Using Remote Sensing Techniques for Appraisal of Irrigated Soil Salinity

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EXTENDED ABSTRACT

Waterlogging and salinization are the twin evils of the irrigated agriculture in arid and semi-arid areas, which reduce the productivity of agricultural lands adversely. Managing salinity so as to minimize its environmental impact is a prerequisite for the long-term sustainability of irrigated agriculture. It necessitates establishing fast monitoring systems that facilitate taking actions. Remote sensing appears to offer several advantages over the conventional ground methods used to map and monitor soil salinity. This paper describes an integrated approach to assess soil salinity using remotely sensed data. This encompasses spatial analysis of ground truth and satellite data. The study area is located in the District of Faisalabad in Pakistan. The ground truth data of soil salinity from selected sampling points is tied to the corresponding pixels from the satellite image bands. Remotely sensed data based salinity indices (band combinations) and principal components using principal component analysis (PCA) are developed to find out the occurrence pattern of the salinization. Out of the six salinity indices developed, the following proved to be the most promising when compared with ground truth data.

Salinity Index = $(B_2 \times B_3)/B_1$

Where; B_1, B_2 and B_3 are bands of the satellite, IRS-1B LISS-II, in spectral range of band 1 (0.45-0.52 μm), band 2 (0.52-0.59 μm) and band 3 (0.62-0.68 μm) respectively. Regression methods were applied to find the best correlation between salinity data and corresponding pixels on the satellite images. The resulting images were categorized into three distinct classes of saline soils; slightly saline, moderately saline and strongly saline. Using supervised maximum likelihood classification, the images were classified with an overall accuracy of more than 90%. Based on the classified results, saline soils covered 8.7%, 14.2% and 6.6% of the image area in 1991, 1994 and 1997 respectively. The relationship between salt affected soils, waterlogged soils and groundwater quality revealed that 60 to 70% of the salt-affected soils occurred in the zone of shallow water table within 200 cm from ground surface, which is indicative of waterlogged situation. The groundwater in the saline areas is also of hazardous quality, which restricts plant growth except high salt-tolerant crops.

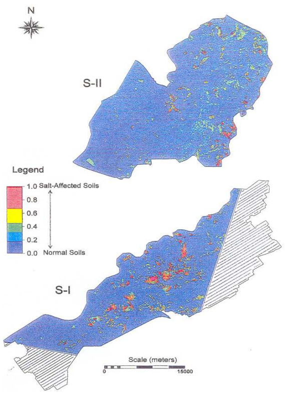


Figure A. Probability density of salt-affected soils

Figure A shows the probability density of salt-affected soils with intensity ranging from zero to unity. “Zero” indicated normal soils and above zero to unity represented intensity of salt-affected soils.

Using satellite data, the principal component analysis (PCA) and the salinity indices are found to be promising techniques for assessment of saline soils. In the scenario of water scarcity (restricted irrigation supplies in supply channels) due to persistent drought, the reuse of poor quality ground water for irrigation and the failure of tile drainage system in the area are likely to disturb the water ecosystem resulting in increased risks of further environmental land degradation.

1. INTRODUCTION

Soil salinity is a severe environmental degradation that impedes crop growth and production. Soil salinity in semi-arid environments where crop water requirements in addition to rainfall are augmented by irrigation supplies is a major concern for the sustainability of the agricultural systems. Salinization is a worldwide problem in irrigated lands, which use large amounts of irrigation water and are poorly drained. FAO (1990) reported that about 20 to 30 mha (million hectares) worldwide are severely affected by salinity and an additional 60 to 80 mha are affected to some extent. At global scale, soil salinization is spreading at a rate of up to 2 mha per year, which offsets a good portion of the crop production that is achievable by expanding irrigation and/or using best management practices at system level. Umali (1993) provided the estimates of irrigation salinity for top four irrigators in the world as India 11%, Pakistan 21%, US 23% and Mexico 10% of the irrigated land. In only New South Wales (NSW) State of Australia, irrigation salinity is estimated to affect 15% of the irrigated land. Irrigation salinity occurs in large and small irrigation systems alike. In recent years, many farmers have been abandoning their rice fields due to the incidence of soil salinity.

Pakistan has a total area of 79.6 mha, with 22.0 mha cultivated (GOP, 1999), and 6.28 mha affected by salinity and/or waterlogging within the irrigation regions (Rafiq, 1990). A land area between 2 and 3 mha is categorised as wasteland due to high salinity and sodicity (Qureshi et al, 1993). It is estimated that 25% of the irrigated land in the Punjab and 40% of the irrigated land in Sindh are salt affected. About 10 to 20 million people live on salt-affected land (Barrett-Lennard and Hollington, 2006) with impoverished productivity and under increased threats of devastating ecosystem. Seepage from supply canals, extensive network of off-farm and near-farm watercourse, and flooded irrigated paddocks is one of the primary causes of secondary soil salinity (Abbas et al., 2005). Waterlogging and salinity have distressing social and economic effects on farming communities. However, the increasing shortage of fresh water resources is likely to trigger increased environmental damage. The falls in river flows and irrigation supply channels, persistent droughts (except the recent monsoon wet season of 2007 have caused inundations and river flooding) have disturbed the water ecosystem resulting into food insecurity and non sustainable farming systems. Engineering, agronomic and biological measures are in practice to control further environmental land degradation and to secure food self sufficiency in staple foods.

Remote Sensing has the ability to predict soil salinity accurately. It saves labour, time and effort when compared to field data collection of lands at risk of white death (salinization). Satellite data has a great potential for monitoring salinization in both spatial and temporal extents (Abbas, 1999). Past research shows mapping and assessing of soil salinity using remote sensing data like aerial photography, videography, infrared thermometry and multispectral scanners (Mougenot and Pouget, 1993; Singh, 1995; Tripathi et al., 1997; Dwivedi and Sreenivas, 1998). Remote sensing appears to offer several advantages over the conventional ground methods used to map and monitor soil salinity.

- Remote sensing is timely, faster than ground methods and provides better spatial coverage.
- Remote sensing data can be used as input into a geographic information system (GIS) for further analysis and comparison to other data. Sensors with improved resolution are able to recognize more details for better results and precision. The users can select the band or bands required for their particular needs.
- Using remote sensing, soil salinity can be mapped both directly, by reflectance from bare soil, or from the salt crust, and indirectly from vegetative coverage and health.
- Saline soils with visible salt efflorescence on the soil surface are easier to map using remote sensing and are considered to be strongly saline soils.
- Vigorous growth and type of vegetation are easily recognised in satellite images. Therefore, plant vigour and type can be used to identify the extent of soil salinity. Such areas are usually moderately to weakly saline.

Reliable and up-dated information on the spatial and temporal variability of soil salinity is required to effectively manage the limited natural resources and maintain a viable agricultural industry that is highly dependent on conjunctive use of surface and ground waters with varying salinity levels. Both, improved water use efficiency and environmental stewardship are indeed complementary goals. In this paper, we developed remotely sensed based salinity indices and had evaluated the application of principal component analysis (PCA) to predict salinity in the irrigated region.

2. STUDY AREA

The irrigated land in the District of Faisalabad was selected for this study. The study area consists of two parts: S-I and S-II, and is located in the south-western part of Rechna Doab (the region lying between two rivers – The Ravi and The Chenab). The area is bounded by geo-coordinates 31˚ 02′ to 31˚ 45′ N and 72˚ 50′ to 73˚ 22′ E. The climate is characterised by large seasonal fluctuations of ambient temperatures and rainfall. The summer is long and hot, from April to September; with max temperature soaring to 49 ˚C. Winter maximum is 27 ˚C during the day and the minimum falls near zero at night. The monthly maximum, minimum temperatures and the rainfall of the region are given in Figure 1.

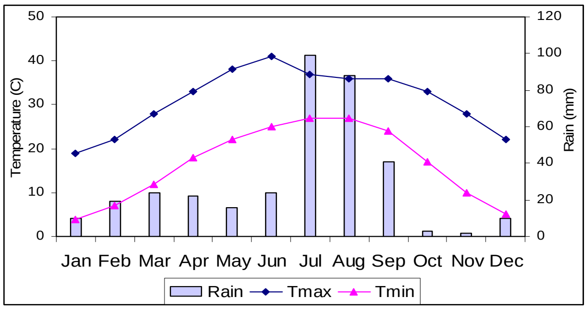


Figure 1. Average maximum, and minimum temperatures, and monthly rainfall of Faisalabad

The location of the study area is given in Figure 2. The soils are mainly alluvial deposits with wide range of moderately coarser to moderately fine medium textured material. The region has been very productive and extensively irrigated. It provided valuable information about the severity of the salinity problem and availability of the ground truth data. Medium textured loam is the major surface soil and loamy sands in the subsurface. Physiographically, the area is nearly level to very gently sloping lands with mean elevation of 190 m above sea level. The average land gradient is 0.02% from north-south to south-west directions. The aquifer depth varies from 300 to 500 m. The phreatic surface was 20 to 30 m deep before the gravity irrigation system was introduced in 1856 during the British regime. By 1960s, the watertable has risen creating waterlogged conditions that resulted in secondary salinization.

3. METHODS

In the present study, two types of data have been used: satellite data (1992-1995) and field data (Electrical conductivity (ECe) and sodium absorption ratio (SAR) of soil) from 70 locations within the study area. The multi-temporal IRS-1B LISS-II images in four spectral bands with spatial resolution of 36.25 m were georeferenced to UTM projection. The band data was corrected for geometric distortion. The principal component analysis (PCA) and band combinations were applied to assess saline soils. The principal component analysis is carried out in terms of mean, standard deviation, correlation coefficient and variance / covariance matrices. The PCA is based on the computation of eigen vectors and eigen values. The first component (PC-I) accounted for 77.3%, 80.1%, 73.9% and 88.3% of the variance for 1992, 1993, 1994 and 1995 data respectively. The PC-II and PC-III were not significant according to the variance level. The PC-IV represented the random noise. Therefore,

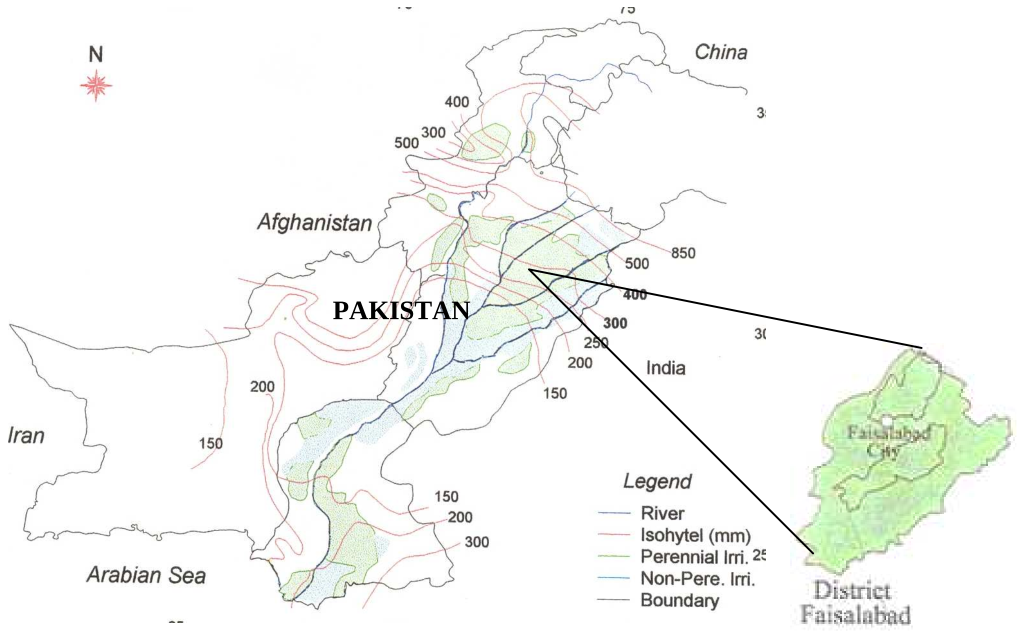


Figure 2. Rainfall distribution and irrigated areas of Pakistan and the location of the study area

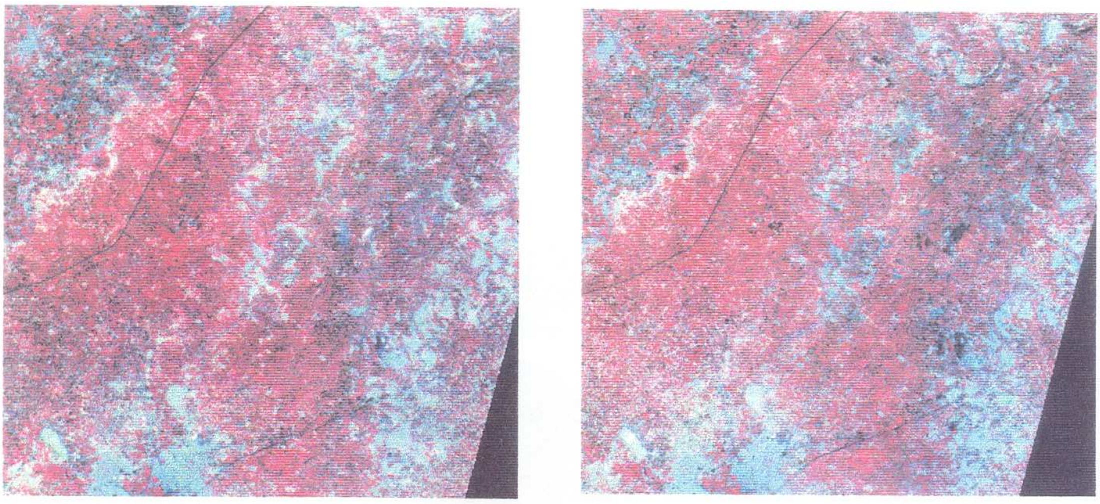
PC-I data was used to predict soil salinity.

The band combinations through development of salinity indices (SI) were applied to satellite data. Band selection was dependent on the spectral reflectance as DN (digital number) of the selected pixels of land use classes. The salt-affected soils had relatively higher reflectance compared with other land use. It is noticed that first three bands (B_1, B_2, and B_3) are promising in developing relationship. The infrared band (B_4) did not yield reliable information when compared with ground truth data. However, the B_4 was in included in S_6 to compare and validate the results. The following indices were developed and tested.

$$S_1 = \frac{B_1}{B_3} \tag{1}$$

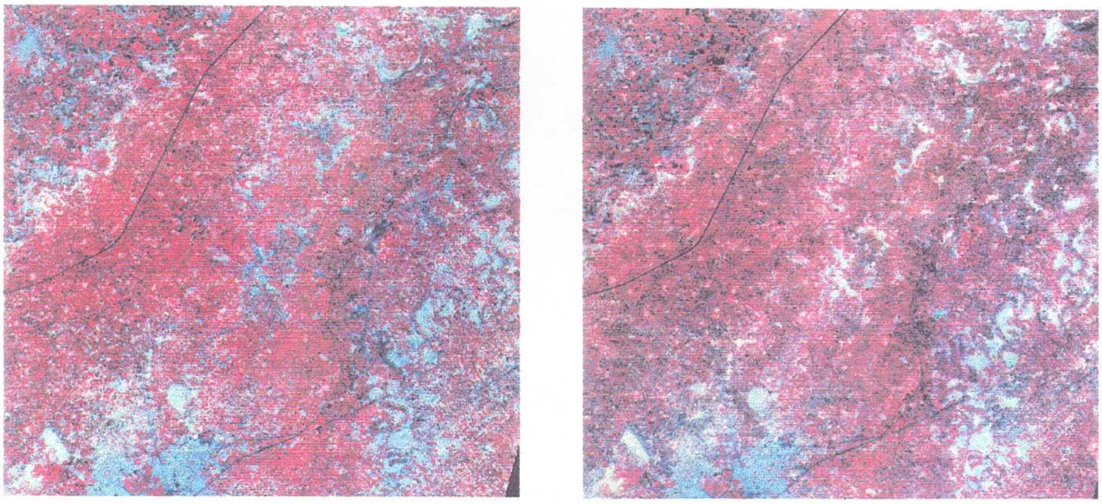
$$S_2 = \frac{(B_1 - B_3)}{(B_1 + B_3)} \tag{2}$$

$$S_3 = \frac{(B_2 \times B_3)}{B_1} \tag{3}$$



June 18, 1992

June 5, 1993



June 14, 1994

June 1, 1995

Figure 3 False colour composite images of the study site.

$$S_4 = \sqrt{B_1 \times B_3} \tag{4}$$

$$S_5 = \frac{(B_1 \times B_3)}{B_2} \tag{5}$$

$$S_6 = \frac{(B_3 \times B_4)}{B_2} \tag{6}$$

Table 2. Classification of salt-affected soils

Class	ECe (dS/m)	SAR (meq/l)
Salt free	< 4	< 13
Saline-nonsodic	> 4	< 13
Saline-sodic	> 4	> 13
Nonsaline-sodic	< 4	> 13

Source: USDA (1954) Handbook No. 60

4. RESULTS

Figure 3 shows the false colour composite (FCC) generated by band combination of B_3, B_2, and B_1 (red, green and blue). The FCC demonstrates white patches followed by light bluish tone of different dimensions indicating salt efflorescence of salt-affected soils. It revealed that salt-affected and water logged areas are clearly delineated compared with other land use classes. Likewise, the presence of these salts showed higher spectral signals as DN (digital number) values and cross-validated by ground truth data as unique property of the salt-affected soils. This obviates that salinity could be easily interpreted from the satellite images.

Normal and salt-affected soils exhibit differences in ground surface conditions. Salt-affected soils are characterised by the presence of various accumulated salts in the soil profile. This distinctive feature can be identified using satellite data. It is noteworthy that spectral response of salt-affected soils is higher than those of normal soils. It shows that salty soils reflect more incident light energy in visible spectrum and this characteristic is extremely useful in segregation of saline soils. Matternichet and Zink (1997) found that salt had high spectral reflectance in the visible window particularly in the blue band. The soil salinity affects vegetation density and crop growth, which is detected by NDVI (normalized differential vegetation index) and the false colour composite.

Table 1. Classification of soil salinity

Class	ECe (dS/m)	Description
Salt free	ECe < 4	▪ No visible salts on the soil surface ▪ Crop growth remains uniform
Slightly saline	4 < ECe > 8	▪ Visible salts on the soil surface ▪ Crop growth is uneven and patchy
Moderately saline	8 < ECe > 15	▪ Salts are fairly visible on the soil surface ▪ Plant growth is very patchy and restricted
Strongly saline	ECe > 15	▪ Soil surface is fluffy ▪ Salts are fairly visible ▪ Soil supports indigenous vegetation ▪ Salt tolerant crops are possible to grow

Source: Ghassemi et al. (1995)

The supervised classification, using maximum likelihood algorithm, was carried out for land use analysis. The bare soil and salt-affected soils were two distinctive classes since normalized difference of bare land and salt-affects soils determined was 3.05 and 0.53 respectively. After assigning those pixels representing salt-affected soils with higher reflectance (DN), the values of electrical conductivity of soil (ECe) and sodium absorption ratio (SAR) from the ground truth data, the images were classified according to Tables 1 and 2.

The salinity indices were applied and the images obtained were compared ground truth data. The salinity index "S_3" showed highest correlation between observed and predicted ECe data. In order to validate the predicted data, the correlation between the measured salinity data and the predicted values was carried out. The results of the salinity index are highly correlated with B_3, B_2, and B_1 and ECe, SAR (Table 3).

Table 3. Correlation matrix of band data, salinity index and salinity parameters

	B_1	B_2	B_3	B_4	SI	ECe	SAR
B_1	1						
B_2	0.98	1					
B_3	0.96	0.98	1				
B_4	0.30	0.36	0.31	1			
SI	0.98	0.99	0.99	0.39	1		
ECe	0.73	0.75	0.73	0.39	0.74	1	
SAR	0.76	0.77	0.75	0.33	0.76	0.81	1

Figure 4 represents the temporal pattern of the different categories of saline soils using the principal component analysis.

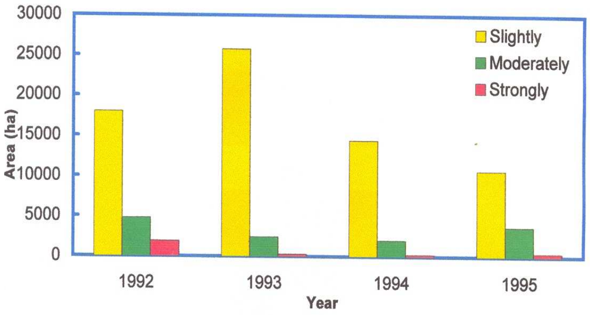


Figure 4. Existence pattern and temporal change of saline soils

The criterion defined in Table 1 was adopted to assess the overall salinization. The analysis shows that the total image area for 1992, 1993, 1994 and 1995 is 133102.1, 128568.9, 139744.7 and 141168.3 ha while the area under salinity is 18.5%, 22.2%, 12.0% and 10.5% of the image area in 1992, 1993, 1994 and 1995 respectively.

The images of both ECe and SAR were combined in a mathematical manipulation using the software ILWIS (Integrated Land and Water Information System) to assess various levels of salinity and sodicity. The temporal analysis was performed by an overlay procedure through pixel to pixel comparison of the changes that occurred between consecutive years at the same time. Table 4 shows the temporal extent of salinity and sodicity as defined by USDA and locally implemented by WAPDA (1997), given in Table 2.

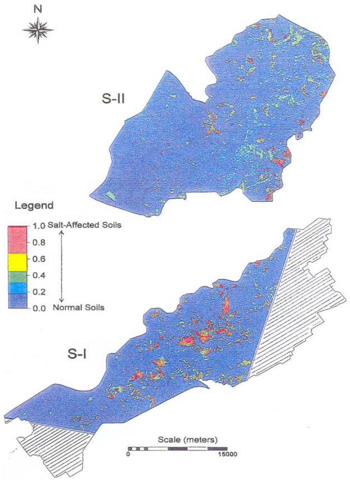


Figure 5. Probability density of salt-affected soils

Figure 5 shows the probability density of salt-affected soils with intensity ranging from zero to unity. The normal soils are represented by a zero and salt-affected soils demonstrate their occurrence by probability ranging from more than zero to unity in the satellite data. Later this image was further categorised into two distinctive classes for quantification and shown in Figure 6. This results into 7.5% and 3.8% as saline soils of the total image area in S-I and S-II regions respectively. The quantitative data is shown in Table 5.

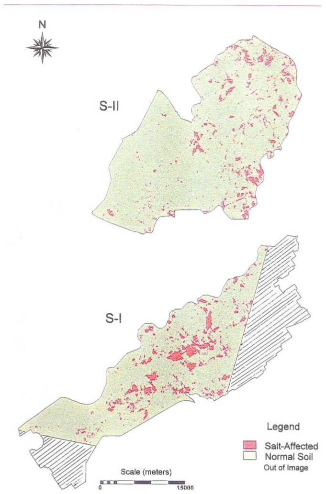


Figure 6. The occurrence pattern of salt-affected soils in the region

5. CONCLUSIONS

Soil salinization in Pakistan and elsewhere has caused an unrepairable loss of lands to productivity within a few decades. This has threatened the sustainability of agricultural industries and it will take millions of years to reclaim. It is vital to establish fast monitoring systems that facilitate taking actions. The present study demonstrates the potential of using satellite data for monitoring degraded lands with soil salinity. Salt-affected soils have been found to reflect more incident energy in comparison with normal soils and other classes of the land use in the visible and near-infra spectrum of the satellite data. The images were classified using supervised maximum likelihood classification with an overall accuracy of more than 90%. The principal component analysis (PCA) and the salinity indices are found to be promising techniques for prediction of saline soils from satellite imageries.

Table 4. Temporal extent of salinity and sodicity of the salt-affected soils

Type of salt-affected soils	1992		1993		1994		1995	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Saline-nonsodic	7258	5.5	6348	4.9	0	0	5067	3.6
Saline-sodic	17407	13.1	22203	17.3	16764	12.0	9745	6.9
Sodic-nonsaline	0	0	0	0	204	0.2	0	0

Table 5. Overall salinization of the region

Soil type	S-I		S-II		Total	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Normal soils	46119.1	92.6	68575.8	96.2	114694.9	94.7
Salt-affected soils	3707.2	7.5	2717.0	3.8	6424.2	5.3
Total image area	49826.3	100.0	712912.8	100.0	121119.1	100.0

6. ACKNOWLEDGEMENTS

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