MODELING EVAPOTRANSPIRATION FOR IRRIGATED CROPS IN JORDAN USING REMOTELY SENSED DATA

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ABSTRACT

A study was conducted in Mafraq, Jordan, between 32°15′ and 32°50′ north latitude and 36°15′ and 36°50′ east longitude, to investigate the potential use of remotely sensed data to estimate evapotranspiration (ET). Evapotranspiration values were estimating by integrating high resolution (ASTER) and coarse resolution (MODIS) data in the ALARM model. The first part of the study focused on identifying crop types and developing a relationship between plant canopy height (PH) and Normalized Difference Vegetation Index (NDVI) from ASTER. The second part of the study concentrated on modeling actual ET through the integration of data from the previous stage and from the MODIS satellite with the ALARM model. Field surveys and data collection, from March to October 2005, included 37 farms with a total of 247 plots representing irrigated vegetable crops in the area. The ET was calculated using the ALARM model with input parameters of land surface temperature, leaf area index, surface albedo, view angle, view time from 1-km MODIS data and plant canopy height derived from its empirical relationship with ASTER NDVI.

Results showed that ASTER satellite imagery could provide an adequate identification of different irrigated vegetable crops in the study area. The use of estimated PH derived from its relationships with ASTER-NDVI instead of ground measurements was not a significant source of error for estimating ET. The average performance of the ALARM model showed a strong spatial variability

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from one site to another depending on the individual components of each site (total irrigated area and type of irrigated crops). The calculation approach of ET using the ALARM model with MODIS satellite data and crop parameters from ASTER data can be used to provide spatial distribution of actual ET. Therefore, the calibrated approach from this study could be used as a new tool for estimating ET for the irrigated area of Mafraq and similar irrigated regions in Jordan. The study also demonstrated the importance of radiometric correction for satellite images before using them in similar studies.

INTRODUCTION

Irrigated agriculture in Jordan has been growing rapidly. The irrigated highlands in Jordan increased from approximately 3,000 ha in 1976 to more than 43,000 ha in 2007. Groundwater is the main source of irrigation in the highland areas of Jordan. Approximately 6,000 ha are irrigated with fossil water in Disi and Jafer areas and about 33,000 ha are irrigated in the Jordan valley. The available fresh water supplies in Jordan were approximately 826 million cubic meter (MCM) in 2003 of which 520 MCM were used in agriculture (63.5 % of the total water use in Jordan). Urban water uses accounted for approximately 32.5% while industrial uses accounted for 4%. The total available water resources per capita are decreasing as a result of population growth (annual rate of 2.5% in 2004) and are projected to fall from the current 160 m^3/capita/year to about 90 m^3/capita/year by the year 2025.

Conventional field surveys and traditional mapping methods are fairly comprehensive and reliable for estimating crop evapotranspiration. However, they are often subjective, costly, time consuming and are prone to errors due to incomplete ground observations. Consequently, objective, standardized and possibly cheaper/faster methods that can be used for differentiating crop types, estimating cropped area and monitoring crop growth and requirement are imperative. As an option, remotely sensed data (RS) can provide systematically high quality spatial and temporal information about crop type, crop area and crop evapotranspiration (Sawasawa, 2003).

The RS technology can provide real-time monitoring system of cropped areas at an acceptable accuracy (Apan *et al*., 2003). Also, it can regularly provide objective information on the agricultural conditions of large land surface areas as well as small areas with reasonable cost. The use of remote sensing for mapping, assessing and monitoring agricultural crop conditions has been increasing. Several studies have focused on developing methodologies for mapping crop types and areas. These studies have either focused on the use of remotely sensed vegetation indices derived from spectral reflectance of near infrared (NIR) and red bands or focused on the use of digital classification techniques of single satellite imagery.

In Jordan, there has been relatively little practical contribution from remote sensing regarding irrigated areas in the highlands of the country. Further studies are needed to correlate crop parameters (plant canopy height and fractional vegetation cover) to remotely sensed vegetation indices and to identify and select image processing algorithms pertinent to vegetation assessment and monitoring and produce a quantitative data in time and space. Therefore, the first part of this study focused on developing a methodology for differentiating crop types and correlating crop parameters (plant canopy height, fractional vegetation cover and crop coefficient) with Normalized Difference Vegetation Index (NDVI ;defined as the difference between the near-infrared and red reflectance of vegetation normalized with their sum) from Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTER) satellite and correlating crop parameters with days after planting (i.e. seasonal behaviour and patterns).

The second part of the study focused on integrating the data from previous stage and that of Moderate resolution Imaging Spectroradiometer (MODIS) satellite in the Analytical Land Atmosphere Radiometer Model (ALARM) to investigate and assess evapotranspiration rates in Mafraq area. The advantage of this approach over traditional methods is that ASTER-derived parameters like NDVI provide information on ground cover, plant height, and planted area at high spatial resolution while, MODIS-derived data are available free on the Internet and on a daily basis and do not require in-situ crop measurements. However, the integration of these products with models like ALARM has not been investigated in many areas of the world including Jordan. The overall goal of this study was to examine the perspective potential of remotely sensed data to estimate evapotranspiration by integrating ASTER and MODIS derived data in ALARM model.

STUDY AREA

The total area of Jordan is about 88,778 km^2 and more than 80 % of the country's area is arid and receives less than 200 mm of annual rainfall. The average annual precipitation rate over Jordan is about 93.6 mm. Generally, the climate is Mediterranean, with a long dry hot summer, a rainy winter, and a relatively dry spring and autumn seasons. Irrigated agriculture in Jordan (76,000 ha) falls under two categories in term of management and source of water. In the highlands (43,000 ha), privately managed individual farms are irrigated by groundwater from private wells. In the Jordan Valley (33,000 ha), the publicly managed irrigation system uses surface water of Yarmouk River and side wadis as well as recycled wastewater. Agricultural development in Jordan depends mainly on the availability and quality of water resources, and this requires further improvement of irrigation water management (Jitan, 2005).

The Mafraq Governorate constitutes one of the most important irrigated areas of the highlands of Jordan. Within four years between 2000 and 2004, the area under cultivation in the governorate has increased by 60%, (from 30,900 ha to 49,800 ha) (DOS, 2004). The study area represents the most important irrigated area in Mafraq Governerate, about 100 kilometers north-east of the Capital Amman. The study area is located between latitudes $32^{o}15'$ and $32^{o}50'$ North and longitudes $36^{o}15'$ and $36^{o}50'$ East and covers about 700 Km^2 (Figure 1). The average altitude is about 686 m above sea level.

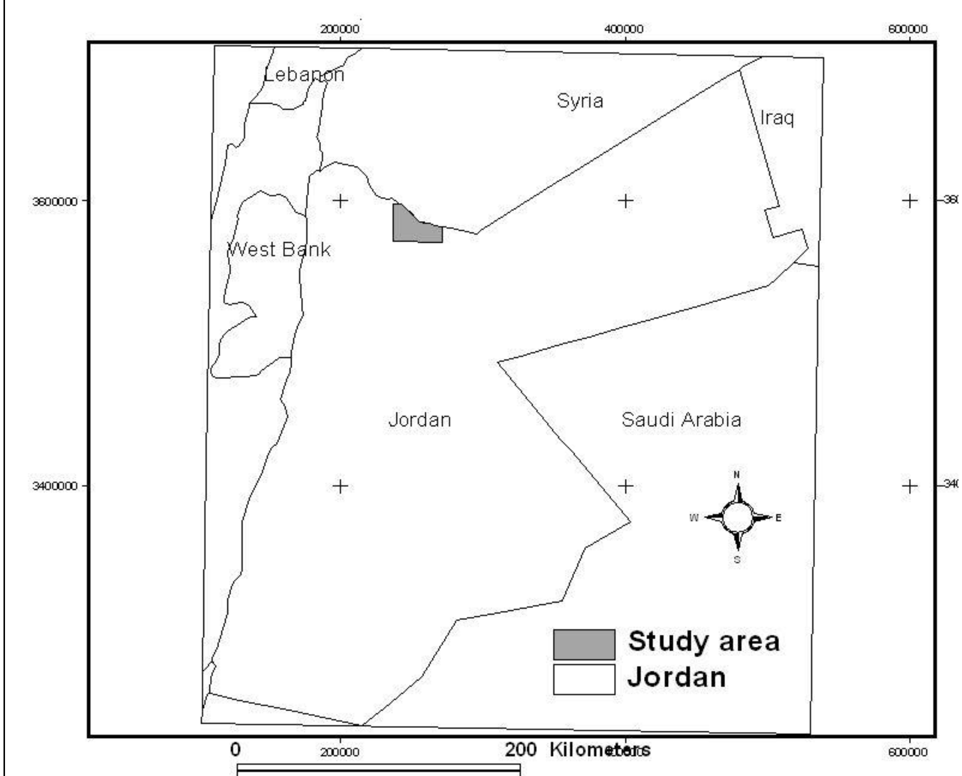


Figure 1. Location of the study area.

The study area is located in the Arid Mediterranean, cool bioclimatic zone, with a long dry hot summer, a cold winter, and a relatively dry spring and autumn seasons. The main irrigated vegetable crops are tomatoes, water melon, cauliflowers, cabbage and sweet melon. Drip irrigation is the dominant form of irrigation in this area.

METHODOLOGY

Assumptions

Vegetation density is the most obvious physical representation of cropped areas. The density and health of plants can be monitored using remotely sensed images that measure chlorophyll activity and vegetation vigor. The spectral reflectance is a manifestation of all important factors affecting the agricultural crop and the cumulative environmental impacts on crop growth and is strongly correlated to the canopy parameters. These parameters are mainly affecting crop evapotranspiration and spectral data (NDVI) is an indicator of crop type and its parameters (Singh *et al*., 2002). This assumption is supported by the high resolution of ASTER (15 m) and the reasonable spectral width of Near Infrared (NIR) and red (R) bands.

Remotely sensed vegetation indices:

The unique spectral signature of green plants is the principle behind the use of vegetation index (VI). The VI offer a quick and easy technique for converting image data from several wavebands to a single value or visual representation that can be interpreted by someone with little training in remote sensing technique, may have some relationship to the amount of vegetation in a given image pixel and can tell something useful about vegetation (Terrill, 1994).The vegetation indices provide information on the state of vegetation on the land surface; vegetation is the result of a complex relation between land and land use, and provides means for monitoring and estimating changes over time. The most commonly used vegetation index is the normalized difference vegetation index (NDVI): This is a ratio based VI, ranges between -1 and +1, and calculated by the difference of the Near Infrared (NIR) and red (R) bands as ratio to their sum (Sawasawa, 2003).

Since satellite data can help in estimating some key-variables related to vegetation phenology. VIs offer opportunities for monitoring the spatial and temporal variability of K_c. Use of remotely-sensed vegetation indices, such as NDVI has been tested to predict crop coefficients at field and regional scales (Ray and Dadhwal, 2001; Jitan, 2005).

Radiometric correction of ASTER satellite imagery

Hand-held multispectral radiometer (Cropscan Inc., USA) was used to measure both incoming and reflected radiation for five optical spectral bands. Including red (0.63–0.69 μm) and near-infrared (0.76–0.86 μm) bands. The NDVI calculated from these measurements was defined as field measured NDVI (difference between near-infrared and red reflectances divided by their sum). Field measured NDVI was taken on 12 May, 2005, i.e on the same day of ASTER image acquisition. Digital numbers associated to red and near-infrared channels were extracted from ASTER satellite imagery and used to calculate ASTER NDVI. Values of ASTER NDVI were compared to the corresponding field measured NDVI for each field using linear regression analysis. For most crops, significant linear relationship with strong correlation was observed. Except for squash, the correlation coefficient (r^2) ranged from 0.93 to 0.98 for the different irrigated vegetable crops.

The overall correlation between ASTER and field NDVI values for all irrigated crops had an r^2 value of 0.96 and slope of about 0.5 which indicated strong and significant (p=0.05, n=60) linear relationship (Figure 2). Based on the above results, the images from April, June and September, 2005 were radiometricaly corrected using May image as a base image (master) (Emar Suifan, 2006).

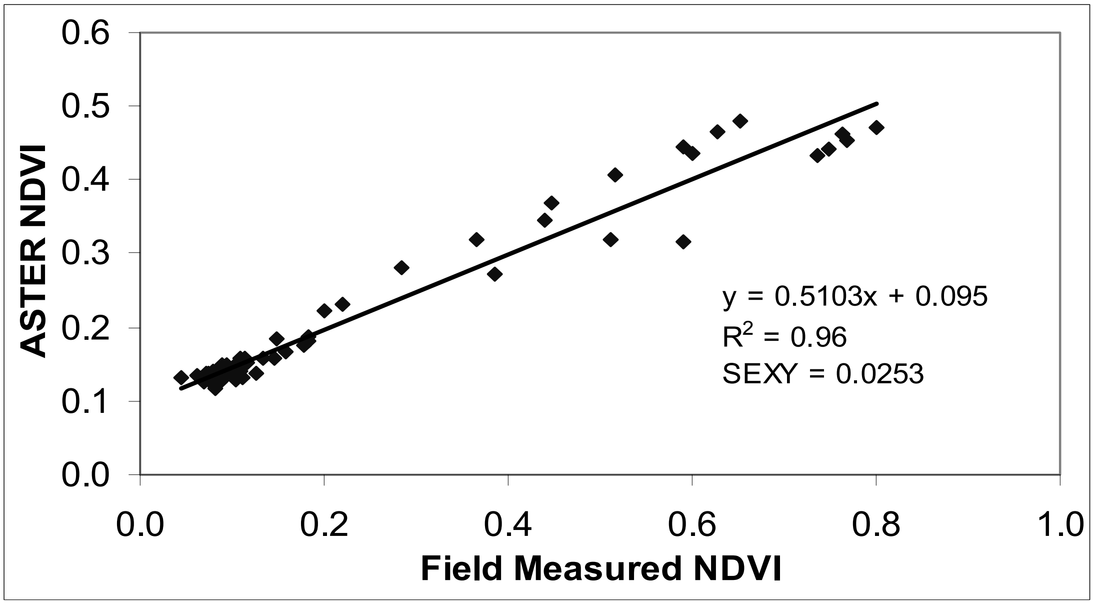


Figure 2. Relationship between ASTER-NDVI and Field measured NDVI for all crops, used for absolute radiometric correction of ASTER image of May, 2005.

RESULTS AND DISCUSSION

The relationships between plant canopy height (PH) and fractional vegetation cover (GC) for various vegetable crops in the study area were determined (Emar Suifan, 2006). The two crop parameters exhibited similar seasonal patterns. Significant correlations were observed between PH and day after planting (DAP) and between GC and DAP. The correlation coefficients (r^2) between PH and DAP ranged from 0.77 for sweet melon to 0.96 for squash. The correlation coefficient between GC and DAP ranged from 0.80 for cauliflower to 0.95 for squash. Additionally, correlations for GC and DAP did not follow a similar trend to PH and DAP. For eggplant, as an example, r^2 between PH and DAP was 0.82 while r^2 between GC and DAP was 0.93. The minimum r^2 between GC and DAP was higher than that between PH and DAP.

Average, maximum and minimum values of plant canopy height and fractional vegetation cover for different irrigated vegetable crops for one season are summarized in Table 1. These values and derived mathematical relationships were considered as the first guideline for irrigated vegetable crops in Mafraq area and can be used in the different applications, particularly estimating crop evapotranspiration. In this study, these empirical relationships were used to estimate daily plant canopy height required for estimating the surface roughness and aerodynamic resistance for heat transport which is needed for estimating daily evapotranspiration and adjusting crop coefficient (K_c) for local conditions.

Table 1. Mean, maximum and minimum plant canopy height (PH) and fractional vegetation cover (GC) for different irrigated vegetable crops.

Crop Type	Growing season (day)	Mean		Minimum		Maximum	
		PH (cm)	GC (%)	PH (cm)	GC (%)	PH (cm)	GC (%)
Cabbage	105	25	51	2	0.2	50	99
Cauliflower	126	36	56	4	1	73	99
Eggplant	158	56	49	2	2	100	92
Pepper	188	42	30	2	1	92	68
Sweet melon	132	15	52	3	1	26	99
Watermelon	107	14	34	2	1	30	76
Tomato	170	34	42	3	1	57	73
String beans	102	22	22	1	1	45	44
Squash	102	48	55	1	1	70	95

NDVI for irrigated vegetable crops

The core element of the use of remote sensing technology in monitoring irrigated crops was the identification of crop type and the derivation of crop coefficient (K_c). Initial results of correlating NDVI with days after planting (DAP) showed a significant polynomial relationship with correlation coefficient values being more than 0.90 for the different irrigated vegetable crops. Visual interpretation of the relationship between DAP and NDVI (Figure 3) showed that the NDVI values were nearly constant during the initial stage of most irrigated vegetable crops. This period varied from one crop to another. Similarly, the length of development stage varied according to crop type with sharp increase in NDVI values for some crops and uniform increase over a large period for others.

The relationships between FAO-K_c and NDVI for each crop are shown in Figure 4. The relationship between K_c and NDVI is linear with high correlation coefficient (above 0.94) for all irrigated vegetable crops. These results agreed with the previous comparative studies of linear relationship between K_c and NDVI (Jitan, 2005). Therefore, one can conclude that it is possible to use remotely sensed satellite data to derive K_c for the different irrigated crops in our study area and similar environments.

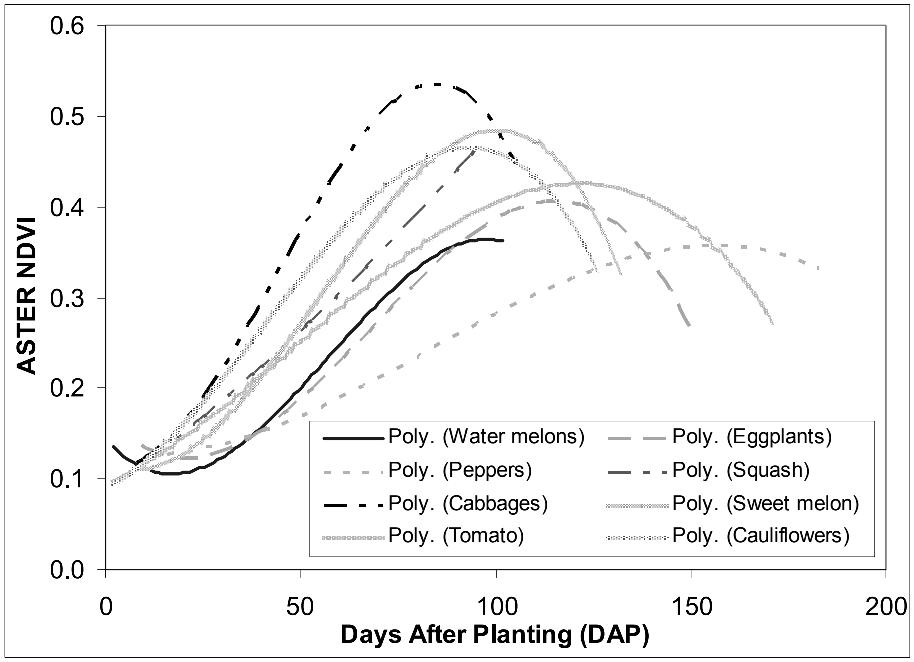
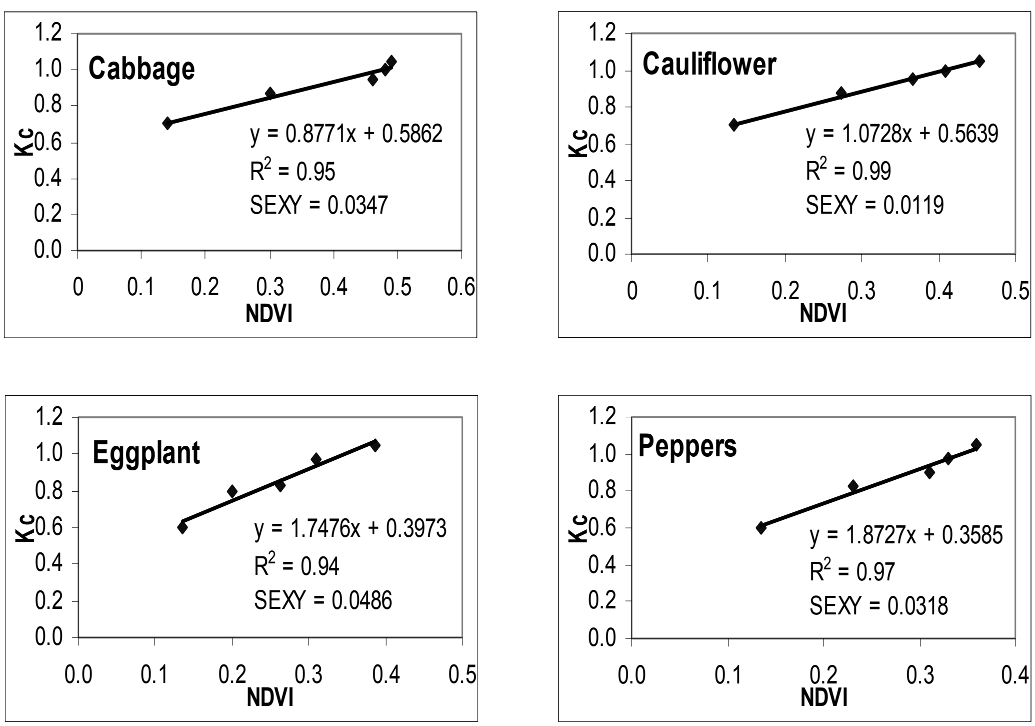


Figure 3. Summary of NDVI-time profile for the different irrigated vegetable crops.



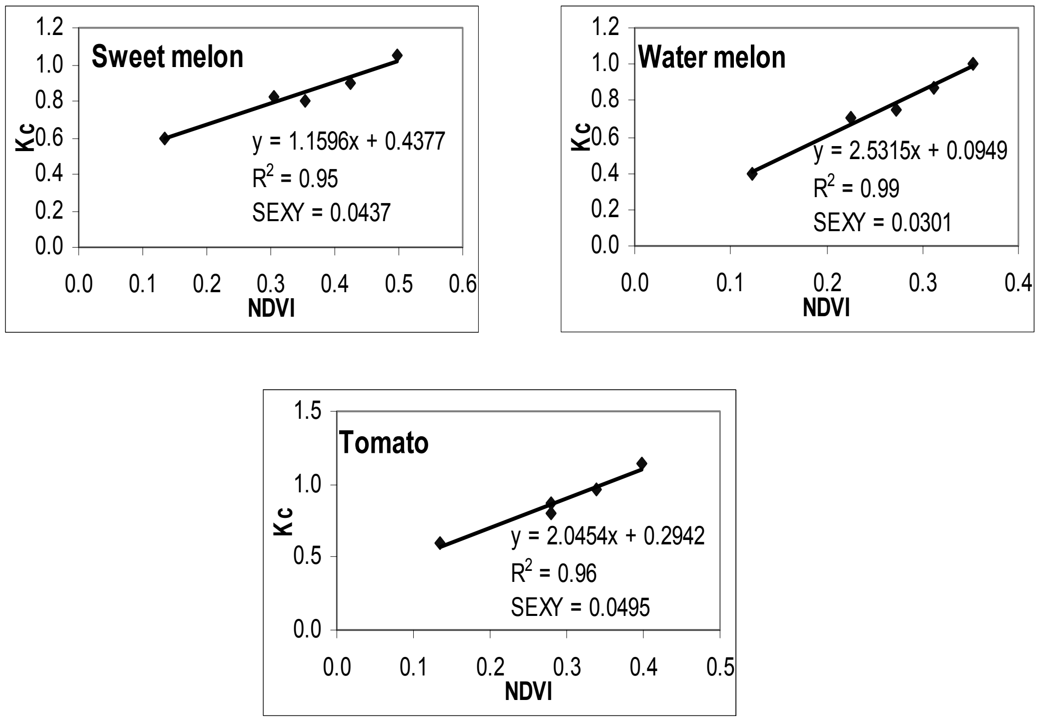


Figure 4. Relationship between ASTER-NDVI and Crop coefficient (K_c) for different irrigated vegetable crops.

Evapotranspiration and Remote Sensing

Daily crop evapotranspiration (ET) values during the summer growing season from first of April to the end of September 2005 were calculated by two methods: First, using the reference (grass) evapotranspiration (ET_o), and the crop coefficient (K_c), ($ET=ET_o*K_c$). The ET_o was calculated using the FAO-56 Penman-Monteith equation. It was developed for a hypothetical well-watered and actively growing uniform grass of 0.12 m height with a surface resistance of 70 sm^{-1} and albedo of 0.23 (Emar Suifan, 2006). Standard crop coefficient (Kc) values of every growing stage (initial, mid and end) and for every crop planted in the study area were taken from FAO-56 document and were adjusted for local conditions.

Second, using the Analytical Land Atmosphere Radiometer (ALARM) model to estimate actual crop evapotranspiration (ET), with input parameters like leaf area index, surface albedo and land surface temperature from the low resolution MODIS satellite images; climatic data from Maqraq Air Port weather and plant canopy height was either measured in the field or estimated from the empirical relationships (derived between plant canopy height and DAP or between plant canopy height and ASTER-NDVI). Since MODIS image had pixels with a resolution of about 1 km^2, ALARM was used to estimate the daily crop evapotranspiration for crops planted in a pixel area. Consequently, the weighted average plant canopy height for the crops planted in the pixel was computed for the use by the model.

The ALARM model was applied for 19 MODIS pixels to compute daily crop evaportanspiration (ALARM ET) for the days in which ASTER images were acquired. Different data were used in the model including measured plant canopy height, estimated plant canopy height from days after planting (PH vs DAP), and estimated plant canopy height from ASTER-NDVI (PH vs NDVI). The plant canopy height was necessary to calculate crop aerodynamic resistance for heat transport. The daily ALARM ET values, estimated from the three plant canopy height values were compared to observe the differences and to check the validity of equations derived between plant canopy height and both DAP and NDVI.

Some, but not significant, variations were observed among the different ALARM-ET values estimated from the three plant canopy height values. However, the maximum difference between ALARM-ET values calculated using measured plant canopy height and estimated plant canopy height from days after planting and estimated plant canopy height from NDVI was ±0.06 mm/day for pixels 1, 3, and 4 for the Julian days of 100, 192, and 248. Meanwhile, there were no differences between ALARM-ET values estimated from the three plant canopy height values for other pixels and other Julian days. These results indicated that the use of estimated plant canopy height from the derived relationships of plant canopy height from days after planting (DAP) or from NDVI instead of ground measurements is not a significant source of error for estimating ET.

The ALARM model was applied in every MODIS pixel to compute the actual daily crop evaportanspiration (ALARM ET). Additionally, weighted average crop evapotranspiration for each pixel was calculated based on FAO-56 Penman-Monteith equation (FAO-PM ET). The daily ALARM ET and the daily FAO-PM ET values were compared to evaluate the differences, as presented in Figure **5**. The weighted average ET from FAO-56 PM in a specific pixel for a given period was calculated as the sum of individual crop evapotranspiration calculated for each irrigated crop divided by the total area of the pixel.

Evaluation and calibration of the ALARM evapotranspiration results

To adjust daily crop evapotranspiration values, which were estimated from ALARM model using MODIS remotely sensed data, the estimated daily ALARM-ET for each pixel was compared with the corresponding weighted average daily crop evapotranspiration calculated using FAO-56 PM equation. Regression analysis was performed between the ET values computed from ALARM and FAO-56 PM, and consequently, a calibration coefficient (C) was calculated for each pixel using linear regression analysis and the least square error technique.

The regression analysis showed that the calibration coefficient for ALARM-ET values ranged from 0.26 to 0.86. The daily calibrated ALARM-ET for each pixel was calculated using the corresponding calibration coefficient (C). Daily ET values from the both ALARM and calibrated ALARM were compared to the FAO-PM values.

Evapotranspiration values obtained from FAO-56 Penman-Montieth equation with those obtained from ALARM model had a RMSE range of 0.76 - 2.80 mm/day with an average RMSE of 1.64 mm/day compared to a RMSE range of 0.18 - 0.64 mm/day with an average RMSE of 0.40 mm/day obtained using calibration coefficient.

The difference between ALARM ET and FAO-PM ET values was evident and varied from one pixel to another. The average performance of ALARM model showed a strong spatial variability from one site to another depending on the individual components of each site (total irrigated area and type of irrigated crops). Generally, the difference between ALARM ET and FAO-PM ET decreased with increasing the irrigated area planted with vegetable crops and fruit trees or with increasing the total irrigated area and decreasing the rangeland area. On average, the ALARM model gave the highest overestimation in the sites with the lowest average irrigated area (vegetable crops and/or fruit trees) or with the highest rangeland area, and gave ET values close to FAO-PM ET values in the sites with relatively large irrigated area or with relatively small rangeland area.

The evapotranspiration values, which were derived from ALARM model using MODIS remotely sensed data, were higher than the evapotranspiration values derived from the FAO-56 PM method. This might be attributed to a lower radiometric surface temperature obtained from MODIS than the actual land surface temperature.

When the calibration coefficient (C) was used to adjust ALARM ET values to fit the FAO-PM ET values, the ET values became very close. Regression analysis of both linear line and second degree polynomial line were drawn between FAO-PM ET and calibrated ALARM ET for each pixel, the latter gave the better trend. The best relationship between calibrated ALARM ET and FAO-PM ET for all pixels (for the study area) is shown in Figure 5. A second degree polynomial line with a correlation coefficient of 0.97 was obtained for this correlation which emphasizes the need and the importance of calibrating modeled ET with other methods.

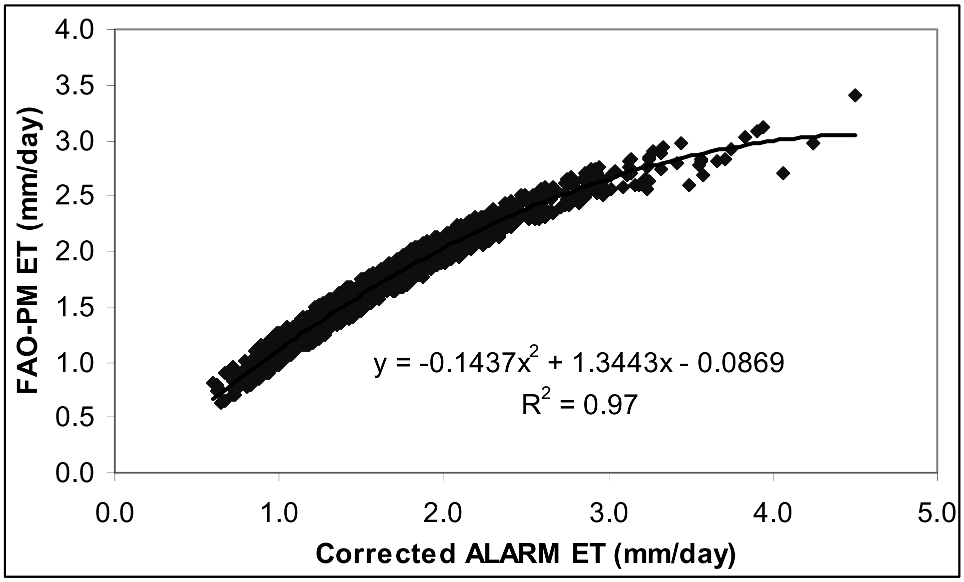


Figure 5. Relationship between calibrated ALARM ET and FAO-56 PM ET (mm/day).

The use of accurate and real time results of ET at regional scale is highly recommended for better management of water resources in the irrigated highland areas of Jordan. It was possible from ALARM-ET to build regional ET and to provide the spatial and temporal changes of ET, these results could provide the decision makers with the required data about the water budget in the irrigated areas for sustainable operation and management strategies of these areas.

The ALARM model can be used to estimate actual crop evapotranspiration (ALARM ET) for an area of 86.49 ha with input parameters like leaf area index, surface albedo and land surface temperature from low cost MODIS satellite images. ASTER satellite imagery or any other high resolution satellite imagery can be integrated with the model to estimate total irrigated area and crop type. Calibration coefficient (C) for ALARM ET can be estimated from the empirical relationship derived between C and the total irrigated area or C and the total rangeland area. Calibrated ALARM ET can be calculated by multiplying ALARM ET with the corresponding calibration coefficient. The FAO-PM ET can be calculated from the derived relationship between calibrated ALARM ET and FAO-PM ET. This approach can be used as a guideline and tool capable to provide consistent, frequent and real time data ET data for the region.

CONCLUSIONS

The calculation approach of ET using the ALARM model with MODIS satellite data and crop parameters from ASTER data can be used to provide spatial distribution of actual ET. The calibrated approach from this study could be used as a new tool for estimating ET for the irrigated area of Mafraq and similar irrigated regions in Jordan. The study also emphasized the importance of radiometric correction for satellite images before using them in similar studies.

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