ESTIMATING IRRIGATION WATER USE FOR DATE PALM USING REMOTE SENSING OVER AN OASIS IN ARID REGION

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ABSTRACT

Date palm needs sufficient water of acceptable quality to reach its potential yield. The present study conducted in Al-Hassa Oasis located in the Eastern Region of the Kingdom of Saudi Arabia aiming to estimate the daily, monthly and annual actual evapotranspiration (ETa) for date palm using Landsat-8 satellite data during 2017/2018. Also, an attempted was made to compare between the computed ETa and the actual water applied in the field. The Surface Energy Balance Algorithm for Land (SEBAL) supported by climate data was used to calculate the ETa. The SEBAL model outputs were validated using the FAO Penman-Monteith method coupled with field observation and measurements. The results showed that the highest daily ETa value observed during the summer season was 9 mm.day^{-1}, and the lowest value was 2 mm.day^{-1} in winter. The mean monthly water applied in the farms was 15% higher than that suggested by SEBAL during the peak summertime. The annual ETa varied between 800 and 1,400 mm.year^{-1}, while the annual irrigation requirement for date palm was in the range of 11000 – 13000 m^3.ha^{-1}. The validation measure showed a significant agreement level between the SEBAL model and the FAO Penman-Monteith method with RMSE of 0.84 mm.day^{-1}. The study concludes that the ETa calculated from the satellite data and the SEBAL model is useful for guiding the daily operation of date palm water management at the farm scale. Also, this information is essential for water planners and policymakers to formulate strategies and make decisions for managing water resources over large agricultural areas.

Keywords: Actual Evapotranspiration (ETa); Landsat-8 Data; SEBAL Model; Date Palm

تقدير استخدام مياه الري لنخيل التمر باستخدام الإستشعار عن بعد لإحدى الواحات بالمناطق الجافة

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المستخلص

يحتاج نخيل التمر إلى كمية كافية من المياه ذات الجودة المقبولة للوصول إلى الانتاجية المتوقعة. أجريت هذه الدراسة في واحة الأحساء التي تقع بالمنطقة الشرقية من المملكة العربية السعودية بهدف تقدير البخرنتح الفعلي (ETa) اليومي، الشهري و السنوي لنخيل التمر باستخدام بيانات القمر الصناعي لاندسات-8 خلال العام 2018/2017. أيضًا تمت مقارنة ETa المحسوب و كمية المياه الفعلية المطبقة في الحقل. استخدمت خوارزمية توازن الطاقة السطحية للأرض (SEBAL) المدعومة بالبيانات المناخية لحساب ETa. تم التحقق من صحة مخرجات نمذجة SEBAL باستخدام طريقة Penman-Monteith الخاصة بمنظمة الزراعة و الأغذية التابعة للأمم التحدة (FAO) بجانب المشاهدات والقياسات الحقلية. أوضحت النتائج أن أعلى قيمة يومية لـ ETa لوحظت خلال موسم الصيف كانت 9 ملم/يوم، وأدنى قيمة كانت 2 ملم/يوم كانت أثناء الشتاء. وجد أن متوسط المياه الشهرية المطبقة في المزارع أعلى بنسبة 15٪ من المعدل الذي اقترحته نمذجة SEBAL خلال ذروة الصيف. تراوحت ETa السنوية بين 800 و 1400 ملم/السنة، في حين تراوحت متطلبات الري السنوية لنخيل التمر بين 11000 - 13000 متر^3/السنة. أظهر قياس دقة التحقق وجود توافق كبير بين نمذجة SEBAL وطريقة Penman-Monteith بمتوسط خطأ قياس للجذر التربيعي (RMSE) يبلغ 0.84 ملم/يوم. خلصت الدراسة إلى أن ETa المحسوبة من بيانات الأقمار الصناعية ونمذجة SEBAL تساعد في عملية إدارة مياه ري نخيل التمر اليومية على نطاق المزرعة. كما أن هذه المعلومات ضرورية لمخططي المياه وواضعي السياسات لصياغة الاستراتيجيات واتخاذ القرارات المناسبة لإدارة الموارد المائية في المناطق الزراعية الكبيرة.

الكلمات المفتاحيه: البخرنتح الفعلي (ETa) ؛ القمر الصناعي لاندسات-8 ؛ نمذجة SEBAL ؛ نخيل التمر

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INTRODUCTION

The date palm tree (*Phoenix dactylifera*) is one of the oldest known fruit crop in the world, which originated from subtropical regions (1, 2). Date palm is the most widely cultivated fruit tree in the Kingdom of Saudi Arabia (KSA), and commercially is the most important tree in the life of people and their heritage (3). KSA is one of the leading countries of date production in the world. It comes second to Egypt with a total production of more than 1.1 million tons from an area of about 172,000 ha (1). Groundwater is the primary source of water for agriculture in KSA. The limited precipitation and the vast increase in the area of agricultural land have put pressure on groundwater usage. Date palm needs sufficient water of acceptable quality to reach its potential yield (4, 5). The amount of irrigation water required for date palm in most areas of the world is ranging from 13,000 to 36,000 $m^3.ha^{-1}$ (6). This variation is mainly due to the climatic conditions, ages, and varsities of date palm trees and water stress due to infections and salinity. Irrigation methods and water management for date palm at farm level are critical matters for sustaining date palm water productivity in the long-term (7). From the earliest times, different methods were used to calculate the water requirements of different crops. As a result, numerous methods were developed and adopted for date palm. Some of these methods are more accurate than others and some are comparatively more convenient to use. The Penman method widely accepted as the most accurate method of calculating water requirements for crops (6). This method makes use of daily climatic information (e.g., maximum and minimum temperatures, wind velocity, humidity and radiation per day) to calculate the reference evaporation (ET_0). Moreover, Sperling et al. (8) indicated a number of methods used in the measurement of actual water use by crops such as micro-metrological-based methods (Bowen ration and Eddy covariance), plant physiology (sap flow), hydrological methods (soil water sensing) and direct measurement of mass water balance (lysimeters). However, remote sensing has been increasingly employed in recent years to assess the actual evapotranspiration and became a significant factor for determining irrigation water requirement for many crops (9, 10, 11, 12). Remote sensing is a cost-effective tool for quantifying large-scale agricultural areas along with providing detailed information over the small areas. Measuring actual water use of a date palm tree is not an easy task, but it can be done (13). In Saudi Arabia, seasonal actual water use of date palm trees was monitored with both Bowen Ratio Energy Balance (BREB) method and Soil Water Balance (SWB) approach (14). Also, studies reported that in North and West Africa, the annual total ETa of the date palm was in the range of 1,000 – 2,000 mm (1). The accuracy of determining water requirement of date palm based on how accurate crop coefficient was determined. Crop coefficient (kc) values of date palm estimated to be in the range of 0.8 – 0.99 in most cultivated areas in Saudi Arabia (15). The determination of date palm water requirement in most studies conducted in Saudi Arabia was based on either direct measurement (i.e., lysimeters) or theoretical methods such as the Penman-Monteith equation and both methods are difficult to be implemented in vast agricultural areas. However, biophysical modelling methods like the surface energy balance algorithm for land (SEBAL) and METRIC systems have contributed valuable data for irrigation water management (16, 17, 18). Therefore, the use of satellite data coupled with the biophysical modelling can help in monitoring and managing the water status for date palm in the large-scale farming system. The obtained information is crucial for policy makers and water planners to develop and formulate strategies for agricultural water resources management in Saudi Arabia. Furthermore, there is a gap between irrigation water supply and demand for date palm in most farming regions in Saudi Arabia. Accordingly, accurate determination of date palm ETa is essential for establishing a complete irrigation system that performs water management and sustainable. The main objectives of the study were to assess the potential of Landsat-8 data for estimating the daily, monthly and annual ETa for date palm in Al-Hassa Oasis, Saudi Arabia. Also, efforts were made to compare between the ETa derived from the satellite data and the actual water applied in the field.

MATERIAL AND METHODS

Study area

Al-Hassa Oasis is one of the leading and old agricultural centres in Saudi Arabia. It is located about 300 km east of the capital Riyadh and 70 km west of the Arabian Gulf (Figure 1). It covers an area of about 220 km^2 with an average altitude of 150 m above the sea level. Date palm plantation is the main agricultural activity in the area, and the number of the cultivated date palms is around three million (19). Irrigation networks in Al-Hassa Oasis were operational since 1971 to irrigate more than 22,000 farms. The oasis boundaries are mainly defined by the existing irrigation network layout. The area has a hyper-arid climate with a high temperature in summer exceeding 45°C, and low in winter often reaching 0°C. It is characterised with a low annual rainfall of about 50mm, which occurs mainly during the winter season (20). Sandy loam soils dominate the soil type in Al-Hassa Oasis, and most of the agricultural land in the oasis is covered with saline soil (21).

Remote Sensing data

A series of Landsat-8 satellite data collected over the study area during 2017/2018 from the United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov/). A total number of 23 images were collected between April 2017 and March 2018 to cover the summer and winter seasons. The main characteristics of these data are shown in (Table 1). All the obtained satellite images have a cloud cover of less than 10%, and they have been geometrically and radiometrically corrected. A global digital elevation model (DEM) generated from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), which is known as ASTER GDEM also obtained from the USGS. It is a 30 m grid size DEM produced by the National Aeronautics and Space Administration (NASA) and the Ministry of Economy, Trade, and Industry of Japan (METI).

Field data

Field measurements and observations were collected from three different sampling farms located within the oasis boundaries (Figure 1) throughout the study period (Apr. 2017 to Mar. 2018). The sampling farms planted with date palm trees of different ages ranging between 15 and 25 years. Each of these farms covers an area of 0.5 ha, and they are irrigated with a drip irrigation system (Figure 2). The total number of trees was 120, 112 and 100 for the sampling farm 1, 2 and 3 respectively. The most dominated date palm variety in the three sampling farms is Khalas. However, Ruzaiz and Shishi cultivars also exist to a lesser extend in the sampling farms. The obtained field data include irrigation duration, irrigation intervals and the amount of applied water for irrigation at the farm level. Climate data were collected from two meteorological stations located in Al-Hassa Oasis. These data include air temperature, relative humidity, wind speed, net radiation, and vapour pressure and all of them were collected on hourly and daily basis during the study period.

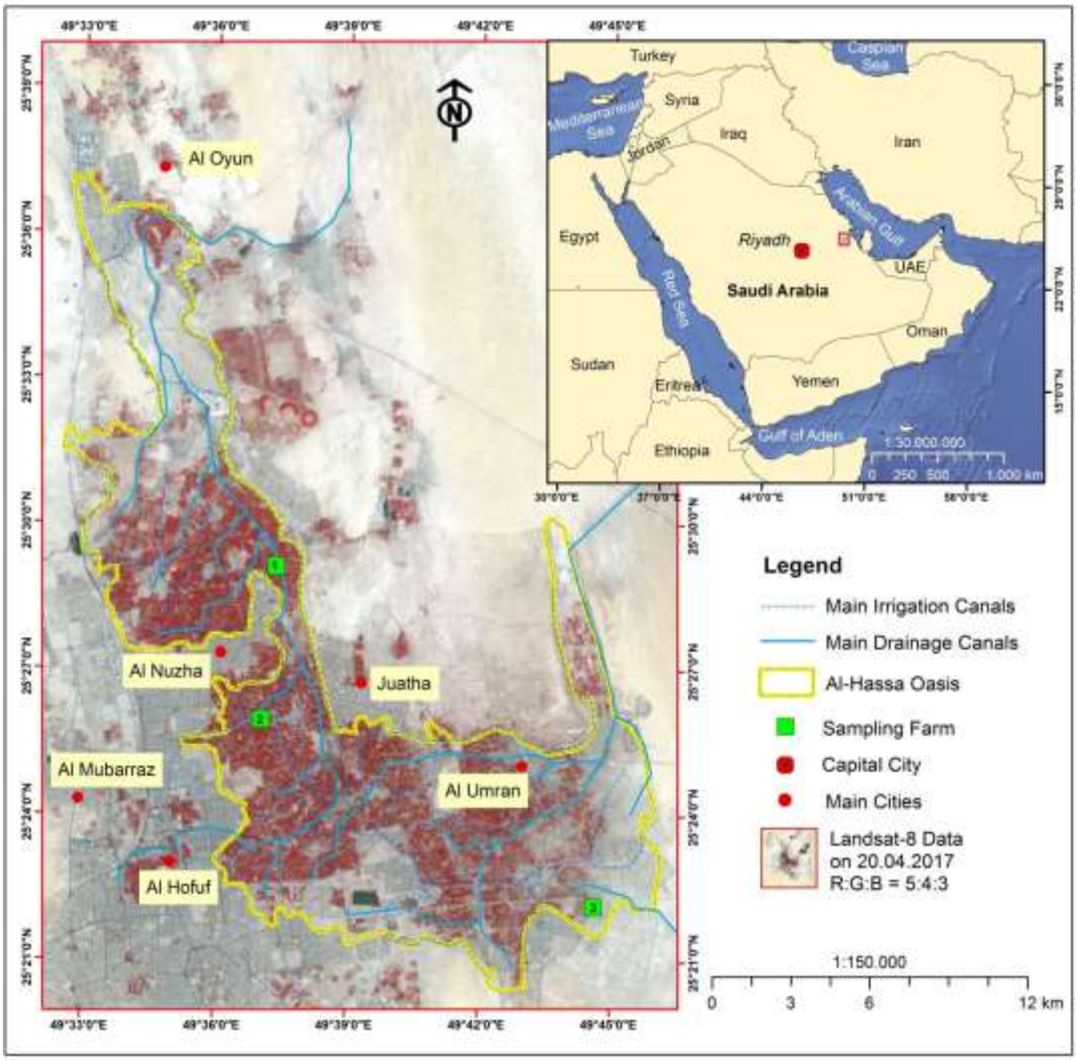

Figure 1. Location of the study area

Table 1. Specification of Landsat-8 data used in this study

Sensor	Bands	Spectral Range	Pixel Size
Multi-spectral (OLI)	**1,2,3,4,5,6,7,9**	**0.40 - 2.45 µm**	**30 m**
Panchromatic (OLI)	**8**	**0.50 - 0.650 µm**	**15 m**
Thermal (TIRS)	**10, 11**	**10.50 - 12.50 µm**	**100 m**

Estimation of the actual evapotranspiration (ETa) for date palm

The Surface Energy Balance Algorithm for Land (SEBAL) developed by Bastiaanssen et al. (22) and Bastiaanssen et al. (23) was used to calculate the actual evapotranspiration from satellite images (Figure 3). The SEBAL key input data consist of satellite measurements of surface albedo, leaf area index (LAI), normalized difference vegetation index (NDVI) and surface temperature. Also, the DEM and land use map were used as additional input data. The DEM was used for topographic and atmospheric correction (24). However, the land use map was used mainly to differentiate between the land-use and land-cover (LULC) types in the study area (Figure 4). Thus, the land use map was not used in the calculation of the ETa. The LULC of the study area were classified based on the differences in reflective behaviour of the surface cover types. The reflective behaviour is affected by the age of plantations, crop type, photosynthesis dynamics, soil type, type of undercover and the other biophysical process. In addition to the satellite data, the SEBAL model requires minimum inputs of routine weather data parameters (refer to the Data section). The SEBAL model scripts were formed using the Spatial Modeler Tool of the ERDAS IMAGINE 9.2 software. Mapping and visualisation of the data were made using the ArcGIS 10.2 software.

Validations and statistical analysis

The produced ETa by Landsat-8 and SEBAL model was validated using the FAO Penman-Monteith method (6). This method was used to calculate the reference crop evaporation (ET0) from the actual climate data in the study area. Consequently, the date palm water requirement was computed using ET0 and the date palm crop coefficient (kc) (ETa = ET_0*kc). The kc values of date palm were set between 0.9 and 0.99 based on the study conducted by Al-Amoud et al. (15) in different regions of Saudi Arabia. Furthermore, a flow-meter was fixed at the primary water source of each sampling farm to measure the amount of applied water for each irrigation time. The monthly irrigation water utilised by each sampling farm compared with the ETa computed by SEBAL model. Table 2 shows the amount of irrigation water consumed in the sampling farms. In order to make a valid comparison between the actual water used in the farms and the ETa calculated by SEBAL, the later was multiplied by the farm area to obtain the volumetric water in each sampling farm. However, to avoid the risk of salinity in the root zone of the date palm tree, a leaching requirement of 10% was suggested to be added for the volumetric water resulted from SEBAL (25). A linear correlation and root mean square error (RMSE) between the measured (FAO-Penman Monteith) and modelled (SEBAL) daily ETa was calculated using the Microsoft Excel 2010 software (26). Also, the same software was used for statistical analysis and charts of the data.

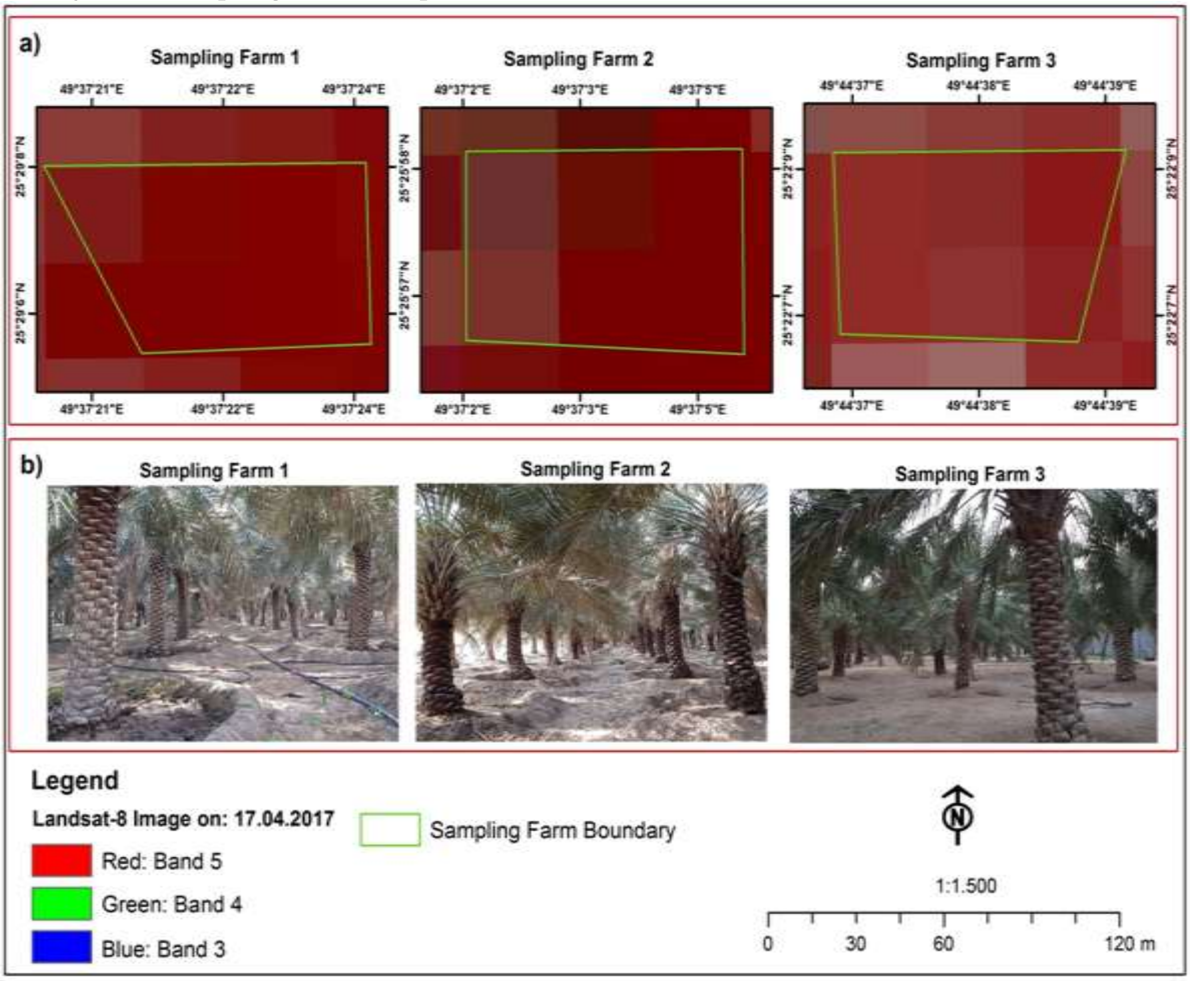

Figure 2. Sampling Farms Shown as: a) false colour image of the farms form Landsat-8 data; b) photographs of the date palm farms

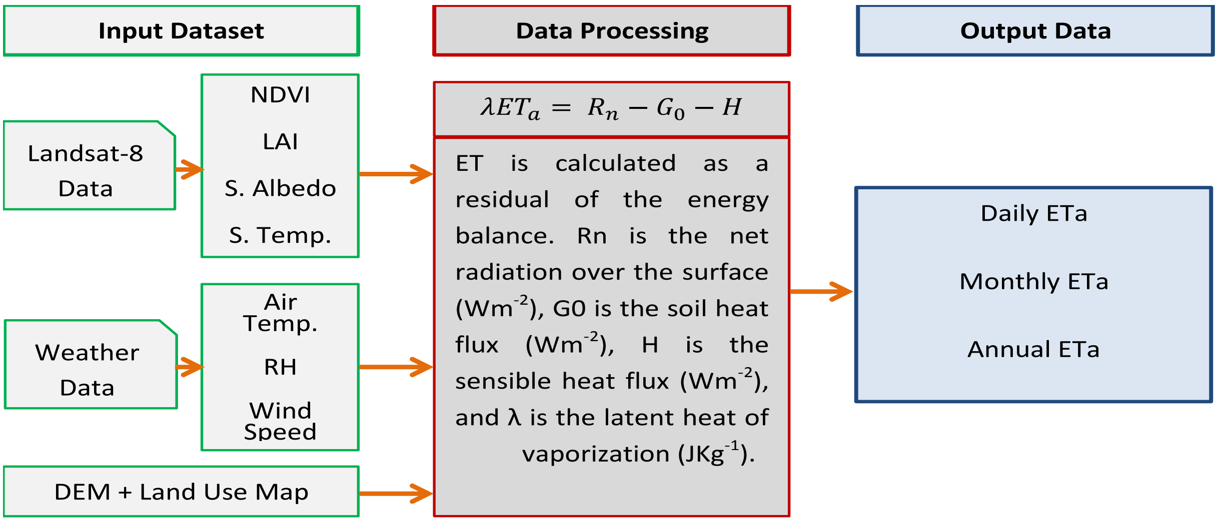

Figure 3. SEBAL flowchart methodology for calculating the actual evapotranspiration, (NDVI = Normalized Difference Vegetation Index, LAI = Leaf Area Index, S. = Surface, Temp. = Temperature, RH = Relative Humidity, DEM = Digital Elevation Model

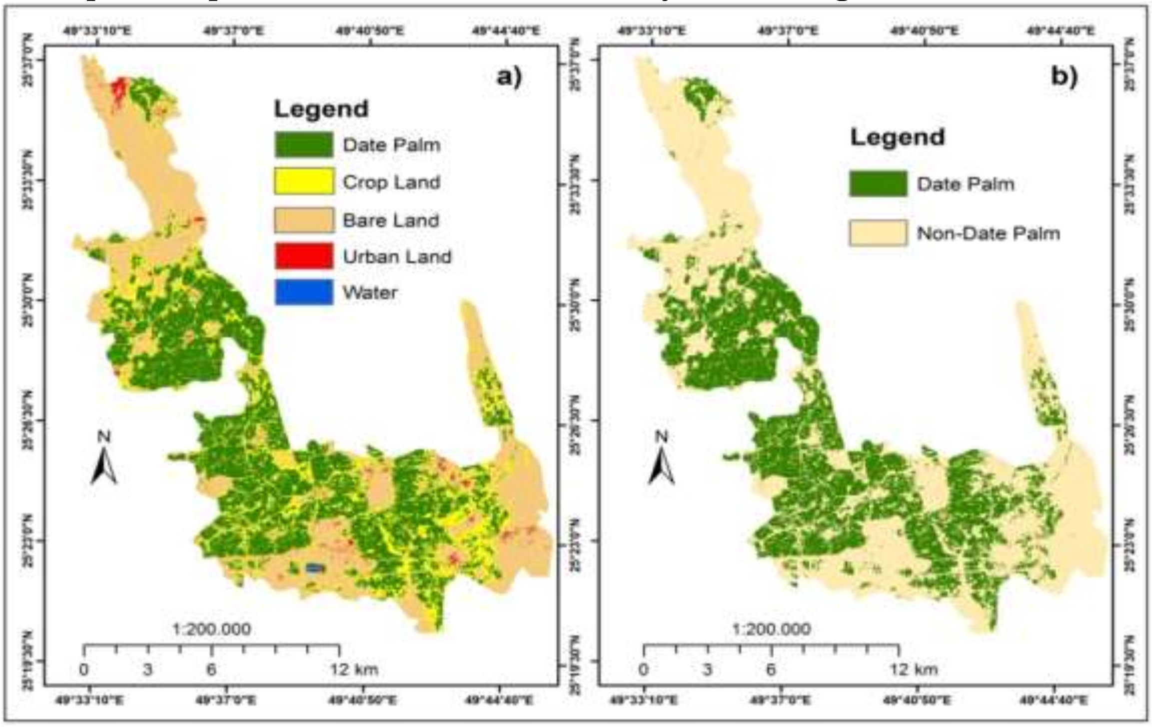

Figure 4. Land use map of the study area. a) land-use and land-cover map; b) date palm delineated area

Table 2. Applied irrigation water in the sampling farms during the study period

Farm Sampling[1]	Applied Water (m^3)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Farm 1	523.25	472.36	522.93	419.40	545.61	465.40	902.22	803.32	844.81	603.98	506.00	521.00	7130.36
Farm 2	498.84	448.20	498.78	401.80	546.72	468.66	867.78	805.40	809.82	568.02	482.76	497.00	6893.78
Farm 3	381.25	343.75	380.63	390.60	436.19	373.06	774.25	711.80	714.31	448.44	368.38	380.69	5703.34
Average	467.8	421.4	467.4	403.9	509.5	435.7	848.1	773.5	789.6	540.1	452.4	466.2	6575.80

RESULTS AND DISCUSSION

Actual evapotranspiration over Al-Hassa Oasis: Figure 5 shows the daily ETa values of the date palm in Al-Hassa Oasis for the period April 2017 to March 2018. During the summer season, the ETa values were higher in July with a 9 $mm.day^{-1}$ compared to 4 – 6 $mm.day^{-1}$ for April – June. For the winter season, the ETa values ranged between 2 and 3 $mm.day^{-1}$ in the period November – February. Nevertheless, the daily ETa in September, October and March showed little variation from the ETa patterns appeared in the summer and winter time because these months are considered as a transition period between the seasons. The difference in the ETa values along Al-Hassa Oasis for the different seasons were mainly attributed to the age of the date palm trees, the density of the trees, trees varieties and the water supply schedule. Haj-Amor et al. (27) indicated that under Saharan oases conditions the soil texture, plot size, and farmers' practices in particular irrigation duration have significant effects on irrigation water requirement by the date palm. However, in Tunisia Askri et al. (28) found that during summer high irrigation frequency and shallow groundwater are needed to maintain high water content and low salinity at the root-zone, and accordingly the date palm transpiration rates can be increased. However, these factors have no significant effects during the winter season. The monthly ETa for date palm in Al-Hassa Oasis was displayed in Figure 6. The high rates of ETa were found to be between 120 and 180 $mm.month^{-1}$ for July, August and September. However, at the beginning of the summer in April, May and June the ETa rates were 60 – 100 $mm.month^{-1}$. In the winter time throughout the period Oct. 2017 – Mar. 2018, the ETa were ranged between 40 to 80 $mm.month^{-1}$. Although the seasonal variations affect the monthly amount of water used by date palm trees, the water requirements of the date palms also change with their different production stages. Date palms experience heat and air humidity stress during the hot summer climate. Accordingly, during the summer period of extremely high temperatures (up to 47°C) and vapour pressure deficits that exceeds 40 millibars, the date palm stomata will partially close to prevent cell moisture depletion and plant wilting. Hence, the stomatal resistance during the summer increases and this affects the ETa because it is not related to the moisture conditions of the root zone. Chennafi (29) reported that the monthly water requirement of date palm in El-Hadjira Region of Algeria was found in the range 49.6 to 240.6 mm. However in Kuwait, the monthly ETa of date palm varied from 74 mm in January to 392 mm in June based on the FAO CROPWAT decision support system calculations (30). The annual ETa for date palm in Al-Hassa Oasis were shown in Figure 7. The ETa rates of date palm trees ranged between 800 to 1,400 $mm.year^{-1}$ during the period Apr. 2017 – Mar. 2018. The change in the annual volumetric water between the SEBAL model and the utilised water in the sampling farms was in the range 14% – 22% (Figure 8). These changes were reduced to 4 – 11% when the salinity leaching requirements were added to SEBAL volumetric water estimates. Accordingly, based on SEBAL results over the sampling farms, the amount of annual irrigation water needed for the date palm in Al-Hassa Oasis ranged between 11,000 – 13,000 $m^3.ha^{-1}$. The annual water consumption for date palm is highly variable, and this might be attributed to the type of irrigation system and the age variations of date palm trees along the oasis. Also, the non-uniformities of date palm water consumption might be associated with using traditional irrigation systems in many parts of the oasis. Carr (1) showed that the annual ETa of date palm in Saudi Arabia ranged from 2136 to 2829 mm under flood irrigation system compared to 600 – 800 mm when using a drip irrigation system. Also in Saudi Arabia, Alazba (31) found that the annual ETa of date palm varied between sites from 1500 – 2000 mm based on the estimations of the Penman-Monteith model. However, according to FAO (32) data, the annual water demand for date palm varies from 1300 to 3100 $mm.year^{-1}$ in Algeria. Also, reports showed that date palms in the lower parts of Egypt use 1000 $mm.year^{-1}$ compared to 1500 $mm.year^{-1}$ in the upper parts (1). The annual ETa obtained by this study was found to be inconsistent with that indicated by Mahmoud and Alazba (17) in the western and southern regions of Saudi Arabia using SEBAL model and field observations. They reported that the mean annual distribution of ETa was ranged from 717 to 1322 $mm.year^{-1}$ for the majority of the agricultural land including the date palm.

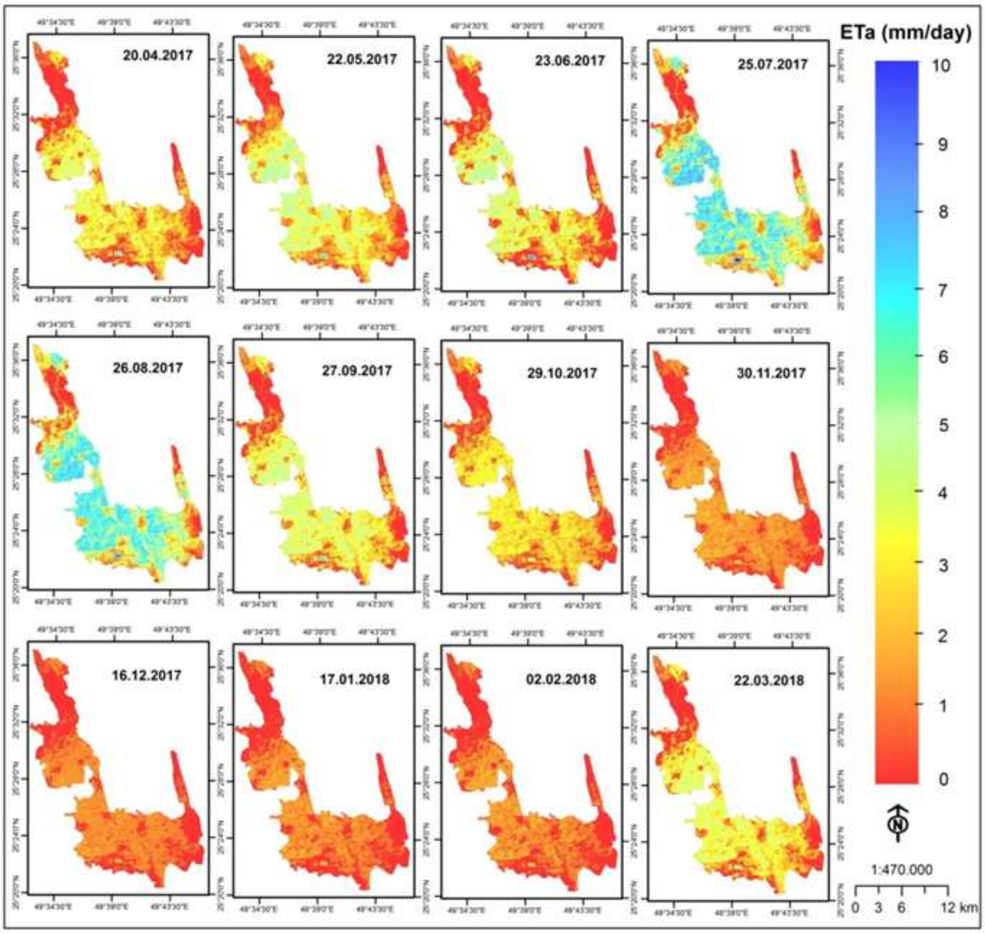

Fig 5. Daily ETa for date palm in Al-Hassa Oasis

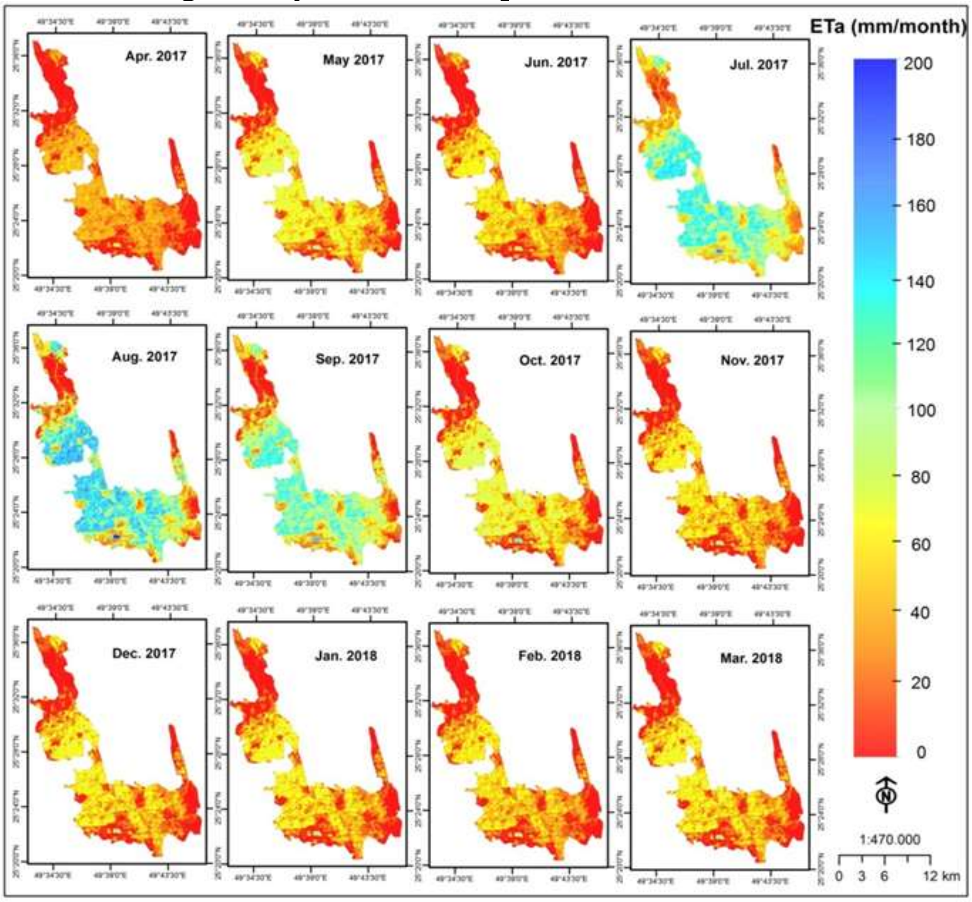

Fig 6. Monthly ETa for date palm in Al-Hassa Oasis

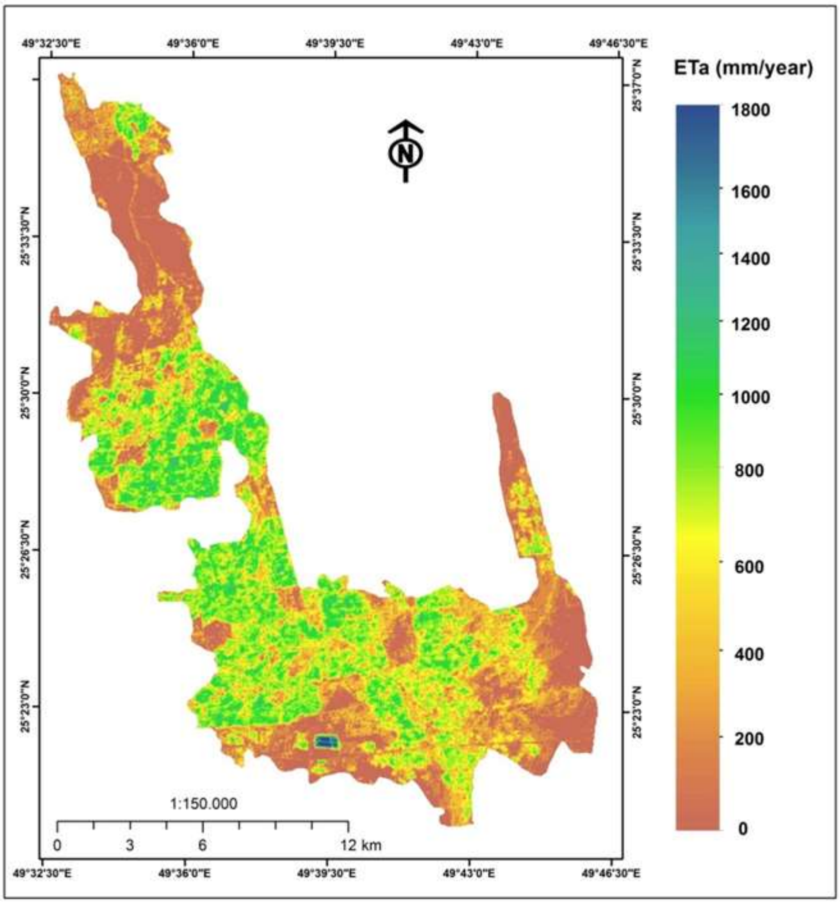

Fig 7. Annual ETa in Al-Hassa Oasis during Apr. 2017 – Mar. 2018

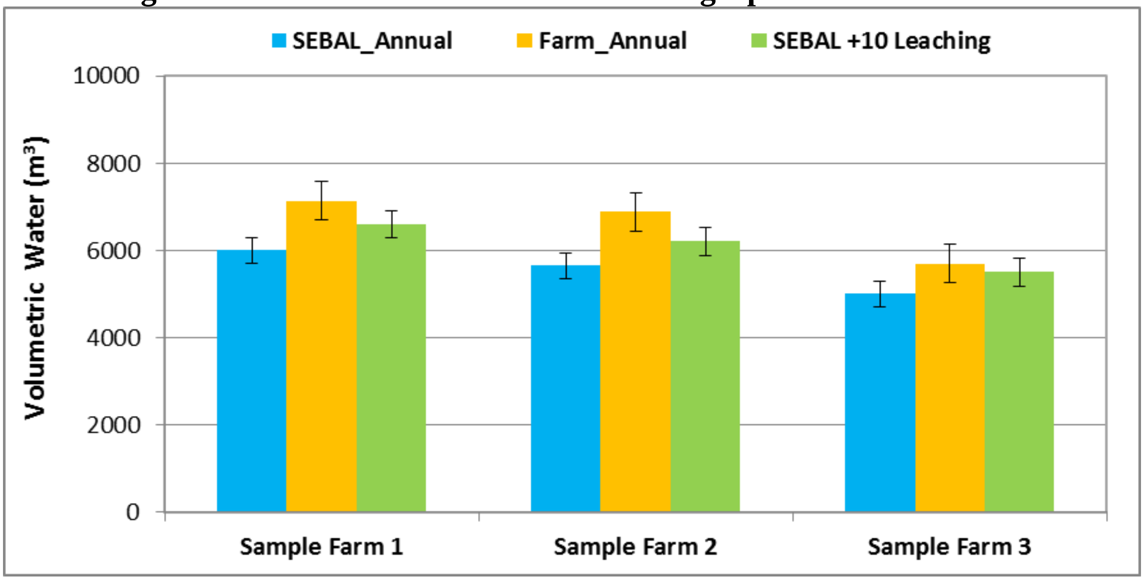

Figure 8. Annual volumetric water at farm level. Farms have the same area of 0.5 ha. Bars denoted standard error; percentages indicate the rate of change

Validation of the actual evapotranspiration at the farm scale: The validation measurements for ETa between the SEBAL model and the FAO Penman-Monteith method at farm level are shown in Figure 9a. A significant agreement level was observed between the two methods during the study period. The RMSE between the measured and modelled daily ETa was 0.84 mm.day^{-1} (Figure 9b). Nevertheless, during July there is a slight difference between the two methods. This difference might be due to the calculation of the ET0 and Kc; the SEBAL model does not require information on Kc because the biophysical properties were underlying the ET0 computations estimated as part of the SEBAL process. The spatial distribution of date palm kc showed that it was ranged between 0.3 to 0.5 during the early summertime (April – June), while for the peak summer season (July and August) it was 0.9 – 1.2 (Figure 10). The kc of date palm for the winter season during November, December, January and February was in the range of 0.5 – 0.7. However, during the transition periods between the seasons (September, October and March), the kc was in the range of 0.6 – 0.8. The variation of kc during the summer season might be due to the dust on date palm trees from desert sands and absence of rainfall. Mazahrih et al. (33) indicated that the kc of date palm trees varies during the growing season from 0.5 to1.2 based on the stage of growth. The comparison between the actual water applied in the farm and the predicted one by SEBAL showed clear differences between the two methods of water application (Figure 11a). The irrigation water used by date palm in the farms was found to be 26% higher than that estimated by SEBAL during the peak summer season in July. However, this percent was decreased to 15% when the SEBAL model has considered the leaching requirements. The irrigation water utilised at farm level indicates that the amount of water applied in the farms exceeded the minimum water requirements suggested by SEBAL. Nevertheless, in August the water used in farms was less than that proposed for leaching by 8%. This is mainly because the farmers reduce the irrigation during the final stages of fruit maturation to improve the date fruit quality. Hence only one irrigation event occurred in August with an interval of 30 days, although the irrigation duration is kept minimal with the other months (Figure 11). Carr (1) reported that restricting irrigation during fruit-stalk development of date palm reduced the incidence of premature drying and dropping of fruit bunches. Also, Zhen et al. (34) concluded from their study in Israel's Arava Valley that fruit load has a pronounced effect on physiological behaviours and water use of the cultivated date palm. However, a comprehensive survey undertaken in an oasis located in Southern Tunisia showed that irrigation intervals were found to be double than the expected one. This attributed to inappropriate farmers' practices at the field level, and also the irrigation duration was almost twice beyond the expected rule (35).

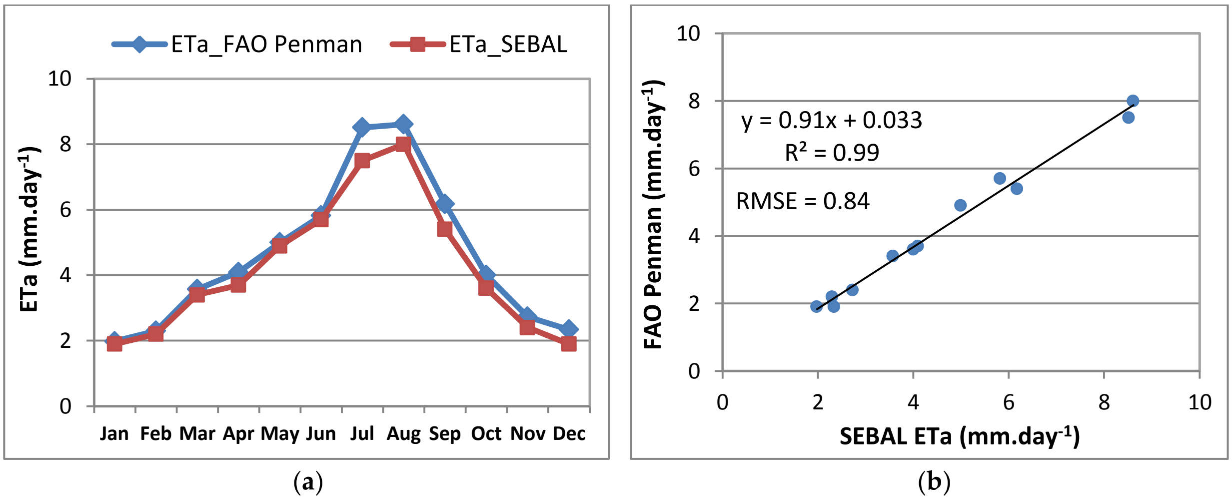

Fig 9. Estimation of daily ETa. a) Comparison between the measured (FAO Penman-Monteith) the modelled (SEBAL) daily ETa; b) Linear correlation between the two models

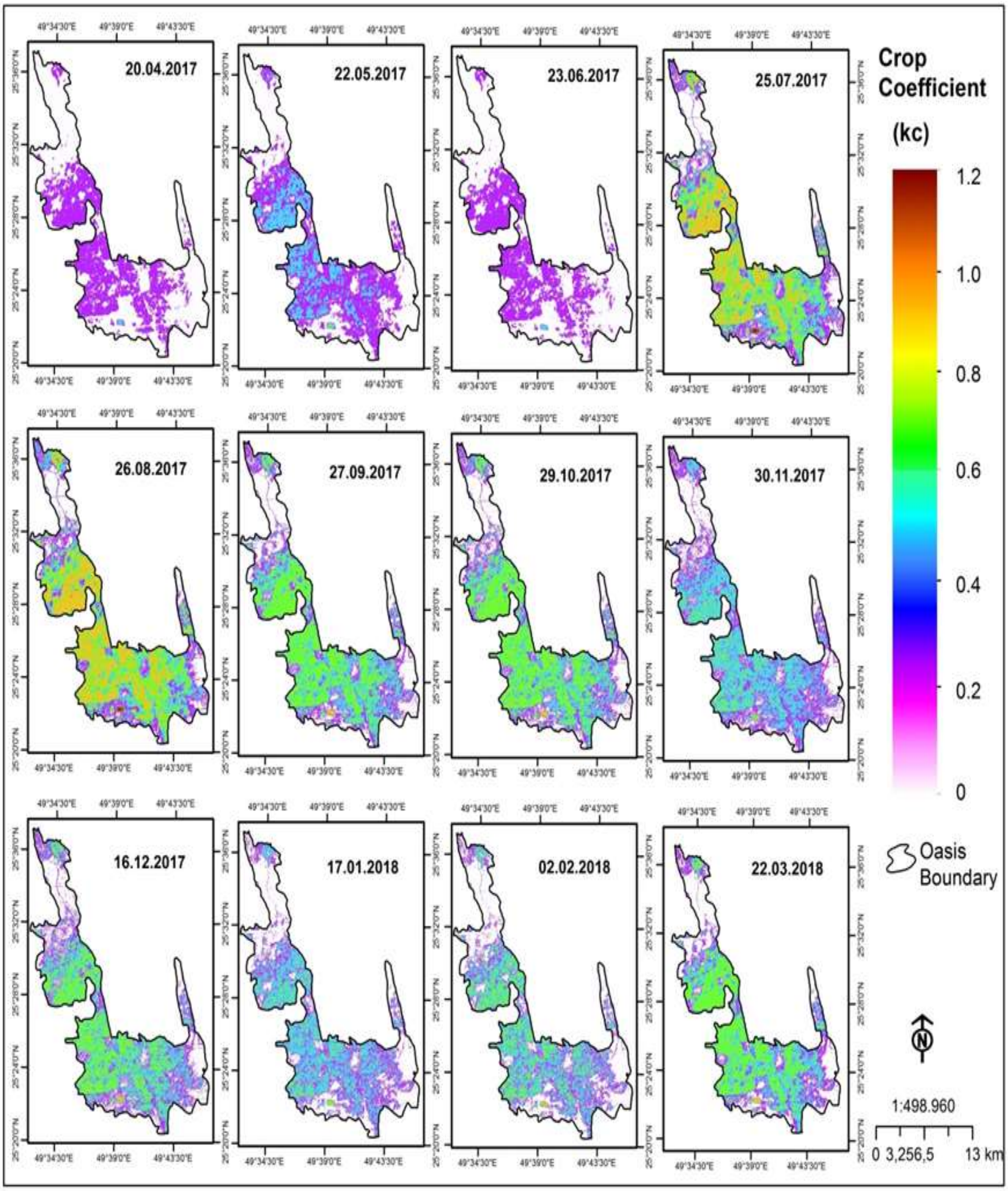

Fig 10. The spatial distribution of date palm kc in Al-Hassa Oasis

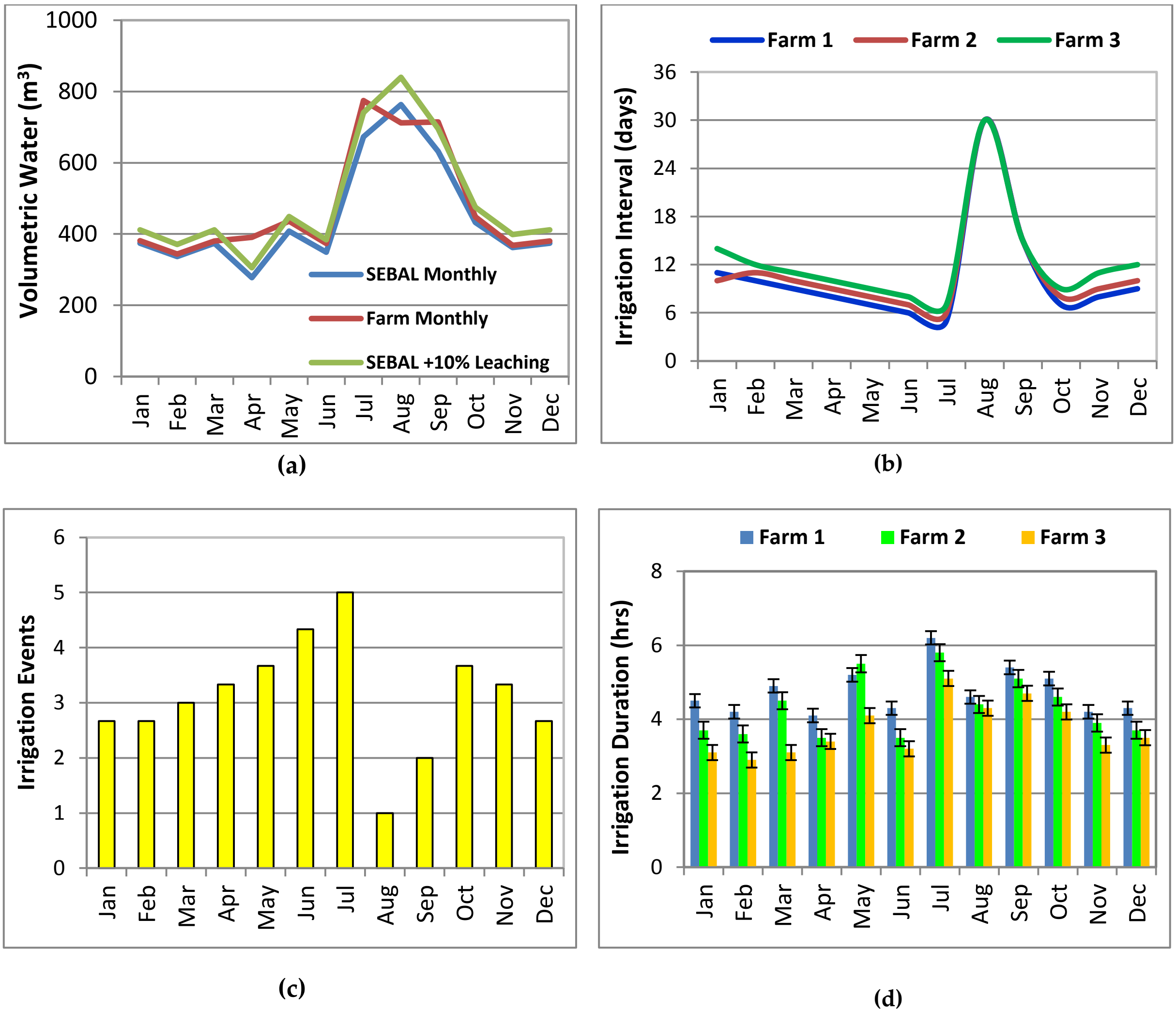

Fig 11. Monthly irrigation practices at the farm level. a) Volumetric water consumption; b) Irrigation intervals; c) Irrigation events; d) Irrigation duration. Bars denoted standard error

(a) (b)

Fig 12. Views from fields showing water management at farm level: (a) hazard of waterlogging; (b) efficient water use

CONCLUSIONS

The actual crop water consumption (i.e. ETa for date palm) was investigated in this study to understand the irrigation water dynamics in Al-Hassa Oasis. However, the spatial distribution of the agro-hydrological processes and total water use patterns need further investigations. The current water resources situation in Al Hassa Oasis is critical because the groundwater used to irrigate the date palm is non-renewable. However, the Saudi Irrigation Organization (ISO) is acting to make use of wastewater as an alternative source of irrigation. Nevertheless, it is important to mention that most of the farms in the oasis irrigate from private wells. The date palm daily ETa was found to have a peak value of 9 mm.day^{-1} during summer, while the lowest ETa of 2 mm.day^{-1} was recorded in the winter season. The mean monthly water applied in the farms during the peak summertime was found to be 15% higher than that suggested by SEBAL including the salinity leaching requirement. The annual ETa was varying between 800 and 1,400 mm.year^{-1}, while the irrigation requirement for date palm was found in the range 11000 – 13000 m^3.ha^{-1}. This study demonstrates the power of spatially distributed remote sensing data and the biophysical modelling to quantify critical processes of the soil-crop-atmosphere continuum. The spatial data produced by Landsat-8 data and SEBAL model will allow a thorough analysis of the irrigation practices for the different growing seasons in Al-Hassa Oasis and also in regions of similar conditions. However, on-farm validation measures need to be improved to monitor soil salinity, soil moisture, water table and irrigation uniformity. Furthermore, over-irrigation in Al Hassa Oasis indicated that on-farm irrigation efficiency requires attention. High irrigation efficiency with low percolation losses can induce soil salinisation, whereas a low efficiency, on the contrary, creates a hazard for waterlogging (Figure 10). This study considered a minimum rate of salinity leaching requirement; thus the irrigation water requirements should consider the leakage, farm distribution and runoff losses. In addition to these measures, reducing the total water use over Al-Hassa Oasis may lead to sustainable agricultural water management in the oasis.

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