one saline water pumps which make 27% of 79 scavenger wells were operating less than 30% of the design operational efficiency. This clearly shows that controlling up-coning by using saline water pump would not be achieved if this low operational efficiency of saline water pumps continues for long period (say 1 to 2 years). We also identified three locations (marked with red colour in Fig. 12) where at least three saline water pumps were running below 30% of the design operational efficiency.

As fresh water not being abstracted to the designed amount, a low operational efficiency of saline water pumps will not create any up-coning problem. Instead, this will reduce amount of effluent in the drainage system that can provide some temporary relief to the downstream population and agricultural farms. However, this can be only true if fresh water pumps also run continuously below the design operational efficiency.

The combined operational efficiency of scavenger wells is shown in Fig. 13. Combined operational efficiency of scavenger wells were determined by combining operational hour readings of the both pumps (fresh and saline). We identified four locations where at least three scavenger wells were running below 30% operational efficiency (marked with red colour in Fig. 13). Twenty-six scavenger wells which make 33% of 79 scavenger wells were operating less than 30% of the design operational efficiency. This clearly shows that both objectives (recovery of fresh water and controlling up-coning) of the scavenger wells installation were not being achieved in practice. Only two scavenger wells were running slightly higher than 50% of the design operational efficiency and rest were operating with much lesser operational efficiency. The average combined operational efficiency was calculated as 34.3% of the design operational efficiency. We state that the low combined operational efficiency of scavenger wells may cause chances of waterlogging in the region and reduce land market values as crop production could significantly reduce.

The analysis of operational hours data for JRS-36 tube well shows that saline pump of JRS-36 was running for 9.1 hours per day and fresh water pump for 6.4 hours per day. Both pumps were supposed to be running for 14.4 hours per day. The operational efficiency of fresh water and saline water pumps of JRS-36 were 44.5% and 63.0% respectively. The combined operational efficiency of JRS-36 was found as 53.8% (7.74 hours per day). Compared to other scavenger wells, JRS-36 has relatively higher operational efficiency of both pumps, which support our selection of JRS-36 to check up-coning phenomenon by conducting pumping test on JRS-36.

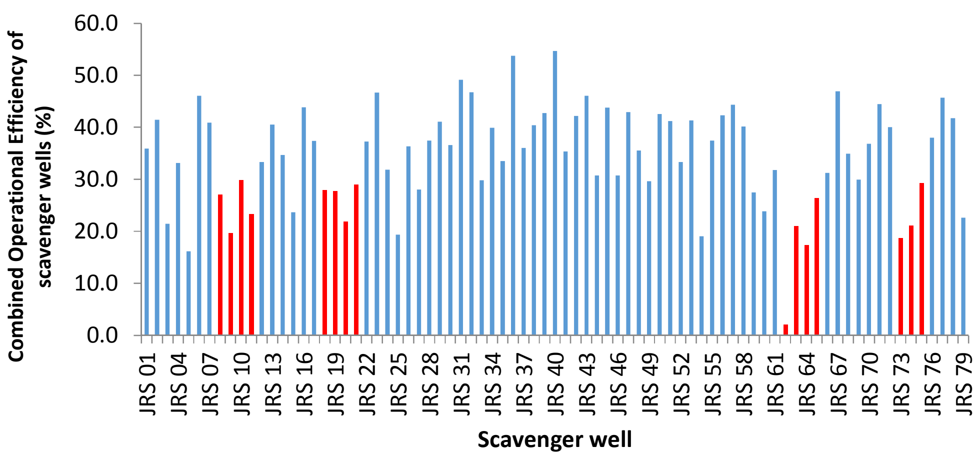

Figure 13. Combined operational efficiency of scavenger wells (both fresh and saline water pumps)

CONCLUSIONS

On the basis of the evidence gathered during the investigation and above discussion, following conclusions are drawn.

- The operational efficiency of fresh and saline water pumps was very low for the studied scavenger wells. The objectives of scavenger wells were not being fully achieved in the study area. If scavenger wells run with low operational efficiency for long period, the area will again be waterlogged and farmers may start installing skimming wells to abstract fresh groundwater for meeting crop demands. If this happens, up-coning problem will occur and will make aquifer saline and unfit for irrigating crops using groundwater.

- All the scavenger wells installed along the right side of Jamrao canal were working with less running hours as compared to the design operational hours (i.e. 14.4 hrs per day). This low operational efficiency ultimately reduces the Net Present Value (NPV) of the scavenger wells.
- The chances of up-coning are negligible and no evidence was found for the occurrence of up-coning during the study period. However, the main reason for having low chances of up-coning is attributed to low operational efficiency of fresh water pumps.

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