Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2016.1196558

57 (2016) 29178–29191
December

Taylor & Francis
Taylor & Francis Group

Operational efficiency and up-coning problem of scavenger wells in lower Indus Basin of Pakistan

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Received 2 September 2015; Accepted 15 May 2016

ABSTRACT

Groundwater in lower Indus Basin of Pakistan is available in thin aquifers. Abstraction of fresh groundwater can cause up-coning and ultimately degrade water quality in the freshwater aquifer. Up-coning is the saline water intrusion in the freshwater aquifer. Once quality of freshwater is deteriorated because of up-coning, it is very hard to make it again fit for irrigation usage. Thus, it is always advised to abstract groundwater on sustainable level without affecting freshwater aquifer permanently. 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. The combined operational efficiency of freshwater and saline pumps was 34.3%. The operational efficiency of saline water pumps was slightly higher (37.7%) than the freshwater water pumps (30.7%). We also performed a constant rate pumping test on one of the scavenger wells (i.e. JRS-36) to check whether any chances of up-coning were happening if the both pumps (freshwater and saline water) of the selected scavenger well were operational. The pumping test revealed that chances of up-coning were negligible if the pumps were run within the design operational hours (14.4 h per day).

Keywords: Lower Indus Basin; Scavenger well; Groundwater; Operational efficiency; Up-coning; Water quality

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Presented at The 2nd IWA Malaysia Young Water Professionals Conference 2015 (YWP15)
March 17–20, 2015, Kuala Lumpur, Malaysia

1. Introduction

In lower Indus Basin of Pakistan, seepage from the irrigation delivery system and deep percolation from agricultural fields have formed thin freshwater layers floating over deep saline groundwater [1]. The thickness of fresh groundwater under or nearer to the canals (recharging sources) is more and it decreases linearly as distance from the centre of the canals increases [2]. Pumping of fresh groundwater from the thin freshwater layer (say between 30 and 90 m depth of aquifer) may cause up-coning of saline groundwater and may deteriorate quality of pumped water [3–5]. The sustainable use of fresh groundwater from thin freshwater 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 typically 102 m^3/h or less. The skimming wells can be used by small farmers to supplement canal water supplies for boosting crop production. Scavenger wells are used to abstract more freshwater from thin layer of fresh groundwater [6,7].

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 in 1932, Kotri Barrage (1955) and Guddu Barrage (1962). In irrigated agricultural fields, waterlogging is often accompanied by salinity as waterlogged soils prevent leaching of the salts imported by the irrigation water. Salts are a major water quality factor in choosing disposal options for subsurface drainage in arid and semi-arid irrigated areas [8]. 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. Salinity Control and Reclamation Project (SCARP) was started in 1960 in Sindh Province where about 10,000 tube wells were installed for lowering water table and providing freshwater for irrigation purposes [9]. 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.

1.1. LBOD-1 project and scavenger wells

The second programme for combating waterlogging and salinity problems is the left bank outfall drain Stage 1 (LBOD-1). The LBOD-1 project became operational in 1985 [7]. 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.

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). Out of 361 scavenger wells, 79 are installed on the right side of Jamrao canal. These tube wells are labelled as Jamrao Right Scavengers (JRS). 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 start of LBOD project, 91% of irrigated agricultural land had a severe waterlogging problem and 9% of the area was moderately waterlogged. The recorded average water table depth was <0.15 m. The cropping intensity was below 30% and the maximum yield of major crops such as cotton, wheat and rice was 1,080, 1,400 and 1,400 kg/acre, respectively [10]. In 2010–2011, the country's average yield per acre for cotton, wheat and rice was 725, 2,933 and 2,039 kg/acre, respectively [11]. It shows that the production of cotton (per unit land) was higher in the study area compared to the average yield in Pakistan. However, rice and wheat productions (per unit land) were much lower in the study area. Maximum land value was less than Rs. 40,000 per acre (about 700 US dollar) [12].

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 (i.e. JRS 36) installed at the right side of Jamrao canal to determine if any up-coning occurs if the tube well was run for more than the design hours (14.4 h per day). We also determined the operational efficiency of all 79 scavenger wells installed at the right side of Jamrao canal to evaluate whether the design objectives of the scavenger wells were being achieved.

1.2. 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

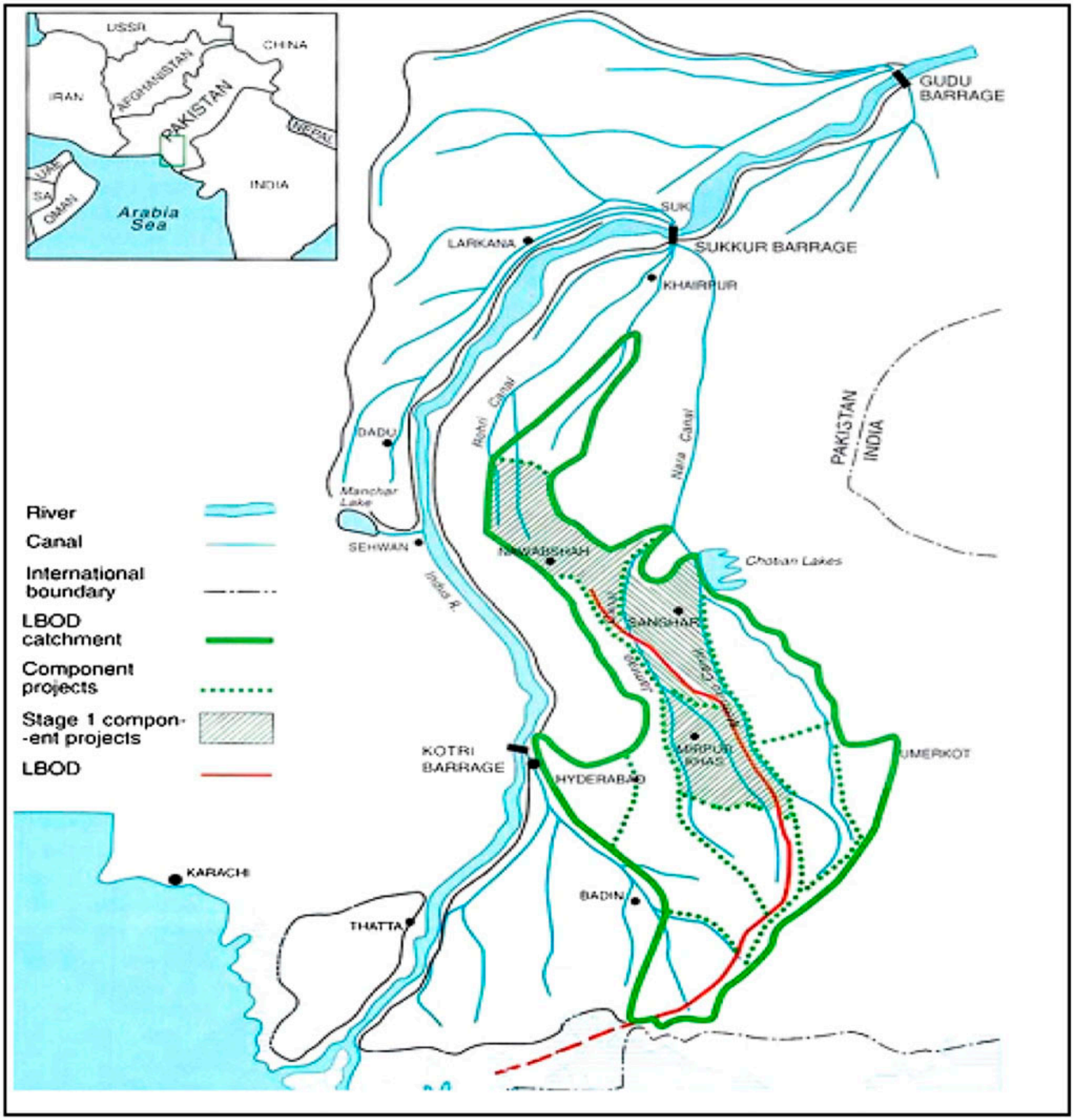

Fig. 1. Map of LBOD and its components.
Source: [1].

Fig. 3, scavenger wells pump both the fresh and the saline groundwater but through separate outlets. Fresh groundwater is used for irrigating agricultural fields, while saline groundwater is thrown into the open drains which ultimately dispose of in the Arabian Sea.

Groundwater quality stratification with freshwater 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 [13].

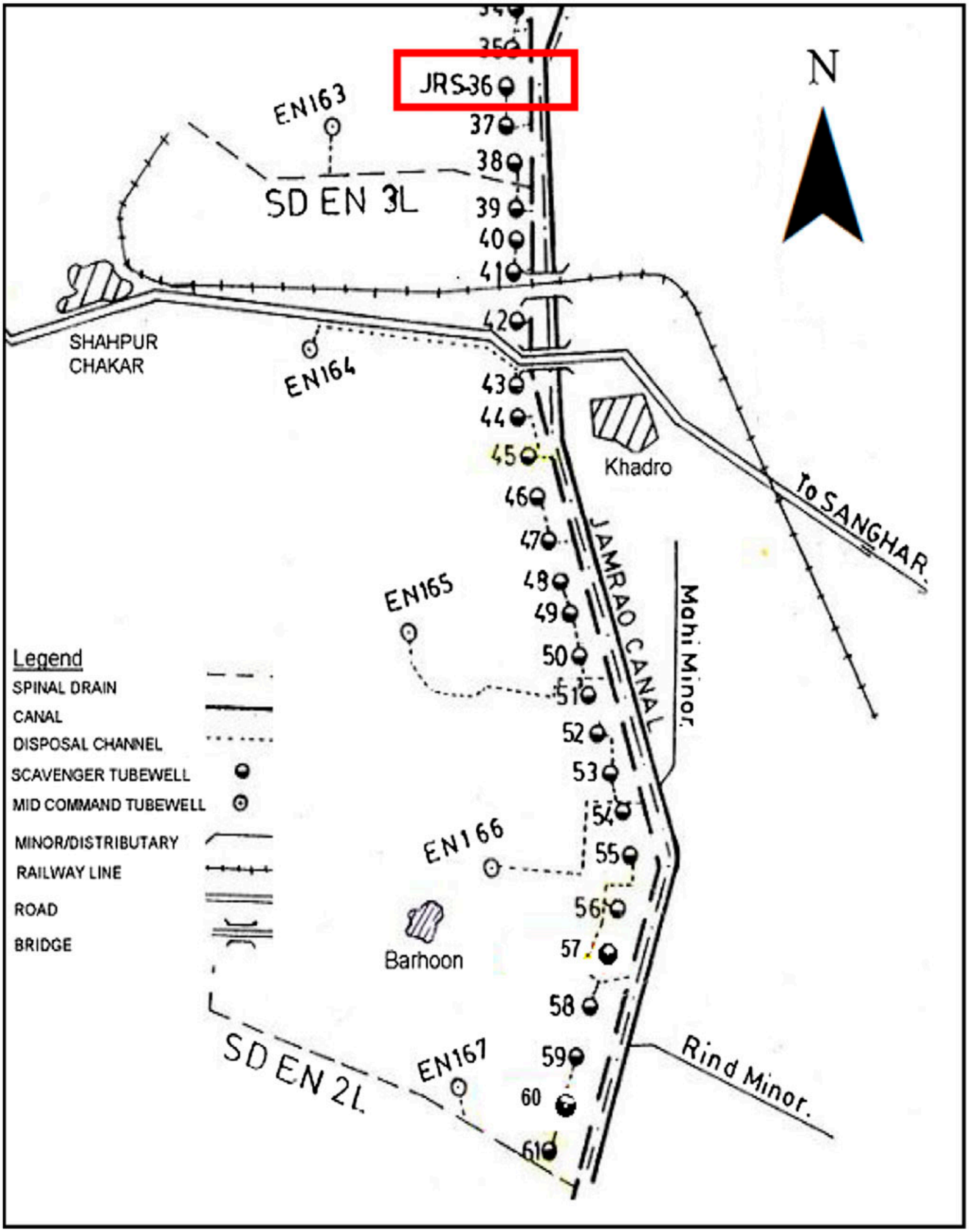

Fig. 2. Scavenger wells on right side of Jamrao canal.
Source: [1].

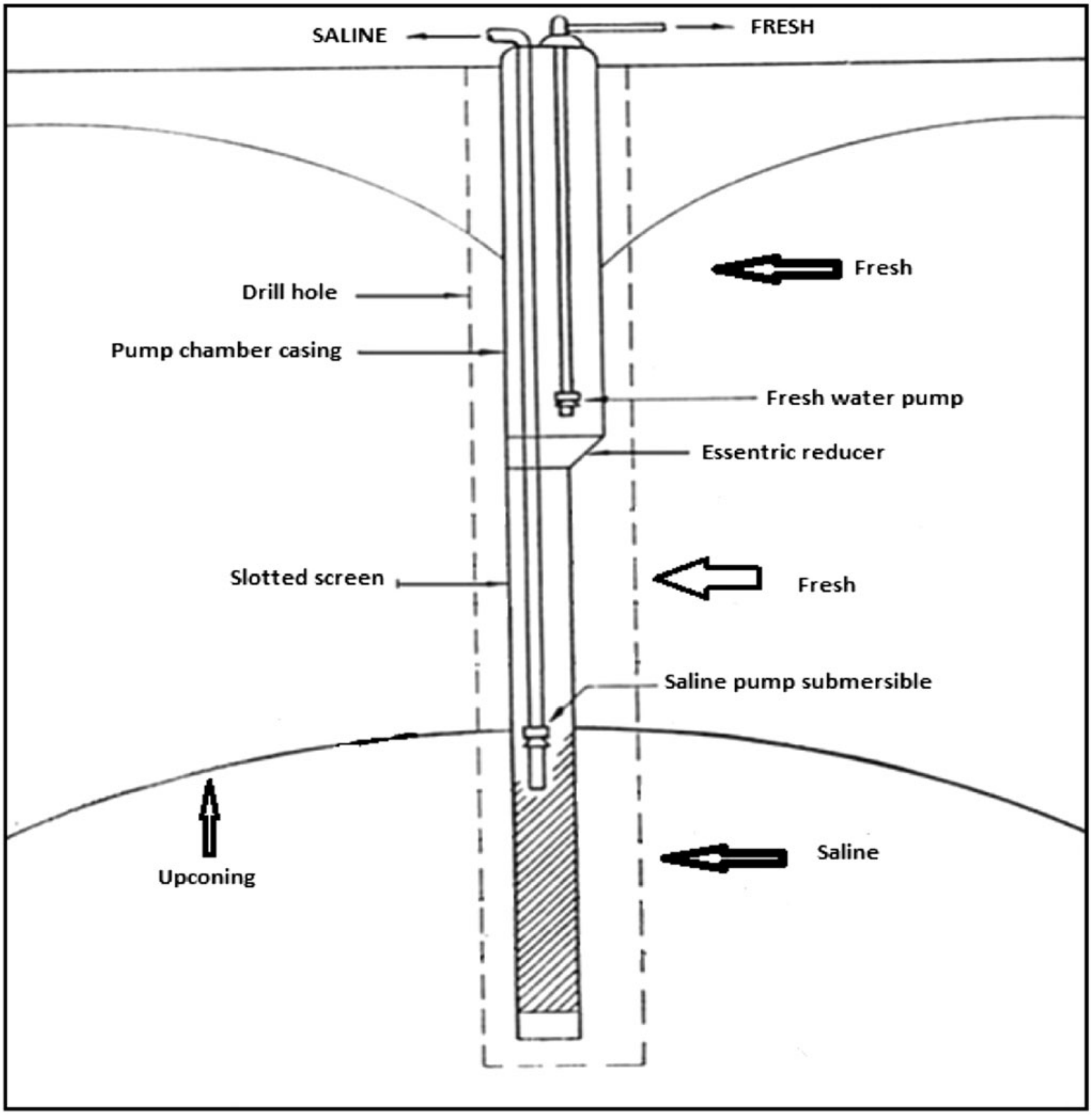

Fig. 3. Schematic diagram of scavenger well.

Three different skimming concepts have been studied in relation to the Lower Indus groundwater basin in Sindh [14].

(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 groundwater but through separate outlets provided that the fresh/saline interface or transition zone is confined by streamlines. No mixing takes place and the freshwater can be used, whilst the saline effluent is disposed to waste.

If the fresh groundwater layer is thin, scavenger wells may be the best (or even the only economically viable) method of skimming [15]. 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.

The study may have two main objectives to achieve: (1) determining operational efficiency of 79 scavenger wells and (2) observing up-coning phenomenon under constant rate pumping test. Since the installation of scavenger wells in LBOD project area in 1994–1995, operational efficiency of these tube wells has not been determined. In this study, thus, we have determined operational efficiency of 79 scavenger wells by visiting each and every tube well and collected data of operational hours on the digit board. The raw data were then used in Eqs. (9) and (10) and operational efficiency was calculated. The second phase of the study was to observe up-coning phenomenon by running a constant rate pumping test on the selected scavenger well (i.e. JRS-36). A 26-h pumping test was performed to check whether up-coning occurs when the scavenger well operates more than the design operational hours (i.e. 14.4 h per day), we performed a pumping test on JRS-36 tube well.

2. Methodology

2.1. Governing equations for scavenger well design

When water is being pumped out through scavenger well, the freshwater and the saline water layers behave as [16]:

(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.

The effect of drainage options on the induced canal seepage is shown in Table 1. An increase in canal seepage occurs under all scavenger well operation conditions (between 17 and 20%) [17]. Induced canal seepage is very sensitive to the distance of tube well from centre of the canal. However, mid-command wells, seepage wells and interceptor drains also show the same feature as shown in Table 1. If scavenger well, mid-command well and the interceptor drain (i.e. Option 6) are combined and practiced as a single drainage option, the induced canal seepage will be 20% higher than the drainage Option 2, i.e. “mid-command wells only”. On the other hand, if seepage well, mid-command well and the interceptor drain (Option 4) are placed as a drainage option in the study area, it will cause 17% more induced canal seepage of Option 2, i.e. the “mid-command wells only”.

2.1.1. Freshwater recovery

The freshwater recovery is dependent only upon a limited number of key parameters. These include [16]:

(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 200–230 ft (61–70 m). Modelling showed that a contrast in vertical permeability of 10–1 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 (4.25–6.1 m).

2.1.2. Maximum freshwater recovery ratio

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

Table 1
Effect of drainage option on induced canal seepage

Option no.	Drainage option	Canal seepage ($m^3/d/m$)	Percentage increase relative to Option 2	Percentage increase relative to 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

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

where

$$\text{RATIO} = 0.01 \times (a \times \text{AQTHI} + b) \times \text{DINT} \quad (2)$$

$$\text{SRP} = \text{WTOP} + \text{DINT} \times \text{LS}/\text{AQTHI} \quad (3)$$

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

where Q_{um}/Q_c (max) is maximum ratio of freshwater 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 Eq. (3) as the distance of a so-called screen reference point from the top of the saturated aquifer (Fig. 4). 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 freshwater lens thickness, effective aquifer thickness and anisotropy ratio, derived from model simulations, and Kh/Kv is anisotropy ratio [16].

2.1.3. Well capacity

The well capacity thus easily follows from:

$$Q_w = \text{WS} \times Q_{cs}/F \quad (5)$$

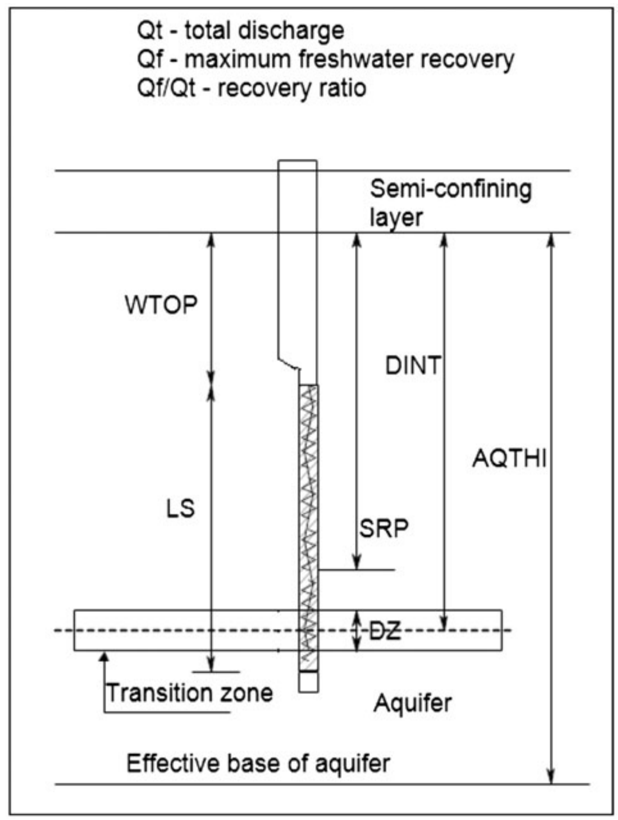

Fig. 4. Parameters of a typical scavenger well (modified after [16]).

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 h).

2.1.4. 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:

$$\mathrm{WS} = Q_{\mathrm{w}} \times F / Q_{\mathrm{cs}} \tag{6}$$

All the parameters were defined earlier.

2.1.5. Equation for drawdown

Drawdown is calculated from the equation:

$$S_{\mathrm{w}} = 1.32 \times Q/K \times L \tag{7}$$

where S_{w} is well drawdown, m, Q is discharge rate, m^3/d, K is permeability, m/d and L is length of well screen, m.

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

2.1.6. Optimization of freshwater recovery

The geometry of the freshwater lens, which attains its greatest thickness towards the centreline of the canal, favours a good 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 freshwater recovery favours the maximization 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 freshwater recovery is constrained by the thickness of the transition zone at the well screen during well operation. The optimization of freshwater recovery obviously minimizes the effect of the transition zone if the screen length is at a maximum [18]. The optimization well screen is related to the controlling parameters as follows:

$$\mathrm{LS}_{\mathrm{opc}} = \sqrt{\frac{0.5 \times A \times \mathrm{DZ} \times \mathrm{AQTHI}}{(1 - \mathrm{RATIO}) \times \mathrm{DINT}}} \tag{8}$$

where additionally, $\mathrm{LS}_{\mathrm{opc}}$ is optimum screen length for maximum freshwater recovery; and

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

Since the design discharge capacity of the well is closely related to the screen length, with 50–56 ft (15–20 m) 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.

2.2. 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 60 m (190 ft) and high abstraction rate i.e. 1.25 cusecs freshwater 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 μS/cm throughout the pumping period, the lower pump water quality was "steady state" where the electrical conductivity (EC) of the discharge water is relatively constant. Drawdown at well was found as 15 ft (4.58 m) 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. 5. Operational efficiency of scavenger wells was determined from the operational hours recorded on digital board for each scavenger well and using following equations:

$$E_{\mathrm{fwp}} = \left(\frac{H_{\mathrm{fwp}} \text{ per day}}{14.4}\right) \times 100 \tag{9}$$

$$E_{\mathrm{swp}} = \left(\frac{H_{\mathrm{swp}} \text{ per day}}{14.4}\right) \times 100 \tag{10}$$

where

$$H_{\mathrm{fwp}} \text{ per day} = \frac{\text{Total fresh water pumping hours}}{365.25 \times 18}$$

$$H_{\mathrm{swp}} \text{ per day} = \frac{\text{Total saline water pumping hours}}{365.25 \times 18}$$

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

3. Results and discussion

3.1. Constant rate pumping test

3.1.1. Water table level fluctuation

Water table level in piezometers during the pumping test is shown in Fig. 6. The water table levels

Table 2
Salient features of JRS-36 scavenger well (modified after [19])

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 freshwater	900 µS/cm

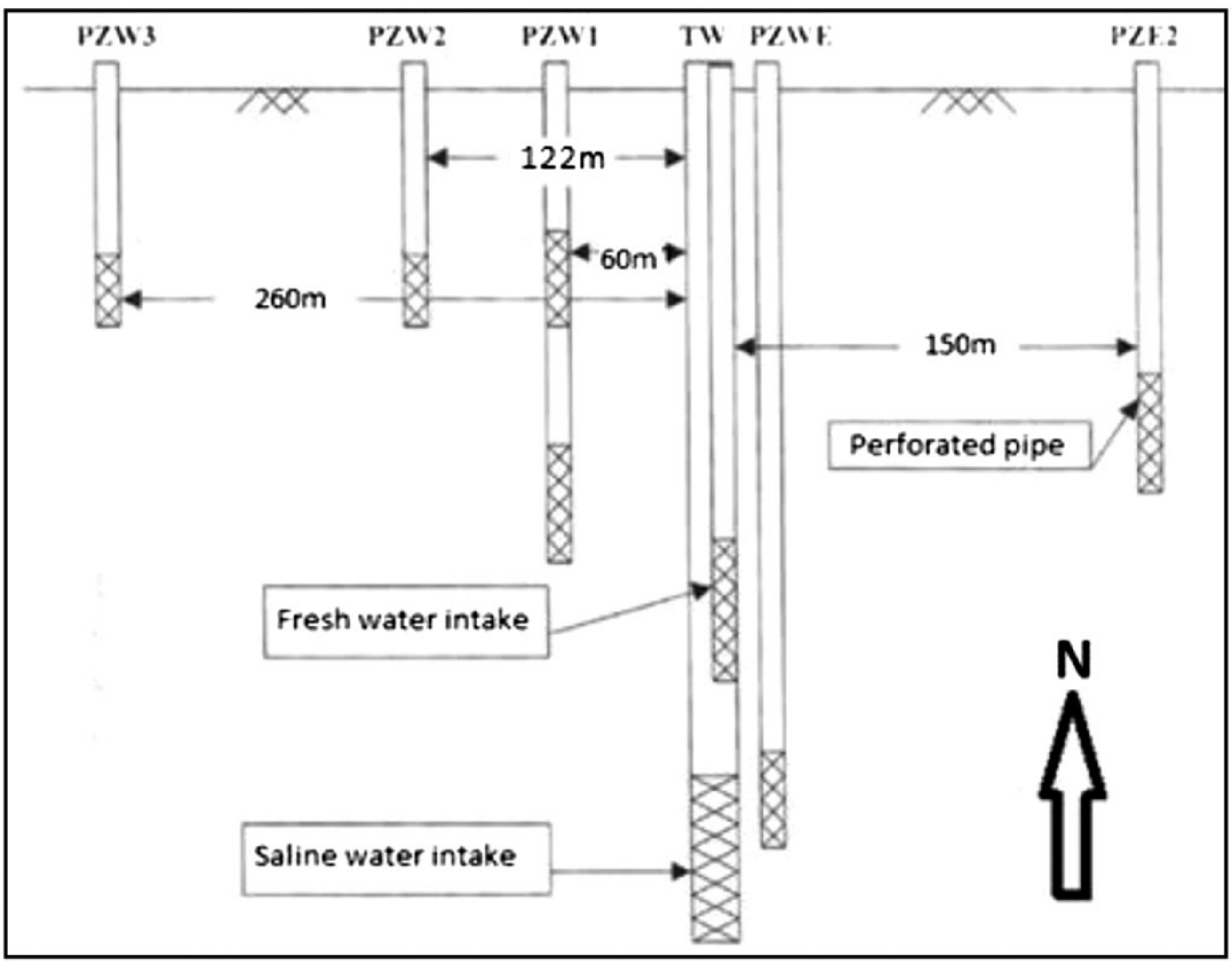

Fig. 5. Location of piezometers around the JRS-36 tube well.

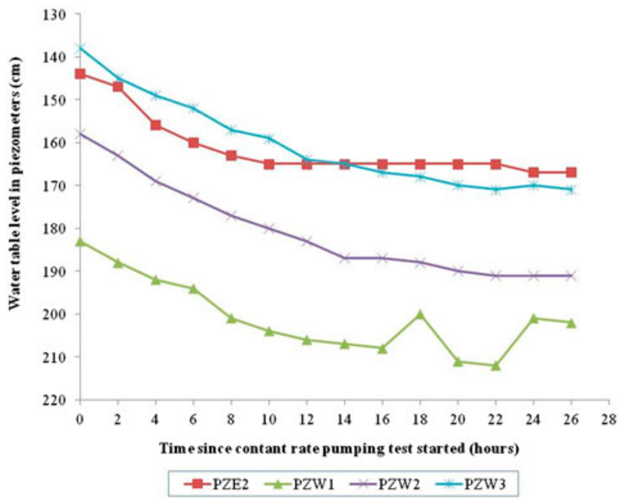

Fig. 6. Water table levels at the piezometers during the pumping test.

before the constant rate pumping test were 144, 183, 158 and 138 cm at PZE2, PZW1, PZW2 and PZW3, respectively. The initial water table level was shallow for two piezometers, i.e. PZE2 (close to Jamrao Canal) and PZW3 (far away from JRS-36 tube well). This could be because of high canal recharge and low effect of the tube well operation (bigger radius of influence). We also found that the rate of drawdown at the second half of the pumping test (i.e. 14–26 h since the start of the test) was milder than the rate of drawdown in the first half of the pumping test (i.e. 2–12 h). This trend in drawdown could be because of groundwater flow from larger area of the aquifer.

3.1.2. Drawdown in piezometers

Table 3 presents some of the pumping test results including drawdown in each piezometer. Total drawdown at PZE2, PZW1, PZW2 and PZW3 piezometers was 22.8, 29.4, 33.6 and 32.4 cm,

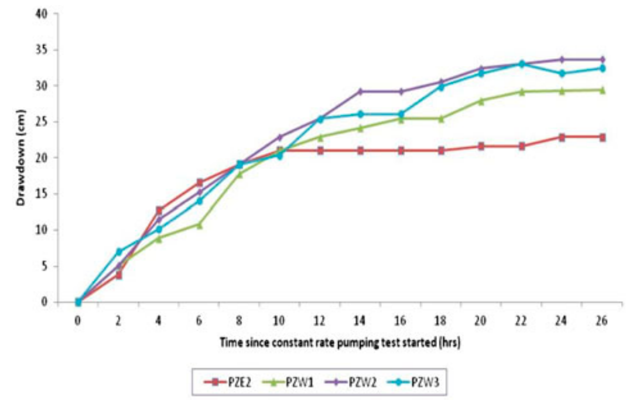

Fig. 7. Drawdown at piezometers during the pumping test.

respectively. This shows that piezometers PZW2 and PZW3 had more drawdown compared to PZE2 and PZW1 piezometers. The change in drawdown for last 6 h of the pumping test was very low indicating steady state condition. PZE2 shows rapid drawdown at the start of the test, and gradual and slow increase after ten hours of the test (Fig. 7). Drawdown recorded at PZW1 remained in fluctuation during the whole period of the constant rate pumping test. Some sudden increase in the level of water table at 10th hour of the pumping test was due to the irrigation water application to the nearby agricultural land and/or because of induced canal water seepage (Fig. 7). If the reduction in drawdown was because of the induced canal seepage, it could be uneconomical to run tube well for 26 h continuously.

Results obtained at PZW2 show a gradual increase in the drawdown and owed to the position of piezometer in barren land. 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 has shown the same trend as of the PZW1. A continuous operation of

Table 3
Piezometers and tube well data

	Parameters				
Piezometer	Distance from JRS-36 tube well (m)	Total drawdown in 26-h pumping test (cm)	Rate of drawdown (cm/h)	Total variation in EC (µS/cm)	Total variation in 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

JRS-36 tube well for 20 h or more could cause induced seepage and must be avoided to make freshwater abstraction more economical. Here, we emphasize that the drawdown in JRS-36 and PZWE might be slightly different as gravel pack could block actual drawdown to appear in the piezometer. However, we believe that the difference in drawdown was not significant. Moreover, there was no facility for measuring drawdown at JRS-36 itself. Thus, we assumed that the drawdown in PZWE was representing drawdown in JRS-36 during the pumping test.

3.1.3. Water quality variation

Water quality in terms of EC and TDS parameters for the five piezometers was checked at 2-h interval and did not find any significant variation in water quality during the pumping test. For example, the highest and the lowest EC values at JRS-36 were 1,290 and 1,100 μS/cm, respectively. An average change of 190 μS/cm units is not significant. The water quality of JRS-36 tube well remained below 1,300 μS/cm EC value and that is suitable for irrigation usage [20]. We also found that water quality was slightly inferior between 2 and 8 h of the pumping test (Fig. 8). This change in water quality could be because of inflow from barren land adjacent to JRS-36 observation well. It should be noted that EC value for JRS-36 tube well in 1995, the year of tube well installation, was 1,300 μS/cm (Table 2) and it was slightly higher than the observed EC values during the pumping test (1,100–1,290 μS/cm). This slight difference in groundwater quality could be because of the intensive irrigation applications in the area since the operation of scavenger wells.

A slightly higher change in water quality was observed at PZW3 piezometer. The highest and lowest EC values for PZW3 water samples were 6,480 and 6,110 μS/cm, respectively. Water quality at PZW3 piezometer was unfit for any uses including irrigation. There was a trend in water quality deterioration during the pumping test for PZW1, PZW2 and PZW3 piezometers. However, this trend was not detected for water samples collected from JRS-36 and PZE2 piezometers. This could be interpreted as low chances of up-coning at JRS-36 scavenger well. However, this finding could be validated from more pumping test on JRS-36 scavenger well and also pumping tests on the neighbouring scavenger wells.

The highest and lowest TDS values at JRS-36 were 634 and 550 mg/l, respectively. The difference between the highest and lowest TDS values was not significant (i.e. 84 mg/l) during 26-h pumping test except at PZW3 where a change of 265 mg/l in TDS was observed (Table 3). The trend in deterioration of water quality was not observed at piezometers except for PZW3 where water quality was getting inferior from the start to the end of the pumping test (Fig. 9).

3.2. 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

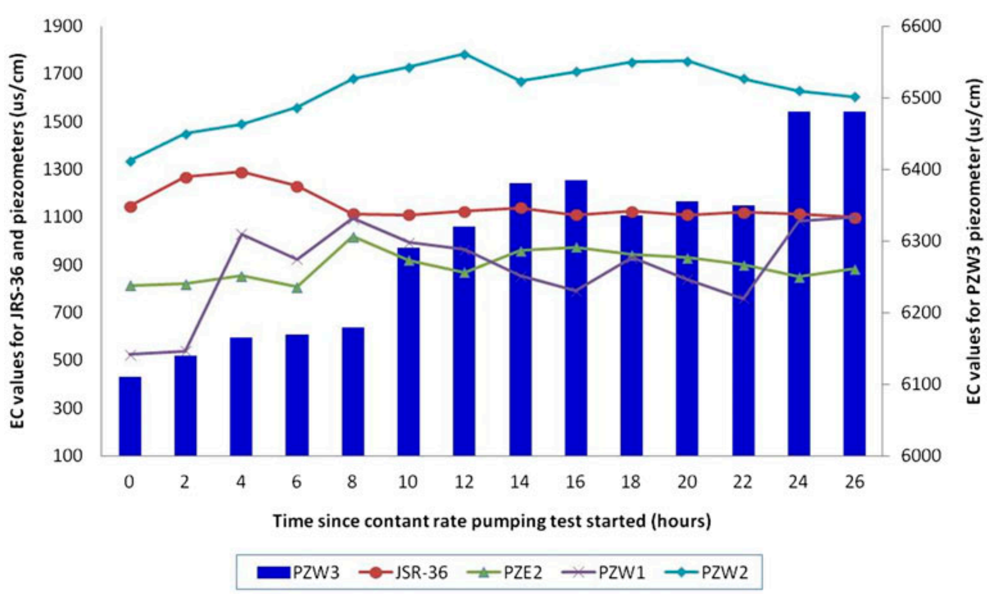

Fig. 8. Variation in EC during the pumping test.

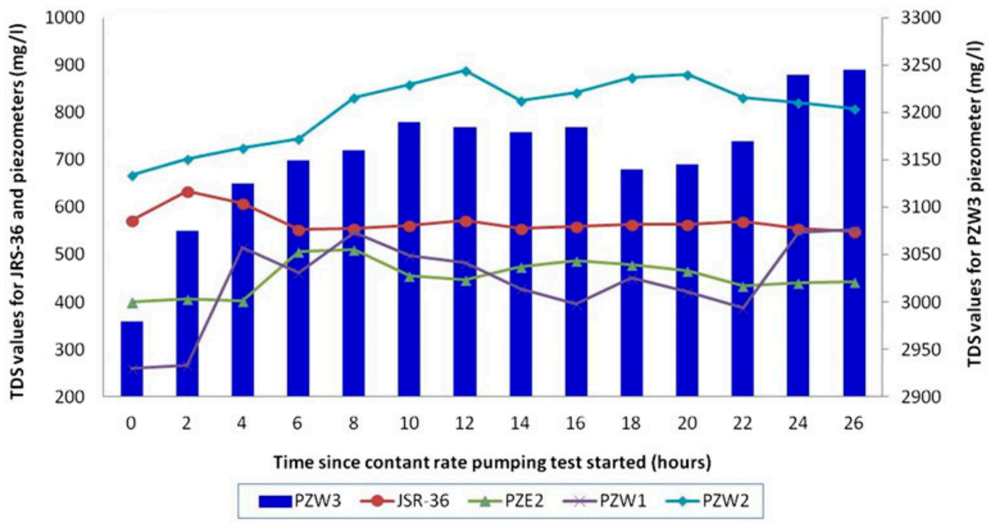

Fig. 9. Variation in total dissolved solids (TDS) during the pumping test.

for 14.4 h 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) and (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 and (2) not much freshwater is abstracted for meeting irrigation and other demands for freshwater. The low efficiency of the scavenger wells in the study area could be attributed to many factors. Firstly, it takes long time to repair a tube well if it gets mechanical, electrical and/or even hydrological problems. Secondly, frequent outage of electricity stops scavenger wells from operation and this problem further aggravates in monsoon season where transmission lines generally get problem. The other minor problems that might be contributing in low operation efficiency could be no demand of freshwater from farmers, overflow of drainage system in the vicinity of the tube well, negligence of tube operator and conflict amongst the farmers on allocation of freshwater share.

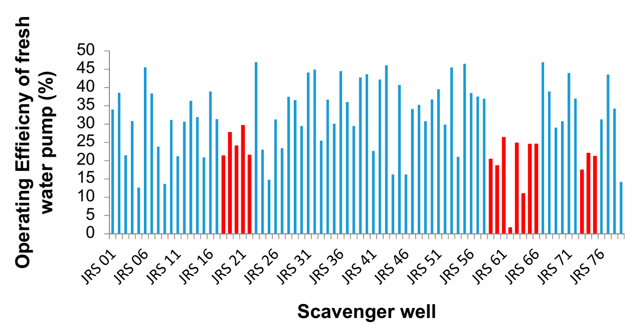

Fig. 10. Operational efficiency of freshwater pump of scavenger wells.

The analysis of operational hours data for the selected 79 scavenger wells shows that none of the freshwater pumps of 79 scavenger wells had current operational efficiency above 50% of the design operational efficiency (Fig. 10). Thirty-five freshwater pumps which make 44% of 79 scavenger wells were operating less than 30% of the design operational efficiency. This clearly shows that freshwater recovery from the scavenger wells was very small. We also identified that at least three locations (marked with red colour in Fig. 10) where three more 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 freshwater pumps was merely 30.7%, which means that each freshwater pump of the scavenger wells on average was running 4.4 h per day. However, these pumps were designed to run for 14.4 h per day to control up-coning problem and abstract freshwater for irrigation and other purposes. The low average operational efficiency of freshwater pumps indicates that the farmers were deprived of freshwater for irrigating their agricultural farms and this in turn can significantly affect their farm income.

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 freshwater pumps). On average, each saline water pump was running for just 5.4 h 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. 11). 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 longer period. We also identified three locations (marked with red colour in Fig. 11) where at least three saline water pumps were running below 30% of the design operational efficiency.

As freshwater 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 the 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 freshwater pumps also run continuously below the design operational efficiency. In case of higher efficiency of freshwater pumps, up-coning can occur in the areas with low saline water pump efficiencies.

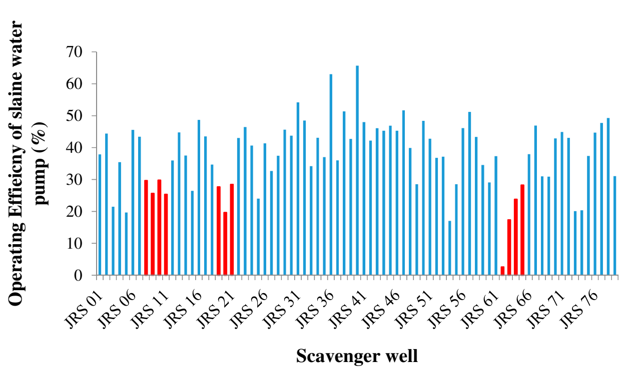

Fig. 11. Operational efficiency of saline water pump of scavenger wells.

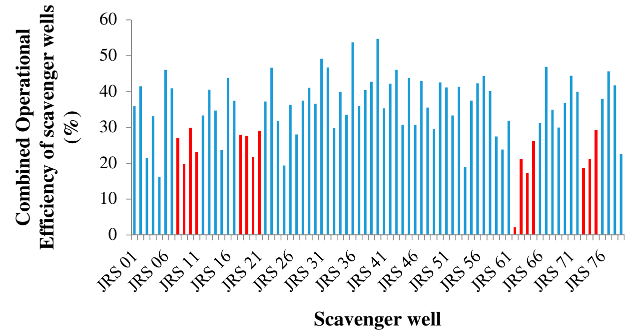

Fig. 12. Combined operational efficiency of fresh and saline water pumps.

The combined operational efficiency of scavenger wells is shown in Fig. 12. Combined operational efficiency of scavenger wells were determined by combining operational hour readings of both the 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. 12). 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 freshwater 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 h per day and freshwater pump for 6.4 h per day. Both pumps were supposed to be running for 14.4 h per day. The operational efficiency of freshwater 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 h 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.

4. Conclusions

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

(1) 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.
(2) 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 h per day). This low operational efficiency ultimately reduces the net present value (NPV) of the scavenger wells.
(3) 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 freshwater pumps and induced canal seepage.

Acknowledgements

This study was partly funded by the Ministry of Higher Education (MOHE) Malaysia and the Universiti Teknologi Malaysia (UTM) under TRGS-Flood Grant with Vot no. 4H827 and FRGS Grant Vot no. 4F539. This study was also supported by the Asian Core Programme of the Japanese Society for the Promotion of Science (JSPS).

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