Controlling Groundwater Tables Through Localized Sub-Surface Evaporation Basin: A Case Study of Rechna Doab

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ABSTRACT

In the Indus basin, under valley movement of groundwater is very limited due to its flat topography. However, the micro relieves provide some natural gradient for groundwater to flow in the low laying areas within the basin giving rise to watertable and inducing soil salinity. Drainage of these areas is complex as there is no outlet to dispose of the drainage effluent. This necessitates the need for exploring alternative localized drainage solutions for the reclamation of these lands. One approach could be to use these low laying areas as permanent discharge sites for providing drainage to the abutting areas. By digging sub-surface evaporation basins (SEB), the shallow groundwater of these areas can be directly exposed to the atmosphere. This will increase the rate of groundwater evaporation equivalent to the open water evaporation. Due to difference in gradient, the influx of groundwater to the sub-surface basin will increase resulting in watertable declines in the adjoining areas. This paper presents the results of field study carried out in the Rechna Doab of Pakistan to evaluate the effectiveness of sub-surface evaporation basin to reclaim shallow watertable soils. The field data collected over thirteen months indicate that gradient has been developed towards SEB from all sides, after nine months. The field data is also used to calibrate the groundwater flow model MODFLOW. The calibrated model is then used to calculate number of scenarios to study different design parameters of the sub-surface evaporation basin and their effect on groundwater flow regimes.

INTRODUCTION

Pakistan has one of the loftiest irrigation systems in the world. This irrigation network is mainly confined to Indus Basin, which is irrigating an area of about 16 million hectare. At the time of introduction of this large-scale irrigation system, provision of subsurface drainage as a part of irrigation system was not felt because the groundwater table depth was ranged between 20 to 30 m below the soil surface in different canal command areas (Sarwar, 2000). The operation of the Indus Basin irrigation system is based on a continuous water supply and is not related to actual crop water requirement. Thus, due to inadequate drainage system and continuous seepage over the years from unlined earthen canals and from a large network of distributing channels and percolation losses from irrigated fields, the groundwater table increased rapidly within the crop root-zone (1.5 m). This

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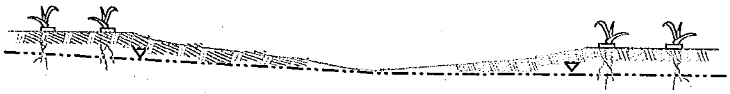
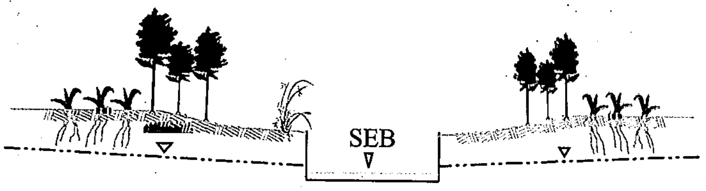
created the environmental problems like waterlogging and salinity that have badly affected the agricultural productivity. Mirbahar and Sipraw (2000) reported that Pakistan has 37.5% of gross command area (GCA) as waterlogged (watertable shallower than 3m below the surface) of which 15% is severely waterlogged (watertable shallower than 1.5m).

Due to flat nature of the Indus Basin, natural subsurface drainage through down-valley movement of groundwater is very limited. However, the micro relieves provide some natural gradient for groundwater to flow in the low laying areas within the basin giving rise to watertable and inducing soil salinity. Disposal of drainage water from these areas, specially the isolated farms, which have no setup of surface/subsurface drainage, is a serious problem. To dispose of the drainage effluent from these areas it is important to explore some alternative drainage solutions for the reclamation of these lands at farm level. One option could be to use these low laying areas as permanent discharge sites for providing drainage to the abutting areas. By digging sub-surface evaporation basins (SEB), the shallow groundwater of these areas can be directly exposed to the atmosphere. This will increase the rate of groundwater evaporation than the bare soil evaporation. Due to difference in gradient, the groundwater will move towards the sub-surface evaporation basin and thus declining watertable in the adjoining areas (Figure 1). Singh and Christen (2001) reported different options being practiced in Australia, for the removal of saline effluent from irrigated areas. According to the authors, evaporation basins are accepted as a viable, short and long-term disposal option among the other options like: river disposal, disposal bores, pipeline to the sea, and desalination. Thus, a field experiment was done in Rechna Doab area to check this approach. The main objective of this study was "to evaluate the effectiveness of sub-surface evaporation basin for watertable control in low lying areas".



Before SEB



After SEB

Figure 1: SEB conceptual framework.

EXPERIMENTAL DESIGN

The subsurface evaporation basin (SEB) experiment was conducted at Soil Salinity Research Institute (SSRI), Pindi Bhattian. An area of four hectares, left abandoned due to waterlogging and salinity, was selected for this experiment. The area had sandy clay loam texture with the loam surface. SEB was constructed in the center of the experimental area. On the western side of the study area, there was guava orchard, have mixed cropping with rice-wheat rotation in kharif and rabi, respectively.

The dimensions of SEB were 36.58×36.58×1.83 m^3 (120×120×6 ft^3). Slope of 1:1.5 was given to all four sides of SEB. To check runoff into SEB from rainfall or from irrigation to adjacent fields, a 3.05 × 0.61m^2 (10×2 ft^2) bank was constructed around the SEB. Perforated pipe of 10.16 cm (4 inch) diameter was installed at east and north side of SEB, to measure the water level within the evaporation basin.

To see the effect of SEB on groundwater levels in the vicinity area, a network of sixteen piezometers was planned at 1.52, 15.24, 30.48, and 45.72 meter (5, 50, 100 and 150 ft respectively) distance from each corner of SEB. The schematic diagram of piezometers network is shown in Figure 2.

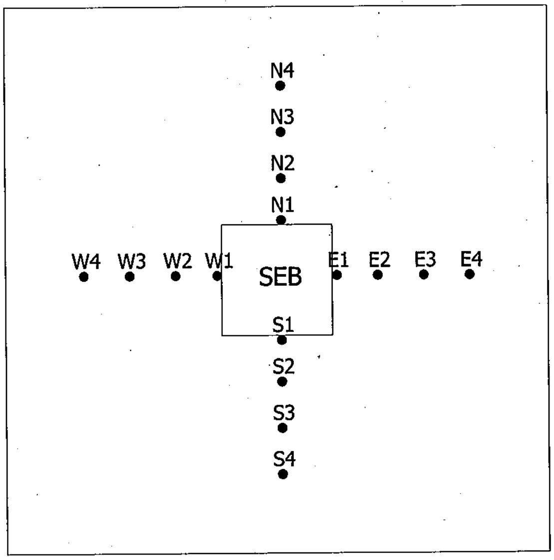


Figure 2: Schematic diagram of piezometer network at experimental site.

EXPERIMENTAL MEASUREMENTS

The experimental measurements aimed to see the effect of SEB on water tables in the area. The groundwater piezometric level was monitored using piezometers network made of 38 mm PVC pipe 3.96 m deep, with 0.91 m screen covered with cloth. After lowering the piezometer pipes in the boreholes, concrete structures were made for leveling as well as security purposes. The concrete structure was made in 38.7cm^2 shape from top and 10.16 cm in depth. The length of blind pipe above this structure was about 15-20 cm. Thus the total length of the piezometeric pipe in the ground was 3.66 m. The piezometers were sealed from the bottom by bail plug. The water level indicator (WLI) was used to collect the groundwater levels data. The WLI consists of a probe, a graduated cable or tape, and a cable reel with built-in electronics. The probe was lowered down in the piezometer until the buzzer indicated contact with water. Depth-to-water measurement was read from the tape. The water level in the piezometers was monitored on weekly basis for thirteen months. Drawing lithological logs at piezometer sites, lithological information was also collected. Rainfall was measured on the site with rain gauge.

One of the key components for the evaluation of SEB is evaporation. It is a useful tool to identify any significant change in the basin performance. Daily pan evaporation was measured using the four-foot diameter Class-A evaporation pan. The pan water level reading was adjusted when rainfall was measured, to obtain the actual evaporation. Figure 3 shows the weekly average values of pan evaporation during the study period.

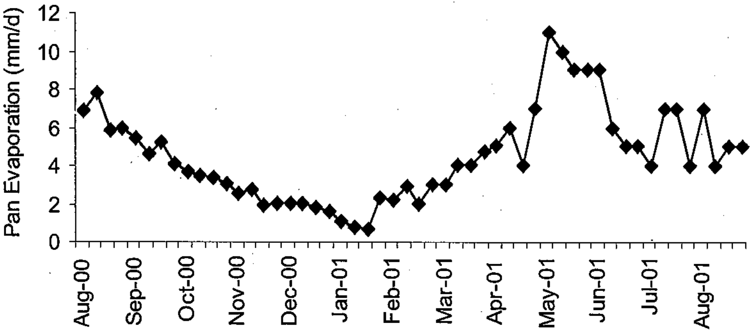


Figure 3: Weekly averages (mm/d) of pan evaporation during the study period.

GROUNDWATER LEVEL FLUCTUATIONS

Figure 4 shows the well drain-ability of the soil. Whenever there is rain, it has quick impact on groundwater levels of the study area. In this figure, groundwater

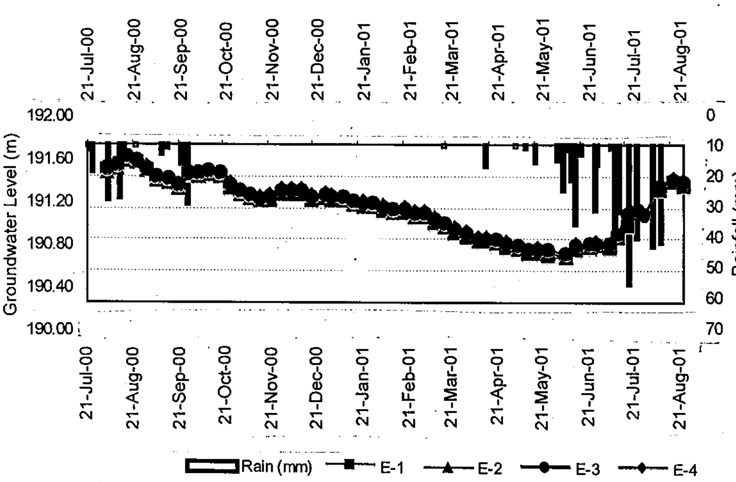


Figure 4 Effect of rainfall on groundwater fluctuations.

fluctuations data for all piezometers located in eastern side of SEB were plotted. Maximum water level of 191.82 m with a minimum value of 190.60 m was observed in the piezometer E-3 over the study period. Similar trend was also observed for the piezometers on northern, southern and western sides of the evaporation basin.

MODEL APPLICATION

Mathematical modeling is commonly used for simulating groundwater systems with complex behaviors as it permits the predictions of the response of the aquifer to applied stresses and presents alternative suggestions for its use. In this study PMWIN (Chiang and Kinzelbach, 1996), which is a complete simulation system for modeling groundwater flow (with MODFLOW of McDonald and Harbough, 1988), was used.

The MODFLOW, a modular three-dimensional finite-difference groundwater flow model, can simulate and predict the hydraulic behavior of groundwater systems. This model uses different iterative solutions to solve the finite-difference equation for groundwater flow. Hydrogeological layers can be simulated as confined, unconfined, or a combination of confined and unconfined. External stresses such as wells, can also be simulated. Boundary conditions include specified head, specific flux, and head-dependent flux. The partial differential equation describing three-dimensional movement of groundwater through porous material can be written as:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)-W=S_s \frac{\partial h}{\partial t}$$

where K_x, K_y, K_z are values of hydraulic conductivity along x, y, and z coordinate axes. W is the volumetric flux per unit volume and represents sources and/or sinks of water. S_s is the specific storage of the porous material, h is the piezometric head, and t is the time.

The MODFLOW has been applied to study groundwater flow pattern under the SEB. Data collected from the field is used to calibrate and validate the model. Subsequently, the sensitivity with reference to SEB depth, width and rain is determined.

DOMAIN DISCRETIZATION

The SEB catchment is considered as 4-hectare command area. The area has been divided into 20 rows and 20 columns with each cell of 10m × 10m dimensions. The SEB is located in the center of the simulation network. The simulation domain of 13m in the vertical perspective is divided into three layers. The top layer is considered unconfined and second layer is considered convertible between unconfined and confined with varying hydraulic conductivity, whereas the third layer is considered confined. The piezometers are placed in the second layer as shown in Figure 5.

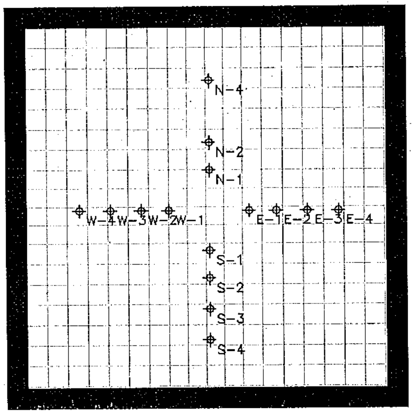


Figure 5 Model Domain

INITIAL AND BOUNDARY CONDITIONS

The initial groundwater levels are taken as per the data collected during the 1st week of August 2000, and are shown in Figure 6. No effect of groundwater recharge and pumping is considered from the catchment vicinity. No flow boundary conditions are considered; and groundwater level at the boundary is taken equal to the initial groundwater conditions.

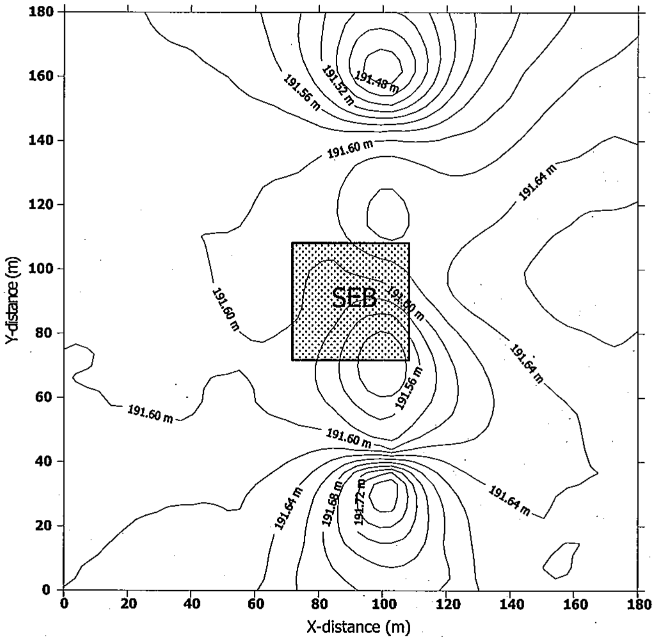


Figure 6 Groundwater levels during the first week of August 2000 (initial conditions).

CALIBRATION AND VERIFICATION

Calibration and verification refers to matching of observed and simulated hydraulic heads. Observed hydraulic heads of all observation wells except N-3 are used to calibrate the model. Calibration was done by using a composite value of hydraulic conductivity under no flow boundary conditions and transient flow in the modeled area. The comparison of the simulated and known heads for observation well N-1 is shown in Figure 7. The figure shows good agreement between the observed and simulated hydraulic heads. Agreement between simulated and measured values was quantified by the root mean square error (RMSE). The RMSE represents how much the simulation overestimates or underestimates the actual field measurements (Sarwar, 2000).

$$\mathrm{RMSE}=\left[\frac{\sum_{i=1}^{n}(M_i-S_i)^2}{n}\right]^{1/2}$$

where M_i and S_i are the measured and simulated values at the day i and n is the number of days of observation.

The RMSE for N-1 was 1.28 cm. The RMSE values for all the other piezometers are given in Table 1. The comparison shows that the discrepancies in the measured and simulated groundwater table depths were small with the RMSE ≤ 3 except N-4 and S-4, who have root mean square error values of 4.49 and 4.4 respectively.

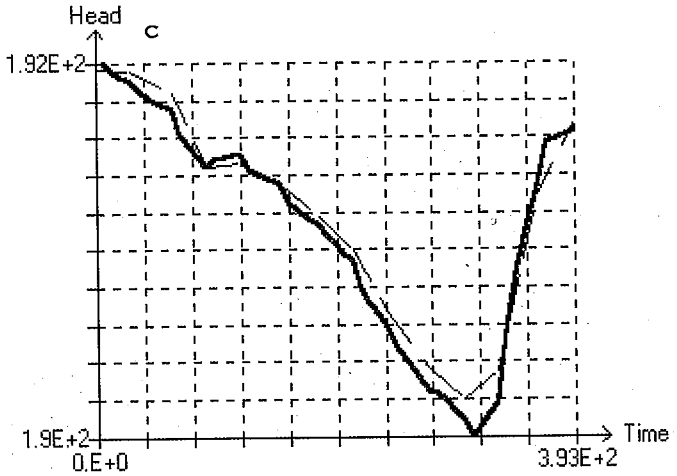


Figure 7 Calibration of observation well N-1.

Table 1 Root Mean Square Error for each piezometer over the study period.

OW ID	RMSE (cm)	OW ID	RMSE (cm)
E-1	1.06	N-1	1.28
E-2	1.82	N-2	1.18
E-3	2.25	N-4	4.49
E-4	2.37	S-1	3.00
W-1	0.95	S-2	2.66
W-2	0.88	S-3	1.72
W-3	0.84	S-4	4.40
W-4	0.94		

GROUNDWATER FLOW PATTERN

The results of the modeling study show that the gradient starts developing towards SEB after 4 weeks. The complete gradient is developed towards SEB from all sides after nine months (39 weeks), lowering the water table up to 0.94m. It became steeper after 43 weeks, showing a difference of 12.31 cm between the extreme cell of the catchment and the center of SEB. Figure 8 shows the different stages of gradient development towards SEB.

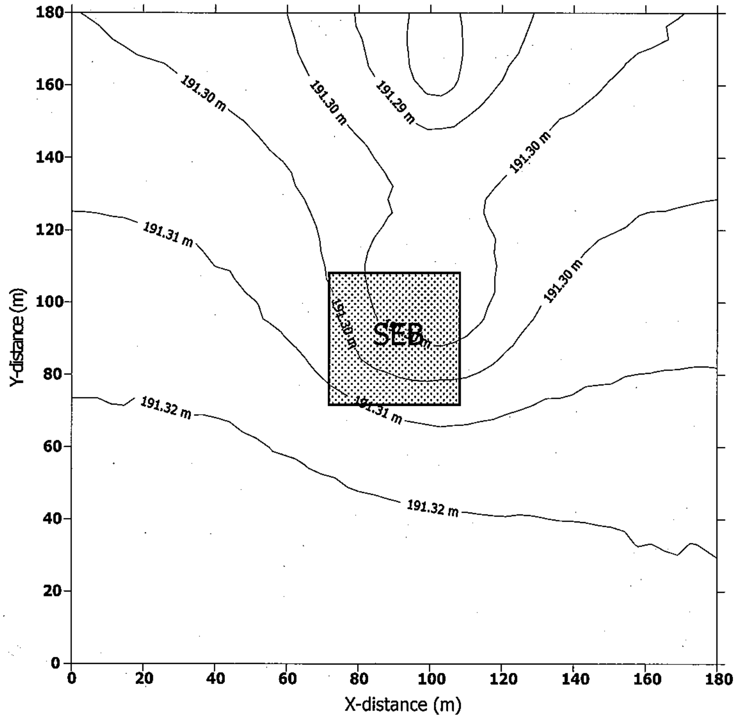


Figure 8a Different stages of gradient development towards SEB (a) after 16 weeks (b) after 42 weeks.

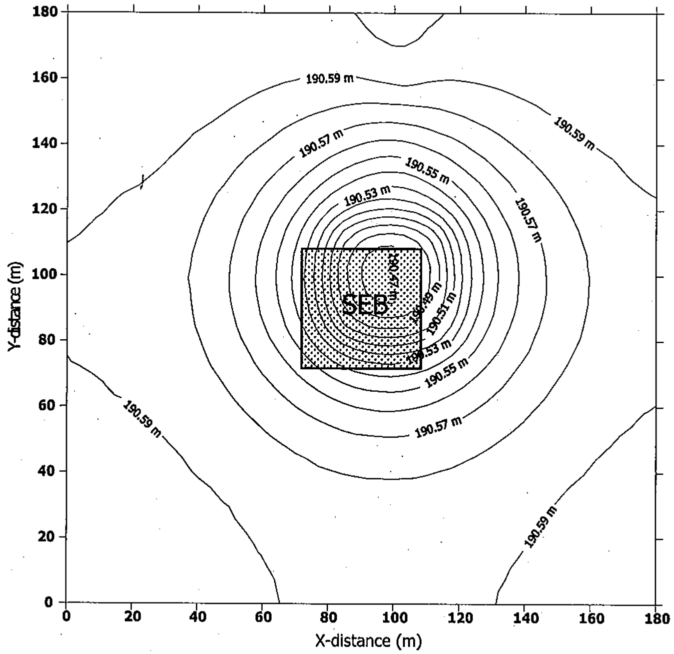


Figure 8b Different stages of gradient development towards SEB (a) after 16 weeks (b) after 42 weeks.

OPTIMIZING THE DESIGN OF SEB

The calibrated model (MODFLOW) was used to optimize the different design parameters of SEB. The sensitivity of the following variables was studied:

- Depth of SEB
- Cross-section of SEB
- Rainfall probability

A total number of 14 runs were executed for simulating different scenarios. Run 1 was executed as the base run. The remaining simulation runs were executed by changing only one parameter in the base run. A summary of runs is given in Table 2.

Table 2 Summary of model runs

Run No.	SEB Depth (%)	SEB Area (%)	Rainfall (%)*
1	100	100	Actual
2	100	50	Actual
3	100	75	Actual
4	100	125	Actual
5	100	150	Actual
6	50	100	Actual
7	75	100	Actual
8	125	100	Actual
9	150	100	Actual
10	100	100	25
11	100	100	50
12	100	100	75
13	100	100	100
14	No SEB		Actual

* *Rainfall probability of last 30 years (1970-99) rainfall data of Faisalabad meteorological station*

DEPTH OF SEB

Figure 9 shows the relationship between the change in the actual depth of SEB (1.8 m = 100%) and water elevation difference. The water elevation difference shows the gradient towards the center of SEB from the boundary of the catchment. Figure 9 is based on the results of model runs 1 to 5. The data are analysed for two scenarios i.e. dry spell (pre-monsoon) and wet spell (post-monsoon). In pre-monsoon high values of gradient are observed because there is no recharge in the catchment area from surface and water moves towards SEB due to topographic difference. In this case water moves towards SEB and evaporates at higher rate than the bare soil evaporation. Thus, during the dry spell (pre-monsoon) the gradient towards SEB becomes steeper as there is increase in evaporation basin depth. With the decrease in SEB depth water elevation difference also becomes less. But the overall graph trend shows the increase in gradient with the increase in SEB depth. There is apparent change in gradient up to 125% of actual depth, and after this depth there was no noticeable change in the gradient. In post monsoon the water level goes up in all the catchment as well as ponding in the SEB. This may be the reason for non-development of gradient towards SEB.

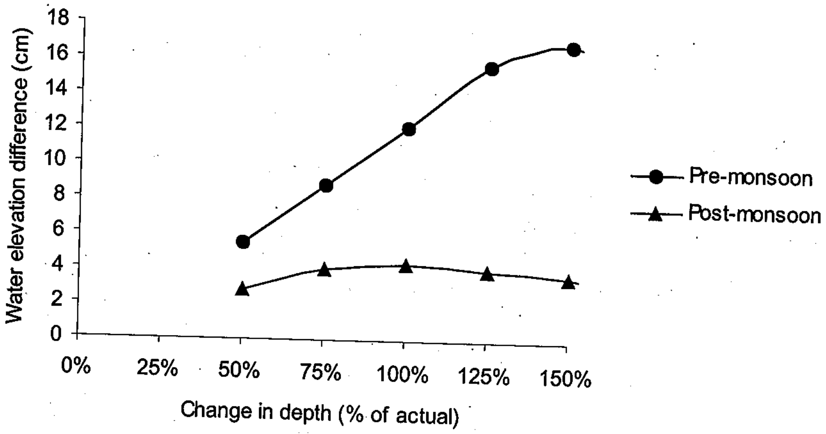


Figure 9: Effect of depth change in gradient development towards SEB.

CROSS-SECTION OF SEB

Figure 10 shows the relationship between the SEB cross-section and resulted changes in water elevation differences. Hundred percent cross-section represents the SEB dimensions as 36.5 × 36.5m. Thus, the cross-section of SEB is changed for different scenario calculations and it is kept in square shape in all the cases. A linear relationship is observed between the SEB cross-sections and resulted gradient (Figure 10). On the average 1.75 cm change in gradient is calculated in pre-monsoon, with 25% change in SEB cross-section. These results are based on the model runs 1, 6, 7, 8 and 9. In post monsoon conditions the trend is same but change is not so apparent. The reason is same as in case of SEB depth.

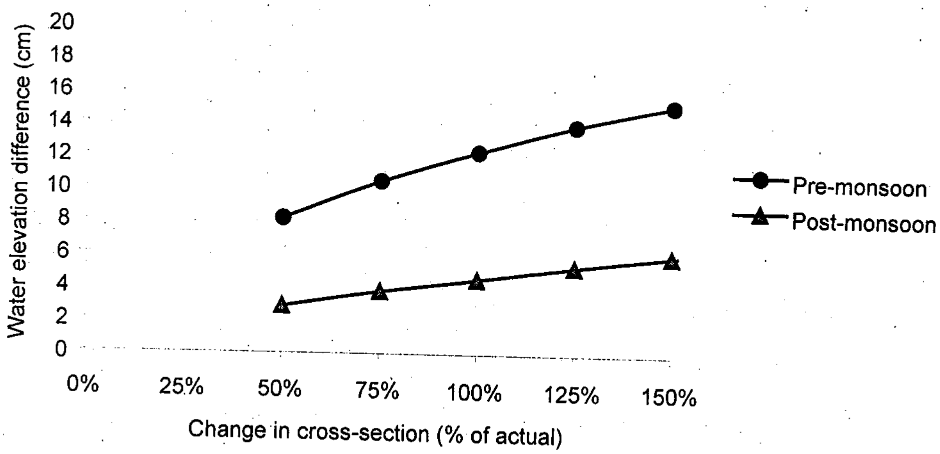


Figure 10: Effect of cross-section change in gradient development towards SEB.

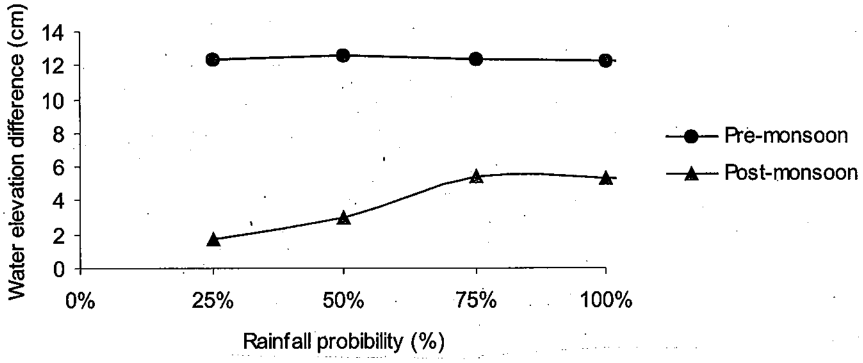


Figure 11: Effect of rainfall probabilities in gradient development towards SEB.

RAINFALL PROBABILITY

Rainfall data of last 30 years (1970-1999) from Faisalabad meteorological station is analysed for this scenario calculation. For this purpose monthly data are sorted out in ascending order. The values available in the first row are said to be 100% (04 mm) probability. The values in seventh, fifteen and twenty-second row are taken as 75% (134 mm), 50% (278 mm) and 25% (475 mm) rainfall probability, respectively. These rainfall probabilities are used as model inputs. Figure 11 is based on the model runs 10, 11, 12 and 13 for these probabilities. No clear impact of rainfall was observed in this special case, under pre-monsoon conditions. Some gradient has been developed towards SEB after monsoon at 75% rainfall probability, which is not so apparent and is comparable with the values of gradient developed after monsoon in case of depth and cross-section scenarios.

From the above discussion it can be concluded that under the existing Hydrogeological conditions, the changes in SEB depth show better impact on gradient development as compared to SEB width. Changes in rainfall have no clear impact on gradient development towards SEB.

CONCLUSIONS

- Following conclusions are drawn from this study:
- Complete gradient is developed towards SEB after nine months.
- Under the existing Hydrogeological conditions, increasing depth of SEB is more effective than increasing width.
- SEB may possibly be more useful in the areas with high horizontal hydraulic conductivity (K_h) and low vertical hydraulic conductivity (K_v), predominantly saline and waterlogged soil conditions.

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