STRATEGIES FOR SAFE EXPLOITATION OF FRESH WATER THROUGH MULTI–STRAINER SKIMMING WELLS IN SALINE GROUNDWATER AREAS

Dr. Muhammad Mehboob Alam, Hassan Mehtab Jaffery, Muhammad Hanif*

ABSTRACT

Due to growing population of Pakistan, there is a tremendous pressure on our agriculture sector to increase its production to meet the food and fibre requirement. Water is a basic need to increase the agriculture production and to bring more areas under cultivation. The exploitation of groundwater resources is increasing because of limited surface water availability. Statistics indicated that number of public and private tubewells have increased to more than 5 lacs. Over exploitations of groundwater caused a number of environmental problems including salt water intrusion and increase in the soil and groundwater salinity. A large number of fresh water tubewells have started pumping saline groundwater in various parts of Pakistan indicating up-coning of saline groundwater in the relatively fresh water aquifers. Use of poor quality groundwater for irrigation is considered as one of the major causes of salinity in the areas of irrigated agriculture. Indiscriminate pumping of the groundwater of marginal quality through skimming fresh water overlain by saline groundwater can not be helpful in the long run. It can add to the root zone salinity and ultimately reduction of crops yield.

Mona Reclamation Experimental Project (MREP) is conducting a collaborative research study on “Root Zone Salinity Management using Fractional Skimming Wells with Pressurized Irrigation” under a research and studies portfolio of the country wide National Drainage Programme (NDP) MREP, IWMI Pakistan and Water Resources Research Institute of PARC are collaborators in this joint research effort. MREP is responsible to specifically address the objective of the study to identify and test a limited number of promising skimming well techniques in the shallow fresh water aquifers which could control the saline water up-coning phenomenon as a consequence of groundwater pumping.

Detailed investigations have been done at various locations in the north-central part of Chaj Doab (Sargodha Region) in the Indus Basin of Pakistan to develop strategies for the safe exploitation of fresh upper groundwater layer through multi-strainer skimming wells in the areas having deeper saline groundwater. Results of detailed investigations are given in this paper.

A methodology was designed for investigations and to study the movement of saline-fresh water interface. For this purpose deep observation wells were installed and water samples from various depths over a period of wells operational hours have been collected. Water quality of these samples was tested to evaluate the movement of saline-fresh water interface. Results indicated that there exists a relatively fresh water aquifer above the depth of 20 m. Relatively impervious layer and clay lenses of variable thickness exists at various locations in the area. There is relatively less contribution from the lower aquifer as compared to the lateral movement of water to the well above the impervious layers. The skimming wells were operated for a different number of hours and water quality evaluated.

---

* Project Director, Senior Engineer and Jr. Agri. Officer, Mona Reclamation Experimental Project, WAPDA, Bhalwal. Phone: +92-0455-42756, Fax: +92-0455-42663, E.Mail: pd_mona@hotmail.com

The results show that the quality and quantity of the pumped groundwater can be improved with intermittent pumping for 4-6 hours per day under drought conditions and recovery of the watertable is quick. Moreover, the intermittent pumping maintained a minimum suction lift that helped get a relatively good discharge. Continuous long term pumping proved to be dangerous which can cause saline water intrusion. It is recommended to avoid long term pumping of skimming wells. Intermittent short hours operation can be helpful for safe exploitation of fresh water and make skimming well operation more cost effective. It is further added that 4-6 strainers make these skimming wells cost effective as compared to having a large number of strainers in a skimming well.

1. BACKGROUND

In preview of the exploitation of fresh groundwater, the problem of drainage is complicated by the fact that the native groundwater that existed in the pre-irrigation period was saline because of the underlying geologic formation being of marine origin. This is now overlain by a fresh water zone as a result of seepage between the native pre-irrigation water table and existing water table.

However, in some areas, the thickness of the shallow groundwater zone ranges from less than 60 meters along the margins of doabs to 30 meters or more in the lower or central parts of doabs (Sufi and Javed, 1988). In such areas, private and public tubewells are likely to draw a substantial portion of their discharge from the saline zone unless special care is taken. Hafeez et al. (1986) reported that the pumped water in the shallow fresh groundwater zone has become more saline with time and many of the deep tubewells were shutdown at the request of farmers. Ashraf et. al. (2001) and Asghar et. al. (2002) tested various skimming well interventions.

It has been estimated that nearly 200 billion cubic meters of fresh water is lying on saline groundwater mostly in the form of a thin layer (Sufi et al., 1992). Obviously, if proper technology is applied, the referred thin fresh water layer can be skimmed from the aquifer with minimum disturbance of the saline zone. In the short-supply environment of Pakistan, such extractions would become a significant part of supplemental irrigation.

Private sector is showing a great interest in the exploitation of pumping groundwater and related technology. Tubewells are being installed even in the thin fresh groundwater zones with discharge rates from 28 to 45 l/s. If such tubewells are not replaced with fractional skimming wells, there can be a serious concern that the water pumped will become increasingly more saline with time. Resultantly, many tubewells will have to be abandoned. As a matter of fact, in the Mona Reclamation Experimental Project (MREP) many large public wells (discharges 70-120 l/s) had to be shut down on the request of farmers as these tubewells were pumping water of high salinity and sodicity. Water analysis of these tubewells is given in Table 1.

Table I. Water quality data of abandoned deep wells at MREP Bhalwal.

Tube Well No.	TDS (ppm)	SAR	RSC (meL^{-1})
MN 116	3520	23.3	2.23
SHP-20	6080	36.0	-
MN 138	3006	10.1	-
MN 93	1408	12.0	4.1
MN-80	1910	17.0	8.0
MN 37	2240	15.1	4.1

Therefore, it seems imperative to introduce skimming well technology to address the future water quality concerns. For thin-layered fresh-water zones underlain by saline groundwater, low capacity fractional wells (discharge rates 6 to 9 l/s) have been and are being tried in the Mona Reclamation Experimental Project (MREP) to avoid the eventual pumping of saline water from the groundwater reservoir. These interventions are being tried under the research component of the World Bank funded National Drainage Programme (NDP). The main objectives of the study are given in the following section as:

Objectives

1. To identify and test a limited number of promising skimming well techniques in the shallow fresh-water aquifers which could control the saline water upconing.
2. To encourage and support in-country manufacturers to develop low-cost fractional skimming well adaptable within the local setting of Pakistan; and
3. To implement an irrigation scheduling program aimed at root-zone salinity management with skimmed fresh (in a relative sense) water applied by low-cost pressurized systems.

This paper is a part of the input which contributes towards the main objectives of the study. The specific objective of the intervention elaborated in this paper is to evaluate and identify appropriate strategies for skimming relatively fresh groundwater from unconfined aquifers underlain by saline groundwater and promote their potential at farmers fields.

Description of the study area

This study was conducted in the north-central part of the Chaj Doab. The area is located between Jhelum and Chenab Rivers in the Indus Basin of Pakistan. The study area is bounded by the Lower Jhelum Canal to the east and the Shahpur Branch Canal to the north. The area is 48 km east to west and 13 km north to sourth, covering 71,742 hectares in 83 villages. The soils of the area range from coarse to moderately fine, with the predominance of moderately coarse texture soil class. Most of the area is underlain by saline groundwater. However, upper water quality is useable. Water quality of a few selected villages is given in Table 2.

Table 2. Selected villages based on the spatial analysis of deep groundwater quality in the study area.

S/No.	Name of village	Deep groundwater quality
1	Ratto Kala	Marginal
2	Chak 1/NB	Marginal
3	Thathi Noor	Marginal
4	Jalar Waraichan	Marginal
5	Chak 6/ML	Marginal
6	Nabi Shah Bala	Marginal

Climate

The climate of the area is characterized by a large seasonal variations in temperature and rainfall. Usually the temperature during winter ranges from 7^{o}C to 20^{o}C. In summer, May-July extending to august, the weather is extremely hot with temperature more than 40^{o}C. Mean annual rainfall and evaporation are 460 and 1625 mm, respectively. The canal water supply is usually less than farm irrigation water demands. Although, the rainfall in Pakistan is markedly variable in magnitude, time of occurrence and its spatial distribution (Khan and Muhammad, 2000), it contributes significantly in meeting crop water requirements. Already, the recent dry spell in the region has marginalized this benefit of precipitation both in the kharif (summer) and rabi (winter) cropping seasons.

2. MATERIAL AND METHODS

Farmers were the main focus of the skimming well study with respect to their existing practices, management skills and capacity to accept and adopt the technology. The essential elements of the proposed strategy were: (i) joint learning and joint actions; (ii) participatory appraisal and design; (iii) participatory implementation; and (iv) participatory monitoring and evaluation.

On the basis of a detailed Participatory Rural Appraisal (PRA) and Diagnostic Analysis (DA), four multi-strainers skimming wells were monitored and evaluated for groundwater quality and movement of saline-fresh water interface. Salient features of these skimming wells are given in Table 3. Detail of the investigations is as follows:

Table 3 Description of skimming wells selected for the study

Well configurations	Discharge (lps)	Power modes	Irrigation methods
3-strainers	16-17	15 HP – Electrical	Surface
4-strainers	20-22	18 HP – Diesel Engine	Innovative surface
6-strainers	26-27	18 HP – Diesel Engine	Surface/innovative
16-strainers	25-28	Tractor	Surface

3–strainers skimming well

A 3-strainer skimming well was selected at the Phularwan farm of Mona Reclamation Experimental Project (MREP), Bhalwal. The bore No. 1 was 20.4 m deep with 14.3 m strainer; bore No. 2 was 15.8 m deep with 9.7 m strainer and the bore No. 3 was 9.7 m deep with 3.6 m strainer. The diameter of the strainers and suction pipe was 15 cm and 10 cm, respectively. The suction pipe extends to a depth of 9 m in each well. Layout of the strainers and observation wells is shown in Figure 1.

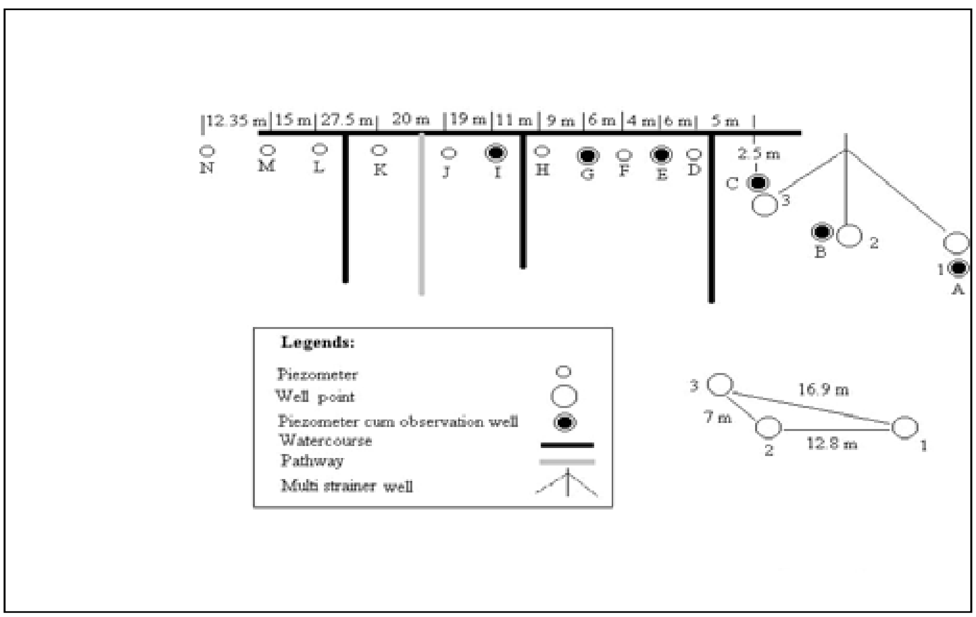

Figure 1. Layout of strainers and observation wells

To investigate the effect of pumping on the quality of groundwater, observation wells up to 30 m depth, were installed in the vicinity of the skimming well. The small diameter pipes (25.4 cm) perforated from the bottom were installed to collect samples from 3 to 30 m depths with an interval of 3 m. The casing was then, removed from the soil and the bore was allowed to refill and collapse. Piezometers were also installed near the skimming well to observe the watertable fluctuations.

4 and 6-strainers skimming well

Four and six strainers skimming wells were selected at farmer's field to address the concerns related to the number of strainers under the specified hydro-geological conditions and the horizontal distance of strainers from suction pump. Each strainer had 6.7 m of screen length. Well penetration ratio was estimated to be equal to 60% of the relatively fresh groundwater depth. In order to minimize suction losses and to distribute suction evenly over all the strainers, strainers were installed at the periphery of a circle having 1.5 m radius from the suction point. Both the wells were monitored from October 2000 to July 2001 for variations in quality and quantity of pumped groundwater. These wells were operated intermittently for 4-6 hours/day.

16-strainers skimming well

A 16-strainer skimming well has been installed by a farmer at Nabishah Bhalwal (Table 3). The diameter of each strainer was 5 cm and it extended up to 17 m depth. The upper 6 m was blind and the bottom 9 m was perforated. Piezometers were installed 60 cm away from each strainer to observe the groundwater contribution from each strainer. One observation well was installed near the pump at a distance of 1.5 m and another at 8.54 m away from the pump to monitor the spatial and temporal changes in the groundwater quality. Configuration of strainers is shown in Figure 2.

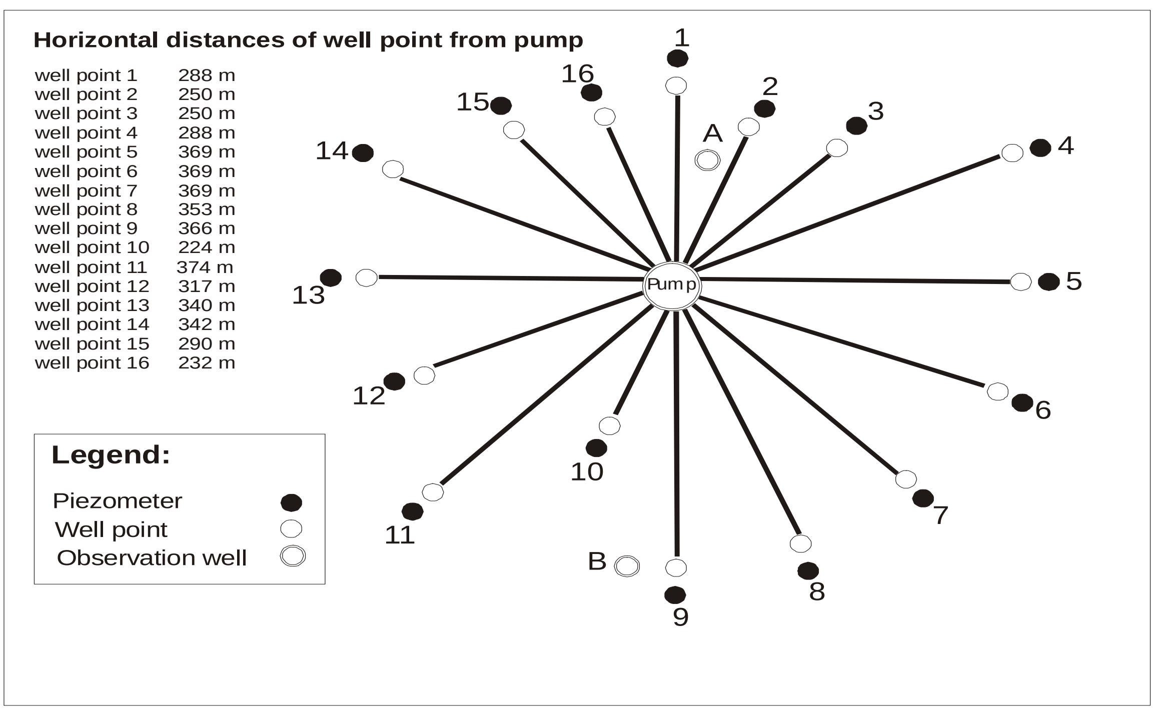

Figure 2. Location of piezometers and well points of 16-strainers skimming- wells at Nabi Shah, Bhalwal.

A 90 degree V-notch weir was installed in the diversion channel of the skimming well to measure the variation in discharge with time. A rip-rap was constructed in the diversion channel to control the turbulence in water. A small hole was made on the upstream of the V-notch in the sidewall of the diversion channel and was connected to a transparent pipe. A graduated roller was smeared with the transparent pipe to measure the head over the weir. A water level recorder was used to measure the watertable fluctuations. A suction pump was used to take water samples from the observation wells. First the vacuum was created in a flask. The flask was then attached to the pipes of the observation well. Due to the vacuum in the flask, considerable amount of water from the obsevation wells (upto 1 litre) was sucked into the flask and was analyzed for electrical conductivity (EC). This method provides water sample from the required depth without any contamination. An EC meter was used in the field to measure the EC of the groundwater. The EC of the pumped water was measured at start and at closing of the pump. The EC meter was frequently calibrated for accurate and reliable data on the groundwater quality.

3. RESULTS AND DISCUSSIONS

Pumped water salinity

The 3-strainer skimming well was monitored for 97 days. During this period, the well was operated for 71 days with an average pumping time of 5 hours per day. The daily operational hours were decided based on the time normally it takes for the water levels to become almost steady state. The well discharge was about 17 lps. About 21726 m^3 (18 acre-ft) of water was pumped during the observation period. The electrical conductivity of the pumped water was measured during pumping at start and before closure. The EC reduced from 1.72 to 1.45 dS m^{-1} during the observation period (Table 4).

Table 4. Effect of intermittent pumping on the quality and quantity of pumped groundwater

Observation period (days)	Pumping days	Operational hrs/day	Discharge (lps)	Volume of water pumped (m^3)	Decrease in ECw (dS/m)	Skimming well
97	71	5	17	21726	1.72-1.45	3-strainers
304	180	5	22	71280	1.45-1.25	4-strainers
304	180	5	27	87480	1.25-1.20	6-strainers
70	41	6	28	24796	1.20-0.90	16-strainers

The 4-strainers skimming well was monitored for 304 days. During this period, the well was operated for 180 days with an average pumping time of 4-6 hours/day. The discharge of the well was about 22 lps. The EC of pumped water reduced from 1.45 to 1.25 dS/m during the observation period from October 2000 – July 2001 (Table 4).

The 6-strainers skimming well was also monitored for the 304 days. During this period, the well was run for 180 days with an average pumping time of 4-6 hours/day. The discharge of the well was about 27 lps. The EC of pumped water reduced from 1.25 to 1.20 dS/m at the end of observation period (Table 4).

The 16-strainer skimming well was monitored for 70 days. During this period, the well was operated for 41 days with an average pumping time of 6 hours per day. The discharge of the well was about 28 lps. About 24796 m^3 (20 acre-ft) of water was pumped during this period. It was estimated that a skimming well of 28 lps could irrigate an area of about 20 acres on weekly rotation basis with 6 hours of pumping per day. The EC of the pumped water reduced from 1.2 to 0.90 dS m^{-1} at the end of the observation period (Table 4). Sufi et al. (1998) also showed that a well installed with 45% penetration ratio and 50% reduced discharge improved the water quality from 1.27 to 0.375 dS m^{-1}. The decrease in electrical conductivity of the pumped water, during the observation period indicates that intermittent pumping helps to maintain the pumped water quality for a longer period.

The improvement in salinity level of the pumped water was most probably due to the pumping of salts from the shallow aquifer to the ground surface and the replenishment of the groundwater from (I) the recharge from the surrounding areas under the hydraulic gradient that developed due to pumping of water; (ii) seepage of water from the soil surface and from the nearby water sources, and (iii) rainfall that contributes to groundwater. A total of 130.5 mm rainfall was recorded at Nabishah site during the study period.

Soil salinity profile

Figure 3(A, B, C) through 4(A, B) show variation of electrical conductivity with depth of the samples, taken from various observation wells related to 3-strainers and 16-strainers skimming wells. For both the skimming wells, the salinity profiles behaved almost in the similar fashion, i.e. salt concentration first decreased with depth, then, increased upto certain depth and again reduced as the depth from the soil surface increased. It indicated that there exist two gradients of salinity below the soil surface. (i) Salinity increased from shallow depth (3 m) towards the soil surface. The reasons for an increased salt concentration near the soil surface may be; (a) application of poor quality water and leaching of salts to shallow depths; (b) pumping of salts from the shallow depths to the soil surface and the replenishment of the same with the freshwater from both the skimming wells had been kept fallow for long time. The water evaporating from the soil surface mainly comes from the groundwater, which transports salts alongwith it. The salt concentration at the soil surface increased with time, as evaporation proceeded, thus developing a downward salt concentration gradient. This is particularly true if soil remains fallow for several months. The shallow watertable contributes significantly to evaporation and soil surface salinization (Doering et al., 1964). (ii) The salt concentration increases from shallow depth towards the saline-freshwater interface.

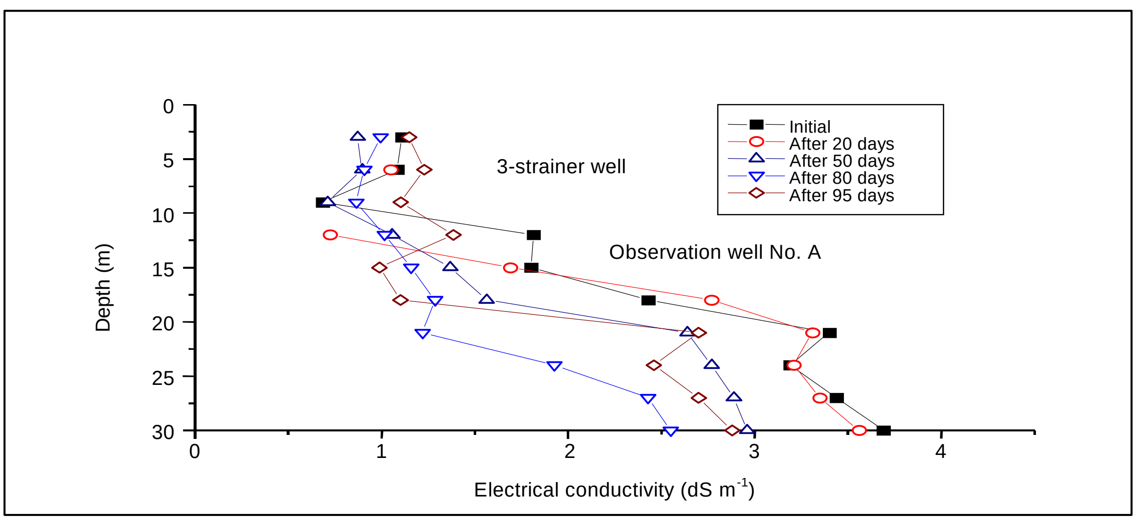

Figure 3-A. Effect of pumping on the salinity of groundwater

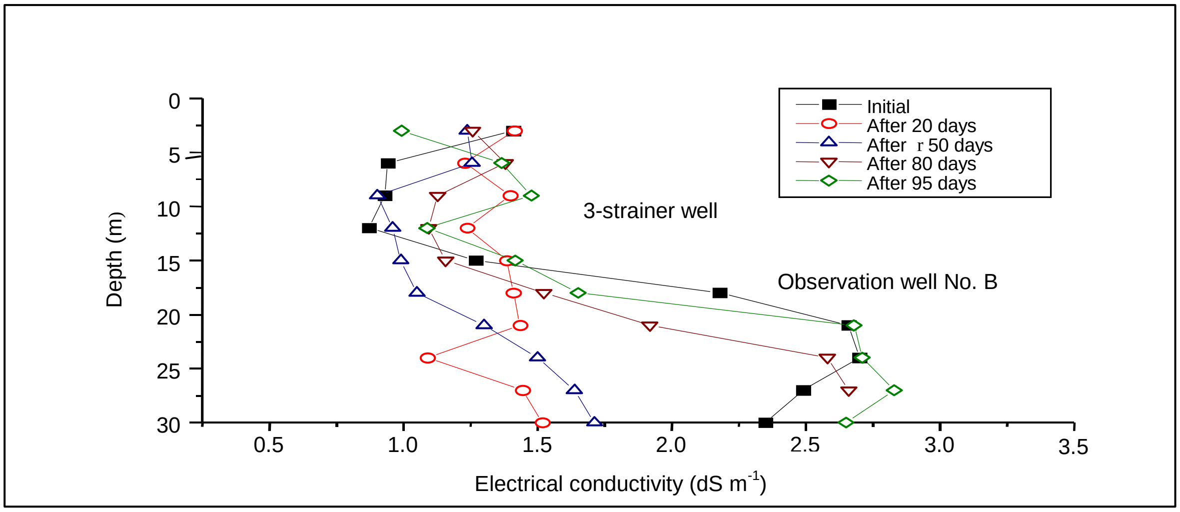

Figure 3-B. Effect of pumping on the salinity of groundwater.

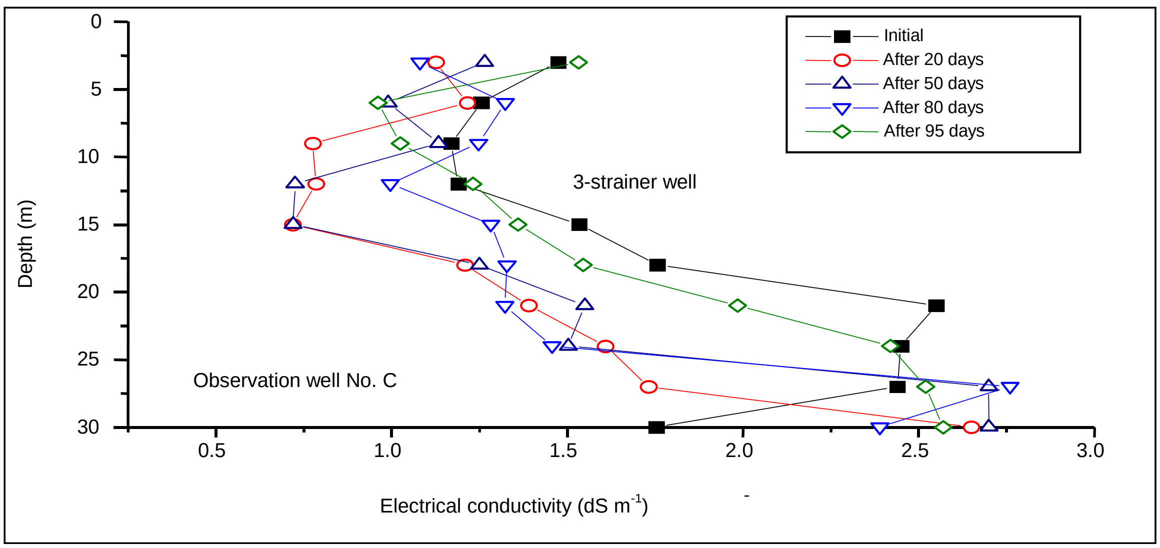

Figure 3-C. Effect of pumping on the salinity of groundwater

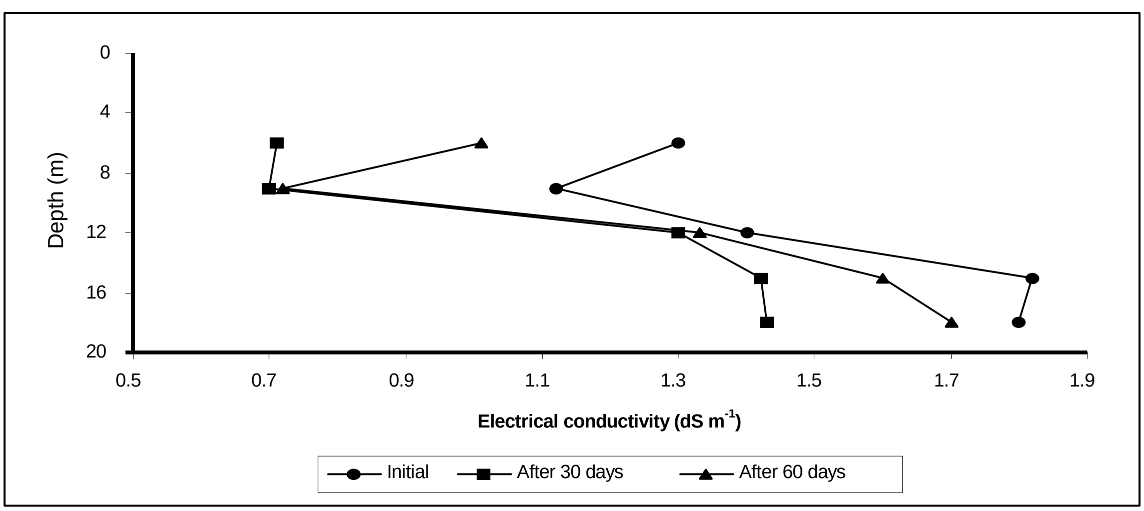

Figure 4-A. Effect of intermittent pumping on the groundwater salinity.

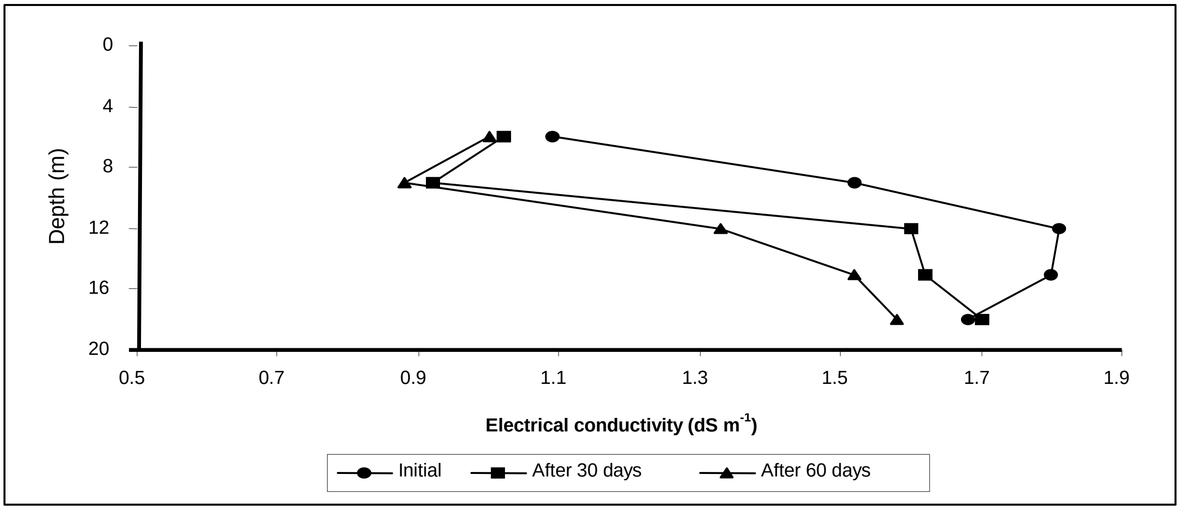

Figure 4-B. Effect of intermittent pumping of the groundwater salinity

It can be seen that during the observation period, the salt concentration, particularly at shallow depths, decreased with time. As discussed hereinbefore, this may be due to the hydraulic gradient that developed due to pumping and flushed the salts towards the strainer and hence pumped out. It thus, appeared that the quality of the shallow groundwater improves with time if the water is pumped only from the shallow depths and there is sufficient recharge available to supplant the pumping water.

Watertable behaviour

Watertable behaviour in various multistrainers skimming wells was studied. Figure 5 shows the watertable behaviour in the piezometer near the well No. 1 of the 3-strainer skimming well. The watertable in the piezometer droped about 1 m within one hour of pumping. The watertable gradually attained almost steady state condition within two hours, most probably due to increased recharge from the adjoining area. Watertable took about 5 hours to attain its original level. During the first recession hour, the recharge rate was quite rapid. However, after one hour, the recession rate decreased.

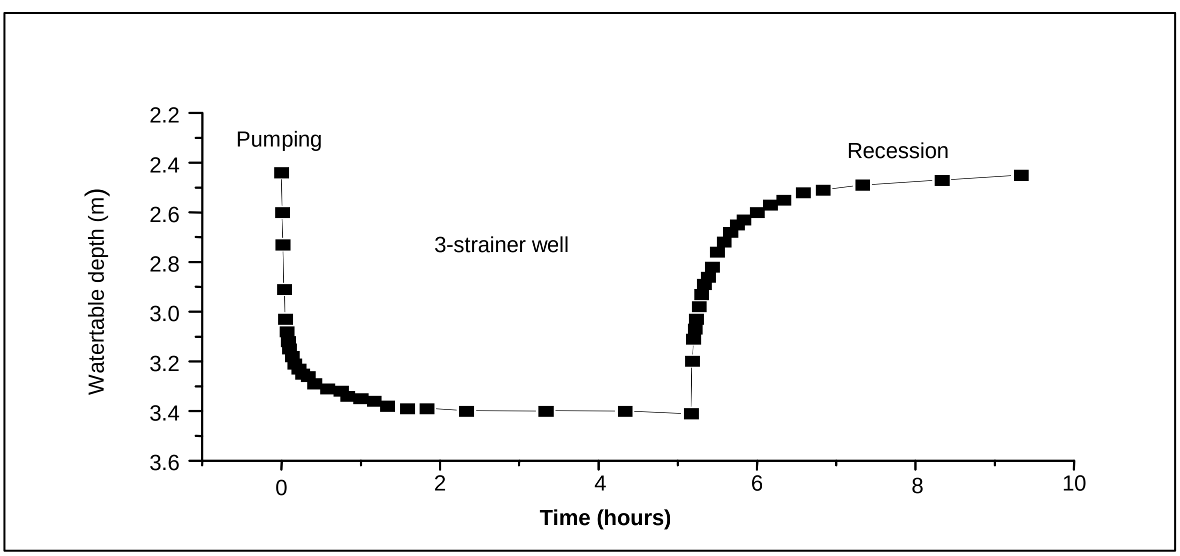

Figure 5. Effect of intermittent pumping of watertable behaviour.

Figure 6 shows the watertable behaviour in the piezometers installed at 60 cm from the 16-strainer skimming well. After 2 hours of pumping, the water level in the piezometers dropped more than 2 m. However, after 4 hours of pumping, the increase in water level became gradual and after about 6 hours the water level in the piezometers became almost steady state. It took about 10 hours to replenish the pumped amount of water. However, the replenishment was quite rapid during the first half an hour.

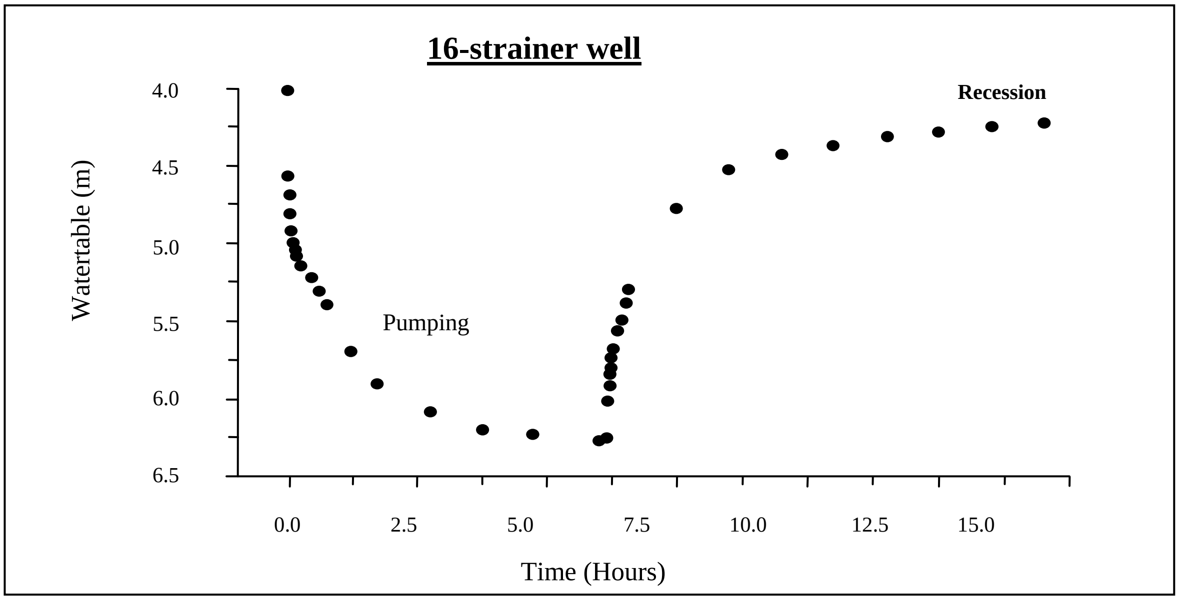

Figure 6. Effect of intermittent pumping on watertable behaviour.

Kemper et al. (1976) suggested that exploitation of groundwater from shallow freshwater aquifer, recharge will have to be localized for pumping out of the aquifer. Under continuous pumping for a longer period, a part of the pumped water may come from the saline aquifer and a part from the fresh water recharged due to the hydraulic gradient. However, if the water is pumped intermittently for a few hours a day, the aquifer will be recharged only from the adjoining area due to the hydraulic gradient that developed near the well and the chances of withdrawal of water from the saline aquifer will be minimal.

With an increase in the draw down, the suction lift increases that affects the efficiency of the centrifugal pump. It was observed that an increase in suction lift from 4 m to 6 m, decreased the discharge of the pump upto 25%. The greater the watertable depth, the greater will be the cost of pumping. Therefore, it is recommended that where shallow layer of fresh water exists over the saline layer, the continuous pumping of water should be avoided.

It was observed during the field trials at Phularwan Farm that as soon as the watercourse starts flowing, the levels in the adjacent piezometers start rising. Though the watercourse near the piezometers was brick lined (old lined watercourse), yet the rise in watertable was quite rapid. To investigate the effect of seepage water on the water level in the piezometers, an experiment was conducted. When the water level in the piezometers became static, the water was allowed to flow in the channel located near the piezometers. Figure 7 shows the effect of flowing water in the watercourse on the water level in piezometers K and L (very close to the watercourse). The water level started rising and declined when the water was stopped in the watercourse. However, water level in the piezometers M and N, which were, located about 30 m from the watercourse showed very small changes in the water level. It also indicates that in the presence of a source of water, the groundwater is recharged quickly and the same fresh water can be pumped from the shallow aquifers without disturbing the saline-fresh water interface. The figure also explains the phenomena of waterlogging and aquifer recharge. If the water contribution from a lined channel to the groundwater is so high that within half an hour, the watertable starts rising, then the seepage from earthen distorted, vegetated watercourses, from unlined canals and distributaries could be foreseen.

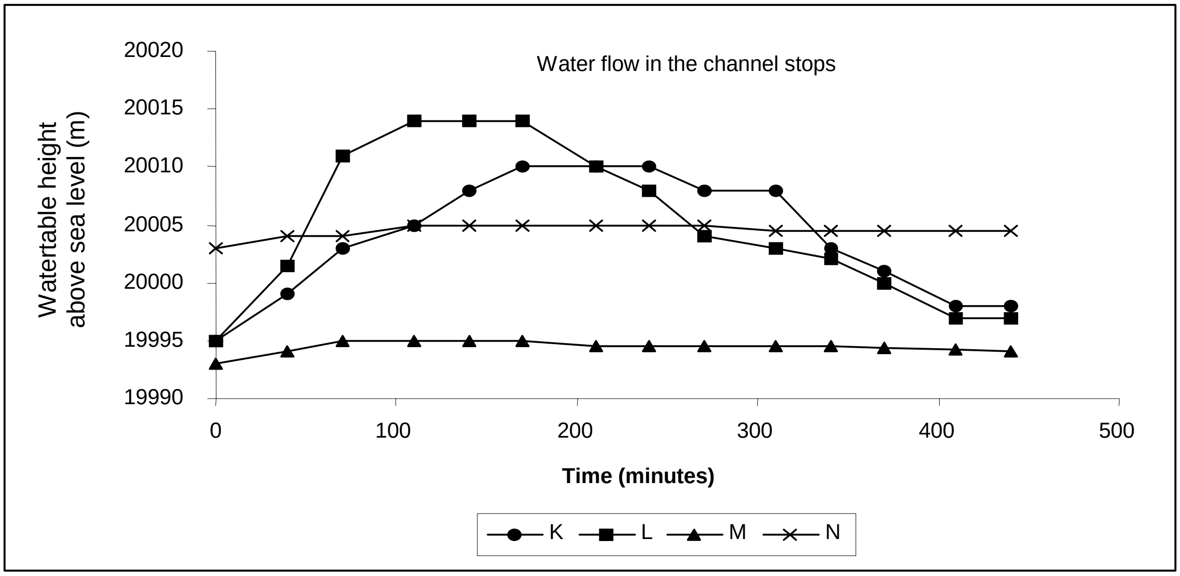

Figure 7. Effect of flow in the channel of piezometric water level.

Intermittent pumping

Impact of the intermittent pumping was observed during of daily operation hours for the observation period (Oct 2000 – July 2001) of a 16 strainers farmer's skimming well. It was observed that depth to watertable declined, less recharge available and pumped water quality also reflected deteriorating trend. Water quality improved again after July 2001 due to excess recharge by the monsoon rains. Percentage distribution of daily operation hours of the skimming well is shown in Figure 8. The discharge rate of the skimming well during the first one hour was about 28 lps. With increase in daily operation from 2 to 12 hours/day, the quality of pumped water deteriorated 3 times more and discharge was reduced from 5% to 30%. Under similar agro-climatic and hydrogeological conditions, if a farmer operates skimming well for 4-6 hours/day, its pumped water quality will remain between 1.00-1.20 dS/m with only 15-20% discharge reduction. It was also observed that recharge from irrigation application, seepage from water sources and rainfall were key parameters that affect the operational management strategies of skimming wells installed in the shallow relatively fresh ground water aquifers underlain by saline groundwater.

Moreover, the strategy of intermittent pumping of water may help solve the problems of: (i) up-coning of saline-fresh water interface; (ii) deterioration of groundwater salinity with time; (iii) decrease in well discharge and efficiency of pump; (iv) energy problems, greater the suction lift, lower will be the discharge of the pump and more energy will be required to pump the same quantity of water; (v) it helps maintain water below the root zone and provide a relief from the disposal of saline effluent.

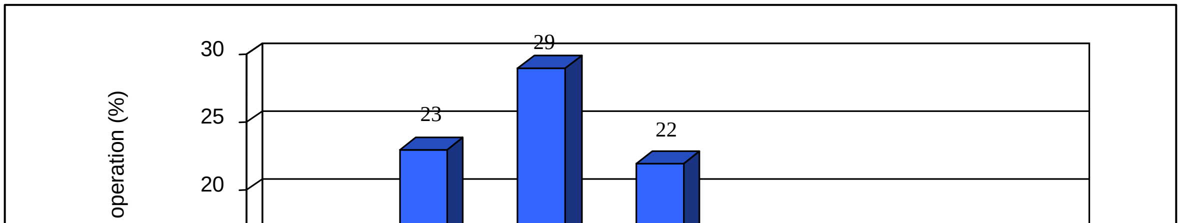

Figure 8. Percentage of daily operational hours observed from June 2000 till December 2001 at Akram Farm, Nabi Shah Bala.

4. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following conclusions are drawn from the study.

- Quality and quantity of the pumped groundwater is highly affected by daily operational hours.
- Skimming well operation for 4 to 6 hours/day is more cost effective.
- Discharge is reduced with time due to continuous pumping.
- Skimming wells with 4-6 strainers and 1.5 m horizontal distance of strainers from suction point may be more cost effective.
- More draw down can occur with more discharge through more well points which can create potential gradient and mobilized salts of surrounding area.
- The rate of recharge is a key parameter that affects the operational management strategies of skimming wells installed in the shallow relatively fresh ground water aquifers underlain by saline ground water.
- Continuous long term pumping proved to be harmful to soil and crop as it can cause saline water intrusion.

Recommendations

The following strategies are recommended based on the experience gained through skimming well testing for safe exploitation of fresh groundwater using skimming wells without up-coning of saline interface .

- Regional groundwater data base must be established to identify the potential area for safe exploitation of fresh ground water through skimming wells.
- Farmers should get their water samples analyzed before installation of skimming wells in

their respective areas to avoid saline water pumping.

- In order to maintain water quality and quantity, fractional wells should be operated intermittently rather than pumping continuously.
- Proper design of skimming wells and operational strategy for the safe exploitation of fresh water overlying saline water should be demonstrated to the farming community and end-users on wider scale.
- Long hour pumping should be avoided for better water quality and mixing of saline water.

REFERENCES

Asghar, M. N., S. A. Prathapar and M. S. Shafique. 2002. Extracting relatively-fresh groundwater from aquifers underlain by salty groundwater. Agricultural Water Management 52 (2202): 119-137.

Ashraf, M., M. Aslam, M. Saeed and M. S. Shafique. 2001. Effect of intermittent pumping on the water quality of multi-strainer skimming wells. Proceedings of the 2nd National Seminar on Drainage in Pakistan, April 18-19, 2001, sponsored by NDP, WAPDA at University of Agriculture, Faisalabad, Pakistan: 200-211.

Doering, E. J., R. C. Reeve and K. R. Stockinger. 1964. Salt accumulation and salt distribution as an indicator of evaporation from fallow soils. Soil Sci., 97: 312-319.

Hafeez, A., Z. A. Piracha and N. Ahmed. 1986. Multi-strainers tubewells for skimming top layer of fresh water underlain by saline water in the aquifer. Mona Reclamation Experimental Project, WAPDA, Publication No. 152.

Kemper, W. D., M. Jahangir and D. B. McWhorther. 1976. Skimming wells report: field studies. Mona Reclamation Experimental Project, WAPDA, Bhalwal, Publication No. 67.

Khan, A. R. and S. Muhammad. 2000. A Spatial-temporal analysis of rainfall in the canal command areas of the Indus plan. Report No. R-104. International Water Management Institute (IWMI) Lahore, Pakistan.

Sufi, A. B., and S. M. Javed. 1988. Review of existing research on skimming wells, Publication No. 3. International Waterlogging and Salinity Research Institute, Lahore.

Sufi, A. B., Y. Hameed and F. A. Zuberi. 1992. Review of design criteria for proper design of skimming wells. Proceedings of ICID 5th International Workshop, Lahore, II, 3.30-3.42.

Sufi, A. B., M. Latif and G. V. Skogerboe. 1998. Simulating skimming well techniques for sustainable exploitation of groundwater, Irriation and Drainage Systems 12: 203-226.