EVAPOTRANSPIRATION ESTIMATION USING A NORMALIZED DIFFERENCE VEGETATION INDEX TRANSFORMATION OF TWO SATELLITES DATA IN ARID MOUNTAIN AREAS

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Abstract

Evapotranspiration (ET) was estimated using a normalized difference vegetation index (NDVI) of satellite data on central Yemen Mountains. A procedure was developed which equated the index to crop coefficients. Evapotranspiration estimates for fields for three dates of Landsat Thematic Mapper data were highly correlated with ground estimates. Service area estimates using landsat Thematic Mapper (TM) and NOAA Advanced Very High Resolution Radiometer (AVHRR) data agreed well with estimates based on National Water Resources Authority (NWRA) gauging station data. Comparisons of ET results with traditional ET models show good agreement. Sensitivity analyses show that the model is accurate even without atmospheric correction.

Keywords: Evapotranspiration; NWRA; Yemen; NDVI; TM; AVHRR

1.0   INTRODUCTION

Evapotranspiration (ET) is integral to the hydrological and climatic processes of the Earth and its atmosphere. The current emphasis on global change research makes it important to understand and measure ET and its effects on Earth processes. Much prior research has focused on the microclimatic aspects of ET to develop the theoretical basis for understanding this process. Given the necessity for assessment of large areas in global change research, methods need to be developed that will address regional, continental and global ET measurements in some quantitative manner.
Remotely sensed data are suitable to assess large areas, and considerable effort has been made to characterize vegetation using satellite data. Basic relationships exist between spectral reflectance and vegetative characteristics. These relationships allow the use of spectral transforms to define biophysical parameters for plants. The normalized difference vegetation index (NDVI) has been shown to be related to plant canopy variables, which also relate to ET.

Ritchie & Burnett (1971), Wiegand *et al.* (1979), Holben *et al.* (1980), Tucker (1979), and Weiser *et al.* (1986) have shown a relationship between NDVI and green leaf area index (LAI), photosyntheticaliy active biomass, and percentage green cover for grass, soybean and corn canopies. The LAI has been related to ET by Stern (1965) for safflower and by Hinkle *et al.* (1984) for corn and soybeans. Hinkle *et al.* (1984), using three different plant densities of corn, found that ET was proportional to density only until the LAI reached 2.7. They further showed that at an LAI of 2.7 the crop coefficient became nearly constant until the crop began to senesce. A crop coefficient is an empirical ratio of measured crop ET to

some reference crop ET (Doorenbos & Pruitt, 1977). The coefficient is used to adjust the potential ET to the actual ET of the crop. Potential ET incorporates climatic data and solar radiation, which define the environmental conditions that are external influences on the ET process.

Bausch & Neale (1987) used a hand-held radiometer, which measured radiance in three bands similar to Landsat thematic mapper (TM) bands 3,4, and 5, to demonstrate the similarity of a seasonal NDVI curve and a basal crop coefficient curve for corn. They concluded that NDVI-derived crop coefficients represent real-time crop coefficients. They further observed that the NDVI reached its asymptote at an LAI of 3.2, very close to values quoted by Hinkle *et al.* (1984). Later work by Neale *et al.* (1989) correlated the spectral crop coefficients to corn ET measured by lysimeters. They also stated that reflectance-based coefficients are sensitive to variable growth rates caused by variable weather conditions.

Further evidence regarding the relationship between LAI and NDVI is shown by Leprieur (1989). He observed that NDVI saturates at an LAI of 3when studying mixed vegetation sites with airborne visible/infrared imaging spectrometer data. Examination of the relationships of LAI to ET, NDVI and crop coefficients shows a generally linear trend until an LAI of 3 is reached.

Beyond this point, increases in LAI result in very little increase in the three related factors. This relationship suggests that the NDVI, if properly calibrated to vegetation, will provide information directly related to ET.

Almhab et al. (2007a) used a relation between NDVI derived from Landsat TM and over a large area, a plot of NDVI versus ET observations from several metrological stations in arid areas. He showed that points of low NDVI correspond to areas of low ET.

A lot of the effort is now concentrating into increasing the accuracy of radiant fluxes, even if Surface Albedo can easily be estimated by common sensors (enabling the calculation of the shortwave net radiation), it takes more specific sensors to estimate the longwave component of the radiation balance. Surface Albedo and temperature can also be the basis for estimates of the upwelling components, while the down welling components are based on meteorological data (Moran et al., 1989, Almhab and Busu, 2008). Soil heat flux can be estimated by the ratio G/Rn through spectral indices (Choudhury et al., 1994, Almhab et al, 2007b and Almhab and Busu, 2008) or by semi empirical equation including Rn, the surface Albedo, the surface temperature, NDVI and the area average Surface Albedo (Bastiaanssen, 1995). The parameterization of turbulent fluxes is having a large part of research in itself, two main parameters are used generally, the Leaf Area Index (LAI, inferred from NDVI) and the aerodynamic resistance (r_{ah}, for momentum and for heat transport). Lastly, some methods exploit image context (Price, 1990; Bastiaanssen, 1995; Tasumi et al., 2000 ; Almhab et al, 2007b and Almhab and Busu, 2008), albeit having certain advantages (like taking advantage of range availability for deriving equations) also are restrictive to areas and often contextual to image conditions, making automation of processes a major constraint.

The objective of this study was to demonstrate the use of NDVI to estimate ET, using available data and procedures. Ground data and procedures were those used by the NWRA for the study areas.

2.0   STUDY AREAS

The Sana'a Basin is located in the western highlands of Yemen opposite the Red Sea and the Gulf of Aden (figure 1). It is mostly an intermountain plain surrounded by highlands from the west, south and east. On a regional scale, the Basin extends across the central part of the Sana'a Governorate (figure 1) and covers about 24% (3250 km2) of its total area (13,550km2).

There is a significant variation in altitude both east-west and north-south. The highest point in the Basin is in the southwest end (Jabal An Nabi Shu'ayb) and has an elevation of almost 3700 meter above sea level (m.s.L) The lowest (about 1900 m.s.l.) is in the northern extremity where the Wadi Al Kharid exits the Basin towards the main basin by the same name. The predominant climate is arid although semi-arid conditions prevail in localized areas, particularly along the western highlands.
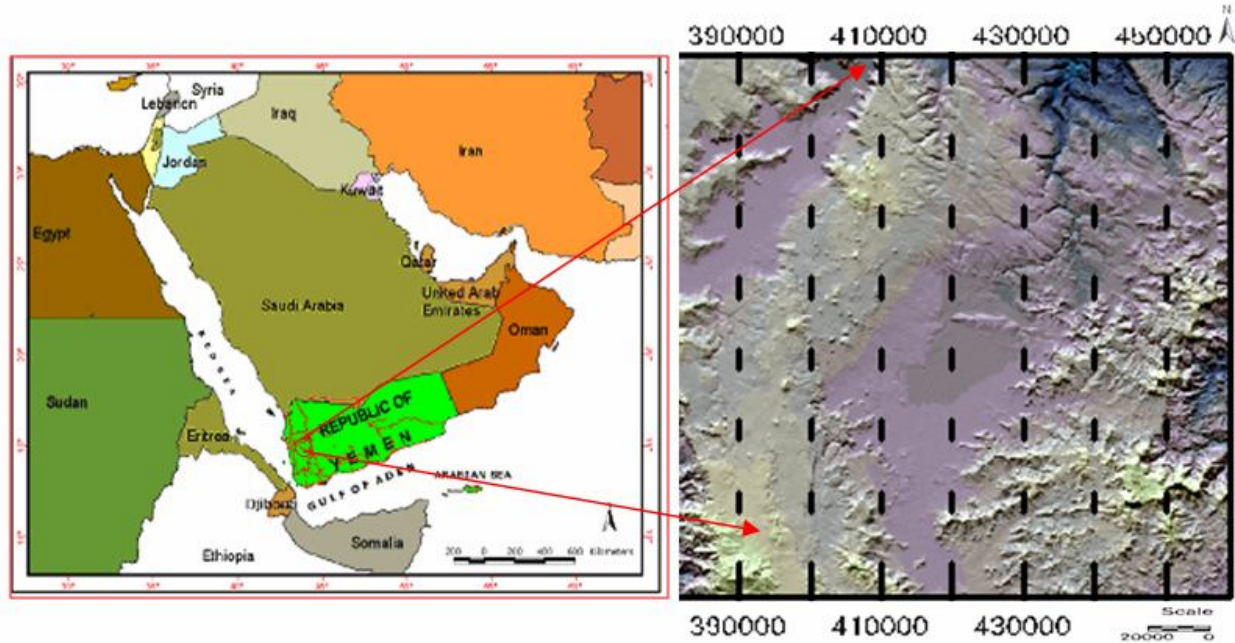
Figure 1: The central Yemen Mountains as seen on DEM (USGA) normalize image

3.0   SATELLITE DATA

Satellite images from two different satellite images one NOAA-AVHRR and one LANDSAT5-TM , were evaluated for Land Surface Heat Fluxes distribution in Sana'a basin central Yemen mountains. These overpass time of these images was 10.30of LANDSAT5-TM and 14.00 of NOAA-AVHRR local time. Both images had favorable weather conditions with little clouds in the study area. Data from the field measurement area were available to assist the calculation of the Land Surface Heat Fluxes in the locations of the study area (Lat: 15.3 N, long: 43.15 E).

Table 1: NOAA-AVHRR and LANDSAT TM image acquisition dates for the integration.

No.	NOAA-AVHHR	Landsat
1	10 June 1998	1 June 1998
2	23 October 1998	
3	31 May 1995	20 May 1995
4	20 December 1995	12 December 1995

4.0 SATELLITE DATA PROCESSING PROCEDURES

Reference ET (ETo) was calculated from meteorological data with the FAO Penman–Monteith equation (Allen. et al., 1998). ETo was calculated as a daily total ET (mm/d) from an imaginary grass reference crop (Jones, 1983). The equation adjusts the equation for (mainly stomata resistance, rs) as a constant, whereas the rs of plants respond in complex ways to environmental factors in natural environments (Jones, 1983; Osmond et al., 1980). Allen et al. (1998) presented the following simplification of the PM equation in the FAO Irrigation and Drainage Paper 56, "Crop Evapotranspiration':

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad \text{(mm)} \quad (1)$$

where:

ETo is the reference evapotranspiration for 0.12 m clipped, cool-season grass (mm/day),

R_n is the net radiation at the crop surface (MJ/m2/day),

G is the ground heat flux density (MJ/m2/day),

T_a is the mean daily air temperature at 2 m height (°C); u_2 is wind speed at 2 m height (m/s),

e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa),

Δ is slope of the vapor pressure-temperature curve (kPa/°C), and

γ is the psychometric constant (kPa/°C).

In Equation 1, ET0 represents the evapotranspiration occurring from a hypothetical well-watered grass surface having clipped height of 0.12 m, a fixed surface resistance of 70 s/m and an Albedo of 0.23. Potential evapotranspiration was also calculated by the Blaney-Criddle method (ETo-bc) (Brower & Heibloem, 1986), for comparison. This method is based mainly on mean monthly temperature. The formula was as follows:

$$u = k f \quad (2)$$

where:

u = semi-monthly consumptive use, in inches;

k = semi-monthly consumptive use crop coefficient (from Blaney-Criddle k factors table); and

f = semi-monthly consumptive use factor, in the form:

$$f = t \text{ x } p/100 \quad (3)$$

where:

t = mean temperature in degrees Fahrenheit for half-month period from selected climatic station; and

p = percentage of daylight hours for half-month period (from Monthly Percentage of Daytime Hours table, adjusted to half-month period).

Empirical methods based on VIs for estimating ET are modifications of the crop coefficient method (Jensen & Haise, 1963) for estimating water demand by irrigated crops. Crop coefficients (Kc) are empirical ratios relating crop ET (ETc) to a calculated reference-crop ET (ETo) that is based on atmospheric water demand (Jones, 1983) over a crop cycle or to actual ET measurements, as in the present study. A Kc curve gives the seasonal distribution of Kc as a function over time or a time-related index, such as growing degree-days. In this form, however, Kc cannot account for variations in crop growth from field to field, as affected by soil type, nutrition, uneven water distribution, or other agronomic factors.

As an alternative, Kc can be adjusted throughout the crop cycle to take into account changes in the fraction of absorbed solar radiation (FARs) by the plant canopy (estimated by VIs) as the crop develops.

A time-series of VI measurements is correlated with measured ETc or ETo to develop a VI–Kc curve over the crop cycle. Once calibrated, these VI-based Kc curves can provide close estimates of ETc within 10% of measured values among fields with different growth characteristics ((Hunsaker et al., 2003).

Choudhury et al. (1994) used a heat balance and irradiative transfer model to study relations among transpiration coefficients (Tc) and VIs. They provided a theoretical basis for estimating transpiration from no stressed crops from VI and Ta data. From the relationship between ET and LAI and between LAI and VI, they developed an equation in the form:

$$ETc = ETo[1-(VImax- VI)/(VImax – VImin)]^n \qquad (4)$$

The term $[1-(VImax-VI)/(VImax\_VImin)]^n$ converts *VI* to a scaled value (0–1) and is derived from the light extinction curve through a canopy as estimated by *VIs*. The exponent ^{n} depends on the crop and the *VI* used. The effects of soil evaporation and crop stresses added scatter and uncertainty into the ET estimates.

Single pixels containing the coordinates for a metrological station were extracted for calculating NDVI and EVI. NDVI (Eq. (5)), and EVI (Eq. (6)) values were calculated from TM $30m^2$ resolution images for the red and NIR bands (30 m for the blue band), and from AVHRR $1000m^2$ resolution images, as described in Almhab et al. (2008):

$$NDVI = (NIR - R) / (NIR + R) \qquad (5)$$

Where:
NIR is the reflectance of near infrared band 4 in Landsat image and band 2 in AVHRR images, R is the reflectance of red band3 in Landsat image and band 1 in AVHRR images

$$EVI=G(NIR-R)/NIR+C1.R+C2.blue+L) \qquad (6)$$

Where: C1 and C2 are coefficients designed to correct for aerosol scattering and absorption, which uses the blue band to correct for aerosol influences in the red band. C1and C2 have been set at 6 and 7.5, while G is a gain factor (set at 2.5) and L is a canopy background adjustment (set at 1.0) (Tian and Min, 1998).

$$SAVI = (NIR - R)(1-L) / (NIR + R-L) \qquad (7)$$

Where: L is set at 0.5.

The resulting EVI images were then used in the ET estimation procedure. Since the application of atmospheric corrections for purposes of data calibration are highly controversial and lacking in acceptable parameters, no corrections were applied.

5.0   RESULTS

Vegetation indexes values over Sana'a basin plots of ET over the study are shows in Figure 2 and 3. ET and VIs had regular annual cycles, Fig. 4 temporal distribution for the dates of ET measurements at the plantation and unplantation Sana'a basin, Yemen. Vegetation indexes values for four images Landsat TM averages, starts on 14 Dec. 1989, 20 May 1995, 12 Dec. 1995 and 01 June. 1998 was presented table 2 below.

Figures 5 show the scatter plot of the regression analysis of the ET estimating from the model developed and that estimation from ground station, for each image date. ET was more closely correlated with EVI than NDVI in this study; show this from r^2 values indicate that NDVI-based ET estimations are equivalent to EVI estimations.

Table 2 shows the image dates and results of the estimates for the VIs, as well as the calculations based on the data from Almhab *et al.a,b* (2007a).

Table 2 : VIs intervals over the study are in Yemen landsat TM

date	NDVI	EVI	SAVI	ET
20 May 1995	0.473	0.232	-	3.991
12 Dec. 1995	0.416	0.394	1.843	3.479
01 June. 1998	0.481	0.526	-	4.063

The unplantation southern Sana'a basin site had significantly lower ET (0.000) than the other three sites. NDVI and SAVI results followed the same pattern as ET. Correlation matrix of ET, VIs, and meteorological variables ET was significantly correlated with both NDVI and EVI for each site and year, but the correlation coefficients were generally higher for EVI than for NDVI (Figure 2 and 3). Most of the correlation coefficients were moderate to strong (0.8–0.9). A correlation matrix showing mean values of ET and meteorological variables is in Table 3. For western, southern and middle of Sana'a basin. Ta was strongly correlated with ET (r=0.82). Pooled ET data had a nearly equivalent r value (0.05) with respect to NDVI as data separated by species, showing that the response to Vegetation index was the same as for individual species. On the other hand, the r values for ET on the other meteorological data were low to moderate. Actual ET of southern and eastern Sana'a basin had a latter onset than predicted by ET_o.

Table 3 : mean values of ET and meteorological variables

N	ET_{PM}	NDVI	VI_{coff}	ET_{RS}
1	5.0	0.19	0.92	4.6
2	3.2	0.35	1.75	5.6
3	4.0	0.35	1.15	4.6

ET_{PM}= ET calculated by FAO Penman-Monteith equation
NDVI = Normalize Vegetation Indexes
VI_{coff} = Vegetation Indexes Coefficient
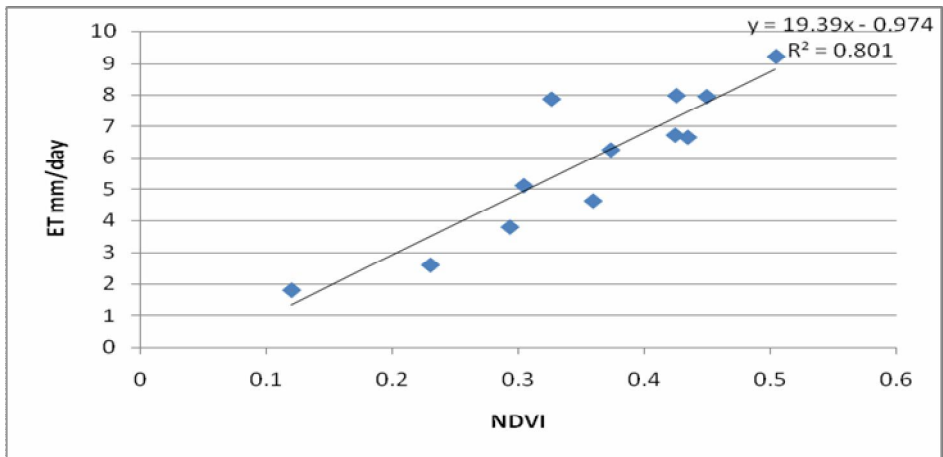ET_{RS}= ET calculated by modified SEBAL model using Landsat TM images

Figure 2: Curve of relationship of daily evapotranspiration (ET24) with vegetation index (NDVI) from TM images
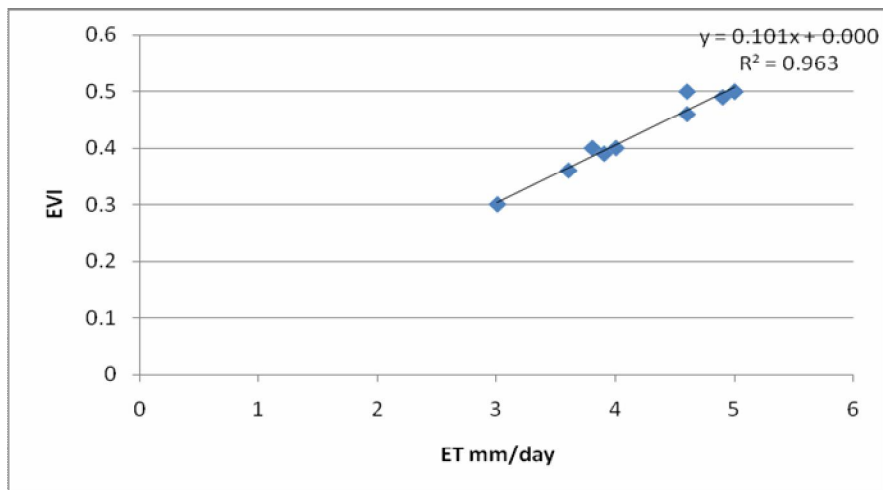

Figure 3: Curve of relationship of daily evapotranspiration (ET24) with vegetation index (EVI) from TM images .
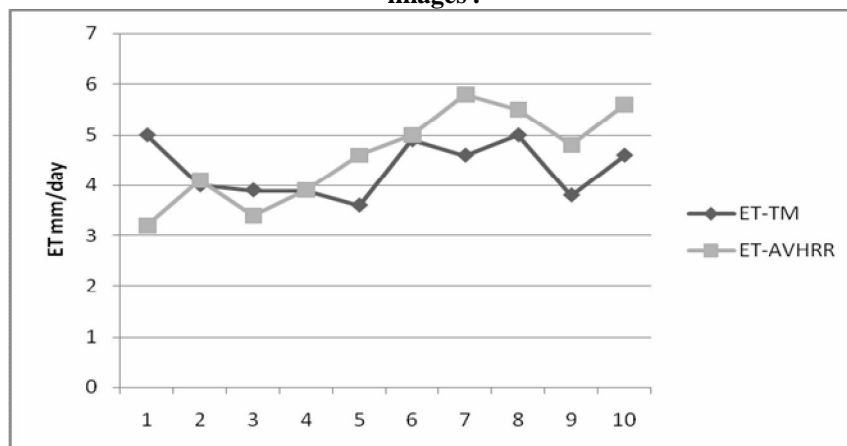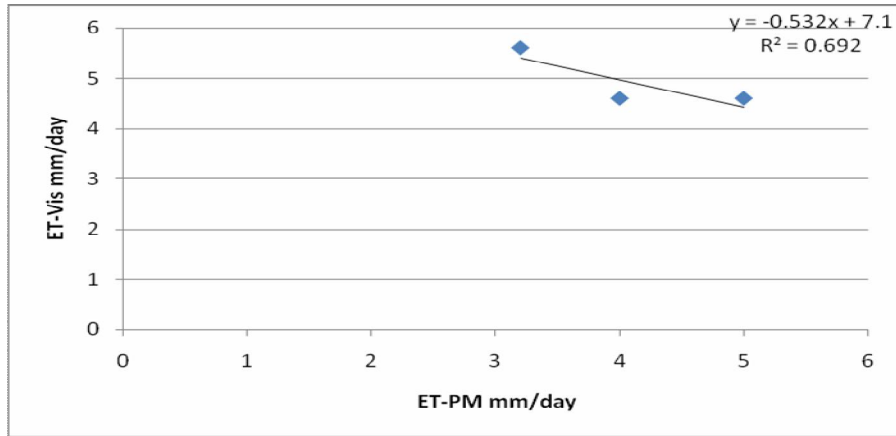

Figure 4: Relationship of daily evapotranspiration (ET24) from TM images and AVHRR in ten point in Sana'a basin June 1998.

Figure 5: Curve of relationship of daily evapotranspiration (ET24) from TM images with (ET24) using Penman Montaith equation.

For the VIs, both TM and AVHRR data were used for the dates previously indicated. Figure6 and 7 show the regional ET estimation by VIs and metrological data with both Landsat TM and NOAA-AVHRR images.
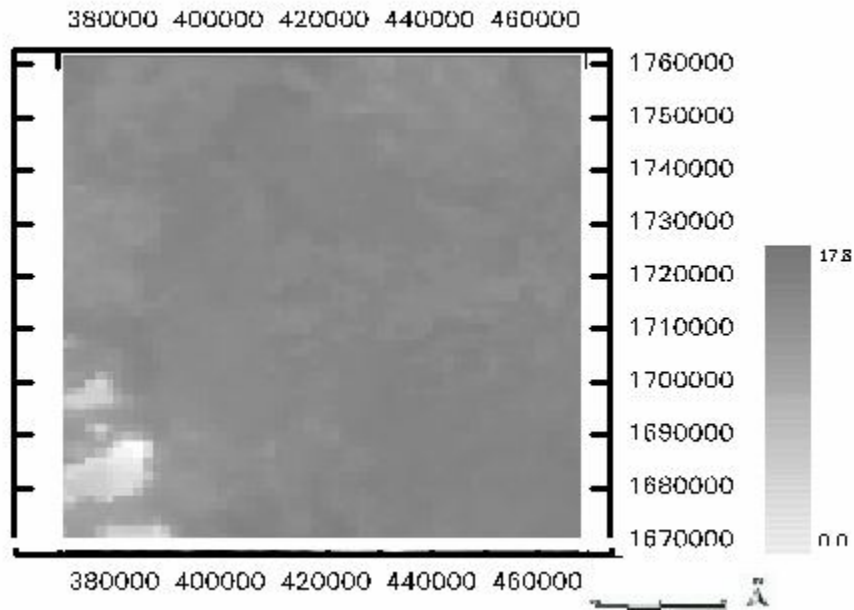
Figure 6: daily evapotranspiration (ET24) estimation by biophysical model and meteorological data on Sana'a Basin, 20th june1998.from AVHRR images
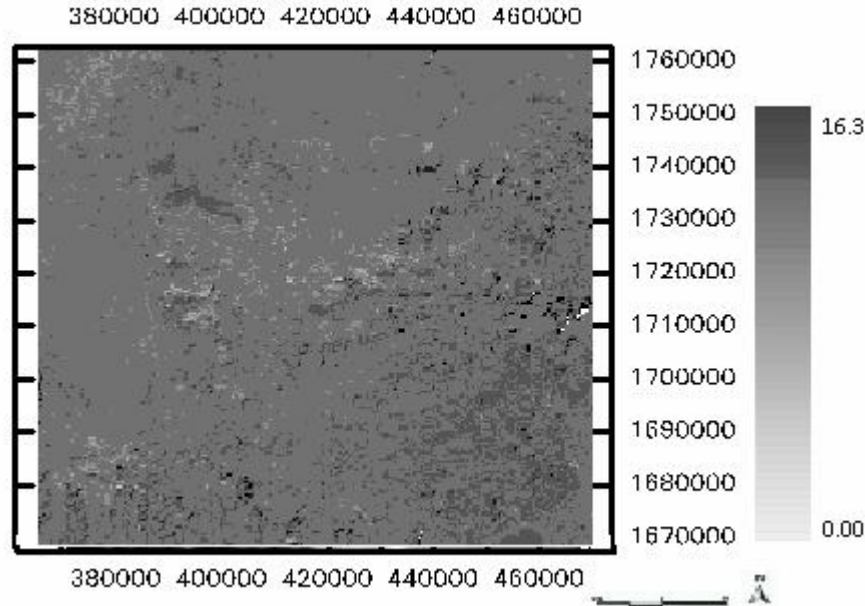
Figure 7: daily evapotranspiration (ET24) estimation by biophysical model and meteorological data on Sana. Basin, 1st june1998 from TM images

As shown in Figure 6 and 7 the Grape and Plum have higher values of ET from other land (groundwater observation). The ET can be determined based on the Vegetation index relationship for locations with various fraction of vegetation cover and soil moisture due to the fact that the points ETo at the metrological stations are relatively easy to measure or can be reasonably assumed using FAO Penman Monteith equation .

6.0   DISCUSSION AND CONCLUSIONS

The unique advantage of the VIs, ET estimation method is that it eliminates the need for identifying each crop and determining the acreage of each. It does require the general knowledge of what the dominant crops are and of their growth stages at the time of data acquisition. Also required are crop coefficients relating to the crops in the image area. Where irrigation is intensively managed, coefficients are usually available. A fallback source is Doorenbos & Pruitt (1977), who devised guidelines for selecting coefficients that take into account crop characteristics, time of planting, stage of crop development and general climatic conditions.

The results of this investigation indicate that NDVI values derived from TM and AVHRR data can be used to define crop coefficients applicable to ET estimation under conditions of unrestricted water availability to the crops.

Even though this study used FAO PM and Blaney-Criddle formula for estimating ETo, preliminary work on other study areas would suggest that the NDVI method would work equally well with other estimation methods that require crop coefficients.

The strong correlation shown in the comparison of estimation methods for the fields using TM data indicate applicability of the method to ET estimation for irrigated crops. Although the spatial resolution and spectral bandwidths of AVHRR differ from TM it would appear that appropriate adjustments can be

made when using the data to produce valid ET estimations. The use of irrigation service areas as test sites does not address the applicability of the method for large areas and diverse vegetation types. The results of this study suggest that further investigations are warranted.

The NDVI method creates a surrogate coefficient based on the parameters of the formula being used. The results of this study suggest the NDVI-ET relationship is valid, and, therefore, the method should be applicable regardless of the mechanism of estimation.

The use of remotely sensed data for ET estimation is a tool for acquiring ET estimates over large areas. It also provides a mechanism for entry of ET estimates into spatial data bases. Further investigations are necessary, however, to establish the validity of the method for non-irrigated cropland, grasslands, and forest vegetation types.

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