Remote sensing for estimating depleted fraction and its implication in the changes of groundwater table in the Roxo irrigation area, Portugal

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ABSTRACT:

Actual evapotranspiration (ET_a), which is one of the components required for determining depleted fraction, could be estimated through a remote sensing technique called Surface Energy Balance Algorithm for Land (SEBAL) with a high reliability as it maps the spatial and temporal structure of ET_a. In this study, fifteen satellite imageries produced from two sensors: four Thematic Mapper (TM) imageries (resolution: 30 m at visible bands and 60 m at thermal infrared bands) and eleven MODIS imageries (resolution: 250 m at visible bands and 1,000 m at thermal infrared bands) were used to compute monthly ET_a of the Roxo irrigation area in Portugal for 2003. Depleted fraction, defined as the ratio of ET_a over precipitation (P) + Irrigation Supply (V_c) informs about the changes in groundwater table in an irrigated area. Groundwater table in the Roxo irrigation area is stable at depleted fraction value of range between 0.6 and 0.7 while water is stored in the aquifer for lower values of depleted fraction. The groundwater table decreases if depleted fraction exceeds this range.

Key words: Actual evapotranspiration, SEBAL, depleted fraction, groundwater table

1. INTRODUCTION

Diversion of water from a source to agricultural fields has been in practice in arid and semi-arid regions to irrigate fields since the existence of human civilization. But higher application of irrigation water does not always result higher crop yield. Excessive irrigation supply may cause crop yield reduction due to rise in groundwater table. The rise in groundwater table has negative effects such as water logging and soil salinity within an irrigated area (Molden and Gates, 1990; Bos, 2004). Productivity of agricultural fields doesn't depend on larger volume of water delivered to the fields, but depends on the better matching water supplies with the crop demand.

Globally, irrigation is the sector that withdraws the largest amount of the fresh water. Around 70 % of the world's total fresh water withdrawals are for irrigation, and it contributes to 30-40 % of the world's food production (Bastiaanssen et al., 2000). From 1995 to 2025, it is estimated that irrigation withdrawals will be increased by 17 %. By the same time, crop yield from irrigated fields should grow by 40 % to meet the needs of a 33 % population growth (Bos et al., 2003). Therefore, an exploitation of the fresh water resources needs efficient methods and management.

Depleted fraction is the ratio that relates three components of the water balance of an irrigated area: actual evapotranspiration (ET_a), precipitation and irrigation supply into the area. Higher value of depleted fraction indicates the decrease of the groundwater table while the groundwater storage rises for lower value. In other words, if value of depleted fraction in a particular month in an irrigated

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area is lower, less amount of water from the precipitation and the irrigation supply is consumed by the crops (Bastiaanssen et al., 2001) and a portion of water goes into the groundwater storage causing groundwater table to rise. Similarly, if the value is higher, more amount of water is consumed by the crops for the evapotranspiration process that causes depletion of the groundwater table (Droogers and Bastiaanssen, 2002).

The main objective of this paper is to investigate the relationship between depleted fraction and change of groundwater level, by using the Roxo irrigation area as an example. In order to achieve this objective, the following steps are carried out: (1) estimation of ET_a in a monthly time step in a study irrigation area employing a remote sensing technique called SEBAL, (2) calculation of depleted fraction using SEBAL-based ET_a values, and (3) analysis of relationship between depleted fraction and change of groundwater level.

2. THE STUDY AREA

Roxo reservoir is located at Beja district of Alentejo Province in southern Portugal. Major sources of water to the reservoir are the river Roxo and its tributaries, which has a catchment area of 353 km^2. Average area covered by the reservoir is 1,378 ha but its water level varies from season to season. The resevoir dam is mainly constructed for irrigation and domestic water supply. But it also provides water to some local industries. An irrigation command area known as Roxo irrigation command area is located in the west of the outlet of the dam. The irrigation system is designed to irrigate 5,040 ha of land. The system has a total length of the canal network to 197,805 m and is based on the gravity flow. Average amount of water supplied by the system for irrigation is 16 million m^3 in a year since 1990.

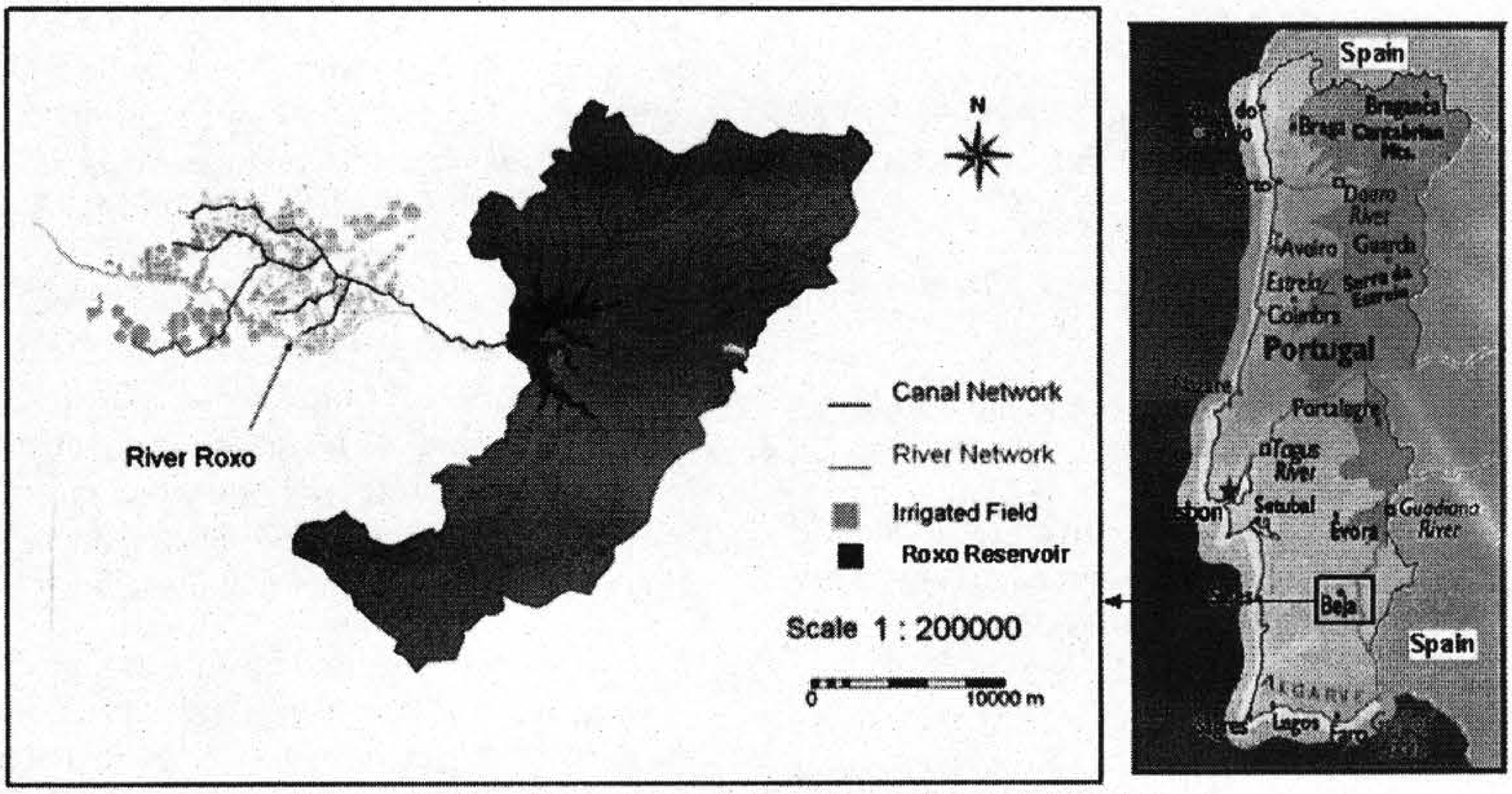

Figure 1: River Roxo, the catchment and the command area

The study area predominantly has a Mediterranean climate. It is much warmer and receives less precipitation than the national average, like any other parts in the southern Portugal. Maximum temperature during the summer goes up to 40°C and minimum temperature in the winter drops down to 5 °C. Minimum and maximum temperatures occur during the month of December and July/August respectively.

The average annual precipitation in the study area is estimated to be about 550 mm. May to September is very dry. The area is wet from the month of October to April; in average, 85 percent of the total annual precipitation occurs during this period. Amount of precipitation is highest in December while July and August are the driest months.

3. METHODS

3.1 SURFACE ENERGY BALANCE ALGORITHM FOR LAND (SEBAL)

A remote sensing technique, Surface Energy Balance Algorithm for Land (SEBAL) developed by a group of scientists led by a Dutch scientist Wim G. M. Bastiaanssen (Bastiaanssen et al., 1998a), was employed to estimate actual evapotranspiration (ET_a) and other energy fluxes in daily and monthly time steps in the Roxo irrigation command area. SEBAL is an algorithm that estimates ET_a and other energy fluxes using remotely sensed data (satellite imageries) of different dates. The algorithm uses remotely sensed data of visible and thermal bands. Specific reasons for employing SEBAL algorithm in this study are briefly described below.

(a) In SEBAL, ET_a is computed as a component of energy on a pixel-by-pixel basis to map spatial variation.

(b) ET_a can be computed over a large spatial scale.

(c) ET_a can be computed for a complete year in a monthly time step.

(d) Very little ground data are required to employ SEBAL. Ground data required to employ the algorithm are instantaneous incoming shortwave radiation at ground, air temperature and wind speed at satellite over-passing time, and potential evapotraspiration and sunshine hour of satellite over-passing date.

(e) For a large irrigation area, SEBAL can estimate ET_a with very low margin of error. For instance, the error goes down to 5 % for an area of 1,000 ha (Bastiaanssen, 1998; Bastiaanssen et al., 2000).

The main assumptions we made about SEBAL were as follows: (a) SEBAL can estimate ET_a accurately in Portugal as its previous applications in other parts of the world (including Spain) have proved it to be efficient and accurate approach to estimate ET_a in irrigated fields (Morse et al., 2000; Allen et al., 2001). (b) Ground data gathered from a weather station are assumed to have high spatial representativity and can be extrapolated over the entire command area. (c) Estimation of ET_a in the study command area is accurate with a greater confidence as the area has a flat terrain with no significant relief.

Ground data were collected from an automatic weather station located at Aljustrel (Roxo) because it was located almost in the middle of the command area. Remotely sensed data used in the study to compute ET_a values were four TM imageries (platform: Landsat-5, resolution: 30 m at visible bands and 60 m at thermal infrared bands) and eleven MODIS imageries (platform: Terra, resolution: 250 m at visible bands and 1,000 m at thermal infrared bands) of different dates. TM imageries from four different dates of 2003 were purchased and analysed. Similarly, MODIS imageries from eleven different dates representing every month of the year 2003 except December were downloaded from the website of MODIS Data Support, NASA (http://acdisx.gsfc.nasa.gov/MODIS/) and studied. Imageries from the cloud-free days were selected. For the month of December, ET_a values were computed through the extrapolation of ET_a values of November.

TM imageries were used in this study for the following reasons. First of all, these imageries have high resolutions because of which agricultural fields under irrigation command could be easily identified by matching them with an official irrigated field map. Secondly, size of the irrigated plots were large enough to provide a higher degree of freedom with regard to resolution and pixels in TM imageries for employing remote sensing based algorithm for evapotranspiration estimation. Smallest plot in the command area had an area of 90 m by 120 m.

Secondly, daily ET_o values for a certain month were summed up. Finally, product of ET_oF and summation of ET_o values for a certain month produced the ET_a for that particular month.

$$ET_{a\_(month)} = ET_oF \times ET_{o\_(month)} \qquad (12)$$

ET_oF values of an imagery date should be used to calculate monthly value of ET_a of that month in which it belongs to. For instance, ET_oF value calculated from an imagery belonging to May should be used to calculate monthly value of ET_a for the month of May and so on.

A GIS-based software called Intergrated Land and Water Information System (ILWIS) was used to compute actual evapotranspiration (ET_a) through SEBAL. At first, TM imageries and MODIS imageries of same or close dates were used to calculate instantaneous and 24-hour ET_a. Later on, MODIS data were calibrated based on TM data to compute monthly values of ET_a (see next sub-section for detail).

3.2 CALIBRATION OF MODIS DATA BASED ON TM DATA

Daily ET_a (in mm day^{-1}) values estimated from four TM and four MODIS imageries belonging to same or close dates were compared to observe the differences, and then MODIS data were calibrated based on TM data. TM imageries used for the calibration belonged to 25th May, 4th July, 21st August and 8th October (all in 2003). Similarly, MODIS imageries used for this purpose belonged to 25th May, 3rd July, 20th August and 7th October (all in 2003). In order to do so, daily ET_a values for perennial landcovers: water, eucalyptus forest, olive trees, pine forest and vines, and seasonal crops like paddy and maize that were growing in the fields during the imagery dates were selected.

Linear regression analysis was performed to know the relationship between the ET_a values computed from MODIS imageries and TM imageries. It was found out that MODIS imageries underestimate the ET_a values by 0.62 in comparison to TM imageries. The value 0.62 was taken as a calibration coefficient for MODIS data. It means that MODIS data were adjusted by dividing them by 0.62. Later on, daily ET_a values calculated from all of the eleven MODIS imageries were adjusted using the calibration coefficient.

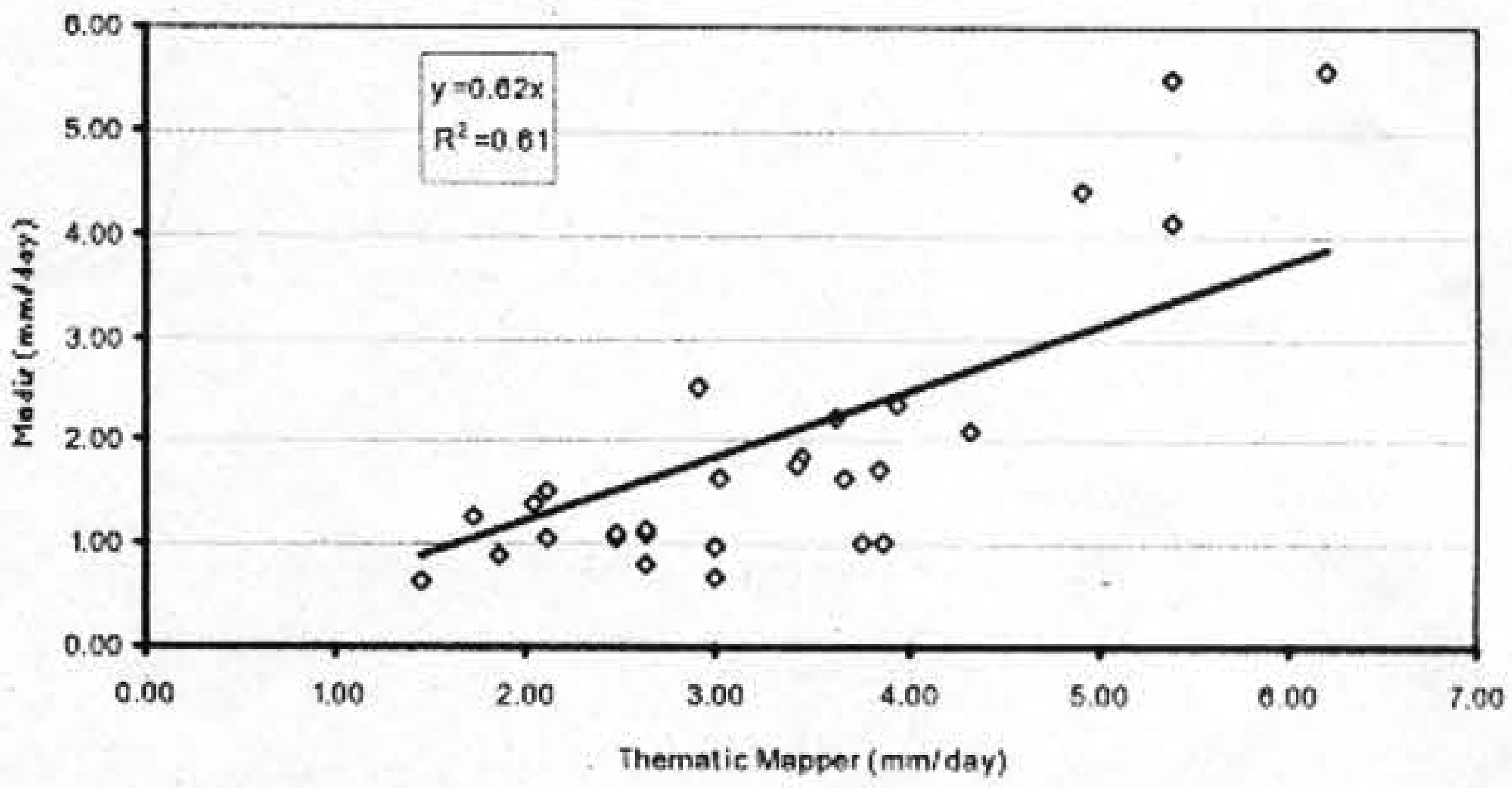

Figure 3: Linear regression between MODIS ET_a data and Thematic Mapper ET_a data

3.3 VALIDATION OF SEBAL-BASED ET_a

Validation of SEBAL-based ET_a was made by comparing ET_a values for water body (Roxo reservoir in this study) obtained from TM imageries with the calculated ET_o (Penman-Monteith method) values of the same date. It was assumed that ET_a in water body would match with ET_o as there was no shortage of water. Hence, comparison between these two was logical.

Table 2: Comparison between SEBAL-based ET_a for water and calculated ET_o

(in mm day^{-1})

Date	ETa	ETo
May 25, 2003	6.2	6.5
July 4, 2003	5.4	6.7
August 21, 2003	5.4	5.7
October 8, 2003	4.9	3.3

There was a very close matching between SEBAL-based ET_a for water body and ET_o. Mean square error was calculated to be 1.11, which was very marginal. It could be said that SEBAL could estimate ET_a with a high accuracy.

$$H = \frac{(\rho_a \times C_p \times dT)}{r_{ah}} \quad (6)$$

where; ρ_a is air density (1.12 kg m^{-3}), C_p is air specific heat (1004.16 J $kg^{-1} K^{-1}$), dT is the temperature difference ($T_1 - T_2$) between two heights (z_1 ad z_2), and r_{ah} is the aerodynamic resistance to heat transport (s m^{-1}). Computation of r_{ah} is the most complicated part in SEBAL procedure. r_{ah} varies with wind speed, and intensity and direction of the H itself, so it can be determined only through iterations.

After computing instantaneous evapotranspiration flux (i.e., λE), actual evapotranspiration for the entire day (24 hours) of the imagery date was calculated. In order to do so, evaporative fraction (Λ) and daily net radiation ($R_{n\ day}$) needed to be determined. They are given by

$$\Lambda = \frac{\lambda ET}{\lambda ET + H} \quad (7)$$

$$R_{n\_day} = (1 - 1.1\alpha)\cdot R_s \downarrow_{g\_day} - 110 \cdot \tau_{\_day} \quad (8)$$

where; $\tau_{\_day}$ is the daily transmissivity given by the empirical formula:

$$\tau_{\_day} = 0.25 + 0.5\frac{n}{N} \quad (9)$$

where; n is actual hour of sunshine in a day and N is the total daytime duration.

$R_s\downarrow_{g\ day}$ is the daily incoming shortwave radiation at ground given by the formula:

$$R_s \downarrow_{g\_day} = 11.5741 \times \tau_{\_day} \times R_s \downarrow_{toa\_day} \quad (10)$$

where; $R_s\downarrow_{toa\_day}$ is the daily incoming shortwave radiation at top of the atmosphere.

Daily actual evapotranspiration ($ET_{a\ day}$) is given by the relation:

$$ET_{a\_day} = \frac{\Lambda \times R_{n\_day}}{28.588} \quad (11)$$

When the ET_{a_day} was computed, monthly ET_a was determined through the following procedure. At first, the reference evapotranspiration fraction (ET_oF) i.e., ratio of daily ET_a to daily ET_o for the imagery date was calculated (ET_o was calculated by employing Penman-Monteith method).

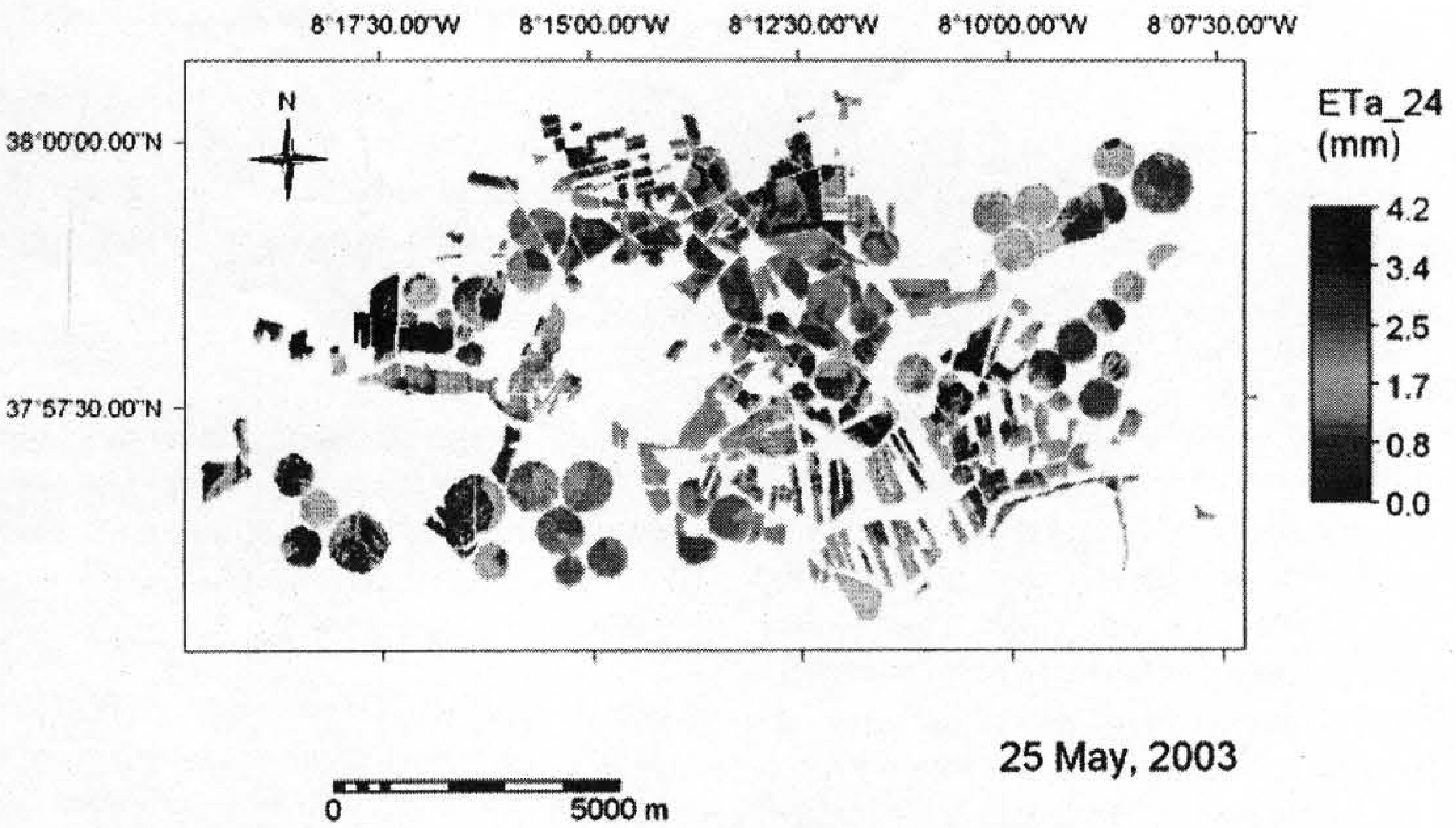

Figure 2: SEBAL-based daily ET_a (mm) in the Roxo command area in 25th May, 2003 (Thematic Mapper imagery)

Secondly, daily ET_o values for a certain month were summed up. Finally, product of ET_oF and summation of ET_o values for a certain month produced the ET_a for that particular month.

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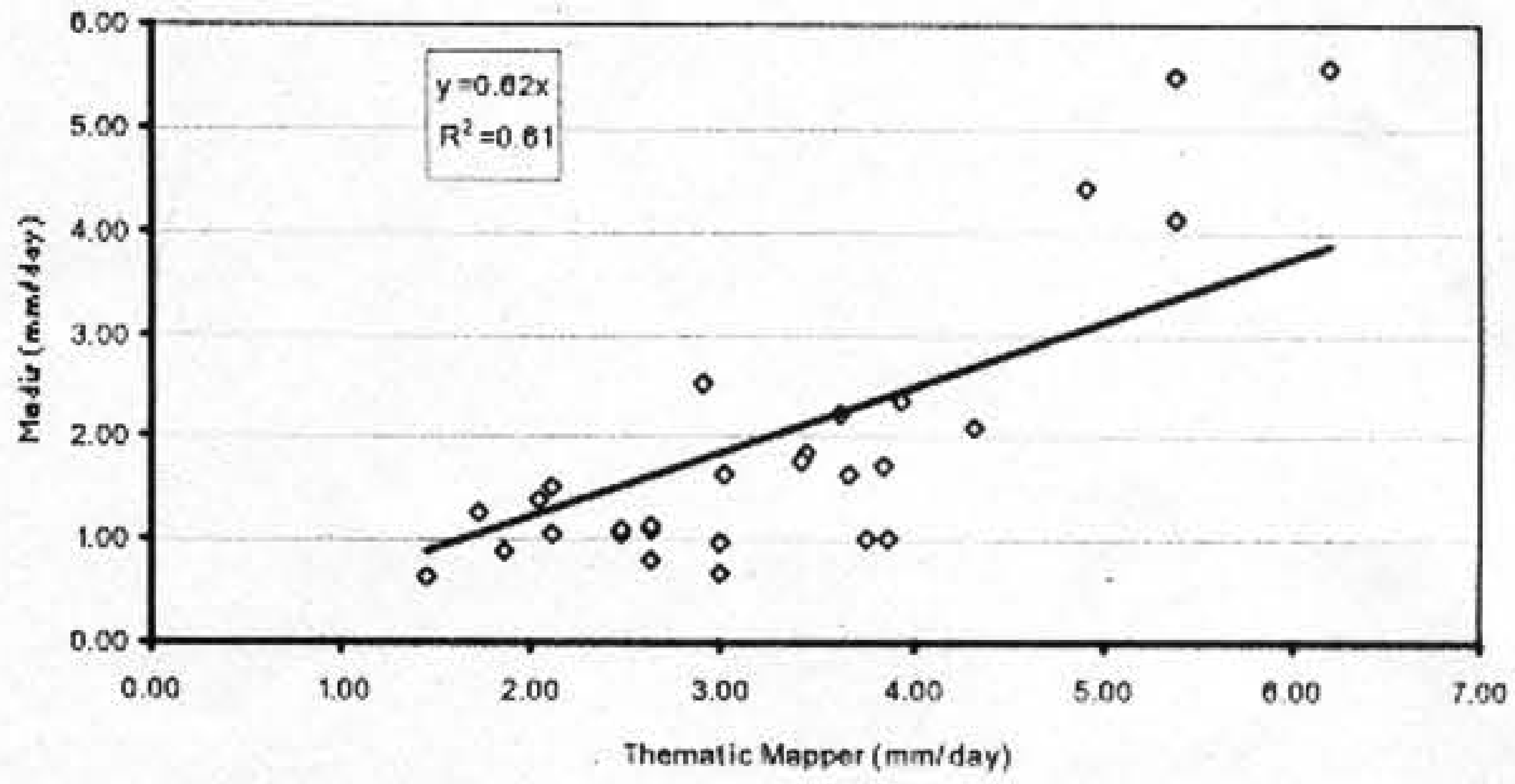

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3.4 DEPLETED FRACTION

Depleted fraction (DF), defined as the ratio of actual evapotranspiration (ET_a) over precipitation (P) + Irrigation Supply (V_c), informs water managers about the changes of groundwater table in an irrigated area. It is computed in the monthly time step. It is given by

$$DF = \frac{ET_a}{V_c + P} \qquad (13)$$

Data for ET_a was obtained through aforementioned remote sensing procedure SEBAL. Precipitation data (P) over the entire irrigation command area on the daily time step was obtained from the local weather station. They were summed up to get monthly precipitation data.

Irrigation supply data (V_c) for the year 2003 in the monthly time step was collected from the local authority. Original data was in the term of volume (m^3 per month). Later on, it was converted to mm by considering the irrigated area as 4,800 ha. It is worth mentioning here that irrigation season in the study command area is from April to October.

Depleted fraction is an indicator that indicates what portion of available water in a field is depleted for crop evapotranspiration process. Higher value of depleted fraction shows that crop depletes more available water and put relatively high amount of water for the evapotranspiration, and vice-versa. If depleted fraction value in a particular month in the command area is lower than 0.6, it indicates the sufficient supply and less amount of water from the precipitation and the irrigation is consumed by the crops and a portion of water goes into groundwater storage causing groundwater table to rise. If the value is in and around 0.6, groundwater storage in the area is stable. If it exceeds 0.6, groundwater storage goes on decreasing due to capillary rise into the root zone of irrigated crops indicating shortage of water (Bos, 2004). If it goes beyond 1, it indicates the short supply.

In an irrigated area, there are basically three sources of inflows: precipitation (P), groundwater flow from upstream (G_{in}) and irrigation supply (V_c). In general, it is assumed that the groundwater inflow is in same order of magnitude as the groundwater outflow (G_{out}). A portion of the precipitation and the irrigation supply ($P + V_c$) is consumed up as actual evapotranspiration (ET_a) to produce crops. The remaining portion is either stored as the groundwater or drained out of the area. Sometime over groundwater storage causes water logging and salinity that decrease the productivity. Therefore, it is also termed as negative effect. Depleted fraction thus can be used as an indicator to assess irrigation water use.

4. RESULTS AND DISCUSSIONS

4.1 SEBAL-BASED ACTUAL EVAPOTRANSPIRATION

The ET_a values were computed over the entire irrigation command area using SEBAL procedure in the monthly time step. We needed to calculate monthly value of ET_a for the entire command area in order to calculate the monthly value of depleted fraction (DF) so that we can investigate on irrigation supply situation and changes of groundwater table in the area.

4.2 DEPLETED FRACTION AND ITS INFLUENCE ON THE GROUNDWATER STORAGE

In the Roxo irrigation command area, the monthly depleted fraction values varied from 0.43 in October to 1.36 in May in the year 2003 (Table 3). This describes the excess of water in October and shortage of water in May. It is logical because October is the beginning of the wet season. Precipitation rises up from this month. Another month having the high value of the depleted fraction was September (1.13). In this month too, there was a short supply of irrigation. Other months that have higher depleted fraction and closer to 1 were June (1.09), July (1.01) and August (1.02) which shows that gap between demand and supply during these months was matching. It also indicates the timely irrigation supply during these months. However, all of this information revealed that the Roxo irrigation system was experiencing the short supply as the depleted fraction during the core irrigation season (May-September) was around or higher than 1.

Table 3: Monthly precipitation, ET_a, irrigation supply (all in mm) and depleted fration

Month	Precipitation	ET_a	Irrigation Supply	Depleted Fraction
January	46.9	38.5	0.0	0.82
February	67.0	40.3	0.0	0.60
March	35.5	41.9	0.0	1.18
April	83.7	46.9	0.0	0.56
May	20.6	69.8	30.7	1.36
June	4.0	95.5	83.7	1.09
July	1.9	103.0	99.8	1.01
August	0.0	93.3	91.5	1.02
September	34.4	71.9	29.4	1.13
October	129.9	55.7	0.9	0.43
November	68.2	23.9	0.00	0.35
December	77.7	20.4	0.00	0.26
Total	569.8	701.1	336.0	0.82*

Critical value for the depleted fraction is considered to be 0.6 from a water balance perspective. The period having the depleted fraction less than 0.6 indicates adequate supply of water. In the month with the depleted fraction less than 0.6, the significant portion of available water percolates into aquifer causing the rise of the groundwater table (Bos et al., 2003). In the Roxo irrigation command area, irrigation supply is available from April to October. If we study the depleted fraction during this period, it is found out that the first and last month of the irrigation season have the depleted fraction value below the critical value. It suggests that there is no need to supply irrigation in these months. Precipitation is enough to meet the water requirement in this time. Data from the local authority also shows that very little amount of water was released in the canals during these months.

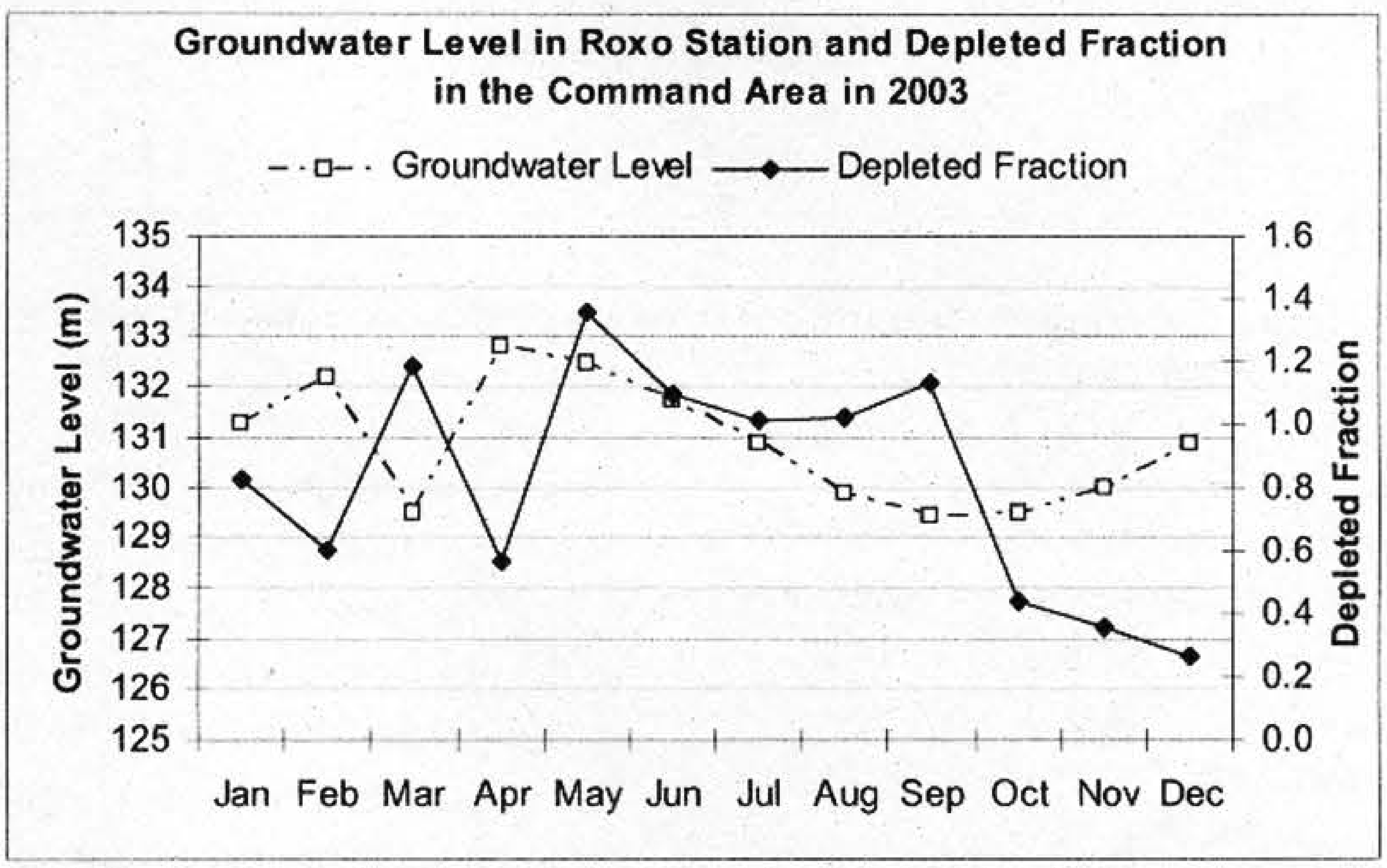

Figure 4: Groundwater level and depleted fraction in the irrigation area in 2003

For the efficient management of an irrigation system, monthly depleted fraction value between 0.5 and 0.8 is recommended (Bos, 2004). If this range is maintained, it will provide sufficient water for leaching accumulated salts as well as provide high crop yield per unit water consumed (Bos, 2004). It is important to understand that ET_a and V_c aren't independent to each other. They significantly influence each other. V_c can be reduced to increase depleted fraction, but less water will be available for actual evapotranspiration, which will also decrease accordingly.

Monthly groundwater table measured for the year 2003 in the Roxo station, which is located 5 km east of the irrigation area (groundwater table data within the irrigation area is not available), and monthly depleted fraction values are studied to see the relation between them. The groundwater table data is the data that was measured in the last minute of the last day of a month (i.e., at mid-night hour). For instance, value of the groundwater table for the month January was measured in 31st January 2003 at 12:00 am and so on.

If monthly values of depleted fraction (x-axis) are plotted against the rate of change of the groundwater table (y-axis), the trend line intersects the x-axis near the value between 0.6 and 0.7 value of depleted fraction. It means that groundwater storage is stable at a depleted fraction of range between 0.6 and 0.7 while water is stored in the aquifer for lower values of depleted fraction. If the value of depleted fraction exceeds the value of range between 0.6 and 0.7, the groundwater storage decreases. The present study has thus conformed to the findings of Bos (2004).

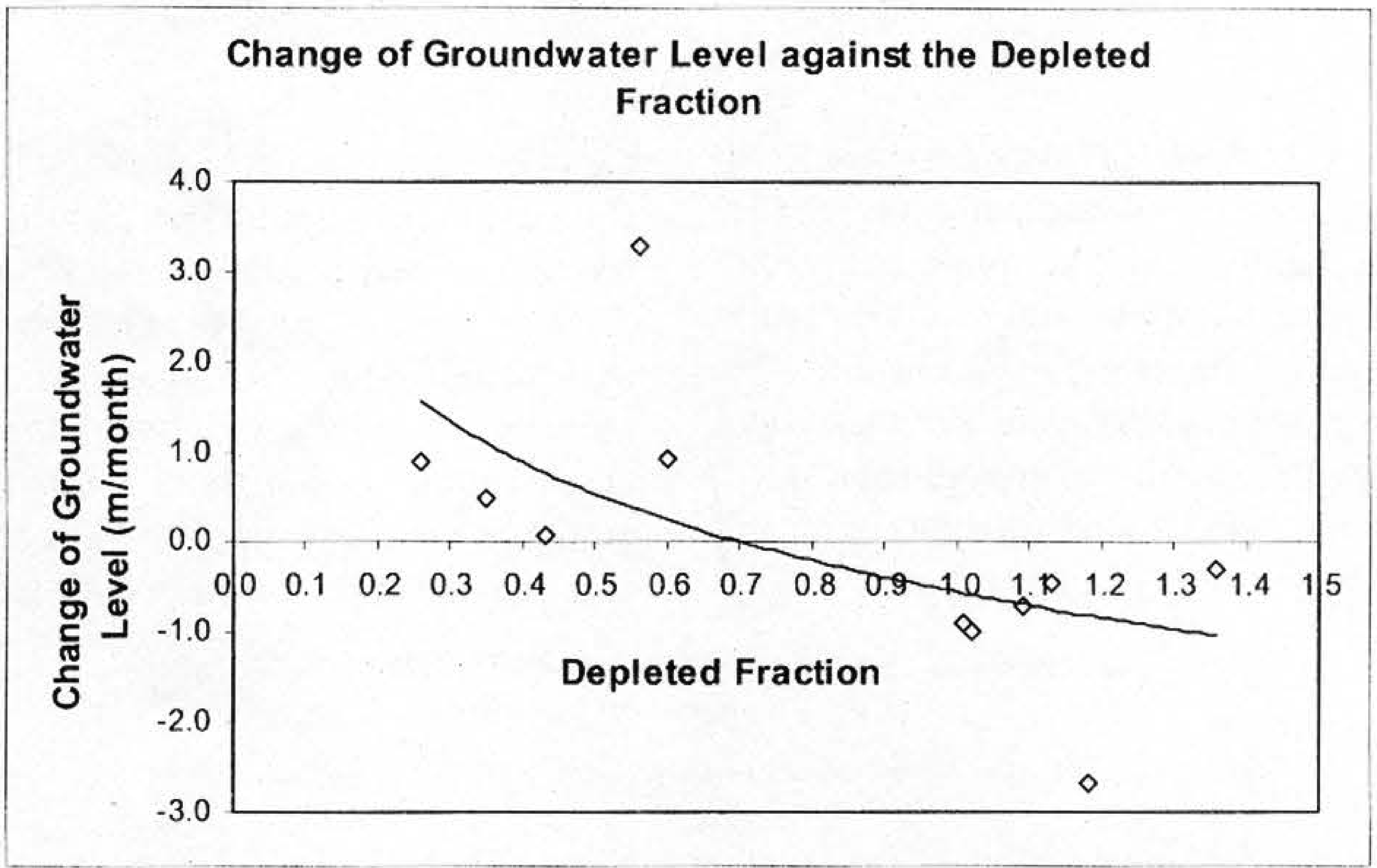

Figure 5: Change of groundwater level against the depleted fraction

5. CONCLUSIONS

Satellite remote sensing technique is a reliable approach to compute the change of groundwater table in an irrigated area. Since the SEBAL algorithm maps ET_a values in spatial and temporal scales, average value of ET_a estimated by this algorithm could be believed to be nearer to the reality. It ultimately implies that depleted fraction values based on the SEBAL-calculated ET_a values have a high reliability. Groundwater table is stable at a depleted fraction of range between 0.6 and 0.7. Water percolates into sub-surface and is stored in the aquifer for the lower values causing the rise in the groundwater table. If the value lies beyond the range between 0.6 and 0.7, the groundwater table drops down.

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