Applications of GIS for the Evaluation of Agro-Environment in the Semi-Arid Areas of Pakistan

Shahid Ahmad, Rakhshan Roohi and Akram Kahlown*

Abstract

The country's geographical area covers around 88.2 million ha including the Northern Areas. A great diversity of bio-climates and correspondingly a great diversity of vegetation types and fauna characterize the country. The major habitats in the country consist of: a) flood plains, arid plains, sand and piedmont deserts and a variety of forests; b) grassy tundra and cold deserts; and c) lakes, rivers, swamps, and coastal marine habitats. Physiographically, the country can be divided into three main regions: a) high northern mountains; b) Indus plain; and c) lower and more arid western highlands. In addition, there are piedmonts, deserts and delta areas. Ecologically, the country is described as diverse showing almost every type of physiography and climate. GIS application helped to describe agricultural environments in Pakistan. Two case studies were conducted. For the first case study, as a first step, seasonal aridity and crop growth indices were used to characterize and classify the agro-climates. The country experiences two distinct seasons namely winter and summer seasons. The summer season is wet due to the Monsoon rains. Due to the seasonality, the agro-climate is characterized on a seasonal basis instead of annual. The aridity index refers to the ratio of 50 % probability of rainfall and actual crop evapotranspiration. The aridity classes ranged from humid to hyper-arid. Based on the seasonal aridity classes, 18 zones were delineated. The crop growth index reflects the temperature availability for crop growth and is estimated, as the ratio of growing degree-days available to those required by a particular crop. The crop growth classes defined ranged from deficit to excess. A total of 9 zones were defined by superimposing the seasonal crop growth maps. These two indices contributed to the classification of 57 agro-climates in Pakistan. The other element of the agro-environment is the agro-relief. Various classes can be identified considering the land use systems prevailing in the country. Pakistan is also facing the problem of water shortage and poor quality of groundwater. Long-term data of groundwater monitoring from the MONA Reclamation Experimental Project, Bhalwal, Sargodha were used to characterize and classify the groundwater in the second case study. For this purpose, parameters like groundwater, salinity, sodicity and high bicarbonate level were used. The paper also highlights other applications related to agro-environments in Pakistan. The information generated will be of immense value to the planners, researchers and educationists in the country.

Country's background

The country's geographical area covers about 88.2 million ha including the Northern Areas. The country shows a great diversity of bio-climates and correspondingly a great diversity of vegetation types and fauna. The major habitats in the country consist of : a) flood plains, arid plains, sand and piedmont deserts and a variety of forests; b) grassy tundra and cold deserts; and c) lakes, rivers, swamps, and coastal marine habitats.

Physiographically the country can be divided into three major regions: a) high northern mountains; b) Indus plain; and c) lower and more arid western highlands. In addition, a relatively small area in the Northwest of

Water Resources Research Institute, National Agricultural Research Center, Park Road, Islamabad, Pakistan;
* MONA Reclamation Experiment Project, Bhalwal, Sargodha, Pakistan

the Indus plain comprises the Pothwar plateau and Salt range, with elevations ranging between 450 to 600 m. The plateau has a badland topography due to dissection by water and wind erosion (NCS, 1991).

Notwithstanding the diversity of topography and climate, Pakistan is basically a dry country in the warm temperate zone. Except for a small strip of the subtropical terrain in the Punjab and the wet zone on the southern slopes of the Himalayan and Karakoram mountain ranges, most of the country consists of arid or semi-arid steppe land. In all, in more than three-fourths of the country, the precipitation is less than 250 mm (NCS, 1991).

The forest area accounts for 5.3 % of the country's geographical area. This area is defined legally and not biologically because of the difficulty due to the colonial legacy. It appears that there has been a significant reduction in natural forests over the last 30-40 years, a process which is still continuing (GOP *et al.*, 1992; NCS, 1991). The loss of vegetation especially in watershed areas exerts a direct impact on erosion of top fertile soil and increased the sediment load in the stream flow. The sediment load in the stream flow ultimately affects the live storage of the large hydropower reservoirs, leading to a reduction of the capacity for storage of water and power generation.

The main source of surface water is the Indus basin irrigation system. It consists of the river Indus, eastern tributaries, Jhelum, Chenab, Ravi and Sutlej, and northern and western tributaries, Kabul, Swat, Haro and Soan. The Indus Water Apportionment Accord assumes a total allocable supply of 141 billion m^3, which is 12 billion m^3 higher than existing canal withdrawals. This increase is based on the assumption that the outflow into the delta can be decreased from its current average level of 25-30 billion m^3 to about 12 billion m^3.

The system fed by glacier and snowmelt and rainfall primarily outside the Indus basin, records average annual river flows of approximately 172 billion m^3. However, flows exhibit considerable variations, both annually and seasonally: annual flows ranged between 231 billion m^3 in 1959-60 and 124 billion m^3 in 1974-75, and the average *Kharif* flow of 142 billion m^3 is over five times the average *Rabi* flow of 27 billion m^3 (WSIPS, 1990).

The Indus system contains three main artificial reservoirs at Mangla, Tarbela and Chashma with an original total live storage capacity of 19 billion m^3 which had been reduced to 18 billion m^3 by 1988. The recent estimates made by WAPDA indicated that about 22 % and 17 % of the live storage capacity of the Tarbela and Mangla reservoirs have been lost, respectively. As a result, presently the total live storage capacity in the three large reservoirs amounts to about 15 billion m^3 (GOP *et al.*, 1992).

The importance of the agricultural sector in the economy of Pakistan results from the fact that it accounts for 25 % of the gross domestic product of the country and provides job opportunities to 55 % of the labor force. It also accounts for 80% of the total export earnings of the country. Within the agricultural sector, irrigation plays a predominant role as it provides 90 % of the total wheat production of the country and almost 100 % of cotton, sugarcane, rice, fruits and vegetables mainly within 16.4 million hectares of the Indus basin. Also, the irrigation sector plays a major role in the industrialization process of Pakistan with the production of cash crops (cotton, sugarcane, citrus, mango) and dairy cattle.

During the 1960s and 1970s, the country benefited from the technological development of the Green Revolution through improvements in self-reliance in agriculture and food products due to significant increases in cropping intensities and crop yields. The irrigated area increased from 9.1 million hectares in 1947 to about 18 million hectares in 1998 (GOP, 1998). This doubling in irrigated area in 50 years is a major factor in the increase of agricultural productivity. Coupled with an increase in the cropping intensity of 60 % in 1947 to 120 % in 1998, there was a four- fold increase in production compared to the 1947 level of productivity. This four-fold increase was mainly due to the increase in water availability from both surface and groundwater sources. This is a sufficient indicator that water contributed more than the Green Revolution to enhancing production and productivity.

By the end of the 1980s, several signals suggested that the period of agricultural output growth was over, with the productivity per unit of land of the main crops becoming stagnant or even showing a decreasing trend (World Bank, 1994).

With a population estimated at more than 132 million inhabitants today that is likely to reach 171 million by the year 2010, the demand for food products is expected to continue to grow. Thus, unless there are significant improvements in agricultural productivity and total production, at least in the same order of magnitude as those recorded during the Green Revolution period, the imbalance between supply and demand of basic agricultural goods is expected to increase in the future and to threaten the self-reliance objective of Pakistan.

The problems associated with the irrigation system are the main cause for the low productivity of the Indus basin. Although the benefits of irrigation per unit area are fully recognized under the arid environment of Pakistan, as little would grow without irrigation, the irrigation sector has become increasingly the target of criticism and considered to be the main cause for productivity problems in agriculture because of water scarcity, inefficiency, inequity and sustainability issues. The sustainability issues involve salinity and waterlogging. The soil salinity and sodicity are due to the use of poor quality groundwater. About 35 % of the total agricultural water use is derived from the groundwater.

The paper includes two case studies. The first case study deals with the characterization and classification of agro-climates of Pakistan. The second case study deals with the spatial and temporal analysis of groundwater under the MONA Reclamation Experimental Project tubewells. This is a first effort and further strengthening is required to improve the case studies.

Case study on "Characterization and classification of agro-climates of Pakistan"

1 Introduction

The agricultural growth rate in Pakistan should exceed the population growth rate of around 2.6 % to meet the country's requirement for self-reliance and export earnings. This large increase in agricultural production and productivity has to be considered in the context of deteriorating resource base of irrigated and dry land agriculture. This challenge has to be addressed from three angles.

Firstly, we must be able to help the Government to identify location-specific changes necessary to increase production. With the agro-ecological characterization and classification techniques, reasonable estimates of the actual and potential productivity levels can be assessed. These assessments coupled with other sources of information should enable to identify the constraints hindering productivity in the different zones.

Secondly, we must be in a position to assist the Government in identifying priorities. Increased inputs are essential to increase agricultural productivity. These inputs, however, are of too short supply and beyond the reach of the resource-poor farmers. Where and for which crops these inputs and proven technologies can provide guaranteed success can be determined only through characterization of the environments and analysis of the potential.

Thirdly, we must be in a position to fully appreciate and understand the results of research in terms of the environments we are dealing with. Can we really talk about agro-technology transfer unless we know the causes of variations in research findings?

Climate can be mapped by isopleths of individual elements: annual, seasonal or monthly rainfall, temperature, etc. Variability can be linked in such mapping. Each of these elements is a continuum and so, necessarily, is climate as a whole. Most systems attempt to find climatic limiting values, which correspond to changes in natural vegetation - and presumably, in agricultural potential. The Köppen system is broad and simple, and is still the most widely used. Any site can be rapidly and unambiguously placed in a class using annual and monthly rainfall and temperature data only (Köppen, 1936). This can be done with a dichotomous key, readily computerized.

Another logical and widely known classification employs two indices: temperature efficiency and rainfall effectiveness, the latter based on the balance between rainfall and evapotranspiration (Thornthwaite, 1948). Although it is widely recognized, this system lies between two extremes: it lacks the simplicity of application of the Koppen method, while its treatment of the water balance has been superseded by the FAO agro-ecological zone system (FAO, 1981; Kassam *et al.*, 1982).

FAO-UNESCO used a system to classify the climate into six of the nine regional memoirs of the soil map of the world. It is based on decimal classes, in which each number codes for certain properties. The classes, undoubtedly, provide relatively narrowly defined units of uniform climate and agricultural potential, but the system is too complex and idiosyncratic for general use (Papadakis, 1975).

In Kenya, a system was used at the national level, which is both effective and valuable as a basis for planning. It is based on seven water availability zones, defined by rainfall/evaporation ratio, and nine temperature zones (Jaetzold and Schmidt, 1982). The climatic and agro-climatic indices were further defined and divided into four groups, those related to water, temperature, crop response and rainfall intensity (Bunting, 1986).

Rainfall and temperature, humidity and biologically dry periods were used to classify the agro-climate. Number of humid months (precipitation greater than evapotranspiration) was also used as a basis for classification. Various attempts have been made to classify soils and physical environment as a whole (FAO, 1981) and vegetation (UNESCO, 1973).

The major work for agro-ecological characterization was performed by FAO. This methodology involves potential crop selection according to temperature zones in relation to carbon assimilation pathways, potential net crop biomass and constraints on yield, yield reduction by pest and diseases, yield modifications and crop sustainability and potential yield at different levels of inputs. For regional or national classification, temperature during the growing period, seasonality in precipitation and isolines of length of growing period were used and 13 major climates and 13 growing period classes were identified (FAO, 1981). Wageningen model is a similar model to that of FAO except that it is characterized by a greater complexity of agro-climatic analysis and different approaches in treatment of soil effects (Bunting, 1986).

The agro-climatic characterization and classification methodologies have their own advantages and limitations considering the national level and the availability of reliable data. Considering the applicability of the method and the type of quality climatic data available in Pakistan, a methodology with two indices has been developed for agro-climatic characterization and classification to match the climatic and agricultural seasonality.

2 Materials and methods

The Pakistan's base map of 1:3,000,000 scale was digitized using GIS Arc-Info software. The error in digitization was less than 0.02 % in the geographical area. After digitizing the base map, databases of geo-referenced data were developed using Arc-Info.

Historical rainfall and temperature data of 80 geo-referenced locations collected by the Pakistan Meteorological Department were used for agro-climatic characterization and classification. These locations were distributed throughout the country. There are two distinct crop growing seasons prevailing in the country: a) the summer season designated as Kharif covering the period from May to September; and b) the winter season named as Rabi covering the period from October to April.

The procedure for estimating reference crop evapotranspiration and probability of rainfall as defined by Hargreaves and Samani (1986) was used for estimating the seasonal reference crop evapotranspiration and 50 % probability of seasonal rainfall. These predictions were made on a monthly basis and then grouped for both seasons - the Kharif and the Rabi. The crop coefficients developed by PARC (1982) were used to predict the crop evapotranspiration of representative crops. Maize and wheat were selected as representative crops for the Kharif and the Rabi seasons, respectively.

The calculations of the growing degree-days were made by using a method proposed by Roohi and Ahmad (1993). The base temperatures of 10℃ and 5℃ were used for maize and wheat crops, respectively. Two seasonal indices were developed to characterize the agro-climatic zoning. These indices are aridity index (I_a) and crop growth index (I_{cg}). The seasonality was considered for the first time to describe the agro-climate of the country.

1) Aridity index

The aridity index (I_a) was estimated using a ratio of 50% probability of seasonal rainfall and seasonal actual crop evapotranspiration. Maize crop was used to estimate the actual evapotranspiration for the Kharif season, whereas wheat crop was used to estimate the actual crop evapotranspiration for the Rabi season. To estimate the actual crop evapotranspiration from reference crop evapotranspiration, basal crop coefficients of 0.70 and 0.75 were used for the *Kharif* and the *Rabi* seasons, respectively. The Ia can be computed using the following relationship:

$$I_a = R_{0.5} / E_{ta} \quad \cdots (1)$$

where

$R_{0.5}$ - sum of the 50 % probability of monthly rainfall for a given season; and

E_{ta} - sum of the monthly actual evapotranspiration of a representative crop for a given season.

Using the geo-referenced aridity index spatial data, maps for both the Kharif and the Rabi seasons were developed for Pakistan using the Arc-Info software. The spatial variability and the criteria described by UNESCO (1964) were used to classify the aridity classes. The classes used for mapping the aridity index are: a) humid >0.75; b) sub-humid 0.50-0.75; c) semi-arid 0.25-0.50; d) arid 0.05-0.25; and e) hyper-arid <0.05.

The limits described were used to classify the aridity index for both the Kharif and the Rabi seasons and then merged into one map describing the aridity index of both seasons.

2) Crop growth index

The calculations of the growing degree-days were made by using a method proposed by Roohi and Ahmad (1993). The base temperatures of 10℃ and 5℃ were used for maize and wheat crops, respectively. The growing degree-days were used to incorporate the temperature effect on crop growth for both growing seasons prevailing in the country. The growing degree-days (GDD) for each of the growing seasons were computed from mean monthly temperature data using the following relationship:

$$GDD = \sum_{i=1}^{n} (T_{av} - T_{base}) * D_{month} \quad \cdots (2)$$

where

T_{av} - mean monthly temperature for the months of a given season, ℃;

T_{base} - base temperature, 10℃ and 5℃ selected for the *Kharif* and the *Rabi* seasons, respectively; and

D_{month} - days in a particular month.

If $T_{base} > T_{av}$ then $GDD = 0$

The GDD required by maize and wheat crops at different locations for early, medium and late varieties were computed using Eq. 2. From the GDD available and required by selected *Kharif* and *Rabi* seasons crops, seasonal crop growth index (I_{cg}) was computed using the relationship:

$$I_{cg} = GDD_{available} / GDD_{required} \quad \cdots (3)$$

The GDD of 2,500 and 2,000, respectively, required for representative *Kharif* and *Rabi* seasons crops were used. The maps of I_{cg} were developed for both crop growing seasons using Arc-Info. The I_{cg} classes developed for the preparation of the maps are: a) deficit < 0.5; b) moderately adequate 0.5-1.0; c) adequate 1.0-1.5; and d) excess > 1.5.

The seasonal crop growth index maps were merged into one map describing the seasonal crop growth index for Pakistan.

3) Agro-climate

The agro-climate was characterized based on the seasonal indices of aridity and crop growth. The maps describing seasonal aridity and crop growth indices were superimposed to delineate the seasonal agro-climatic zones.

Results and discussion

1) Aridity index

***Kharif* season**: In the *Kharif* season, the aridity index ranges from humid to hyper-arid. A minor area in the northeastern part of the country, covering the districts of Mansehra, Abbotabad, Rawalpindi, Islamabad, Jhelum, and Gujrat, falls under the humid zone, where the aridity index is higher than 0.75. Sub-humid zone lies in the northeastern and the southeastern parts. A narrow belt along with the humid zone, including the districts of Sialkot and parts of Jhelum and Mardan, represents the northeastern sub-humid zone. The southeastern part of the sub-humid zone covers the extreme southeastern corner of the Mirpur Khas district. Similar to the sub-humid zone, the semi-arid zone is located in the northern central part of the country and southeastern part, north of the sub-humid zone. The northern semi-arid zone covers parts of the districts of Sialkot, Gujrat, Jhelum and Mardan, Gujranwala, Attock, Peshawar, Kohat, Tribal areas, Mianwali, Khushab, Sarghoda, Sheikhupura, Lahore, Kasur and parts of Faisalabad, Jhang, and Zhob. The southern part of the semi-arid zone covers most of the Mirpur Khas district (Fig. 1).

The arid zone covers most of the Punjab, Sindh and eastern part of the Balochistan provinces. West of Pishin, Dadhar, Larkana, Dadu and Uthal in the Balochistan province fall under the hyper-arid zone (Fig. 1).

***Rabi* season**: For the *Rabi* season, the aridiy index ranges from humid to hyper-arid. Compared to the *Kharif* season, the *Rabi* season is generally drier and the pattern of dryness fluctuates. The humid zone in the *Rabi* season is squeezed towards the northeastern fringe of the country covering only parts of Abbotabad and Murree districts. The sub-humid zone covers only parts of Rawalpindi, Islamabad, Abbotabad and Mansehra districts. The semi-arid zone covers the northern Pothwar tract and Peshawar and Malakand districts. Whole of the Balochistan and Sindh provinces, the central and southern parts of Punjab and southwestern parts of NWFP fall under arid and hyper-arid zones (Fig. 2).

Annual: The seasonal aridity class maps of the *Kharif* and the *Rabi* seasons were superimposed to prepare one map representing the seasonal aridity classes for both seasons. A total of 18 aridity zones were identified based on both the *Kharif* and the *Rabi* seasons (Table 1).

Table 1 Seasonal aridity zones of Pakistan

Zone	Description of the aridity zones
1	Humid (K*, R**)
2	Humid (K), Sub-humid (R)
3	Humid (K), Semi-arid (R)
4	Sub-Humid (K), Humid (R)
5	Sub-Humid (K, R)
6	Sub-Humid (K), Semi-arid (R)
7	Sub-Humid (K), Arid (R)
8	Sub-Humid (K), Hyper-arid (R)
9	Semi-arid (K), Humid (R)
10	Semi-arid (K, R)
11	Semi-arid (K), Arid (R)
12	Semi-arid (K), Hyper-arid (R)
13	Arid (K), Semi-arid (R)
14	Arid (K, R)
15	Arid (K), Hyper-arid (R)
16	Hyper-arid (K), Semi-arid (R)
17	Hyper-arid (K), Arid (R)
18	Hyper-arid (K, R)

* K - *Kharif* Season (May-September)
** R - *Rabi* Season (October-April)

The humid and sub-humid *Kharif* zones have 3 and 5 *Rabi* zones, respectively, to illustrate the variability in the *Rabi* season. The variability in the *Rabi* season for the humid *Kharif* zone ranges from humid to semi-arid, whereas for the sub-humid *Kharif* zone it ranges from humid to hyper-arid.

The semi-arid *Kharif* zone shows 4 combinations in the *Rabi* season namely humid, semi-arid, arid and hyper-arid. In the arid and hyper-arid zones in the *Kharif* season, the *Rabi* season is either arid or hyper-arid.

2) Crop growth index

***Kharif* season**: Generally the crop growth index in the *Kharif* season is in excess in Punjab, Sindh, southern half of Balochistan and NWFP. Northern fringe of Punjab province falls in the zone where it is adequate while in the northern part of the country, it is moderately adequate (Fig. 3).

***Rabi* season**: In the *Rabi* season, the coastal area covering parts of Thatta and whole of Badin in Sindh and Gawadar, Pasni and parts of Turbat and Uthal in Balochistan falls in a zone where the crop growth index is in excess. The southern half of Balochistan, most of Punjab and almost whole of Sindh fall in the adequate zone. The deficit zone lies in the north of Mansehra and Saidu in the northern part and Quetta, Zhob and Loralai in the northwestern part of the country (Fig. 4).

Annual: The seasonal crop growth zones for both seasons were developed by superimposing the seasonal maps. A total of 9 zones were delineated (Table 2).

Table 2 Crop growth zones of Pakistan

Zone	Description of the crop growth zoens
1	Excess (K*, R**)
2	Excess (K), Adequate (R)
3	Excess (K), Mod.*** Adequate (R)
4	Adequate (K), Excess (R)
5	Adequate (K, R)
6	Adequate (K), Mod. Adequate (R)
7	Adequate (K), Deficit (R)
8	Mod-Adequate (K), Deficit (R)
9	Deficit (K, R)

* K - *Kharif* Season (May-September)
** R - *Rabi* Season (October-April)
*** Mod - Moderately

The crop growth index in both the Kharif and the Rabi seasons ranges from excess to deficit. In the Kharif season, it ranges from normally adequate to excess, whereas in the Rabi season from normally adequate to deficit. However, the 9 zones indicate a considerable variability in the availability of temperature for crop growth.

3) Agro-climatic zones

The agro-climatic zones were delineated, by superimposing the 18 aridity and 9 crop growth zones, representing both the *Kharif* and the *Rabi* seasons. A total of 57 agro-climatic zones were classified out of which 8 zones are relatively small in size. Each zone shows a variability in terms of aridity and crop growth for both the *Kharif* and the *Rabi* seasons.

4) Application of agro-climatic information

The agro-climatic zones can provide very useful information for planning of agricultural research and technology transfer. The identification of benchmark research locations is another useful outcome of this activity. This information can also be used for the planning, management, and conservation of water resources in the country. Water is one of the major limiting factors related to agricultural production in the country. The management strategies developed by Ahmad and Heermann (1992) are a good example for practical use of this information in Pakistan. The variability in climate affects the irrigation schedules in Punjab of Pakistan (Ahmad, 1981).

For detailed crop suitability zoning, the atmospheric demand characterization can be used in conjunction with broad agro-climatic zoning based on aridity and crop growth indices. Furthermore, crop growth models can also provide additional refinement for predicting potential yields. The production functions developed for either selected crops or for different environments will further help to predict crop yields based on edaphic and climatic limitations.

Agro-climate is quite complex, involving not only spatial variability but also temporal variability. In order to consider this variability in agricultural systems, a comprehensive and integrated approach is required. Here agricultural system refers to the total activities, starting from farm planning, plantation, irrigation, harvesting, postharvest storage, and marketing. During this whole process, insects and pests are a continuous threat for the production system. Pests and pathogens have their own ecological amplitudes particularly in relation to climatic factors. The major climatic factors conducive to the development and spread of pests and diseases are temperature and relative humidity.

The agro-climatic zones can provide the basis to delineate the potential epidemiological zones. For example the area where the host is present but the optimal temperature and wetness are not available for a parasite could be a sporadic incidence zone. On the other extreme, main damage area would be where host and optimal temperature and wetness zones overlap. Similarly, potential marginal, potential main, and marginal damage areas could be identified. This whole process requires a continuous feedback from entomologists and pathologists about the climatic requirements of pests and pathogens, which could be incorporated into existing database and useful information could be generated. At the same time, accurate and timely climatic data are required so that considering the existing climatic pattern and potential of the area, management strategies could be developed for effective and timely control of pests and diseases before the occurrence of disastrous outbreaks.

Case study on "Spatial and temporal analysis of groundwater at MONA Reclamation Experimental Project"

1 Introduction

Waterlogging and salinity are the twin problems of the Indus basin irrigated agriculture due to seepage from the large and extensive network of earthen canals and watercourses covering a gross canal command area of 16.4 million hectares. Almost half of the command area was affected by waterlogging and salinity to an extent that agricultural productivity was adversely affected. The government of Pakistan initiated the Salinity Control and Reclamation Projects (SCARP) in the Indus basin during the early 1960s and about 37 projects have been completed. The total program cost was around Rs. 20 billion. The program involved the construction of about 20,801 deep tubewells and 10,344 km of surface and sub-surface drains on around 42,666 hectares of land, with the purpose of controlling the water table and augmenting irrigation water supplies (MREP, 1997).

Soon after the completion of early SCARPs, it was realized that with the increase in the water supplies, conveyance and application losses increased significantly, water quality changed and virtually no improvement in cropping intensities was taking place.

In order to identify the problems related to SCARPs and to develop solutions, the MONA Reclamation Experimental Project (MREP) was implemented in 1965. The area is located at a distance of about 200 km from Lahore, and is a part of Tehsil Bhalwal in the Sargodha district. The Lower Jhelum Canal bounds the project area on the north and the river Jhelum on the east. The northern branch of the Lower Jhelum Canal and the Sargodha-Gujrat road forms the southern boundary. The motorway passes through the center of the project area. The project covers a gross area of 71,742 hectares, with 308 SCARP tubewells in the MONA and Shahpur SCARP Units. The individual design discharges of tubewells range from 28 to 113 liters per second (MREP, 1997).

In the case study, MONA Unit area has been selected covering the gross command area of 44,516 hectares with 138 tubewells. The pre-project water table depth ranged between 0 to 3.35 m during 1965, whereas it changed to 0.61 to 5 m during 1997. The pre-project cropping intensity was 99 %, whereas it was 152 % during 1997 (MREP, 1997).

The case study aimed at conducting a spatial and temporal analysis of groundwater quality and water table depth in the project area to evaluate the changes which occurred in the project area during the last 32 years. The long-term geo-referenced data collected during the implementation of the project were used for GIS analysis.

2 Materials and methods

The map of the MONA REP was digitized using the scale of 1:250,000. The water quality and water table depth data of 138 tubewells were collected from the MONA REP representing the pre- and post-project periods of 1965-66 and 1997, respectively. The tubewell locations were geo-referenced to prepare the tubewell location map.

1) Groundwater quality analyses

The water quality data include parameters like Total Dissolved Solids in parts per million (ppm), Sodium Adsorption Ratio, and Residual Sodium Carbonate in milli-equivalent per liter (meq/l). The total dissolved solids represent the water salinity, whereas the sodium adsorption ratio and residual sodium bicarbonate represent the sodicity level of groundwater. Spatial databases of all the three parameters were developed for the pre- and post-project situation.

Six classes of groundwater salinity were defined covering <500, 500-1,000, 1,000-1,500, 1,500-2,000, 2,000-2,500 and >2,500 ppm of total dissolved solids.

The classes for sodicity were defined at two levels covering the sodium adsorption ratio and the residual sodium carbonate. Four classes of sodium adsorption ratios were defined covering <5, 5-10, 10-15 and >15. Nine classes of residual sodium carbonate were defined covering <1.25, 1.25-2.50, 2.50-3.75, 3.75-5.00, 5.00-6.25, 6.25-7.50, 7.50-8.75, 8.75-10.00 and >10.00 meq/l.

2) Water table fluctuations

The water table depth data collected during the pre- and post-project periods covered the 138 tubewells of the MONA Unit. The water table data were expressed as depth in meter to the groundwater surface from the soil surface at the tubewell. Four water table depth classes were defined covering <1.0, 1.0-2.0, 2.0-3.0 and >3.0 m.

3) Spatial and temporal analyses

Both spatial and temporal analyses were made for the groundwater quality and water table depth. The analyses were conducted to evaluate the changes in the groundwater quality and water table depth during a period of 32 years. The area under a water table less than 3m depth is considered to be waterlogged.

3 Results and discussion

1) Groundwater salinity

Spatial maps of total dissolved solids were prepared for the pre- and post-project periods (Figs. 5 and 6). The comparison of the temporal data indicated that groundwater salinity of around 10.7 % area had changed from less than 500 ppm to 500-1,500 ppm. Improvements were observed in areas with a water quality between 1,500-2,000 ppm. There were no significant changes in the classes with salinity of more than 2,000 ppm (Table 3). Groundwater with less than 500 ppm salinity was considered as freshwater.

The pumping of groundwater from deeper depths has resulted in a redistribution of salts in the profile. This is a serious concern and even the project area has a significant recharge from the canal network or floods in the Monsoon season. The problem will be much more acute in areas having less recharge from the freshwater sources.

2) Groundwater sodicity

Spatial maps of sodium adsorption ratio were prepared for the pre- and post-project periods. The comparison of the temporal data indicated that groundwater sodicity in terms of sodium adsorption ratio did not have any significant effect on groundwater quality as in only 1.90 % of the area the ratio changed from less than 5 to 5-10.

Table 3 Changes in groundwater quality in terms of Total Dissolved Solids (TDS) at MONA REP, Bhalwal during 1965-66 and 1997

TDS (ppm)	Area (%)		Change in area (%) (+ or –)
	1965-66	1997	
<500	37.80	27.13	–10.67
500 - 1,000	33.02	42.45	+9.43
1,000 - 1,500	13.37	18.27	+4.90
1,500 - 2,000	11.67	8.06	–3.61
2,000 - 2,500	3.99	4.09	+0.10
>2,500	0.15	0.00	–0.15
Total	100.00	100.00	0.00

Table 4 Changes in groundwater quality in terms of Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC) at MONA REP, Bhalwal during 1965-66 and 1997

Parameters	Class range	Area (%)		Change in area (%) (+ or –)
		1965-66	1997	
Sodium Adsorption Ratio (SAR)	< 5.00	56.57	54.70	–1.87
	5.00 - 10.00	19.10	22.62	+3.52
	10.00 - 15.00	13.67	12.86	–0.81
	>15.00	10.66	9.82	–0.84
Residual Sodium Carbonate (RSC) Meq/L	< 1.25	50.78	60.88	+10.1
	1.25 - 2.50	15.67	12.63	–3.04
	2.50 - 3.75	9.93	10.42	+0.49
	3.75 - 5.00	7.77	6.70	–1.07
	5.00 - 6.25	6.92	4.33	–2.59
	6.25 - 7.50	4.92	3.00	–1.92
	7.50 - 8.75	2.55	0.65	–1.90
	8.75 - 10.00	1.11	0.49	–0.62
	>10.00	0.35	0.90	+0.55

Only less than 1.0 % of the area changed into classes with a sodicity ratio of more than 10 but it could be considered as an improvement under these classes (Table 4). Groundwater of less than 15 sodium adsorption ratio is considered non-sodic.

Spatial maps of residual sodium carbonate were prepared for the pre- and post-project periods. The comparison of the temporal data indicated that groundwater sodicity in terms of residual sodium carbonate did not have any significant effect on groundwater quality and that there were improvements in sodicity (Table 4).

The reason for the improvement is sodicity is due to the increased use of gypsum and sulfuric acid as amendments for reclamation of secondary sodification.

3) Water table fluctuations

Maps of water table depths were prepared for the pre- and post-project periods (Figs. 7 and 8). The comparison of the temporal data indicated that there was an increase of around 19 % in the area with a water table of less than 2 m depth (Table 5). Area with a water table of less than 3 m depth was classified as waterlogged. Therefore, there was an increase of around 16.9 % in the waterlogged area. This increase was mainly due to the reduced pumping of groundwater because of increased energy prices and discontinuation of use of the tubewells with brackish groundwater. This is a serious concern and a good indication of the poor performance of the reclamation projects.

Table 5 Changes in water table depth from soil surface at MONA REP, Bhalwal during 1964 and 1999

Water table (depth, meter)	Area (%)		Change in area (%) (+ or –)
	1964	1999	
<1	1.07	1.92	+0.85
1–2	7.32	25.52	+18.20
2–3	34.31	32.12	–2.19
>3	57.30	40.44	–16.86
Total	100.00	100.00	0.00

4 Application of groundwater analysis

The temporal and spatial groundwater analyses indicated that there was an increase in groundwater salinity and waterlogging in the project area. This information is useful for the planning of future projects to control waterlogging and salinity.

This information also provided an insight for conducting research to develop skimming wells to pump shallow freshwater which should exert a greater impact on the control of the water table depth than pumping water from deeper depths. In addition, the increase in energy prices requires the development of energy-efficient pumping systems to maintain the water table below the root-zone depth.

The criteria of a water table of more than 3m depth need reconsideration in the freshwater zone, because a water table of more than 1m depth in the freshwater zone is suitable for field crops, except cotton. However, the water table should be more than 3m deep for fruit orchards. As farmers are growing quality citrus in the project area, they want a water table deep enough to grow good quality citrus.

Farmers should be encouraged to grow forest plants with higher water requirements especially in areas with marginal to brackish groundwater quality.

Other applications

There are many other applications for which work is in progress and the results will be presented in the forthcoming symposium. Some of the applications are as follows :

* Merging of agro-relief and agro-climatic indices to develop agro-ecosystem characterization and classification;
* Crop databases on area and yield of crops at district level to develop potential productivity zones of Pakistan;
* Image processing using LANDSAT TM data for analysis of watershed hydrology, soil erosion and potential groundwater recharge zones in the Shahpur dam;
* Image processing of NOAA satellite data for land cover and land use classification of Pakistan;
* Analysis of rural poverty and natural resource endowments in Balochistan province of Pakistan; and
* Ecosystem characterization and classification for natural resources management and conservation of nature in Pakistan.

Acknowledgement

The WRRI-NARC would like to acknowledge the support and technical assistance provided by JIRCAS, Japan in establishing the GIS and Remote Sensing Laboratory at WRRI-NARC, Islamabad, Pakistan. In this regard, the technical assistance and training provided by Dr. Satoshi Uchida are highly commendable because without his support and personal interest this work could not have been completed. The work done by Mr. Arshad Ashraf, Mr. Iqbal Hassan and Mr. Irshad Ullah of WRRI is also fully acknowledged. At the end, the contributions made and guidance extended by the Chairman of PARC and Director General of NARC are highly acknowledged.

References

1) Ahmad, S. (1981): Computer modelling for practical irrigation scheduling in Punjab of Pakistan. Pak. J. Agri. Res., 2(4), 260-268.
2) Ahmad, S. and Heermann, D.F. (1992): Management strategies for scheduling irrigation: wheat and corn. ICID Bulletin, 41(2), 111-126.
3) Bunting, A. H. (1986): Agricultural environments: Characterization, classification and mapping. C.A.B. International, Wallingford, United Kingdom.
4) FAO (1981): Report on the agro-ecological zones project. Vol.I-IV, World Soil Resources, Report 48/1-4, Rome.
5) GOP, IUCN, World Conservation Union, IIED and UNDP (1992): Pakistan national report to UNCED. Environment and Urban Affairs Division, Government of Pakistan.
6) GOP (1998): Agriculture Statistics of Pakistan. Economic Wing of the Ministry of Food, Agriculture and Livestock, Government of Pakistan.
7) Hargreaves, G. H. and Samani, Z. A. (1986): Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture, 1(2), 96-99.
8) Jaetzold, R. and Schmidt, H. (1982): Farm management handbook of Kenya. 3 vol., Nairobi; Ministry of Agriculture.
9) Kassam, A. H., van Velthuizen, H.T., Higgins, G.M., Christoforides, A., Voortman, R.L., and Spiers, B. (1982): Assessment of land resources for rainfed crop production in Mozambique. FAO:AGOA:MOZ/75/011, Field Docs. 32-37, Rome.
10) Köppen, W. (1936): Das geographische System der Klimate. In: Handbuch der Klimatologie. Berlin: Borntrager.
11) MREP (1997): Project profile. MONA Reclamation Experimental Project, Bhalwal, WAPDA.
12) NCS (1991): National conservation strategy. Ministry of Environment, IUCN.
13) Papadakis, J. (1961): Climatic tables for the world. Buenos Aires: published by the author.
14) PARC (1982): Consumptive use of water for crops in Pakistan. Final Technical Report. PK-ARS-69/F6-Pa-251, Pakistan Agricultural Research Council, Islamabad, Pakistan.
15) Roohi, R. and Ahmad, S. (1993): Agroclimatic characterization and classification. In: Proceedings of COMSTECH-NIAB International Workshop on Agroclimatology Pests and Diseases and their Control, Faisalabad.
16) Thornthwaite, C.W. (1948): An approach towards a rational classification of climate.Geogr. Rev. 38, 55-94.
17) UNESCO (1964): International classification for climate. UNESCO.
18) UNESCO (1973): International classification and mapping of vegetation. Ecology and conservation 6. Paris: UNESCO.
19) WSIPS (1990): Water sector investment policy study. Water and power development Authority, Lahore.
20) World Bank (1994): Pakistan Irrigation and Drainage: Issues and options. Report No. 11884 Pak, The World Bank, Washington, D.C.

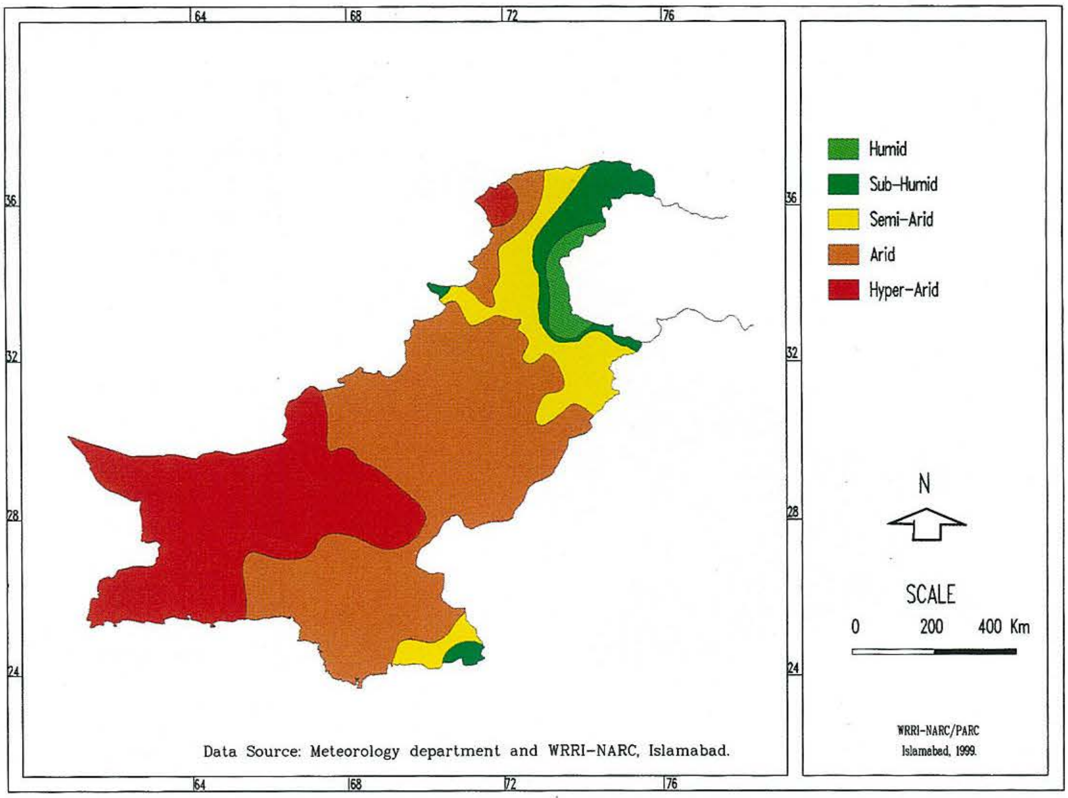

Fig. 1 Pakistan aridity classes (Kharif)

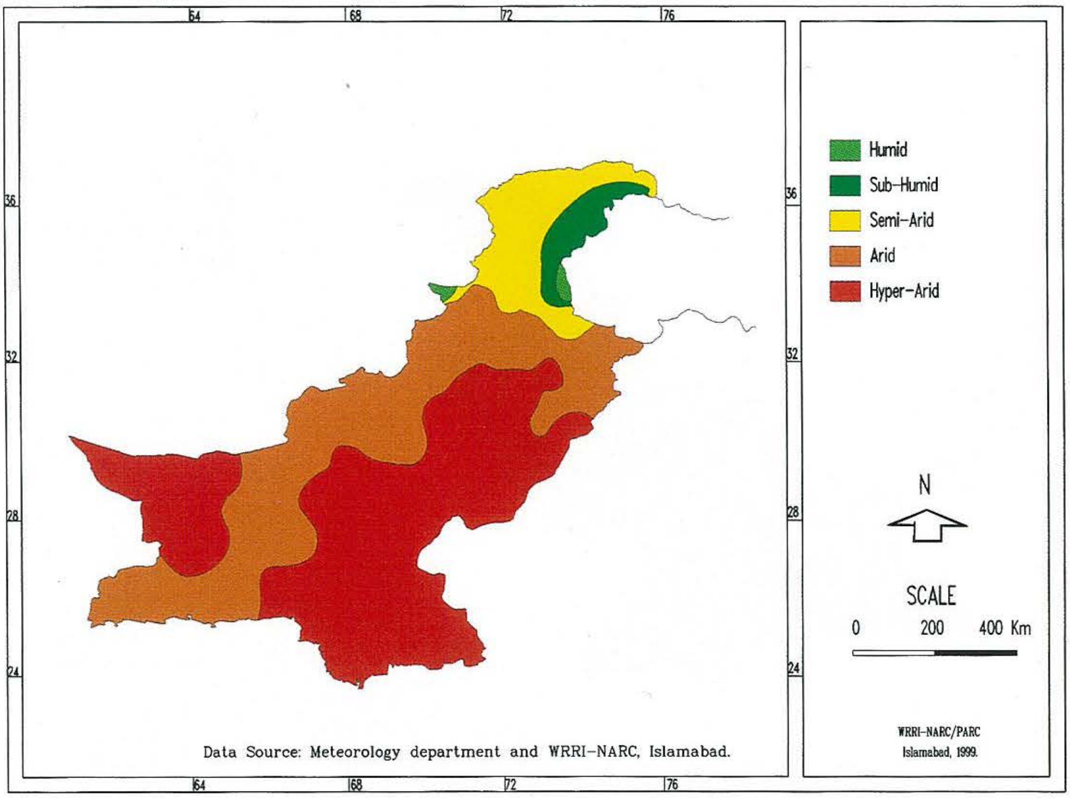

Fig. 2 Pakistan aridity classes (Rabi)

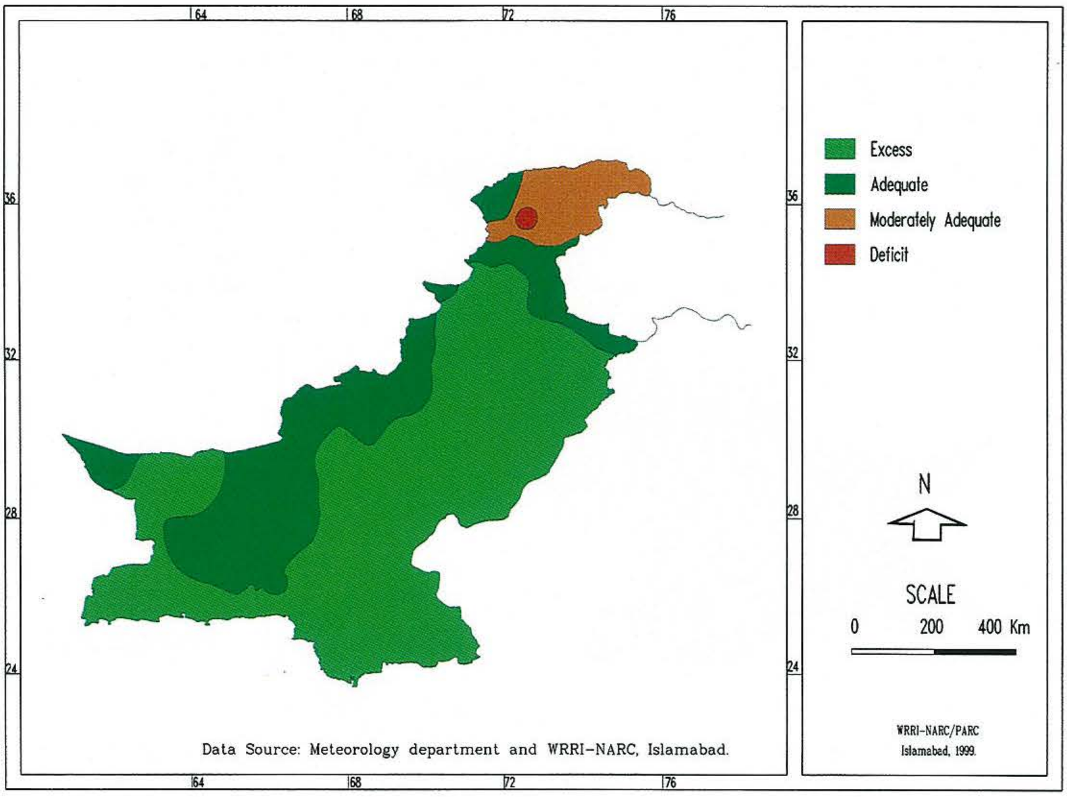

Fig. 3 Pakistan crop growth classes (Kharif)

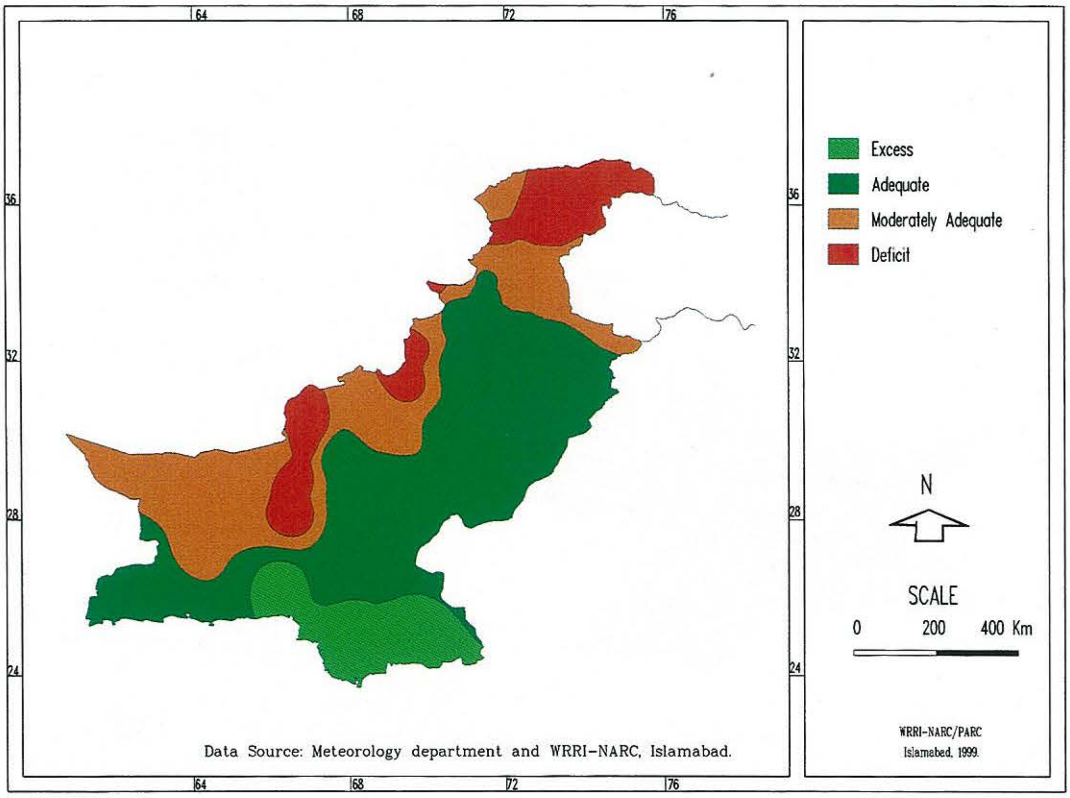

Fig. 4 Pakistan crop growth classes (Rabi)

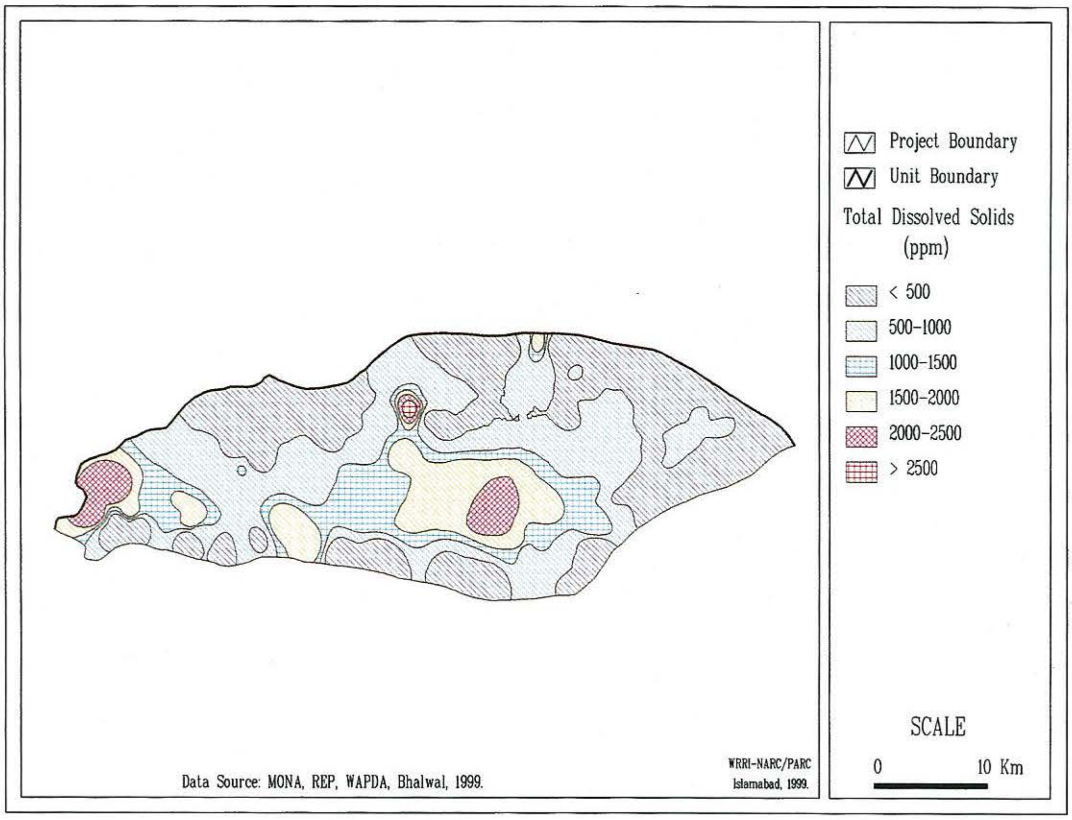

Fig. 5 Spatial distribution of groundwater salinity of scarp tubewells at MONA unit, Bhalwal (1965-66)

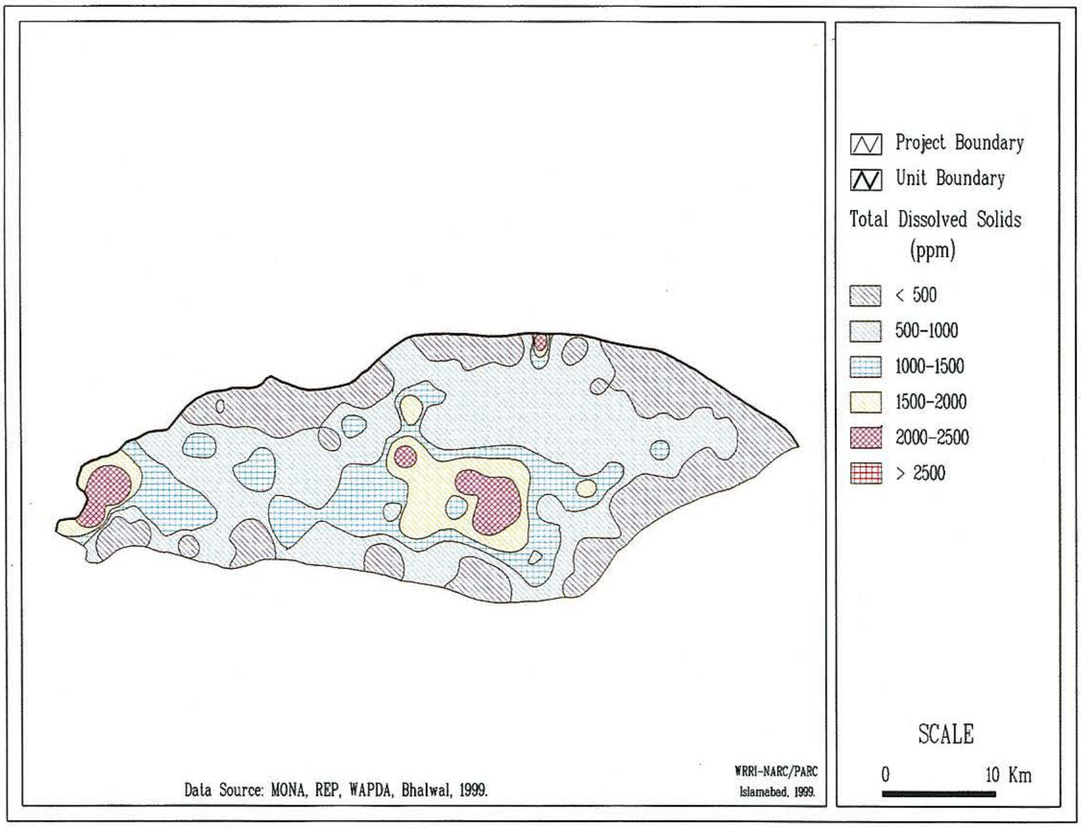

Fig. 6 Spatial distribution of groundwater salinity of scarp tubewells at MONA unit, Bhalwal (1997)

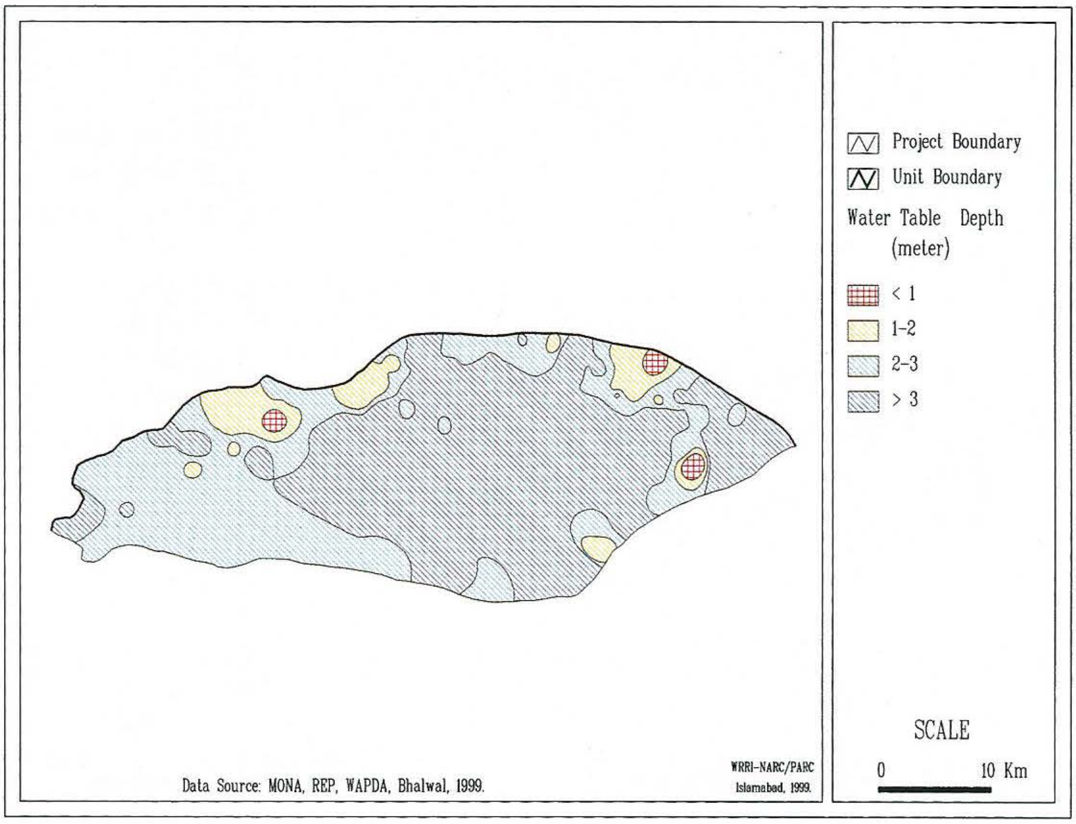

Fig. 7 Spatial distribution of water table depth of scarp tubewells at MONA unit, Bhalwal (1964)

Fig. 8 Spatial distribution of water table depth of scarp tubewells at MONA unit, Bhalwal (1999)