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USE OF REMOTE SENSING AND AGROMETEOROLOGY FOR IRRIGATION MANAGEMENT IN ARID LANDS: A CASE STUDY FROM NORTHWESTERN SAUDI ARABIA

Saif ud din
Yousef A. Al-Rumikhani
Mohammad Sajid Latif

Natural Resource and Environmental Research Institute
King Abdulaziz City for Science and Technology
Riyadh, Kingdom of Saudi Arabia

Efficacy of irrigation management of major crops grown in the Wadi Sirhan area was determined in the present study from agroclimatic data merged with remotely sensed data, and irrigation scheduling efficiencies obtained from FAO guidelines. For computing irrigation scheduling efficiencies, amount of water supplied at different growth stages, soil water depletion, and crop water requirement have been taken into account. An area totaling 104815 hectares with 2505 center pivots of different sizes was selected. The major crops in the area, alfalfa, potatoes, tomatoes, and wheat, occupy 75%, 5%, 3% and 4% of the total center pivot area respectively. The crop water requirements are 2.74 billion m^3 water/year, 34 million m^3 of water/season, 26.086 million m^3 of water/season and 27.14 million m^3 of water/season for alfalfa, potatoes, tomatoes and wheat respectively. An area of 13626 hectares is uncultivated fallow. The water budget of the area is calculated for agricultural development and to develop efficient irrigation management practices. The crop water requirement of the major irrigated crops in the study area can be reduced by 50% without affecting crop yield.

INTRODUCTION

Fresh water is a finite and precious resource that is essential for sustaining life. Global fresh water consumption increased six-fold between 1900 and 2000, both because of population growth and because of rising per capita demand due to irrigation development, industrialization and improved living standards. A potential crisis is looming where available resources can no longer meet needs. This has necessitated adoption of water resource management and conservation.

Ever-growing demands for water have made it necessary for water managers to look beyond the resources of single catchments or even single regions. Increasing costs of new alternative sources have forced a realization that water is not a free commodity available as a right, but a product of limited volume that must be paid for by the user and must be used wisely, and that environmental and social factors must also be considered in the planning and management of water resource projects. The optimum use of the water resources of a particular region has therefore become a complex task, involving a wide range of disciplines and technological skills.

The Afro-Asian deserts had a humid past and well developed civilizations 5000 to 10000 years B.P. before aridity came to these lands. Desertification forced human settlements in these lands to adopt arid land farming. The geological surveys and exploration of arid lands during the last fifty years revealed vast natural resource endowments in parts of the Kingdom of Saudi Arabia and adjacent countries. The discovery of petroleum and groundwater resources in the arid ecosystem generated islands of prosperity in the deserts of poverty. The increase in population in the arid ecosystem of Saudi Arabia resulted in higher demand for food. This necessitated a change from arid land farming to irrigated agriculture, with the chief source of irrigation being groundwater, which in the arid lands of the world is fossil water from a humid past. Groundwater is a non-renewable resource in the fragile arid ecosystems of the world, and its exploitation calls for environmentally compatible and ecologically sustainable water resource management. In the Kingdom of Saudi Arabia, groundwater is non-renewable fossil water of age ranging from 10000 to 28000 years B.P (Edgell, 1997), and it is a major source of irrigation. Irrigation utilizes 80 to 88% of the total water consumption in the Kingdom (Sadik and Barghouti, 1994). The pattern of groundwater exploitation, if not managed, will generate environmental degradation of the fragile arid ecosystem. The present irrigation trend will result in 25% depletion of the groundwater reserves by 2010 A.D. (Al Alawi and Abdulrazzak, 1994). Fossil groundwater reserves may not last for more than 50 years with increasing demand for irrigation. This has prompted the need for science and technology inputs for management of regional irrigation water requirements in the Kingdom of Saudi Arabia. We present a case study from the Al Busayata irrigation schemes, undertaken as R&D program at Natural Resource And Environmental Research Institute, King Abdulaziz City for Science and Technology, Riyadh, to develop a model for growth stage wise crop water requirement to regulate irrigation application rate in the arid ecosystem.

The paper presents a time and cost effective methodology based on using remotely sensed data for crop identification, crop area estimation etc., together with agrometeorological data to evolve efficient irrigation management practices for sustainable agriculture in an arid ecosystem. The multiple data base approach for water resource management has general application to sustainable groundwater development in arid ecosystems.

STUDY AREA

The study area is part of Wadi Sirhan in the Al Jouf region of Northwestern Saudi Arabia (Figure 1). The study area extends from latitude 29.60 N to 30.80 N and longitude 37.90 E to 38.90 E. The area is covered in Landsat TM scene of path-row 172-039 of 15th March 2001.

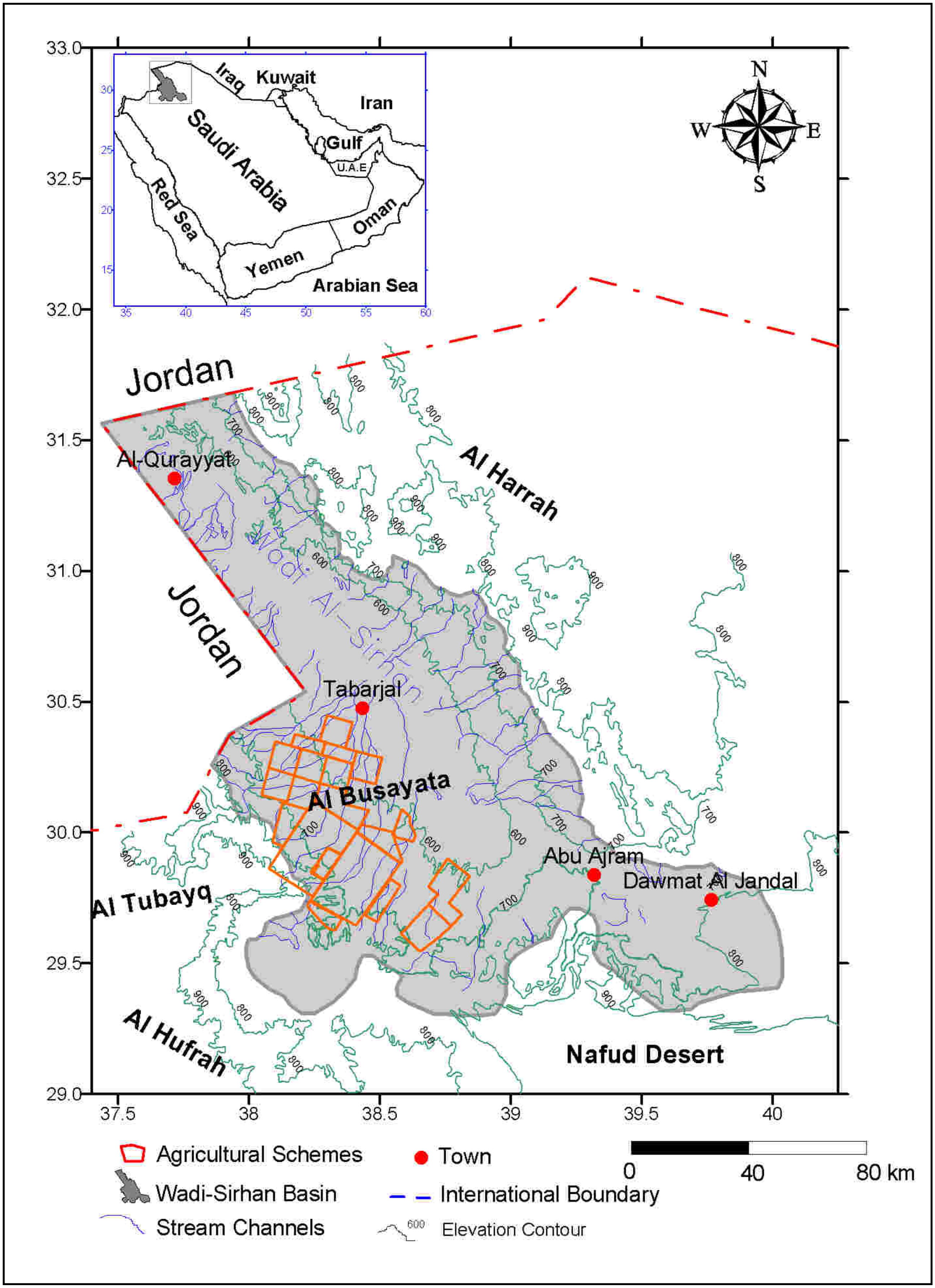

Figure 1. Location Map of the Wadi Sirhan, Al Busayata, Northwestern Saudi Arabia.

METHODOLOGY

Agriculture in Saudi Arabia is mechanized with deep wells providing groundwater for irrigation, through center pivot irrigation systems. In order to evaluate the total water requirement for agriculture, the remotely sensed TM data of Landsat-5 was processed to identify the agricultural lands, calculate the total area under agriculture, and identify crops in the fields. The center pivots in the Wadi Sirhan area were identified and mapped with their corresponding areas from the digital data of Landsat frame 172-039. Digital Image Processing (DIP) of remotely sensed TM data was carried out using Intergraph's MGE Software. The seven bands of the Thematic Mapper, ranging from visible to thermal infrared part of the spectrum were processed. The images were combined in the RGB format to create false color composites (FCC). Different FCC combinations were created i.e. 432, 734, 321, 456.

The FCC's were interpreted using the photographic elements of shape, size, intensity, hue, saturation, texture and association to delineate the center pivots. The center pivots were digitized and stored as an overlay using the Microstation CAD software. 2505 center pivots in the study area have been identified with different dimensions, which cover the total cultivated area of 104814 hectares in the Wadi Sirhan (Rumikhani and Saif ud din, 2003a).

For the purpose of crop identification, supervised classification was adopted (Saxena et al., 1992; Bingfang et al., 1994; De Jong and Burrough, 1995; Dymond et al., 1996; Rumikhani and Saif ud din, 2003b). The area covered by each crop was calculated to estimate the total water requirement in the Al Busayata area.

In the present case the Maximum Likelihood Classification Scheme has been followed because of its emphasis and ability to convert spectral classes into information classes from remote sensing data. The irrigated soil and crops are picked up in the maximum likelihood classification in the Al Busayata area (Hall and Knapp, 1999; Saif ud din and Iqbaluddin, 1999; Siira et al.,1999; Haglund, 2000; Balaselvakumar and Saravanan, 2002). For supervised classification of the TM data training sets, different thematic elements were prepared.

Training sets were prepared by taking ground truth of the Al Rajhi agricultural company and extrapolating to the entire Al Busayata region for purpose of classification. The training set data consists of six data sets for crops, lithology, and land use in the area, which are agriculture 42.3%, rocks 20.15%, drainage channels 0.4%, stabilized sand cover 13.67%, aeolian dune sand 12.25%, saline areas 2.42%, and 8.81% unknown classes.

The total agriculture cover is classified into alfalfa 75%, potatoes 5%, tomato 3%, wheat 4%, plantations 1.37%, and uncultivated fallow 10.63%. The rocks are classified into basalts 26% and carbonates 74%. The statistical data shows twelve classes covering 91.19% of pixels; 8.81 % are in unknown classes. The spectral signatures of the twelve classes in seven bands is given in Figure 2.

In the present study the Maximum Likelihood Classification is used to assign pixels having similar value to a particular class. The spectral reflectances of different classes in seven bands are shown in Figure 2. Maximum Likelihood Classification makes use of the mean measurement vector M_c, for each class and covariance matrix for class c for bands k through I and V_c.

The classification rule states that

$X = C$ if

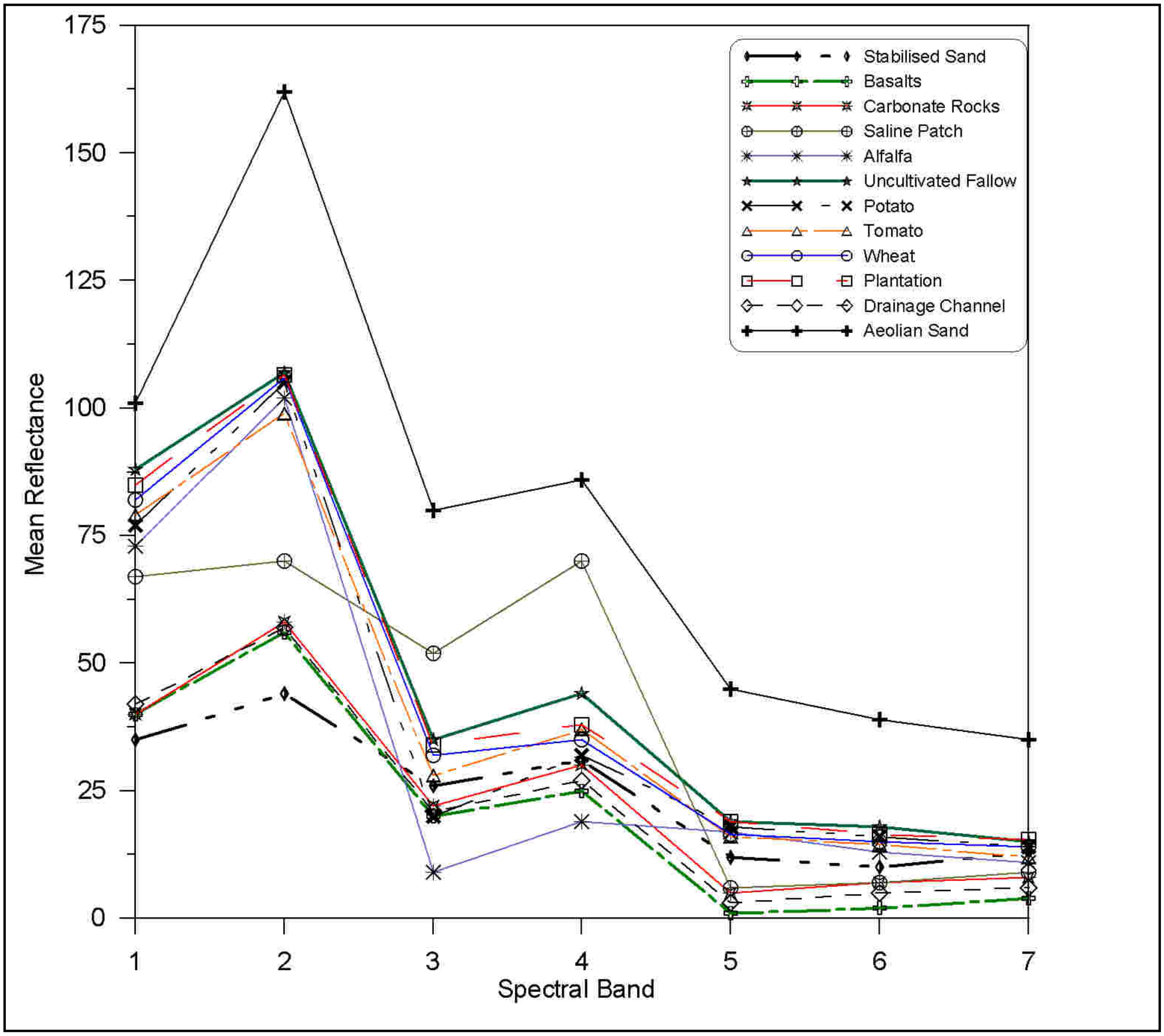

Figure 2. The Mean Spectral Reflectance of twelve classes in each band.

Table 1. The Classified Clusters in the Landsat Image of the Study area

Cluster Name	**Frequency**
Alfalfa	35744761
Potato	2382984
Tomato	1429790
Wheat	2382984
Plantation	652938
Uncultivated Fallow	5066224
Carbonate Rocks	16853444
Basalta	5847646
Drainage	450683
Stabilized Sand Cover	15402076
Aeolian Sand Dune	13802153
Saline Patch	2726630

$p_c \geq p_i$, where i=1,2,3,.......m possible classes

$p_c = \{-0.5 \log [\det (V_c)]\} - \{0.5 (X-M_c)^T (V_c^{-1}) (X-M_c)\}$

where det (V_c) is the determinant of the covariance matrix (V_c).

To classify the measurement vector *x* of an unknown pixel into a class, the maximum likelihood decision rule computes the value p_c for each class. Then it assigns the pixel to the class that has the maximum value (Table 1). The classification has identified the irrigated lands and crops as follows: the circular fields of green are alfalfa, blue are potato fields, yellow are tomato fields, and wheat fields are red in color; magenta colored patches in geometrical shapes are plantations while brown are uncultivated fields. The basalts are characterized by a dark yellowish green color in northeastern part of the image and carbonate rocks are brownish green in color in the southwestern part of the scene; paleo-channels are dark green while the active drainage channels are light green in this classification. The high moisture area has a bright pink color; the stabilized sand is dark colored, while the aeolian sand cover is greenish brown. The saline patch is blue in color (Figure 3).

Irrigation scheduling is one of the critical elements to decide when and how much to irrigate. The amount of irrigation water depends upon the crop water requirement, which varies with climate and cropped area, while the timing and frequency depends on crop growth stages and soil (Doorenbos and Pruitt,1977; Doorenbos and Kassam,1979; Raut et al., 1998). In order to maximize yield, the option usually adopted is over-irrigation, which leads to wastage of the valuable water resource. In the present study the total crop water requirement (*TCWR*) in the area has been estimated from the relationship:

$$(TCWR) = ETc/Ea \times (1 + LR) \qquad (1)$$

where

ETc = Crop Water Requirement in mm/day

Ea = Application Efficiency in percent

LR = Leaching Requirement in mm/day

The crop water requirement (*ETc*) is defined by the relation (FAO, 1984)

$ETc = ETo \times Kc$

where

ETo = Reference Crop Evapo-transpiration in mm/day

Kc = crop coefficient.

The crop coefficient, *Kc,* depends on four major parameters i.e. crop characteristic, time of sowing, stages of crop development, and general climatic condition (FAO, 1984). For each major crop grown in the area, the Kc is taken from the published report of the Ministry of Agriculture, Kingdom of Saudi Arabia (Nimah et al., 1986, Figure 4). The growth stage wise crop water requirement is shown in Figure 4. All crops except alfalfa are seasonal. Alfalfa is a perennial crop that is grown in the region; it is usually has 10 cuttings per annum and the *Kc* value after each cut returns to *Kc* initial (FAO, 1998; Anon., 2001; Kizer, 2000).

The leaching requirement varies for different types of soils, it can be expressed by the relation (FAO,1984):

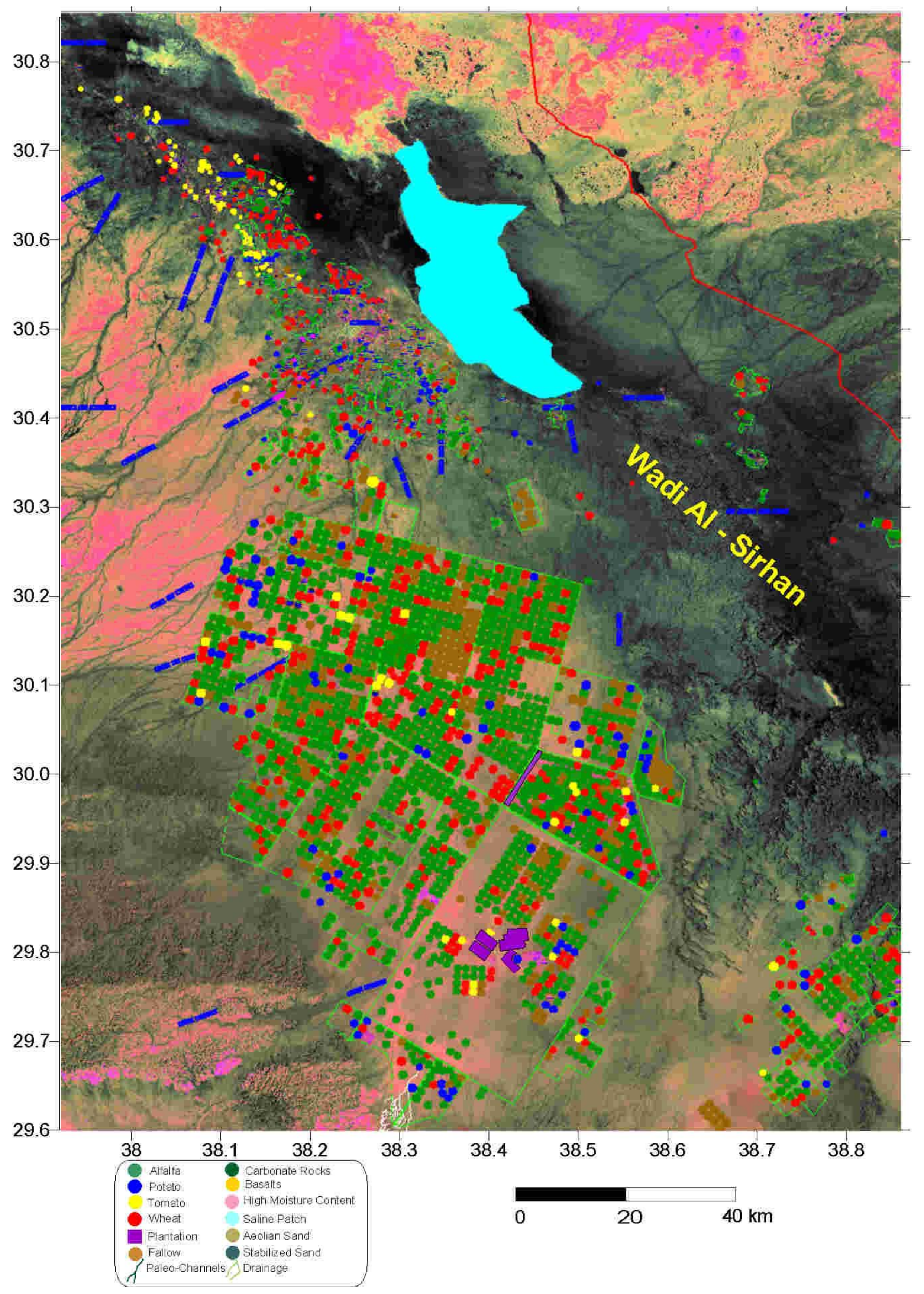

Figure 3. Maximum Likelihood Classified image of Band 432, path row 172-039 of 15th March, 2001

$$LR = ECw/(2\text{Max}ECe) \times 1/LE \qquad (2)$$

where

ECw = Electrical Conductivity of well (mmhos/ cm)

ECe = Electrical Conductivity of soil (mmhos/cm)

LE = Leaching Efficiency in percent

ET_0 was calculated using Penman Monteith equation (FAO,1998): the Penman Monteith Method is adopted as it has been accepted as a new standard for reference evapo-transpiration (FAO, 1998). The Penman Monteith Method was developed by defining the reference crop as a hypothetical crop with an assumed height of 0.12 m, with a surface resistance of 70 s/m and an albedo of 0.23, closely resembling the evaporation from an extensive surface of green grass of uniform height, actively growing and adequately watered. The method overcomes the shortcomings of other methods and is acceptable to nearly all types of climatic conditions.

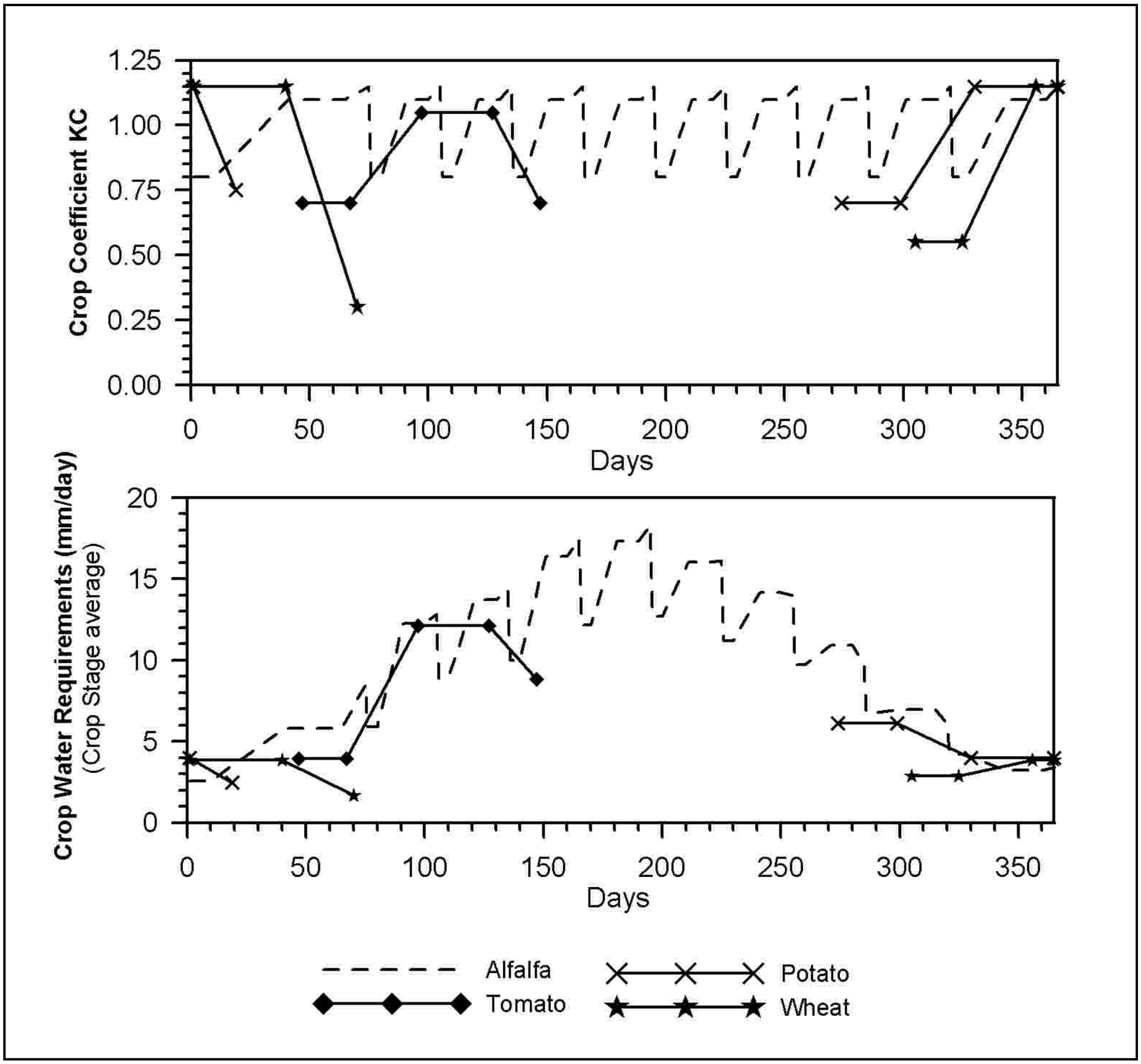

Figure 4. The crop Kc and daily water requirements of the major crops in the study area.

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (3)$$

where

ET_o = reference evapotranspiration [mmday-1],

R_n =net radiation at the crop surface [MJ m^{-2} day^{-1}],

G = soil heat flux density [MJ m^{-2} day^{-1}],

T = mean daily air temperature at 2 m height [°C]

u_2 = wind speed at 2 m height [m s^{-1}],

e_s = saturation vapour pressure [kPa],

e_a = actual vapour pressure [kPa],

e_s - e_a = saturation vapour pressure deficit [kPa],

Δ = slope vapour pressure curve [kPa $°C^{-1}$],

γ = psychrometric constant [kPa $°C^{-1}$].

The weather data has been collected from the weather station Dawmat Al Jandal. The weather database with variables such as temperature (minimum), temperature (maximum), relative humidity, solar radiation, sunshine hour, and wind speed was used to generate the weather information using the weather program (Rumikhani, 2002).

A ten-year average (1990–2001) of weather data was used to calculate potential evapo-transpiration (Rumikhani, 2001a). The growth stage wise crop water requirements is given in Figure 4. Irrigation scheduling based on evapotranspiration values estimated from climatic data is proposed, as this approach is time and cost effective, in comparison to onsite measurement (Menenti et al., 1986, 1989). The amount and time of irrigation can be specified by crop identification and area estimation (Mejerink et al., 1994; Bastiaansen, 1999; Perry, 1999; Omar et al., 2000; Dojri, 2001, Vidhya et al., 2002; Balaselvakumar and Saravanan, 2002), which will aid in estimation of crop water requirement, integrated with the agroclimatic data and from irrigation scheduling efficiencies (Raut et al., 1998, 2001).

RESULTS

There are about 13 soil associations in the study area. But the majority of the center pivots are localized in three soil associations.

There are 4 stages of crop development, Table 2 presents the duration of each stage of the four major crops in Wadi Sirhan. The total crop water requirement has been calculated for alfalfa, potato, wheat and tomato crops (Table 3). The total crop water requirement has been calculated using the Penman-Monteith method (Anon, 1998). The amount of the irrigation water applied to different fields has been estimated by measurement of well discharge and the duration of irrigation. The irrigation scheduling efficiency for different soil associations was computed from stage wise crop coefficients (Anon, 1977).

Table 2. Duration of Growth Stage for Crops

Crop	Growth stage 1 days	Growth stage 2 days	Growth stage 3 days	Growth stage 4 days
Alfalfa 1st cutting cycle	10	30	25	10
Alfalfa subsequent cutting cycles	5	10	10	5
Potato	25	30	35	20
Tomato	20	30	30	20
Wheat	20	30	50	30

Table 3. Total Crop Water Requirement

S.No.	Crop	Season	Total Crop Water Requirement in m^3/ha/season
1	Alfalfa	January – December	34864.00
2	Potato	January – April	6522.00
3	Potato	October – January	5160.00
4	Wheat	November – February	3724.00
5	Wheat	January – April	6473.00
6	Tomato	October – January	3792.00
7	Tomato	February – May	8296.00

DISCUSSION

In the maximum likelihood classification image (Figure 3) twelve classes have been identified as alfalfa, potato, tomato, wheat, plantation/orchards and uncultivated agricultural fallow, hard rock (basalt and carbonate), sand (stabilized and aeolian dunes), drainage channels and saline patches (Sabkah). It has been observed that about 75% of the center pivots have been planted with alfalfa, which covers an approximate area of 78611 hectares requiring 2.74 billion m^3 of water. Five percent of the center pivots, covering an area of 5240 hectares, are planted with potato, which require 34 million m^3 of water. Three percent of center pivots have tomato planted covering an area of 3144 hectares, requiring 26.086 million m^3 of water, and 4% of the area is under wheat plantation covering area of 4192 hectares, requiring 27.14 million m^3 of water. An area of 13626 hectares is lying uncultivated.

In the area a multi-tier aquifer system exists. Two aquifers, namely the Jouf and Tabuk, are exploited for agricultural activity. The average well discharge from the Jouf aquifer is 1500 to 2500 gpm, and wells in the Tabuk aquifer yield 2500 gpm on average. This suggests that the wells of the Jouf aquifer will yield from 8208 to 13680 m^3/day, and the Tabuk aquifer over 14000 m^3/day.

From the analyses of the irrigation data from the agricultural companies in Wadi Sirhan, it appears that the crops are over-irrigated (Rumikhani and Saif ud din, 2001). The Total Crop Water Requirement for *n* of crops in the area and *m* stages can be expressed as:

$$ETc_{depth} = ETc_{CROP\_1} + ETc_{CROP\_2} + ETc_{CROP\_3} + ... + ETc_{CROP\_n} \tag{4}$$

$$ETc_{depth} = KC_{CROP\_1} \cdot ETo + KC_{CROP\_2} \cdot ETo + KC_{CROP\_3} \cdot ETo + ... + KC_{CROP\_n} \cdot ETo \tag{5}$$

$$ETc_{depth} = ETo \cdot \sum_{i=1}^{n} KC_{CROP\_i} \tag{6}$$

For Annual/Seasonal *ETc* having m stage or month;

$$\left(ETc_{depth}\right)_{Annual/Seasonal} = \sum_{j=1}^{m} ETo_j \cdot \left(\sum_{i=1}^{n} KC_{CROP\_i} \right) \tag{7}$$

Annual/Seasonal Crop Water Requirement (CWR) of an area is;

$$\left(CWR_{depth}\right)_{Annual/\,Seasonal}=\left(\frac{1+LR}{Ea}\right)\cdot\left(ETc_{Area}\right)_{Annual/\,Seasonal} \tag{8}$$

If *LR* is variable for all center pivots, then for *NCP* (number of center pivots);

$$\left(CWR_{depth}\right)_{Annual/\,Seasonal}=\sum_{k=1}^{NCP}\left[\left(\frac{1+LR_k}{Ea}\right)\cdot\left(ETc_{Area}\right)_{Annual/\,Seasonal}\right] \tag{9}$$

Hence the annual/seasonal crop water requirements in *mm/day* with leaching requirement for all center pivots is given;

$$\left(CWR_{depth}\right)_{Annual/\,Seasonal}=\sum_{k=1}^{NCP}\left[\left(\frac{1+LR_k}{Ea}\right)\cdot\sum_{j=1}^{m}\left\{ETo_j\cdot\sum_{i=1}^{n}kc_{i,j}\right\}\right] \tag{10}$$

where

k represents the number of center pivots from 1 to L

j indicates the months 1 to 12 (m=12) or growth stages 1 to 4 (m=4)

i shows the no. of crop sowing in the area (1 to n)

LR is the leaching requirements

Ea is the application efficiency (%)

ETo is the evapotranspiration (mm/day)

Kc is the crop coefficient for different growth stages

CWR is the total crop water requirements (mm/day)

The quantity of Total Crop Water Requirement in L/S or m^3/day is given as

$$\left(TCWR_{quantity}\right)_{Annual/\,Seasonal}=K_1\cdot\sum_{k=1}^{NCP}A_k\left[\left(\frac{1+LR_k}{Ea}\right)\cdot\sum_{j=1}^{m}\left\{ETo_j\cdot\sum_{i=1}^{n}kc_{i,j}\right\}\right] \tag{11}$$

where

A_k is the area of kth center pivot and

K_1 is the conservation factor of 0.11574

The existing condition in the irrigated schemes in most of the cases of alfalfa is that the center pivots are continuously irrigating and the wells are stopped only three days before the cutting, assuming the average irrigation of 10000 m^3/day for individual well. Table 4 presents the monthly crop water requirement for each crop grown in Al Busayata. It has been calculated that the average crop water requirement of each center pivot is about 4000 m^3/day, thus there is more 60% over irrigation in wells where each well is connected to single center pivot, which is commonly the case. The wells of the Tabuk aquifer are connected to two center pivots and they have an average discharge of 15000 m^3/day, which suggests that there is 47% over irrigation. Proper scheduling can reduce the consumption by at least 50%. Thus the irrigation can be reduced without compromising the crop yield. The irrigation scheduling efficiency can be achieved by reducing the duration of pumping and the speed of the center pivot may be adjusted as per the stage wise crop water requirement to minimize over irrigation.

With the increase in number of irrigation schedules there has been a decrease in scheduling efficiencies for all the soil assemblages because of the higher application in each time resulting in wastages.

Since for all the crops in the area there are several irrigation applications, highest efficiencies have been obtained when the first irrigation was slightly delayed by 5 to 7 days and the positive effect of better spread of the second and third irrigation might have surpassed the harmful effect of first irrigation application (Raut et al., 2001).

Table 4. Monthly Crop Water Requirement and Irrigation Application for Crops in the Study Area

										Well Discharge 10000 m3/day			
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total Season
Units		Crop – Alfalfa			No. of Crop CP = 1875					Cultivated Area = 78611.2 ha.			
days	31	28	31	30	31	30	31	31	30	31	30	31	365
(m3/ha/month)	905.04	1377.6	2196	3401.1	3918.1	4630.1	5020.8	4423.3	3700.5	2677.1	1608.9	1042.3	34900.84
(million m3/season)	71.15	108.29	172.63	267.36	308.01	363.98	394.69	347.72	290.9	210.45	126.48	81.94	2743.6
		Crop – Wheat				No. of Crop CP = 100				Cultivated Area = 4192.59 ha.			
	31	28	25	0	0	0	0	0	0	0	15	31	130
(m3/ha/month)	1939.14	2326.86	580.46	0	0	0	0	0	0	0	287.26	1182.6	6316.32
(million m3/season)	8.13	9.76	2.43	0	0	0	0	0	0	0	1.2	4.96	26.48
		Crop – Potato				No. of Crop CP = 126				Cultivated Area = 5240.74 ha.			
	30	28	31	21	0	0	0	0	0	0	0	0	110
(m3/ha/month)	1068.55	1890.45	2671.99	950.58	0	0	0	0	0	0	0	0	6581.57
(million m3/season)	5.6	9.91	14	4.98	0	0	0	0	0	0	0	0	34.49
		Crop – Tomato				No. of Crop CP = 75				Cultivated Area = 3144.45 ha.			
	0	13	31	30	26	0	0	0	0	0	0	0	100
(m3/ha/month)	0	793.65	2105.4	3652.1	1771.5	0	0	0	0	0	0	0	8322.65
(million m3/season)	0	2.5	6.62	11.48	5.57	0	0	0	0	0	0	0	26.17

CONCLUSION

Mechanized agriculture in arid lands needs water resource management to eliminate over irrigation. Irrigation through exploitation of fossil groundwater can be sustainable through increases in irrigation frequency and decreases in amount of water used in each irrigation cycle. In the arid ecosystem this will result in groundwater conservation. The case study from Wadi Al-Sirhan suggests that exact crop water requirement should be estimated and irrigation application should be planned accordingly for groundwater conservation without reducing the crop yields.

The time and cost effective satellite remote sensing technology has been utilized to identify the agriculture acreage, crop and its growth stages The interpreted results from remote sensing can be integrated with the crop water model for planning irrigation schedule, duration of irrigation, amount of irrigation, etc., through crop identification, cropped area mapping and growth stage evaluation using maximum likelihood classification of real time remotely sensed satellite data in the arid lands.

Accuracy in quantifying crop irrigation demand and supply obtained through satellite remote sensing can be increased by identifying the crop and the accurate cropped area. It has been observed in many center pivots that the cultivated area has been reduced by removing one or two arms but the well efficiencyand the irrigation scheduling has not been disturbed, leading to loss of precious fossil groundwater.

The study suggests that the agricultural schemes are paying little attention to water resource management, which is leading to huge over irrigation and loss of precious nonrenewable groundwater.

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ADDRESS FOR CORRESPONDENCE
Saif ud din
Natural Resource and Environmental Research Institute
King Abdulaziz City for Science and Technology
Riyadh, Kingdom of Saudi Arabia

Email: suddin@kacst.edu.sa