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Full Length Research Paper

Reference evapotranspiration and date palm water use in the kingdom of Saudi Arabia

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A number of field experiments were conducted to measure reference Evapotranspiration (ETr) and Date Palm water use, in seven popular regions of date palm trees in the Kingdom of Saudi Arabia, during three successive seasons (2005 through 2007). Actual ETr was obtained through lysimeteric measurements, while net date palm water use (ETc), was measured by soil water balance approach. Moreover, water requirements were also computed by Penman-Montieth, for the sake of comparison. The results have indicated that there are some differences in ETr and ETc in various regions, due to the difference in geographical location and impact of climatic factors. Comparison between measured and computed ETr have shown higher trends for measured rates in all regions with an average of about, 7.04 mm/day, and a maximum of 11.7 mm/day. The average daily Date Palm water use, was 184.4 l/day for all regions. Total net annual date palm water use have ranged between 59.4 and 80 m3/tree. Date Palm crop coefficients have ranged between 0.80 and 0.99 for all regions, the average values of crop coefficients for each month is not equal in studied regions. From the economic perspective, the variation of the total net annual date palm water use in the study areas had impacted the average water costs and the net economic returns of date palm farms, accordingly.

Keywords: Date palm water use, Crop Coefficient, Lysimeter, Penman –Montieth, Reference Evapotranspiration, water costs, net economic returns.

INTRODUCTION

Agriculture is considered the biggest consumer of water resources in the world. The consumption of water by agriculture could account for more than 80% of total annual water consumption in some countries of the arid region like the kingdom of Saudi Arabia. In addition, agriculture could be the reason for water degradation because of the absence of proper water management, therefore, there is an urgent need for optimum use of water for agriculture and an extra emphasis should be directed towards water management to prevent water pollution or deterioration of water quality.

Various studies have been conducted in the Kingdom of Saudi Arabia to estimate the reference evapotranspiration (ETr) and water requirements for some crops (Mohammad, 1996; Al-Omran and Mohammad, 2004). One of the first comprehensive studies was carried out by the Ministry of Agriculture (Al-Zeid et al., 1988) for thirteen agricultural zones in the Kingdom, where ETr and water requirements were estimated for most important economic crops using Penman equation. Other study includes; the study carried out by Mustafa et al. (1989) to estimate the reference evapotranspiration in the Kingdom.

Date palm tree (Phoenix dactylifera) is one of the main fruit trees in the Kingdom of Saudi Arabia. The tree is very popular in the country and the total number of date palms has reached about 24 millions and the number is increasing every year. Its production has, also, increased to reach about one million tons per year, which is more than 15% of world production, grown in an area exceeding 160 thousand hectares (MOA, 2010). As the

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trend of palm expansion is continuing, a considerable amount of water will be required for its irrigation, to maintain this expansion. However, due to the limited water resources in the Kingdom, the study of date palm water requirements is essential, as this will lead to accurate application of irrigation water to avoid waste and conserve the precious water.

Date palm tree is usually irrigated by surface method, mainly basin, delivering large volume of water based primarily on farmer's experience and enhanced by the availability of free irrigation water. Date palm is a large tree and its water requirements is comparatively high (Salter and Goode, 1967), its consumption varies from area to another, due to many factors, mainly climate and soil, however, the annual water requirements for a mature date palm may range between 115 and 306 cubic meters depending on the cultivar, climatic conditions, irrigation system and soil type (Al-Baker, 1972). Abu Khaled et al. (1982) found that the total annual consumption of some palms in Iraq was nearly 18 thousand m^3 per hectare, and if we assume that the per hectare of 100 Palm, the Palm consumes 180 m^3 per year, as an average value. Date palm tree is a drought resistant that can withstand salinity up to 4 Dsm/m without any reduction in yield (Ayers and Wescot, 1985). Although the root zone depth is ranging between 1.5m to 2.5 m (Doorenbos and Pruitt, 1977), the tree could uptake 65% to 80% of water within a root zone depth not exceeding 1.2 meter (yaacoob, 1996).

The estimate of date palm tree water requirements in the Kingdom is not established yet, but, there are some rough estimates made by the Ministry of Agriculture and Water (Al-Zeid et al., 1988), and for Al-Hassa in the eastern region of Saudi Arabia, (Hussein, 1986, Hilal et al., 1986, Hussein and Hussein, 1982). The date palm trees estimate of water use could also be made from tree water requirements of other areas of similar climate, such as, Southern California, Egypt, and Iran (Furr, 1975). In recent work (Alamoud and Al-Saud, 2011), using subsurface drip irrigation, date palm water requirements were reduced to less than 40 m^3/tree.

There were also some estimates for several areas, for example, in Qatif, in eastern province of Saudi Arabia, it was found that irrigation water were added at a minimum rate of 13250 m^3 / ha / year, or 53 m^3/tree/year (Khalifa et al., 1983). While in Hofuf region, the minimum water use ranges between 2.3 and 8.3 m^3 / tree in January and August, respectively, and in Qassim for Sukkary variety it was 4 m^3/ tree for each irrigation, with water is added at the rate once every 15 days (Mustafa et al., 1976). There are some theoretical values of the irrigation needs for the palm trees planted in different parts of the Kingdom, the suggested values were ranging between 39585 and 72270 m^3/ha/year for flood irrigation, and between 28275 and 51621 m^3/ha/year for sprinkler irrigation (Sawaya, 1986). In a study conducted by Al-Amoud et al. (2000) on the date palms under three irrigation treatments (50%, 100%, 150% of the evaporation rate of the pan evaporation A), it was found that the annual amount of water rate of 108 m^3 for each date palm is sufficient to obtain the highest efficiency in water use. Al-Ghobary (2000) has estimated the total annual amount of water required by one date palm as 136 m^3 in Najran of south western region of Saudi Arabia. Estimates of Alazba (2004) for the actual annual water use of the date palm were137 m^3 in Eastern region to about 195 m^3 in the central region for flood irrigation, compared to 55 m^3 and 78 m^3/tree for the two regions using drip irrigation, respectively. In Tunisia, it was found also that, the lowest total annual water requirements were equal to 63 m^3 per tree, while the actual water requirements, including all types of losses were 95 m^3/tree (Al-Buzaidi, 1982).

The Date Palms crop coefficient, K_C, found in literatures for areas of similar environment, showed that crop coefficient values for mature date palm grown in hot arid environment vary; values ranging from 0.9 to 0.95 were reported by Allen et al. (1998), Doorenbos and Pruitt (1977), have suggested the range between 0.8 and 1, while Saeed et al. (1990) have obtained a range of values for January and February months for three empirical ET methods between 0.85 and 1.37. Al-Zeid et al. (1988) have suggested the crop coefficients for the various stages of growth as: 0.55, 0.70, 0.75 and 0.55 respectively. The Soil Conservation Service values for crop coefficient fall within 0.65 and 0.80 (SCS, 1970).

The aim of this research work, however, is to measure reference and actual date palm evapotranspiration (ETc) and to estimate irrigation water requirement for the Date Palm trees in the Kingdom of Saudi Arabia.

MATERIALS AND METHODS

Field experiments on date palm trees were conducted in seven agricultural areas popular for date palms in the kingdom of Saudi Arabia (namely; Riyadh, Gaseem, Madinah, Hofuf region, Najran, Makkah and Wadi Addwaser regions), Soil texture in all areas is characterized between sandy loam to loamy sand, locations and soil types are shown in Table 1. The experimental site, in all locations, was selected in the middle of date palm farms, the plot consists of 9 mature trees of the common variety in the area, with distances of 10 meters between trees and between rows of trees. Study was accomplished in five years including preparations, valid experiments were made, however, during three successive years (2005-2007).

Reference crop (Alfalfa) water use was measured using non weighing (drainage) lysimeters. Seven identical lysimeters made of reinforced concrete to withstand pressures caused by water pressure and extended by roots. They were completely isolated to prevent any leakage of water. They were constructed in study farms in all above mentioned regions of the country. Each

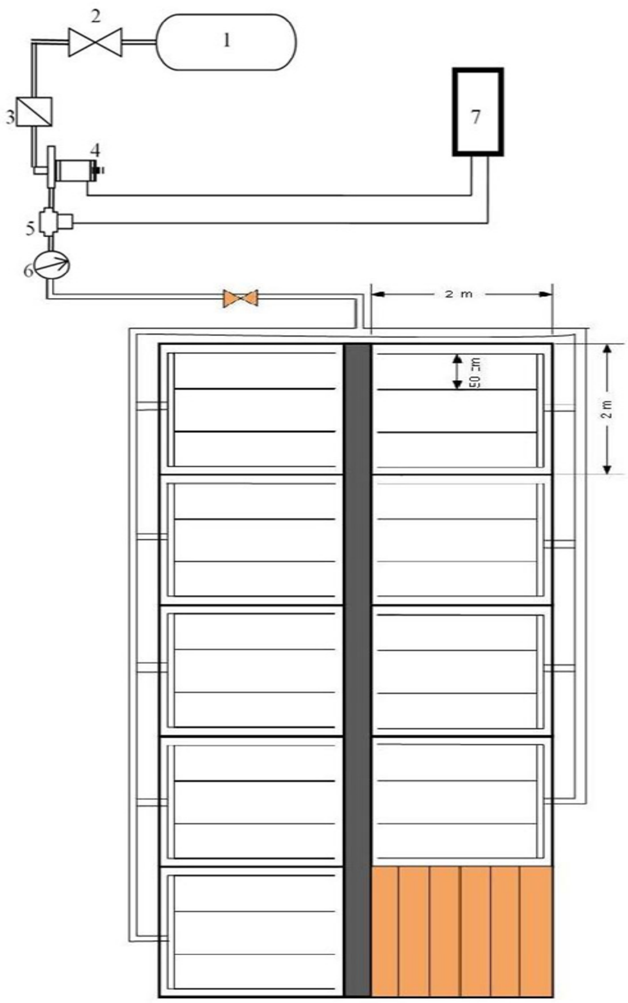

Figure 1. Lysimeter layout

Water Source 1
Gate Valve 2
Flow meter 3
Pump 4
Solenoid Valve 5
Pressure gauge 6
Remote control panel 7

lysimeter consists of nine containers (plots) filled with same field soil, 2.0 × 2.0 surface area by 1.5-m depth, and provided with a drip irrigation system as shown in figure 1. Lysimeters were constructed and evaluated at the experimental farm of University available in the region or in research centers affiliated to Ministry of Agriculture (Table 1). Lysimeters were used to measure reference ET from a well-watered alfalfa (ETr), and located in center of the alfalfa field which is commonly grown in the area. Design, installation, and other considerations to ensure acceptable performance of the lysimeters were carried out as described by Abu Khaled, 1982.

Reference evapotranspiration, ETr was measured using the following water balance equation:

$$ET_r = I + P - D - (\Delta W) \quad (1)$$

Where:

ΔW = change in moisture content storage.

I = irrigation depth added each event, mm.

P = precipitation depth, if there is any, mm.

D = drainage water depth, mm.

Data of irrigation applied, drainage water collected and rainfall were used in balance equation to determine reference evapotranspiration (ETr) which have been utilized in calculating the date palm water requirements. As lysimeters are continuously draining with daily irriga-

Table 1. Geographical farm locations and soils of studied regions

Region	Farm Location	Latitude	Longitude	Altitude (m)	Soil Type
Riyadh	Experimental farm, College of Food and Agricultural Sciences, King Saud University.	24° 38’ N	46° 43’ E	625	Loamy Sand
Qaseem	Agricultural Research Station, Qassim University.	26° 20’ N	43° 59’ E	648	Loamy Sand
Eastern	Agricultural Research Station, King Faisal University, Hofuf.	25° 22’ N	49° 34’ E	179	Sandy Loam
Madinah	Taibah Agricultural Project.	24° 28’ N	39° 36’ E	656	Sandy Loam
Makkah	Agricultural Research Station, King Abdulaziz university.	21° 26’ N	39° 46’ E	307	Sandy Loam
Najran	Horticulture Research Center, Ministry of Agriculture	17° 28' N	44° 6' E	1264	Sandy Loam
WadiAddwaser	Alwatania Agricultural Project	20° 30' N	45° 12' E	628	Sandy Loam

tion, soil moisture content is considered constant and change in moisture storage is negligible, (ΔW =0).

An automatic weather station (Davis Cabled Vantage Pro2 Plus with Standard Radiation Shield*) was installed near each lysimeter to measure the climate parameters that are used to calculate reference evapotranspiration. This station includes rain collector, temperature and humidity sensors, anemometer, solar radiation sensor, UV sensor, and sensor mounting shelf. Console includes indoor temperature, humidity and barometer. Temperature and humidity sensors are enclosed in standard radiation shield.

A drip irrigation system with high uniformity was designed to distribute water for date palms. It was equipped with pressure regulators to control the pressure, and water meters to measure the amount of water added. The pipe network have included all the necessary units and parts such as; valves, filters, water meters and control board as shown in the network design layout (Figure 2). The measured data by sensors were recorded electronically to calculate the change in the moisture content in the root zone (ΔW) at each depth.

The water balance method (Hoffman et al., 1982; Fares and Alva, 1999; Grismer, 2000) was also used to measure ETc for date palm trees. Soil moisture change (ΔW) in the root zone was measured by a soil sensing device known as Watermark*, based on measuring electrical resistance of the soil. Sensors were installed at seven depths in the root zone, separated by a distance of 20 cm, and away from the trunk a distance of 50 cm. Five sensors were used to estimate water content consumed by the tree, while other two sensors were used to estimate deep percolation beyond the active root zone, if the readings were more than that in the previous day, this indicates a deep percolation took place. Therefore, taking the difference between the readings and converted to a depth that represents the amount of deep percolation. All of these sensors were connected to a data logger, and data were recorded daily during the experiment (Figure 3). The data usually were retrieved by computer on daily bases which were used as an input for the equilibrium equation to determine water consumption by date palm trees. The change in the moisture content in the root zone, Δw, is then calculated at each depth. The summation of water content in each sector was representing the total depth of water available in the root zone at a specific time.

*The mention of trade marks does not imply an endorsement of the product, its merely for the benefit of the reader.

The date palm evapotranspiration (ETc) estimation is calculated using the following water balance equation:

$$ET_c = I + P - D - (W_i - W_{i+1}) \qquad (2)$$

Where:

Wi = moisture content at day (i) for all root layers.

Wi +1 = moisture content at day (i +1) for all root layers.

Based on actual reference ETr and actual measured date palm water use, crop coefficients were estimated for date palm trees in all locations. Experiments for reference crop and date palm trees were repeated for three consecutive years to confirm results.

Fertilizer application was the same for all trees in accordance with farm management practice for palm trees. The system was installed and operated in January 2005 through the 2007 season. Harvesting of tree yields started at beginning of August till middle of September of each year.

The date palm actual evapotranspiration (ET_C) is related to the reference evapotranspiration (ET_r) by the following equation (Allen et al., 1998):

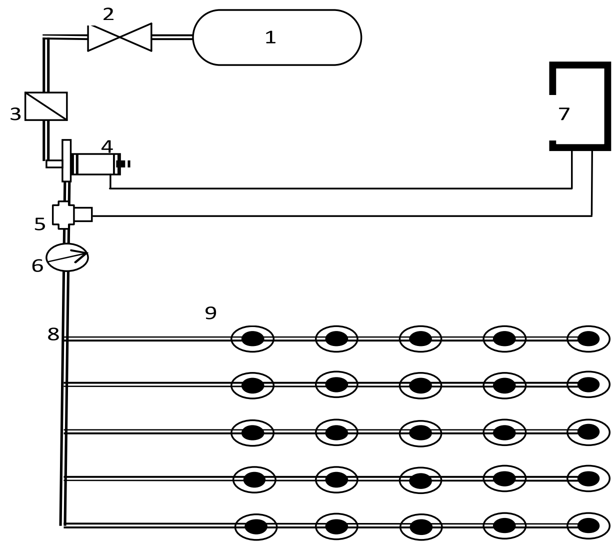

Figure 2. Date Palm Irrigation Layout

Water Source 1
Gate Valve 2
Water meter 3
Pump 4
Solenoid valve 5
Flow meter 6
Remote control panel7
Main pipeline 8
Drippers 9

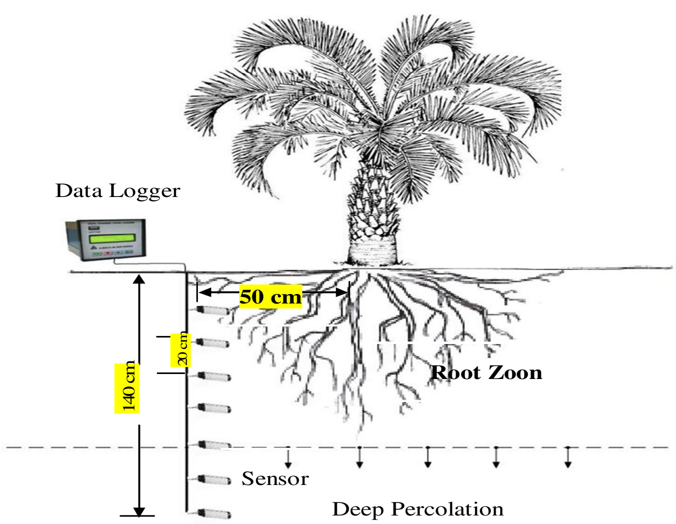

Figure 3. Soil water measurements

$$ETc = ETr \times Kc \quad (3)$$

where,

ET_r = Reference evapotranspiration, calculated using Penman-Monteith equation (mm/day).

K_C = Crop coefficient, which incorporates crop characteristics and averaged effects of evaporation from the soil.

The combined FAO Penman – Monteith method is used to calculate the reference evapotranspiration, the choice of this equation is for being the more universally applicable than other equations (Jensen et al., 1990), and more appropriate for the prevailing circumstances in the Kingdom, it takes the following form:

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (4)$$

Where;
R_n = net solar radiation at the surface of the crop ($MJ/m^2/day$).
G = soil heat flow intensity ($MJ/m^2/day$).
T = average daily air temperature at 2 meter hight (C^o).
u_2 = wind speed at the height of 2 meters (m/s).
e_s = saturated vapor pressure (kPa).
e_a = actual vapor pressure (kPa).
e_s - e_a = saturated vapor pressure deficit (kPa).
Δ = the vapor pressure at saturation and temperature gradient, at air temperature (kPa/ C^o).
γ = moisture constant (kPa/ C^o).
Parameters computations and coefficients are similar to those outlined by Allen et al. (1998)
A computer program was developed to calculate the reference evapotranspiration using Penman - Monteith equation. The total water requirements for irrigated Date Palms were calculated taking into account the irrigation efficiency (70% for surface method and 90% for drip system) and leaching requirements at different salinity levels (0.5, 1, 2 & 3 mmho/cm), using the following equation:

$$TWR = \left(\frac{ETc}{E} \times \frac{1}{1 - LR} \right) \quad (5)$$

Where:
TWR = Total Water Requirement (m^3/ha).
ETc = Net Water use (m^3/ha).
E = Efficiency (%).
LR = Leaching Requirements.

Leaching requirements were calculated using the following equations (Doorenbos and Pruitt (1977):

A. For surface irrigation method:

$$LR = \frac{EC_w}{5EC_e - EC_w} . \frac{1}{LR} \quad (6)$$

B. For drip irrigation system:

$$LR = \frac{EC_w}{2\max .EC_e} . \frac{1}{LE} \quad (7)$$

Where:
EC_w = Electrical conductivity of water (mmho/cm).
EC_e = Electrical conductivity of soil extract (mmho/cm).
max EC_e =Maximum electrical conductivity of soil extract tolerated by date palms (mmho/cm).
LE = Leaching Efficiency (90% for sandy and loamy sands).

The computer program has an extensive data base that includes weather, crop, soil and water data in all agricultural regions.

Testes of significance such as t-test and f-test at %1 level were applied to estimate the levels of significant differences between means of measured and calculated ETr within each region and among all studied areas. Pearson correlation coefficients were, also, applied to estimate the level of correlation between means of measured and calculated ETr within each study areas.

RESULTS AND DISCUSSION

The prevailing weather conditions of the seven regions are shown in Table 2. The areas in all regions are characterized by high temperature in summer with low rain however; the highest average temperature recorded was about 37°C in Hofuf region in July. As for relative humidity, Madinah and Hofuf provinces had an average high of 59% on winter months. Rainfall was generally insignificant, however, the relative high quantities were recorded in Najran and Makkah regions, with less than 20 mm in the months of January and April.

The reference evapotranspiration (ETr) of the seven agricultural regions in Saudi Arabia were evaluated on measurement scale using lysimeters and calculation scale through the Penman-Monteith (P-M) equation. The Monthly measured ETr of alfalfa grown in lysimeters for individual regions, as three year average, are shown in Figure 4. The annual cumulative ETr for all studied regions fall within the range 2253 and 3024 mm/year.

Results have shown that the lowest daily measured ETr rate was 2.4 mm/day, in Najran region, in the month of January, while high summer values have exceeded 11 mm/day, in Hofuf and Wadi Addwaser regions in the months of May, June and July. Seasonal measured ETr values were; 2754, 2669, 2254, 2259, 2506, 2564 and 3024 mm for Hofuf, Madinah, Makkah, Najran, Gaseem, Riyadh and Wadi Addwaser, respectively. The average measured annual ETr rates were: 7.5, 7.3, 6.2, 6.1, 6.9, 7, 8.3 mm/day in Hofuf, Madinah, Makkah, Najran, Gaseem, Riyadh, and Wadi Addwaser regions respectively, with a maximum ETr of 11.7 mm/day in Wadi Addwaser in June. Winter time measured ETc rates were as low as 1.9 mm/day, in Najran region, in the month of January, while summer values could reach to high values exceeding 11 mm/day, as in Wadi Addwaser in the months of June and July.

It is clear from Figure 4, that there is a good fit between measured and calculated ETr, The calculated values using P-M equation followed similar trends as measured values, which seemed to be consistent throughout the year. however, calculated values is found to slightly underestimate ETr, such underestimation showed a consistent behavior in almost all locations due to high evaporative demands. The minor underestimation

Table 2. Average Monthly Climatic Variables in Study Regions of Saudi Arabia

Region	Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Riyadh	Temperature (°C)	13.5	16.0	20.1	25.6	31.2	33.6	34.8	34.8	31.4	26.8	20.4	15.5
	R. Humidity (%)	50.7	40.5	37.4	32.9	19.7	11.8	11.2	13.6	15.5	22.7	37.5	51.2
	Wind Speed (m/s)	2.8	3.3	3.6	3.4	3.2	3.4	3.5	2.9	2.3	2.0	2.4	2.6
	Sunshine (hr/d)	7.63	6.23	4.77	5.78	5.99	5.92	6.23	6.87	8.19	7.8	8.58	8.31
	Solar Radiation (MJ/m2.day)	14.9	15.3	19.9	22.3	25.3	26.4	26.7	26.0	23.0	20.4	15.6	12.1
	Rainfall (mm)	6.76	3.2	24.3	11.5	3.66	0	0	0	0	1	0	8.84
Gaseem	Temperature (°C)	12.7	14.8	18.8	24.8	30.4	33.3	34.4	34.7	31.9	26.9	19.9	14.8
	R. Humidity (%)	54.9	45.7	41.4	35.5	21.0	12.2	12.1	12.6	13.9	21.9	40.7	54.5
	Wind Speed (m/s)	2.6	3.1	3.3	3.4	3.4	3.0	2.9	2.6	2.4	2.4	2.7	2.6
	Sunshine (hr/d)	7.44	6.69	6.15	5.69	6.47	6.83	7.33	7.31	10.31	9.96	9.76	8.85
	Solar Radiation (MJ/m2.day)	12.6	13.9	18.7	21.5	24.6	26.2	26.4	25.4	22.0	19.6	14.0	10.8
	Rainfall (mm)	9.74	11.08	30.98	13.28	11.28	0	0	0	0.8	5.34	4.38	5.58
Eastern	Temperature (°C)	14.8	17.0	21.1	27.1	32.9	35.7	37.4	36.9	33.6	28.8	22.2	16.9
	R. Humidity (%)	57.2	51.9	47.3	40.0	28.3	23.9	25.1	31.9	36.7	43.4	50.9	59.3
	Wind Speed (m/s)	3.7	4.1	4.1	3.7	3.9	4.5	4.4	3.7	3.1	2.7	3.3	3.6
	Sunshine (hr/d)	8.16	7.57	6.15	6.2	7.27	7.42	7.76	8.59	8.59	8.01	9.28	9.21
	Solar Radiation (MJ/m2.day)	14.3	14.7	19.4	22.6	25.4	25.5	25.1	25.1	22.5	19.3	14.8	11.5
	Rainfall (mm)	12.24	1.28	13.46	15.6	12.9	0	0	2.88	0.62	8.58	0	0
Madinah	Temperature (°C)	17.8	19.7	23.4	28.2	32.5	35.5	36.0	36.7	35.0	30.1	24.1	19.8
	R. Humidity (%)	40.9	33.8	28.7	25.1	19.6	12.9	14.5	17.0	15.1	21.3	34.9	41.6
	Wind Speed (m/s)	2.9	3.1	3.4	3.3	3.2	3.2	3.4	3.3	2.9	2.6	2.9	2.8
	Sunshine (hr/d)	6.99	6.59	5.8	7.22	6.68	6.31	7.23	7.32	9.78	9.93	8.71	7.32
	Solar Radiation (MJ/m2.day)	13.4	14.2	19.4	20.8	23.5	23.8	23.6	22.9	20.4	18.4	13.7	12.1
	Rainfall (mm)	0.32	0	11.72	4.28	9.92	0.4	0	3.18	1.36	2.82	4.14	8.96
Makkah	Temperature (°C)	24.4	25.0	27.7	31.4	34.7	35.9	35.9	35.9	35.7	32.8	29.0	25.9

Table 2 continue

	R. Humidity (%)	57.7	53.6	48.6	43.8	37.5	34.4	35.5	40.6	45.2	49.2	57.0	59.4
	Wind Speed (m/s)	1.6	1.8	1.9	1.8	1.8	1.6	1.6	1.7	1.6	1.4	1.3	1.4
	Sunshine (hr/d)	7.48	6.75	5.13	6.45	7.55	7.36	9.38	7.83	10.18	9.68	7.18	6.88
	Solar Radiation (MJ/m2.day)	14.4	15.0	20.3	21.4	23.5	24.5	23.3	21.9	20.1	19.2	14.2	12.9
	Rainfall (mm)	19.66	10.46	9.86	1.78	0.08	0	0	5.08	3.34	9.56	2.56	11.52
Najran	Temperature (℃)	17.1	20.2	23.4	25.8	28.9	30.3	32.0	31.6	28.3	23.4	19.7	17.8
	R. Humidity (%)	44.4	37.8	37.1	35.0	24.6	18.1	19.7	22.7	21.8	28.4	37.0	44.7
	Wind Speed (m/s)	1.7	2.1	2.4	2.4	2.3	2.4	2.8	2.7	2.3	1.8	1.5	1.5
	Sunshine (hr/d)	7.67	7.43	6.67	6.66	6.43	5.9	6.6	7.52	7.89	7.4	7.36	7.63
	Solar Radiation (MJ/m2.day)	17.7	17.9	21.5	21.3	22.5	24.4	22.6	22.7	21.7	21.2	17.8	16.9
	Rainfall (mm)	17.12	10.72	5.08	18.02	1	2.6	14.24	19.34	5.58	0.6	10.6	8.06
Wadi Addwaser	Temperature (℃)	16.9	19.7	23.8	28.8	32.7	34.4	35.5	35.2	32.0	26.8	21.9	18.1
	R. Humidity (%)	45.3	36.9	34.4	27.5	19.3	13.2	13.8	16.2	16.5	23.9	35.4	45.2
	Wind Speed (m/s)	3.9	4.1	4.4	4.1	3.3	2.8	3.3	2.9	2.7	2.7	3.5	3.7
	Sunshine (hr/d)	8.20	7.55	6.25	6.23	7.37	7.44	7.68	8.47	8.52	8.10	9.11	8.81
	Solar Radiation (MJ/m2.day)	16.6	16.6	20.9	23.3	25.0	26.1	25.7	25.2	23.5	21.2	17.5	14.8
	Rainfall (mm)	3	0	3	1	7	0	0	0	0	0	0	0

of calculated ETr could be attributed to the fact that the method includes some empirical functions that are subject to local calibration. The minor difference between calculated and measured may indicate possible need for modification of the method for the hot climate of Saudi Arabia. No calibration, however, were attempted in this work to make such calibration.

The goodness of fit was statistically analyzed showing that there was no significant differences found between means of measured and calculated ETr within each study area, and among all study areas using different tests of significances at % 1 level of significance which imply the consistency of the ETr within and among all study areas. In addition, coefficients of Pearson correlation showed a strong correlation between means of measured and calculated ETr within each study area ranging between a minimum of 0.909 in Wadi Addwaser and a maximum of 0.976 in Riyadh, Table 3.

The results of net annual monthly date palm water consumption, ETc, as three year average, measured by water balance method, for the various regions are shown in figure 5, these figures demonstrate a normal trend influenced by weather conditions such as temperature, a similar trends are shown by Jensen et al. (1990). The annual cumulative ETc for all studied regions falls within the range of 2100 and 2829 mm/year. Seasonal measured ETc values for individual regions were; 2499, 2450, 2136, 2100, 2366, 2393 and 2829 mm for Hofuf, Madinah, Makkah, Najran, Gaseem, Riyadh and Wadi Addwaser, respectively, The average daily net Date Palm water use rates measured were; 203, 200, 155, 161, 185, 190 and 218 l/day for same regions, respectively. The

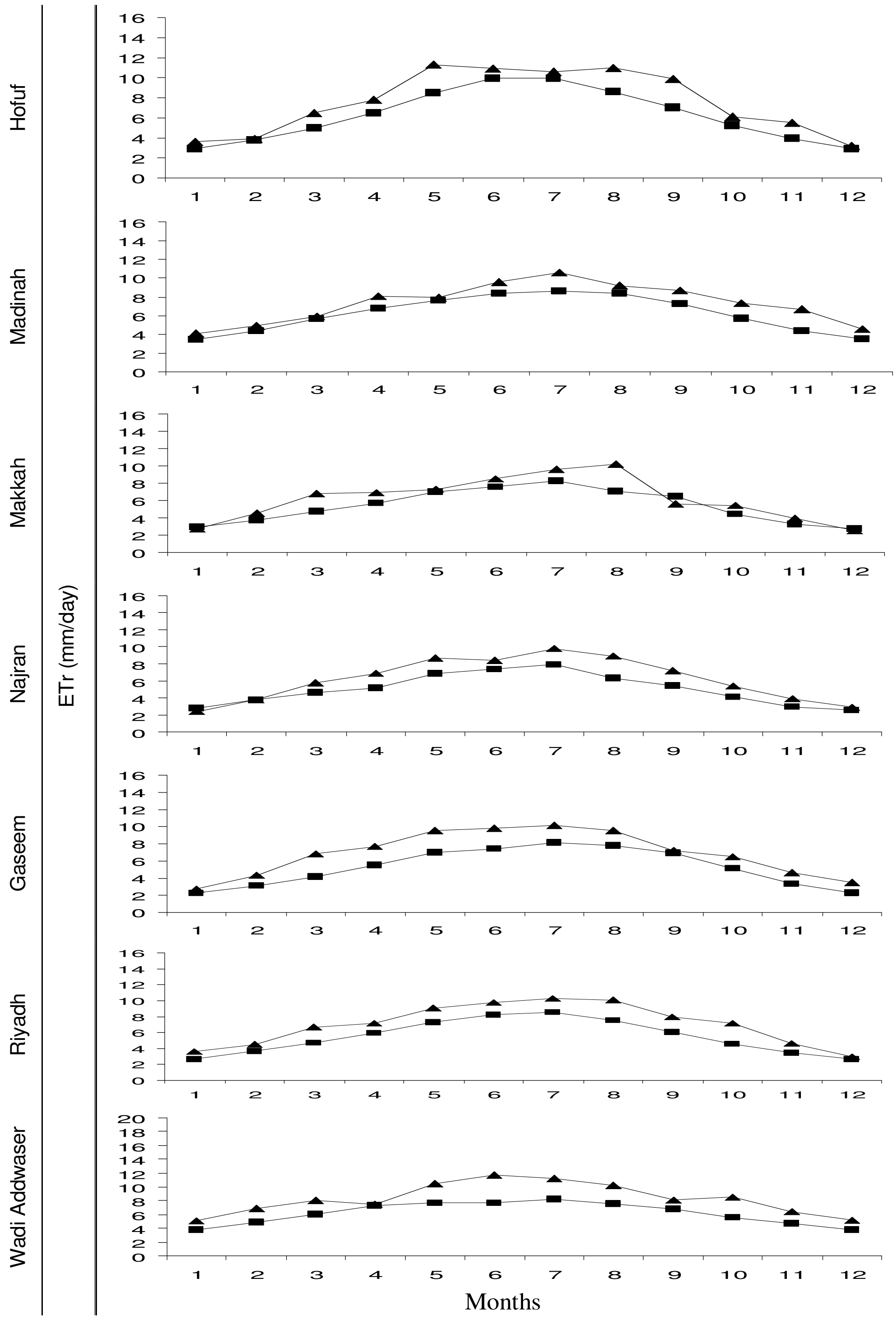

Figure 4. Comparisons of Measured and calculated ETr for All Regions (■: Calculated, ▲: Measured)

values for some regions (Hofuf, Madinah, Najran, Riyadh and Gaseem) are higher than theoretical values reported by Alazba (2004), most likely due to local environments influence.

The comparison between the average net cumulative annual amounts consumed by date palms over the three years of study for all regions are shown in figure 6. It indicates some differences, mainly, due to variations

Table 3. Statistical analysis applied for between means of measured and calculated ETr within each study region, and among all study regions.

Study Areas	Mean ETr-PM	Mean ETr-r	Pearson correlation Coefficients
Eastern	6.19 n.s.	7.53 n.s.	0.963
Madinah	6.18 n.s.	7.30 n.s.	0.950
Makkah	5.31 n.s.	6.16 n.s.	0.917
Najran	5.00 n.s.	6.18 n.s.	0.972
Gaseem	5.24 n.s.	6.85 n.s.	0.962
Riyadh	5.44 n.s.	7.01 n.s.	0.976
Wadi Addwaser	6.17 n.s.	8.28 n.s.	0.909
Average	*5.65*	*7.04*	*0.950*
Max	*6.19*	*8.28*	*0.976*
Min	*5.00*	*6.16*	*0.909*

Source: measured and calculated within the study.
n.s. = no significant differences

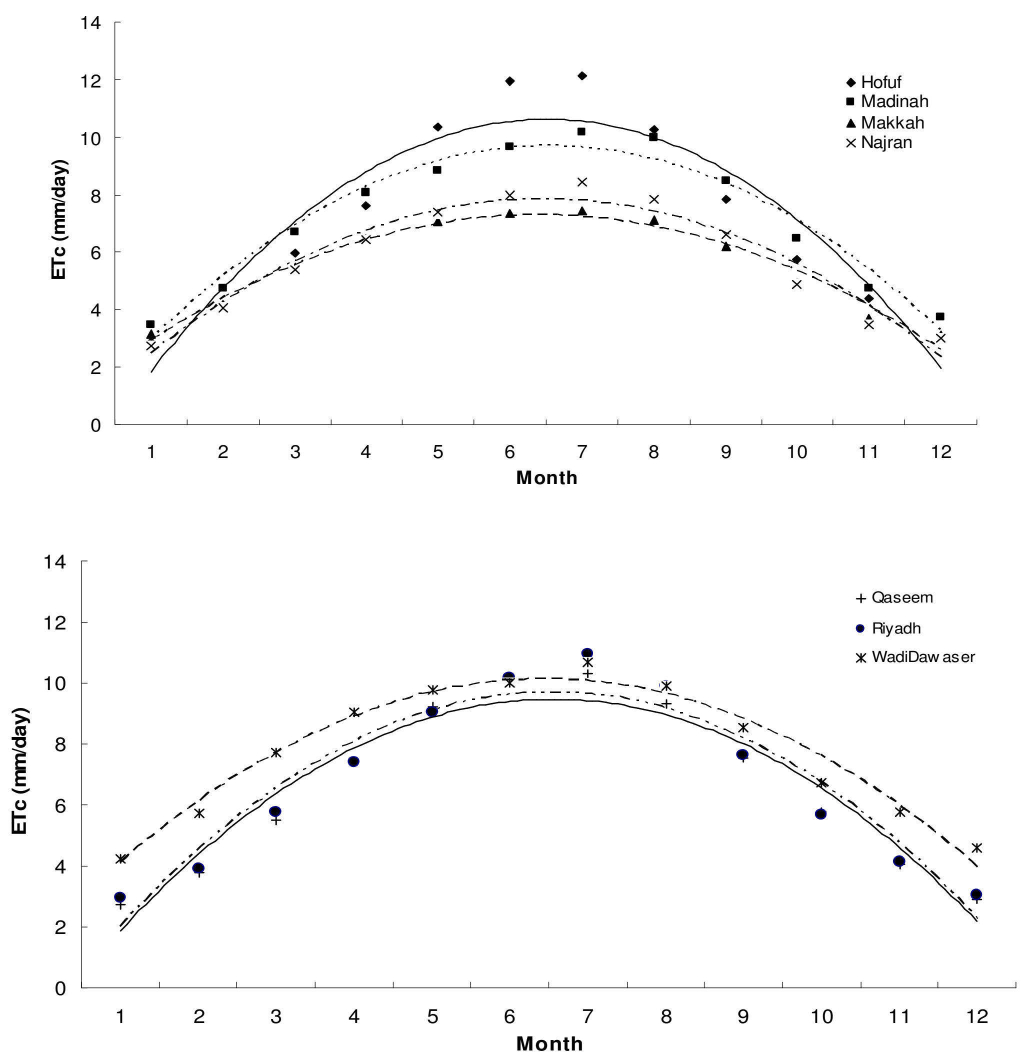

Figure 5. Net Measured Monthly Date Palm Water Use for the Various Regions.

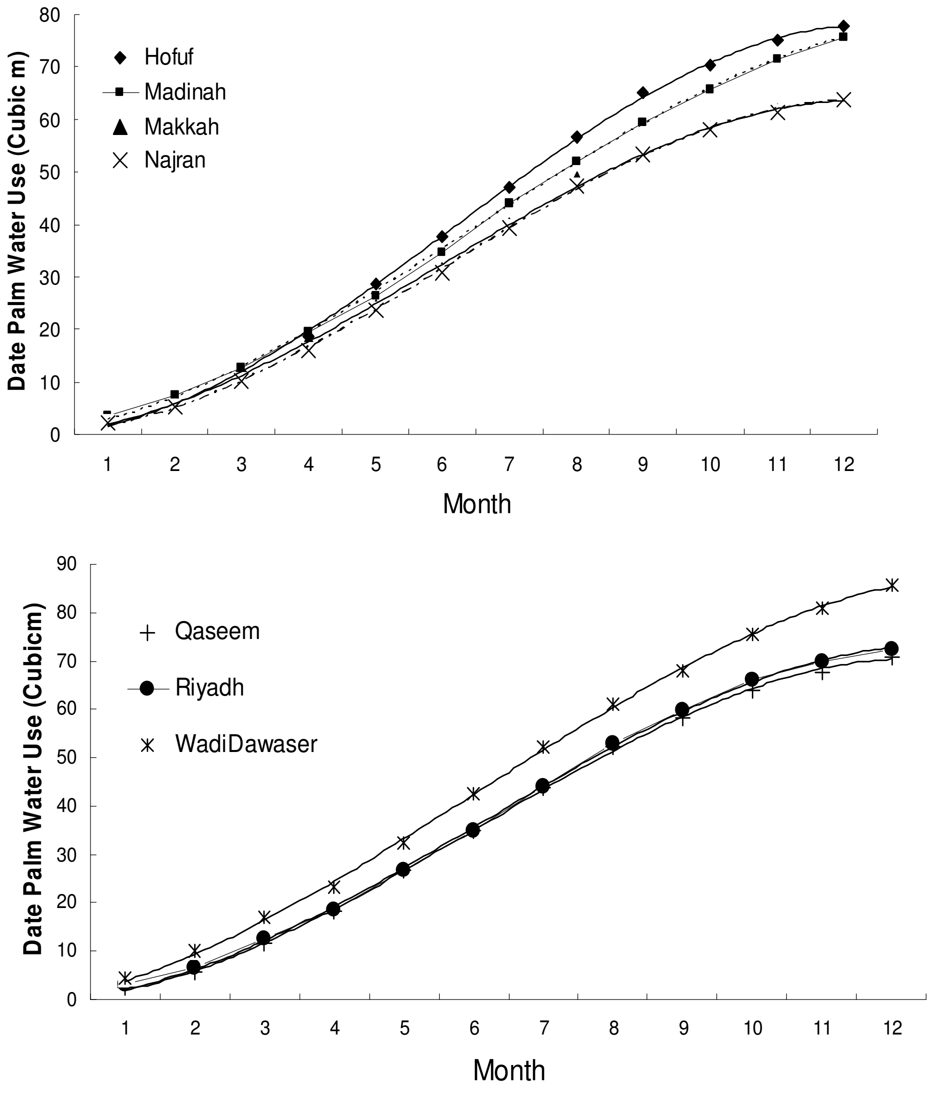

Figure 6. Net Annual Cumulative Date Palm Water Use for All Regions

climatological conditions, soil and/or date variety type. Wadi Addwaser have shown the highest annual amount of 80 m^3/tree, followed by Hofuf of 70.7 m^3/tree, Madinah 69.3 m^3/tree, Riyadh 67.7 m^3/tree, Gaseem 66.9 m^3/tree, Makkah 60.4 m^3/tree and the lowest was 59.4 m^3/tree for Najran.

Date palms crop coefficients, Kc, were computed over the period of study, using equation (2) for all regions, the average monthly Kc vlues are shown in Table 4. The range of Kc's is between 0.80 and 0.99, and the ranges over regions vary, they are: 0.80-0.95, 0.81-0.97, 0.85-0.99, 0.81-0.97, 0.85-0.99, 0.82-0.98 and 0.83-0.97 for Hofuf, Madinah, Makkah, Najran, Gaseem, Riyadh and Wadi Addawaser respectively. Results have indicated that the average values of crop coefficient for each month of the year is not equal in the study regions. The highest obtained Kc value was 0.99 at Makkah and Gaseem on August and July, respectively, while the lowest Kc value was 0.80, at Hofuf region on January, The highest annual monthly average of Kc was 0.913 in Makkah region, while the lowest average was 0.893, in Hofuf region. Crop coefficients, are influenced by climatic conditions as reported also by allen et al. (1998). The average yearly value range of (0.80-0.99) is in good agreement with Doorenbos and Pruitt (1977), Allen et al. (1998) and Alazbah (2004), with regards to trends in Kc values, results have shown maximum Kc's in summer as compared to winter values for all regions, this trend was noticed in all three successive seasons of study for all regions, as seen also by Hoffman et al. (1982).

Several correlation equations based on regression analysis of the alfalfa and date palm actual data for each year were obtained and shown in Table 5.

Based on the measurd ETc, the gross (total) date

Table 4. Date Palm Crop Coefficients (K_C) in the Study Regions

	Study Regions						
Months	Eastern	Madinah	Makkah	Najran	Gaseem	Riyadh	Wadi Addwaser
January	0.8	0.81	0.85	0.81	0.85	0.82	0.83
February	0.86	0.83	0.89	0.85	0.88	0.83	0.87
March	0.92	0.93	0.94	0.93	0.95	0.93	0.94
April	0.93	0.95	0.95	0.93	0.96	0.94	0.95
May	0.95	0.94	0.97	0.96	0.97	0.96	0.96
June	0.94	0.94	0.98	0.95	0.98	0.95	0.97
July	0.94	0.96	0.98	0.96	0.99	0.97	0.98
August	0.91	0.97	0.99	0.97	0.98	0.98	0.97
September	0.88	0.93	0.94	0.92	0.92	0.93	0.94
October	0.87	0.89	0.91	0.9	0.89	0.92	0.91
November	0.86	0.86	0.9	0.89	0.88	0.9	0.9
December	0.86	0.85	0.88	0.88	0.88	0.87	0.88
Average	*0.893*	*0.905*	*0.932*	*0.913*	*0.928*	*0.917*	*0.925*
Max	*0.950*	*0.970*	*0.990*	*0.970*	*0.990*	*0.980*	*0.980*
Min	*0.800*	*0.810*	*0.850*	*0.810*	*0.850*	*0.820*	*0.830*
STDIV	*0.045*	*0.055*	*0.045*	*0.049*	*0.050*	*0.052*	*0.047*

Source: measured and calculated within the study.

Table 5. Correlation equations for annual monthly ET

Regions	Measured Reference ET		Measured Date Palm ET	
	Equation	**R^2**	**Equation**	**R^2**
Riyadh	y = -0.2283x2 + 2.987x - 0.0386	0.9476	y = -0.2352x2 + 3.0934x - 0.8297	0.9419
Mukkah	y = -0.2111x2 + 2.6952x + 0.075	0.8546	y = -0.2182x2 + 2.7936x - 0.5034	0.8480
Najran	y = -0.2228x2 + 2.9206x - 0.7432	0.9473	y = -0.2242x2 + 2.9443x - 1.2541	0.9360
Madeenah	y = -0.1765x2 + 2.4312x + 1.0625	0.9176	y = -0.1896x2 + 2.5907x + 0.1313	0.9253
Eastern	y = -0.2693x2 + 3.5582x - 1.0157	0.9068	y = -0.264x2 + 3.4704x - 1.4304	0.9115
Gaseem	y = -0.2308x2 + 3.0252x - 0.3136	0.9580	y = -0.2392x2 + 3.1211x - 0.8618	0.9407
Wadi Addawaser	y = -0.1877x2 + 2.4459x + 2.5432	0.8605	y = -0.2041x2 + 2.6699x + 1.442	0.8792

palm water requirements (TWR) were calculated for the various regions, and common irrigation systems, the results are shown in figure 7, these values are within the range reported by Al-Buzaidi (1982) and Alazba (2001).

From the economic perspective, the variation of the total net annual date palm water use in the study areas had impacted the average water costs and the net economic returns of date palm farming, accordingly. Results have shown that, water costs represented an average of about 11 per cent from the average variable costs of date palm farming in the study areas, and, water costs ranged from a minimum of about 678 Saudi Riyals per hectare (SR ha^{-1}) in the Hofuf and a maximum of about 2.02 thousand SR ha^{-1} in Madinah, with an average of about 1.45 thousand SR ha^{-1}. The net economic returns of date palm farming, on the other hand, were estimated at a maximum of about 54.6 thousand SR ha^{-1} in the Hofuf and a minimum of about 7.49 thousand SR ha^{-1} in WadiAddwaser with an average of about 22.91 thousands SR ha^{-1} (Alabdulkader et al., 2010), Table 6.

CONCLUSIONS

The three year average ETr of the seven agricultural regions in Saudi Arabia were evaluated on measurement

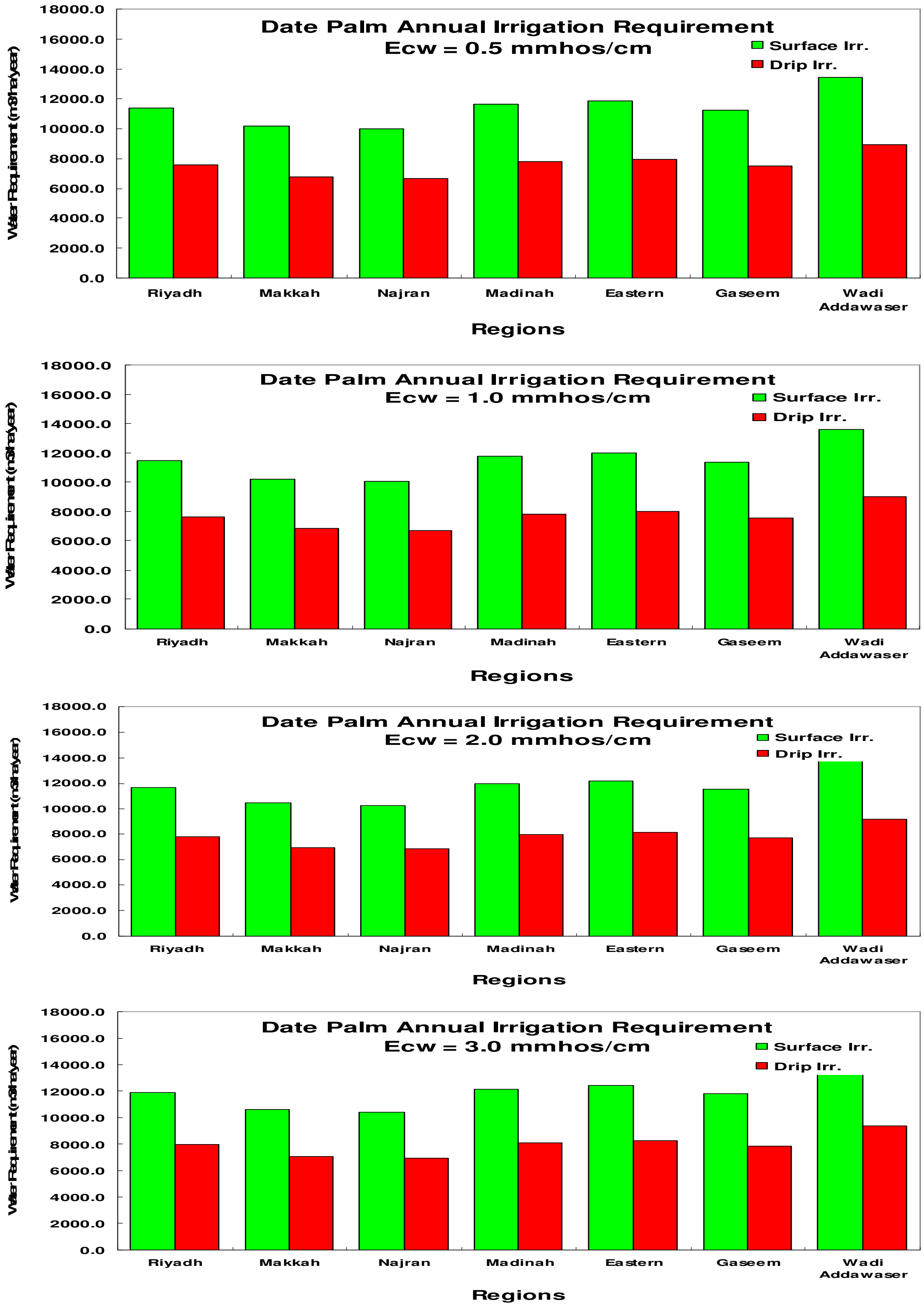

Figure 7. Date Palm Water Requirements for various Irrigation systems and salinity levels for all regions

scale using lysimeters and calculation scale through the Penman Monteith equation. The highest measured monthly values were found to occur in Wadi Addwaser province in the month of June, while the lowest have

Table 6. Economic analysis of date palm trees farming in the study areas.

Study areas	water cost	Water cost as a parentage from variable costs	Net economic returns
	SR/ ha	%	SR/ha
Eastern	673	6%	54,610
Madinah	2,015	12%	35,501
Makkah	1,776	19%	17,935
Najran	1,335	10%	18,825
Gaseem	1,470	7%	11,757
Riyadh	1,503	11%	14,238
WadiAddwaser	1,346	15%	7,492
Average	*1,445*	*11%*	*22,908*
Max	*2,015*	*19%*	*54,610*
Min	*673*	*6%*	*7,492*

Source: measured and calculated within the study.

occurred in the month of Jan in Najran province. The annual cumulative ETr for all studied regions fall within the range 2253 and 3024 mm/year.

It is clear from ETr results that there is a good fit between measured and calculated ETr. The calculated values using P-M equation, follow similar trends as measured values. The trend seem to be consistent throughout the year. However, calculated values is found to slightly underestimate ETr.

The results of three year average net annual monthly date palm water consumption, ETc, for the various regions demonstrate a normal trend influenced by weather conditions. The annual cumulative ETc for all studied regions fall within the range 2100 and 2829 mm/year. The average daily net Date Palm water use rates measured were; 203, 200, 155, 161, 185, 190 and 218 l/day for same regions respectively.

The comparison between the average net cumulative annual amounts consumed by date palms over the three years of study for all regions indicates some differences, mainly, due to variations of climatological conditions, soil and/or date variety type. Wadi Addwaser have shown the highest annual amount of 80 m^3/tree, followed by Hofuf of 70.7 m^3/tree, Madinah 69.3 m^3/tree, Riyadh 67.7 m^3/tree, Gaseem 66.9 m^3/tree, Makkah 60.4 m^3/tree and the lowest was 59.4 m^3/tree for Najran.

The close correlation between actual and predicted values demonstrates the suitability of using modified Peman equation in the arid condition of Saudi Arabia, therefore, Penman Monteith equation could simulate satisfactorily Reference ET with fairly reliable meteorological data.

The variation of the total net annual date palm water use in the study areas had impacted the water costs which represented about 11 per cent of the variable costs, and the net economic returns of date palm farming in the study areas.

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