Mitigation of agricultural drought using deficit but supplemental irrigation methods and practices

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Abstract
This paper presents the hydro-meteorological analysis of the Indus Basin of Pakistan, and compares it with the crop water demands and canal water supplies to identify agricultural drought prone canal command areas. Monthly rainfall data for 35 years (1960-95), from twenty-six weather stations spread across the Indus Basin, was used for the meteorological analysis. Crop water demands at various stages of crop growth was calculated using reference evapotranspiration (ET_0) value obtained from CROPWAT, and canal water supplies were calculated from daily gauge readings recorded at head of the canal. Participatory Rural Appraisal (PRA) was made in these drought prone canal command areas to comprehend the experiences of different farmers in addressing dry spells and water stress conditions. PRA results revealed that farmers rely more in using groundwater to meet the irrigation water demands, and farmers had tendency to over irrigate their cropped lands using canal water conjunctively with groundwater –an approach that runs counter to the conservation of scarce resources. SWAP was used to evaluate these current practices on long-term basis, and concluded that these had tendency to create problems of land degradation and consequent crop yield reductions. Therefore, to address these anticipating problems, the idea of deficit but supplemental irrigation methods and practices was evaluated using SWAP, and the developed guidelines were tested under farmers' management with a purpose of promoting sustainable use of available water resources (quantity and quality) to address dry spells and water stress conditions. Due to socio-economical implications associated with the proposed interventions used for implementing the developed guidelines, both private and public sectors should play their respective roles more actively in educating farmers by introducing the research results to the farming communities.

Keywords
Hydrometeorology, agricultural drought, CROPWAT, SWAP, irrigation practices, PRA, Pakistan

INTRODUCTION

The Indus Basin of Pakistan contains the world's largest contiguous irrigation network having 42 canal commands (Figure 1). This basin consists of mainly alluvium plains laid by the Indus River and several of its tributaries. In the Upper Indus Basin (UIB), the major tributaries of the Indus River namely, Jhelum, Chenab, Ravi and Sutlej divide the land surface into several *doabs* (i.e., land between two rivers). In the Lower Indus Basin (LIB), there is one large river, the Indus itself. Irrigation provides a good deal of protection to agriculture from droughts, but the importance of rainfall should not be neglected, especially in regions with high variability of rainfall both in time and space. There are two major sources of rainfall in Pakistan, the Monsoon Winds and the Western Disturbances.

The Monsoons originate in the Bay of Bengal and usually reach Pakistan, after passing over India, in early July and their activities continue till September. The Indus Basin receives most of its rainfall (almost two-thirds) from the Monsoons. The annual precipitation ranges between 100 mm and to over 750 mm in the Indus Basin, however, it is markedly variable in magnitude in time of occurrence and in its areal distribution. Therefore, this paper presents analyses of the spatial and temporal variation of rainfall to estimate net (effective) rainfall available in the canal commands of the Indus Basin, and compares it with the crop water demands and canal water supplies to identify agricultural drought prone canal command areas.

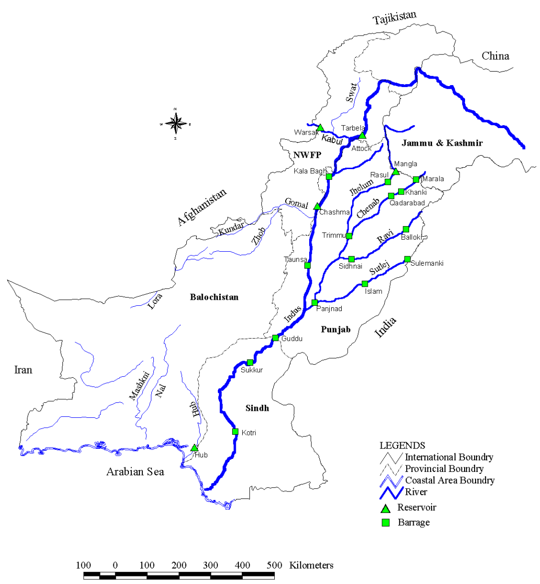


Figure 1 The Indus River System and the Indus Basin of Pakistan.

Farmers, who are the actual managers at farm level, have long history of dealing with dry spells and water stress conditions. Therefore, any guidelines that are developed to help such farmers should be based on the indigenous experiences that farmers already had. Experience has demonstrated that the transfer of many research results and new technologies has found only limited application in a majority of the farmers' field, especially in developing countries. Many research results have proven of little practical value, and farmers often proved more ingenious based on their long experiences in addressing drought and water stress conditions. Defining strategies well adapted to actual farm conditions, while profiting of the wealth of experience of many farmers, requires a more innovative approach integrating research results into actual farm conditions. Therefore, in this study, before recommending the developed guidelines for deficit irrigation, efforts were made to understand the farmers' experiences in addressing dry spells and water stress conditions.

METHODOLOGY

In this study, monthly rainfall data for 35 years (1960-95) from twenty-six weather stations was used for hydro-meteorological analysis of the Indus Basin. The stations were so selected that they cover the whole Indus Basin (Figure 2). The digitized and geo-referenced maps for all the canal commands in the Indus Basin were used in the estimation of the areal distribution of precipitation over all the canal command areas. The missing rainfall data was estimated using standard procedures as suggested by the United States Environmental Data Service. The statistical properties of the monthly rainfall data for the 35-year period were looked-into for the following purposes: (i) checking the adequacy of the rain-gauging network, (ii) data screening and quality checking, (iii) to look into the temporal and spatial variability of rain, and (iv) to study the trends and periodicities in rainfall across the Indus Basin.

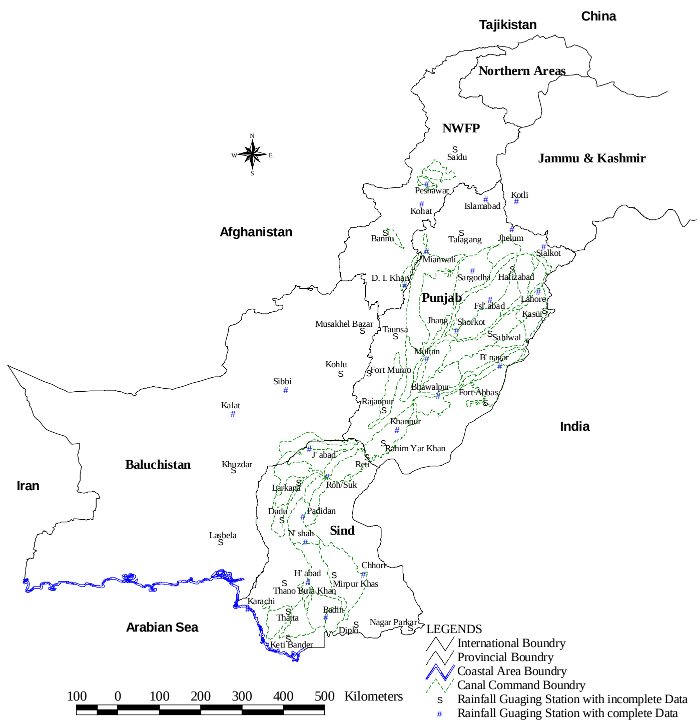


Figure 2. Location of rain-gauge stations and the canal command boundaries.

The point rainfall data for each station was tested to determine whether it could be adequately modeled by a particular frequency distribution. In addition to the point rainfall analysis, the characteristics of the areal rainfall were also looked into at the canal command level. The areal rainfall was estimated using the Isohyetal Method. Isohyetal maps showing contours of equal precipitation were drawn and the interpolation of isohyets between stations was done using the *kriging* method of geostatistics. The application of the *kriging* method accounts for the spatial structure of rainfall over a region and has been proved to be beneficial for hydrologic balance studies and applications in water resources development (Papamichail and Metaxa 1995).

The isohyetal maps thus prepared were then superimposed over the canal command map to obtain the rainfall depth (in millimeters) as well as the rainfall volume (in billion cubic meters) for each of the canal command. Crop water demands at various stages of crop growth was calculated using reference evapotranspiration (ET_0) value obtained from CROPWAT, and canal water supplies were calculated from daily gauge readings recorded at head of the canal (Kaleem Ullah et al., 2001). The comparison of canal water supplies and the prepared isohyetal maps from rainfall data, with the crop water demands, helped in identifying agricultural drought prone canal command areas. In this whole exercise of preparing isohyetal maps from rainfall data and their superimposition over the canal command map, GIS techniques/software (Surfer, Arcinfo and Arcview) were used.

Then, in these drought prone canal command areas, Participatory Rural Appraisal (PRA) was made to identify practices of different farmers in addressing dry spells and water stress conditions. These identified practices were evaluated using the Soil-Water-Atmosphere-Plant relationship (SWAP) model (van Dam et al. 1997) to investigate their likely effects on soil heath and crop yields in the long run. Based on these evaluations, guidelines were developed and tested under farmers' management with a purpose of promoting sustainable use of available water resources (quantity and quality) to address dry spells and water stress conditions. Based on these field and simulation results, practical recommendations were developed for optimizing crop production under various farm conditions.

RESULTS AND DISCUSSION

The long-term average amounts of precipitation for a year, give little information on the regularity with which rain may be expected (Figure 3). The areal rainfall gives a more representative picture rather than point rainfall assumed to be representative of rainfall over an entire canal command area (Figure 4).

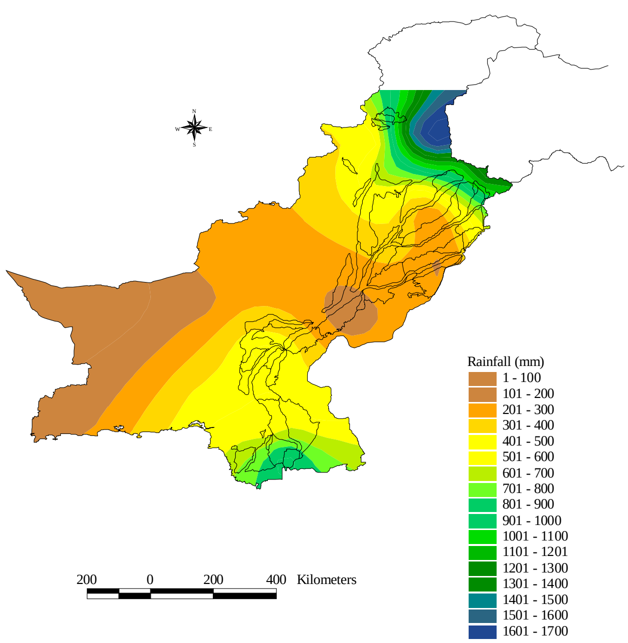


Figure 3. Annual rainfall in Pakistan during 1994-95.

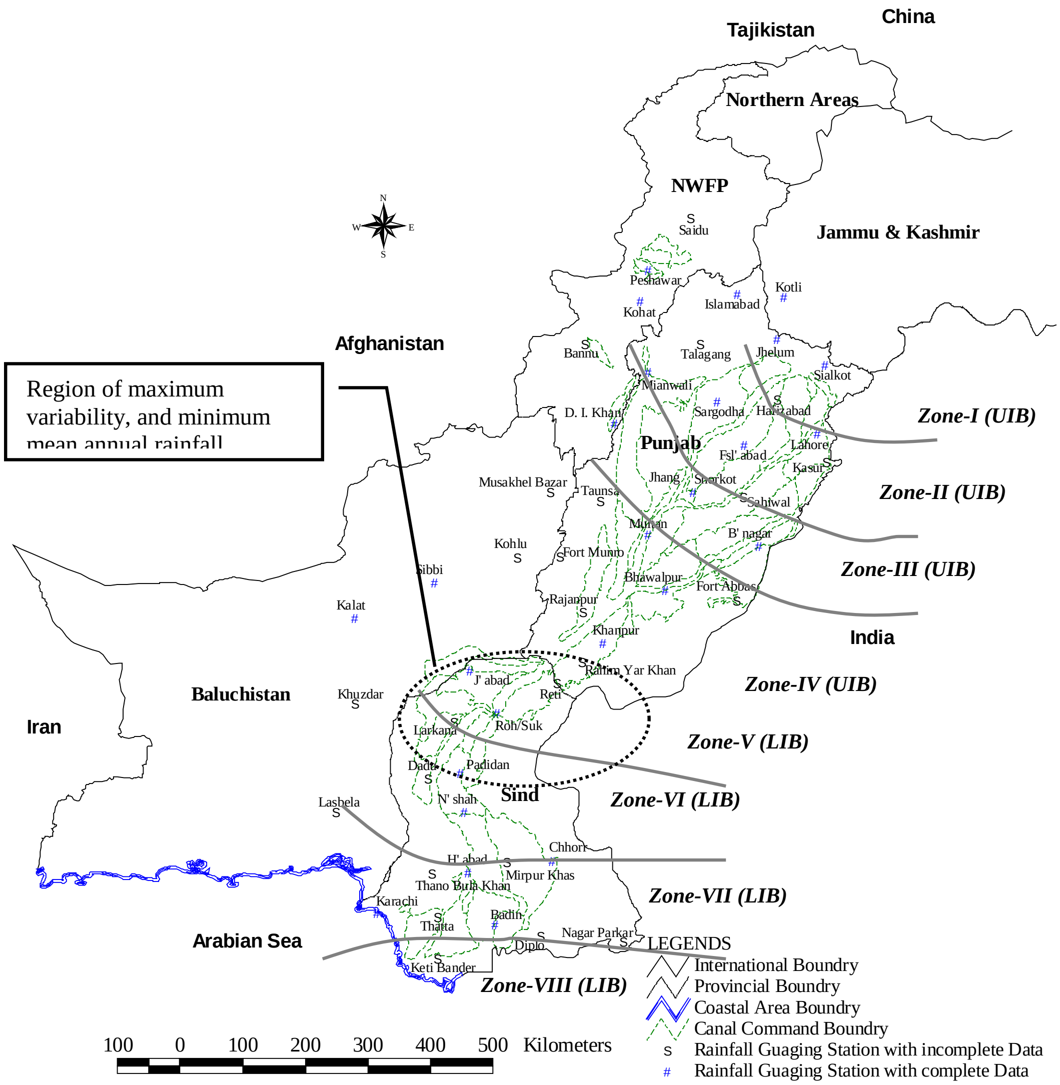
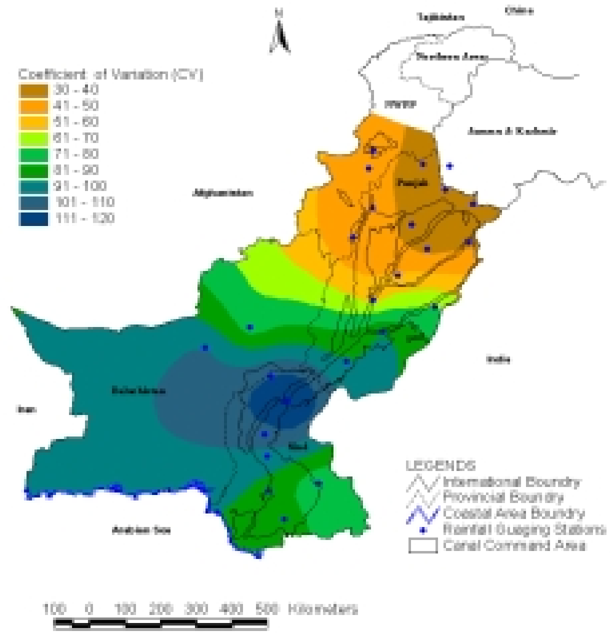


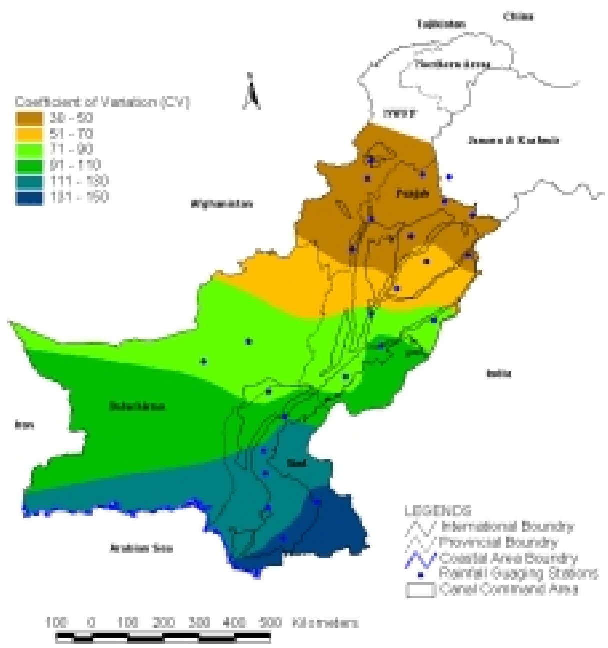
Figure 4. Climatic zones covering the canal command areas across the entire Indus Basin.

The entire Indus Basin was divided into eight distinct zones: **Zone I (UIB)**: Upper Jhelum Canal, Upper Chenab Canal, Maral-Ravi Internal, Raya Branch, **Zone II (UIB)**: Thal Canal, Lower Jhelum Canal, Lower Chenab Canal, Central Bari Doab Canal, **Zone III (UIB)**: Thal Canal, Chashma Right Bank Canal, Lower Jhelum Canal, Lower Chenab Canal, Lower Bari Doab Canal, Upper Dipalpur Canal, Lower Dipalpur Canal, Upper Pakpattan Canal, Haveli Internal, Rangpur Canal, **Zone IV (UIB)**: Thal Canal, Sidhnai Canal, Mailsi Canal, Lower Pakpattan Canal, Upper Bahawal Canal, Qaimpur Canal, Fordwah Canal, Eastern Sadiqia Canal, Dera Ghazi Khan Canal, Muzaffergarh Canal, Punjnad Canal, and Abbassia Canal, **Zone V (LIB)**: Pat Feeder Canal, Desert Feeder Canal, Begari Feeder Canal, Ghotki Canal, **Zone VI (LIB)**: North West Canal, Rice Canal, Dadu Canal, Kharipur East Canal, Kairpur West Canal, Rohri Canal, **Zone VII (LIB)**: Rohri Canal, Nara Canal, and **Zone VIII (LIB)**: Kalri Canal, Pinyari Canal, Fuleli Canal, Lined Canal (Khan and Muhammad, 2000).

The variability of annual rainfall is related to the average amounts. Variability tends to be higher where the average amounts are low (Figure 5).



(a)



(b)

Figure 5. Variability (CV) of rainfall within the Indus Basin: (a) variability of *kharif* season rainfall; (b) variability of *rabi* season rainfall.

As we move from north to the south, in the plains, the variability increases as the mean annual rainfall decreases. It is only the canal commands in the upper most part of the UIB where rainfall seems to be making a somewhat significant contribution towards the total irrigation supplies to crops along with canal and groundwater. This contribution is noteworthy only during the *kharif* season. There are only seven canal commands, out of a total of forty-two in the whole of the Indus Basin, that fall within the zones of moderate to high rainfall (greater than 350 mm). The region of maximum rainfall variability is around Jacobabad and Sukkur. All of the main canal commands of Guddu Barrage and some of the Sukkur Barrage fall within this region. Therefore, these canal commands need protection not only from droughts but also from potential damages that may result from excessive rains.

Participatory Rural Appraisal (PRA) was made in these drought prone canal command areas to comprehend the experiences of different farmers in addressing dry spells and water stress conditions. PRA results revealed that farmers rely more in using groundwater to meet the irrigation water demands, and farmers had tendency to over irrigate their cropped lands using canal water conjunctively with groundwater –an approach that runs counter to the conservation of scarce resources. For instance, 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 groundwater. Wheat received a total of six irrigations: three irrigations from canal water, and three irrigations using 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 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.

A set of simulations was carried out to evaluate the consequences of farmers' current irrigation practices on crops and soil salinity the results are presented in Figure 6. 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 7 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.

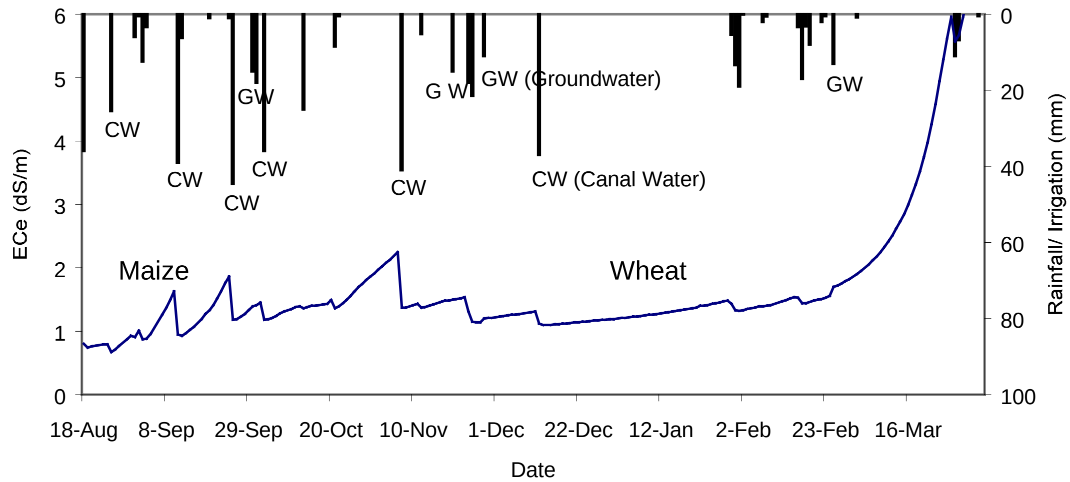


Figure 6. Development of average salinity in the top 1.0 m of the soil profile as influenced by farmers current irrigation practices for maize and wheat crops

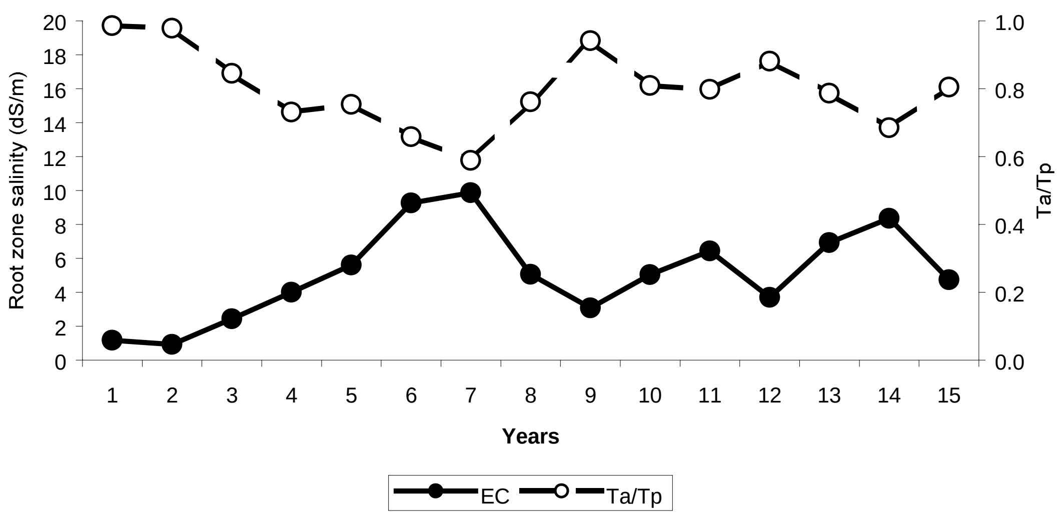


Figure 7. Temporal development of relative transpiration and average root zone salinity in the top 1.0 m of the soil profile as influenced by farmers current irrigation practices for maize and wheat crops

A second set of simulations with the calibrated SWAP was carried out to evaluate the long-term effects of two proposed operational strategies on crop production and development of soil salinity (Table 1). For strategy I, 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. 8 indicate the impacts of long-term use of groundwater through pressurized 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.

Table 1. Operational strategies for sustaining fresh groundwater resources.

Parameters	Strategy I	Strategy II
Discharge rate (l/s)	8	8
Daily operating hours (h/d)	2	4
Operational schedule (d)	7	14
Depth of irrigation (mm)	15	30

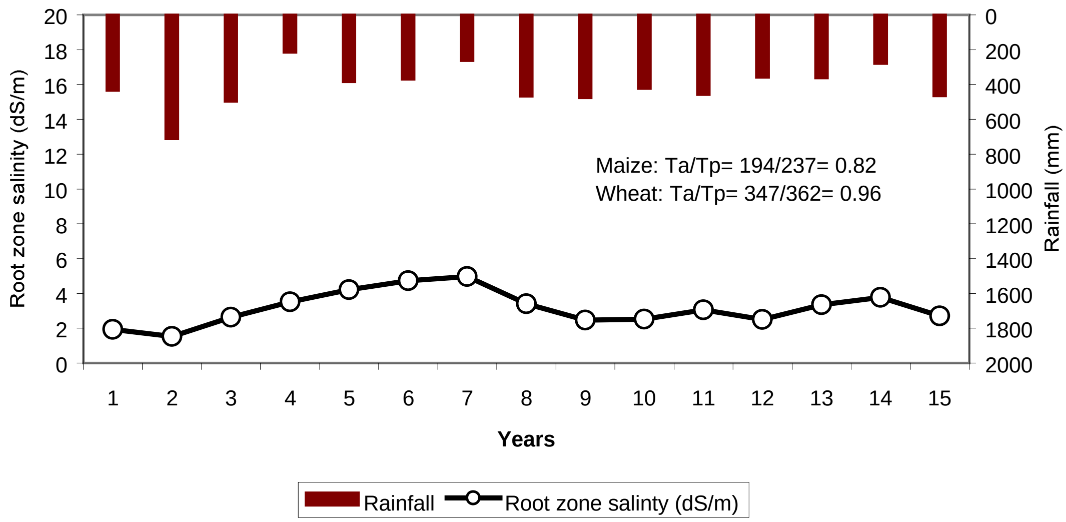


Figure 8. Temporal development of average root zone salinity in the top 1.0 m of the soil profile using raingun sprinkler system following strategy I (Discharge = 8 l/s, Daily operation hours = 2 and operational schedule = weekly).

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 production.

CONCLUSIONS AND RECOMMENDATAIONS

- For the Upper Indus Basin (Zones I and II) rainfall is higher. There are only 7 canal commands, out of a total of 42 in the whole of the Indus Basin, which fall within these two zones of moderate to high rainfall. The canal commands of Zones IV to VIII fall within an area of low rainfall and high variability. Therefore, these canal commands need protection not only from droughts but also from potential damages that may result from excessive rains.
- The farmer's present practices regarding groundwater use could lead to serious land and aquifer degradation problems that can threaten the long-term sustainability of irrigated agriculture. 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.
- The idea of deficit but supplemental irrigation using groundwater with pressurized irrigation methods and practices could sustain crop production, reduce soil salinity hazard and prevent aquifer degradation. The tubewell discharge of 8 l/s with 2 hours per day operation after every week will be the best management strategy for the study. 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.
- Due to socio-economical implications associated with the proposed interventions of using groundwater with pressurized irrigation methods and practices, both private and public sectors should play their respective roles more actively in educating farmers by introducing the research results to the farming communities.

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