Root Zone Salinity Management for Sustaining Crop Production in Saline Groundwater Areas

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Abstract

In the Indus Basin of Pakistan, multi-strainer shallow tubewells often called 'skimming wells' are used to extract groundwater from thin fresh lenses underlain by saline groundwater. Most of these wells face problems such as deteriorating water quality and reduction in discharge due to inadequate designs and poor operational and management strategies. This paper evaluates the current practices of farmers in the Chaj doab area of Pakistani Punjab and suggests improvements in design and operation of skimming wells to ensure long-term sustainability of irrigated agriculture in the area. The effect of existing design and operation of skimming wells on pumped groundwater quality was evaluated using MODFLOW. To study the long-term effects of skimmed groundwater use on crop production and soil salinity development, the soil water flow and solute transport model SWAP was applied. The results revealed that farmers could reduce the number of strainers from 16 to 6 without reducing the anticipated discharges. For the conditions considered, the maximum discharge of skimming wells should be 4-8 l/s and they should not be operated for more than 2–4 h per day. Increasing discharge rate or daily operational hours can disturb the interface between fresh and saline groundwater resulting in reduced quality pumped groundwater. Weekly operational schedules together with recommended discharge rate and operational hours will be the best strategy to use skimmed groundwater for achieving optimal crop yields while maintaining root zone salinity within acceptable limits. To avoid aquifer degradation, skimming wells should be used for supplemental irrigation rather than full irrigation of crops. Due to low discharge rates, skimming wells cannot be used to irrigate crop through surface irrigation methods. Therefore pressurised irrigation methods should be used. The results also suggest that continuation of present irrigation practices could lead to serious problems of land and aquifer degradation. Therefore, farmers need to adjust their irrigation and leaching requirements annually considering crop evapotranspiration, precipitation and salinity status of soils.

INTRODUCTION

In the Indus Basin, the natural groundwater is deep and saline because of the marine origin of the hydro-geologic formation. Percolation of irrigation and rainfall waters has formed fresh groundwater lenses in many locations above the underlying saline groundwater. The thickness of this fresh groundwater lens varies from a few meters to more than 150 m. In general the fresh groundwater lenses are found close to the rivers, and saline groundwater areas are present in the central and lower regions of the *doabs* –area enclosed between two rivers (Figure 1). In fresh groundwater areas, the fresh groundwater lenses are thick (> 38 m). In saline groundwater areas, the thickness of fresh groundwater lenses is thin (< 38 m).

According to Zuberi and McWhorter (1973), saline groundwater areas occupy more than 30 percent of the Indus Basin, mainly in Punjab and Sindh. In saline groundwater areas of the Indus Basin, about 200 Billion Cubic Meters (BCM) of fresh groundwater has accumulated (NESPAK, 1983), and over 20 BCM of fresh groundwater is being recharged annually to these saline groundwater areas (Sufi et al. 1998). Development of appropriate technology and adequate operational strategies for the safe abstraction of this valuable resource can contribute significantly in overcoming the scarcity of water in the Indus Basin (Mirbahar et al. 1997; Saeed et al. 2003). The use of 'skimming wells' can be an effective way of extracting fresh groundwater from thin lenses without disturbing the underlaying saline groundwater layers (Chandio and Larock, 1983; Sufi, 1999). A skimming well is a multi strainer tubewell penetrating partially, but vertically using small bores, into the unconfined aquifer underlain by saline groundwater layer.

The large-scale groundwater exploitation from the Indus Basin aquifer started about 40 years ago when about 1400 deep single-strainer tubewells with 30-75 m depth and discharge capacity of 80 l/s were constructed to combat waterlogging and salinity problems. Since then the utilization of groundwater for irrigation has grown rapidly. Farmers locally developed this technology as a single-strainer shallow tubewells in fresh groundwater areas, and small bore multi-strainer shallow tubewells, referred to as skimming wells, in saline groundwater areas of Punjab and Sindh provinces (Hafeez et al. 1986). The current rates of groundwater use in most of the areas are unsustainable. Rapidly falling water tables and increasing salinity of the pumped groundwater attest that more expensive and poor quality groundwater will have to be used for irrigation in future. This impairs the capacity of this region to feed its growing population.

In saline groundwater areas of Punjab and Sindh provinces, farmers have installed almost 10,000 skimming wells (ACE Halcrow JV Consultants, 2002). Most of these wells are not properly designed and are run with inadequate operational schedules (Saeed et al. 2002). As a result, saline groundwater upconing, i.e. upward movement of saline groundwater in an unconfined aquifer having fresh groundwater lens underlain by saline groundwater layer, occurs and the quality of pumped water is deteriorating and a large number of wells have already been abandoned. Moreover farmers do not have sufficient knowledge on the use of skimmed groundwater for maximizing crop yields and minimizing environmental degradation. Thus, salinity problems are emerging in large areas and salt-affected soils are becoming an important ecological problem with about 6 million ha already affected.

Due to relatively low discharge rates (3-8 l/s) the skimmed groundwater cannot be applied to the fields using surface irrigation methods. Therefore the effectiveness of alternative irrigation methods, such as pressurised irrigation systems, needs to be determined. Application of small volumes of water might trigger the salinity development in these soils due to less leaching of salts. Therefore long term effects of the skimmed groundwater use on crops and soils also need to be evaluated. This paper presents the results of a three year study conducted to develop cost-effective and technically feasible design and operational strategies of skimming wells and to prepare guidelines for managing root zone salinity in areas where skimmed groundwater was used with pressurised irrigation, either alone or intermittently with surface irrigation.

DESCRIPTION OF THE STUDY AREA

This study was conducted in the *Chaj Doab,* the area between Jhelum and Chenab Rivers, which is one of the intensively developed and significantly productive irrigated areas of the Indus Basin. The location map of the study area is shown in Figure 2. The Gross Command Area (GCA) of *Chaj Doab* is 0.95 Mha, and 87 percent forms the Culturable Command Area (CCA). The citrus orchards form the salient features of the landscape due to the suitability of agro-climatic and agro-hydrological conditions for citrus plantation. The percentages of CCA owned by the small, medium, and large landholders are 10, 37, and 53 percent, respectively. The majority of farmers have small and medium landholdings (around 80 percent with 1:1 ratio), however these two types of farmers have citrus orchards only on 6-8 percent of their CCA. In case of large landholders, such orchards occupy around 30 percent of their CCA. Annual cropping intensity is highest for small landholders (147 percent), and the lowest for the large farmers (115 percent).

The cropping seasons vary with individual crops but are generally defined as '*kharif*' from mid-April to mid-October, and '*rabi*' for the remaining year. Main crops of *kharif* season include sugarcane, maize, rice and *kharif* fodder, while wheat and *rabi* fodder are the main *rabi* crops. Two main canals, upper and lower Jhelum canals, irrigate this area. These two canals were designed to supply 4.4 BCM to the area. For the drainage purposes: this area is divided into two main zones: SCARP-II non-saline zone, and SCARP-II saline zone. Alluvial deposits underlie the *Chaj Doab,* the resulting aquifer is unconfined, and is mainly composed of medium to fine sand. Total thickness of the aquifer is more than 300 m, and the groundwater fluctuates between 1.5 and 4 m in a yearly hydrological cycle. The soils of the area range from coarse to moderately fine, with a predominance of moderately coarse texture soil classes.

The climate of the area is characterized by large seasonal variations in temperature and rainfall. During winter, the daytime high temperature ranges from 7°C to 20°C. In summer, from May to August, the weather is extremely hot with daytime high temperatures rising to 20-40°C. Although, the rainfall is markedly variable in magnitude, seasonality and its spatial distribution (Khan and Muhammad, 2000), it contributes significantly in meeting crop water requirements. The mean annual rainfall and reference evapotranspiration are 460 and 1625 mm, respectively. While comparing the cropping season with the climate season, it appears that the critical initial months of both the cropping season are practically devoid of rainfall. The supply of canal water is usually less than residual crop water requirements, which has prompted more and more farmers to groundwater to make up the remaining shortfall, and groundwater extractions are about 4.9 BCM in the study area.

Irrigation water use from different sources by types of landholders is presented in Table 1. Groundwater use (alone or conjunctively with canal water) is more than 50 percent in all types of landholders, however large landholders use more groundwater as compared to small and medium landholders since they can afford to have their own tubewells or purchase the services of tubewells from their neighbours. Thus, the distribution of benefits from groundwater irrigation in the society is not equitable. The current practices of groundwater extraction and its use have favoured the rich at the cost of poor. However, if well installation and operational costs are reduced, nearly all farmers will have their own tubewells. Skimming wells can offer such incentives. Therefore, developing cost-effective and technically feasible design and operational management strategies for skimming wells, is one way of ensuring equitable distribution of benefits from groundwater irrigation among the farming community.

MATERIALS AND METHODS

A GIS-based spatial analysis was carried out to classify deep groundwater quality zones in the study area. The marginal or hazardous groundwater quality zones, which cover around fifteen villages in the study area, were anticipated to have fresh groundwater lenses resulting from deep percolation of irrigation and rainfall waters. From these identified villages, six different sites (two in SCARP-II saline zone, and four in SCARP-II non-saline zone) were selected to carry out the Diagnostic Analysis (DA). The DA used resistivity survey, bore logs (to a depth of 75m), water quality sampling from hand pumps, and shallow wells to investigate salinity and hydro-geological conditions of the aquifer. These investigations confirm the presence of fresh groundwater lenses overlying the saline groundwater and in estimating the thicknesses of these fresh groundwater lenses, groundwater quality at different aquifer depths, and the aquifer composition.

A farmer owned sixteen-strainer skimming well was monitored from June 2000 till December 2001 to study its hydraulic performance and hydro-salinity behaviours under different pumping regimes. In this well, each strainer had 6.7m of screen length, and well penetration ratio was estimated to be equal to 60% of the fresh groundwater lens. The horizontal distance of strainers from suction point varies from 1.5 to 4.6m. For 74% of the times of observed tubewell operations, this well was operated between 2-8 h/d. A schematic diagram of the observed skimming well is shown in Figure 3.

The MODFLOW and MT3D models (Chiang and Kinzelbach, 1996) were calibrated for the Chaj doab conditions (Asghar et al. 2002) and used to study the effect of different penetration depths, operational hours and discharge rates on the quality of pumped groundwater. For model simulations a spatial domain 89m x 89m was divided into 23rows and 23 columns, with each cell of 3.9x3.9m. The vertical domain of 100m was divided into nine layers of variable thickness to accommodate groundwater quality profile, and to allow for simulation of the different well penetration ratios. No flow boundary condition was considered on the sides and the bottom boundaries. The top layer was considered unconfined while other layers were considered convertible between unconfined and confined depending upon the aquifer hydraulic conditions. The multi-strainer skimming well was represented as a single well point in the centre of the simulation network.

The values of horizontal hydraulic conductivity, vertical hydraulic conductivity, and specific yield of the aquifer were taken as 30 m/day, 20 m/day, and 0.4 (-), respectively. For the MT3D, the best-fitted values of the longitudinal, horizontal transverse, and vertical transverse dispersivity were taken as 1.89, 0.378, 0.378m, respectively. The value of the effective porosity of the aquifer was set equal to 0.4 Kemper *et al.* (1976). The initial depth to water table was taken as 1.5m. The initial thickness of fresh groundwater lens was 30m for relatively thick lenses, and 20m for thin lenses.

The operational strategies and resulting quality of skimmed groundwater optimized by MODFLOW simulations were tested for their long-term effects on crops and soil degradations. Soil-Water-Atmosphere-Plant relationship (SWAP) model (van Dam et al. 1997) calibrated by Sarwar et al. (2000) was used for this purpose. SWAP is a one-dimensional model to describe transient water flow and solute transport in a heterogeneous soil root system, which can be under the influence of groundwater. Root water extraction at various depths in the root zone is calculated from potential transpiration, root length density and reduction due to water and/or salinity stress in the root zone. Irrigation applications can be prescribed at fixed intervals or user may choose various irrigation timings, depth and water quality.

A farmer's field measuring 0.4 ha was extensively monitored from July 2002 to April 2003 to gather information regarding irrigation applications, sowing and harvesting dates, groundwater pumpage and other agronomic parameters needed for model application. Maize-wheat cropping pattern was used for simulation, as these are the dominant crops of the study area. Maize is usually sown during the months of July-August to meet the fodder demands for their animals, while wheat is sown during October-November after the maize harvest. The groundwater table, which fluctuated in the range of 1.5 to 4.0m, was used as bottom boundary condition. The upper boundary condition was dependent on daily evapotranspiration rate, actual rainfall, and irrigation. The soil profile was taken as 480 cm and was divided into three soil layers for model application. The soil hydraulic properties of these three layers were defined by van Genuchten and Mualem (VGM) parameters (van Genuchten, 1980) and were adapted from Sarwar et al.

(2000). The details of input parameters used for model simulations are given in Table 2. Long-term simulations were performed for a period of 15 years, as daily rainfall, maximum & minimum temperatures, sunshine hours and wind speed were available from the study area.

RESULTS AND DISCUSSION

Evaluation of farmers' current practices regarding the design and operation of skimming wells

The results of Participatory Rural Appraisal (PRA) and field surveys conducted in the study area revealed that the major factors contributing to the popularity of skimming wells among farming community include: (i) availability of locally manufactured material, (ii) availability of local expertise for drilling, installation and maintenance, (iii) shallower depths to water table that helps use centrifugal pumping units, (iv) technically simple as compared to other groundwater extractions technologies, and (v) economics and affordability. The deterioration of water quality and reduction in well discharges over time were identified as major problems. Due to absence of any design code in the area, every skimming well in the area was different than the others in term of depth of skimming wells, number of strainers and horizontal distance of strainer from suction point. The depth of skimming well in the area ranges between 9 to 27 m and the number of strainers varying from 2 to 26. The results of modeling simulations revealed that initially discharge rate increased considerably with the increase in number of strainers. However, after 6 strainers the increase in the discharge rate was marginal (Figure 4). This shows that farmers could reduce number of strainers to a maximum of 4-6 without reducing the discharges. This will not only reduce the initial installation costs but will have a significant impact on the operational costs.

The horizontal distance of strainers from suction point was found to be between 1.5 to 4.5 m (Figure 3). The common perception of farmers and well drillers in the area was that well discharge increases with the number of strainers. It was also believed that putting all strainers at equal distance from suction point would reduce the well discharges. Therefore most of the skimming wells in the area are installed on the recommendations of local drillers rather than suitability of hydro geological conditions.

Evaluation of the performance of farmers' existing skimming wells

Figure 5 shows the changes in the quality of pumped groundwater as observed in the field during the period from October 2000 to July 2001. The water table tends to decline as the recharge due to rainfall and percolation from irrigation fields was minimal. As a result, quality of the pumped groundwater also deteriorated. From July onwards water table started rising and pumped groundwater quality was improved. This was mainly due to excessive recharge from the monsoon rains. This shows that percolation from rainfall is an important parameter that improves the quality of pumped water from skimming wells installed in the shallow fresh groundwater aquifers underlain by saline groundwater. Therefore restricting pumping from skimming wells during dry periods (April-July) when recharge is low and chances of water quality degradation are high could be a better management strategy for controlling saline groundwater upconing. This is practically feasible as after harvesting of wheat crop in April, fields are usually kept fellow till the sowing of maize in July-August. This intermitted pumping could be a good strategy to control groundwater quality and sustain crop production.

Pumping test were also carried out in the field using sixteen strainer skimming well to study the impact of daily operational hours on pumped water quality and discharge rate and the results are presented in Figure 6. The discharge rate of this skimming well was 28 l/s during the first hour of operation, which was reduced to 26.6 l/s after second hour of operation. With the increase in daily operational hours from 2-12, the pumped water quality deteriorated three fold, and the discharge rate reduced from 26.6 to 19 l/s. This equals to 30 percent reduction in discharge rate when compared with the first hour of operation. Figure 6 clearly demonstrates that in the conditions considered, operating skimming wells from 4-6 hour per day will keep the pumped water quality between 1.0 to 1.2 dS/m while reduction in well discharge will be 15-20%. Increased operational hours can cause drastic reductions in well discharges and a quantum drop in the quality of pumped water. Therefore operational hours of skimming wells installed in the thin fresh groundwater aquifer areas should be restricted to ensure long-term sustainability.

Evaluation of the impact of different operational strategies of skimming wells on aquifer behavior

The calibrated MODFLOW model was also used to study the effect of different discharge rates, daily operational hours and operational strategies on quality of pumped groundwater. The simulations were performed for the aquifers having thin layers (< 38 m) of fresh groundwater underlain by saline groundwater. The summary of simulation runs is given in Table 3.

Figure 7 shows the impact of different discharge rates on the salinity of pumped water. The simulations were performed for one year using calibrated MODFLOW model. The pump was operated for two hours after every week. Weekly irrigation schedule was preferred to comply with the 7-day fixed rotational canal water distribution system called 'warabandi'. This system is widely practiced in the study area to ensure equitable distribution of scarce canal water supplies to all farmers located in a specific canal comand area. This system allows each farmer to take an entire flow of the watercourse once in seven days and for a period proportional to the size of his land holding. As water duty is insufficient, groundwater is usually pumped to supplement canal water supplies.

The simulation results indicate that for the well discharges of 4-8 l/s, the increase in the salinity of the pumped water was marginal. The increase in salinity of pumped water was 1.5 to 1.8 dS/m after 1 year of well operation. However, discharges of 16-28 l/s increases the salinity of the pumped water to over 2.0 dS/m in just two months of well operation. Farmers in the area generally operate their well at 16-24 l/s discharges to generate sufficient flow to irrigate their fields using surface, irrigation methods. This has been one of the major seasons for the failure of most of the skimming wells in this area.

The effect of daily operational hours on the quality of pumped water is shown in Figure 8. In these simulations, each pump was operated after every week to extract 8.0 l/s. The results depicted that restricting well operation to a maximum of 4 h/d can control the saline groundwater upconing. The higher daily operational hours, even following the weekly operational schedule, could degrade the fresh groundwater resource resulting from saline groundwater upconing.

The effect of operational schedule on the quality of pumped water is shown in Figure 9. These results are based on 8 l/s well discharge with a maximum of two hours pumping every week. The results indicate that increasing the time between two consecutive pumping will have a positive impact on the quality of pumped water as it provides more time for aquifer stabilization. Although increasing the duration to 2-3 weeks can further help in maintaining the quality of pumped water, it might not be practically feasible for farmers due to continuous water demand of crops.

Based on the results of model simulations, two operational strategies were considered safe for skimming wells in this area as given in Table 4. In the first strategy the maximum irrigation application depth will be 15 mm while for the second strategy, it can increase to 30 mm. The average irrigation depth applied by farmers using surface irrigation method is about 40 mm. Therefore when skimmed groundwater will be used in isolation for irrigation, surface flooding method will not be suitable therefore pressurised irrigation systems should be preferred. For this study, a raingun system was used for irrigation with the skimming wells. However when skimmed water is used in conjunction with the canal water, surface irrigation methods can also be used for irrigating field crops.

Evaluation of long-term effects of skimmed groundwater use on crops and environment

The interactions of irrigation (skimmed groundwater and canal water) with crop production and soil salinity were studied under actual field conditions. Five irrigations were applied to a maize crop, out of which three irrigations were from canal water using basin irrigation system, and two irrigations were applied through raingun sprinkler system using skimmed groundwater. Wheat received a total of six irrigations: three irrigations from canal water , and three irrigations using skimmed groundwater. During these irrigations to maize and wheat crops, the average depth of canal water applied was around 40 mm; whereas an average depth of skimmed groundwater applied using raingun sprinkler system was 15 mm. The salinity of canal water and skimmed groundwater used for irrigations was around 0.3 and 1.3 dS/m, respectively. Irrigation schedules for wheat and maize together with the source of irrigation water followed by farmers and used for SWAP simulations are given in Table 5.

A set of simulations was carried out to evaluate the consequences of farmers' current irrigation practices on crops and soil salinity and the results are presented in Figure 10. The EC_e values represents the average root zone salinity calculated over a 1.0 m deep root zone. The root zone salinity during the maize season remained below 2.0 dS/m. This can be attributed to sufficient leaching during this period due to excessive monsoon rains. The relative transpiration (ratio of actual transpiration over potential transpiration: Ta/Tp) for maize was 0.96, which means that crop did not suffer from water or salt stress. However, this was not the case for the subsequent wheat crop where soil salinity remained below 2.0 dS/m for initial and middle stages of the crop but markedly increased to 6.0 dS/m in the late growing stage. This shows that the water applied through irrigation and rainfall to wheat was not enough to provide adequate leaching of salts from the root zone. As plants are constrained in their capacity to extract water from roots under highly saline conditions, the relative transpiration of wheat was reduced to 0.88 (12% yield reduction as compared to potential). This suggests that for sustainable crop production in these areas, farmers need to calculate their irrigation and leaching requirements more carefully.

Figure 11 shows the long-term effects of farmers' current irrigation practices on crops and soils. The results indicate that continuation of farmers' current irrigation practices could lead to serious land degradation and crop growth problems due to salinity build up particularly in below average rainfall years. Therefore farmers need to adjust their irrigation schedules every year on the basis of crop evapotranspitaions, precipitation and salinity situations of the soil profile. This is essential to sustain crop production in these areas where canal water supplies are not sufficient and availability of fresh groundwater is very limited.

A second set of simulations with the calibrated SWAP was carried out to evaluate the long-term effects of two operational strategies optimized by using MODFLOW. (Table 3) on crop production and development of soil salinity. The modeling results reveal that the deviations in annual precipitations from an average year are critical to maintain equilibrium between different water and salt balance components. Figure 12 indicates the impacts of long-term use of skimmed groundwater through pressurised sprinkler system on crops and soil salinity. The results suggest that farmers could keep the salinity levels in the root zone below 4 dS/m if they apply 15 mm of sprinkler irrigation after every week to maize and wheat. The ratio of Ta/Tp based on 15 years average for this scenario was estimated to be 0.82 for maize and 0.96 for wheat. The reduction in maize yield was higher than wheat because maize starts facing salinity stress around 2 dS/m whereas wheat can tolerate salinity levels up to 6 dS/m.

Similar results were obtained for strategy II. This strategy also allows farmers to irrigate their fields using surface irrigation methods. Both of these scenarios showed good response to relatively dry years. The slight build up in salinity during dry years was compensated in the subsequent average and above average rainfall years. Therefore on long-term basis, crop production will be sustained due to availability of acceptable quality of groundwater for irrigation.

In the areas where periodic water shortages are experienced and access to groundwater is also limited as in the case of major parts of the Indus basin, the decision of which irrigation strategy to choose should not be a question of which schedule will maximize the crop production, but rather of which one will optimize crop production in a sustainable way within the available water supply and management capacity. The simulation results clearly indicate that in the present water deficient environment of the Indus basin, farmers need to do precise calculations of their irrigation and leaching requirements to halt environmental degradation and foster crop poroduction.

CONCLUSIONS

1. The farmer's present practices regarding design, operation and use of skimmed groundwater are not consistent with the hydro-geological conditions prevailing in the study area. The continuation of these practices could lead to serious land and aquifer degradation problems that can threaten the long-term sustainability of irrigated agriculture in this area.

2. Skimming wells should mainly be used for supplemented irrigation rather than full-scale irrigation with surface irrigation methods. Due to low discharges of skimming wells, pressurised irrigation methods are preferred for irrigating field crops with the skimmed water.

3. To sustain crop production, reduce soil salinity hazard and prevent aquifer degradation, well discharge of 8 l/s with 2 hours per day operation after every week will be the best management strategy for this area. By adopting this strategy long-term availability of groundwater of acceptable quality can be ensured, which is an essential element for sustaining crop production. Weekly operational schedule of skimming wells is in concurrence with the existing 7 days canal water distribution cycle therefore it will be much more practical for farmers.. This schedule can maintain near optimal crop yields without compromising on environmental sustainability.

4. Farmers need to adopt better management strategies for the use of available water resources (quantity and quality) to overcome problems of land degradation and consequent crop yield reductions. Relevant extension agencies should play a more active role in educating farmers by introducing the research results to the farming communities.

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