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Climate and irrigation water use of a mountain oasis in northern Oman

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ABSTRACT

The apparent sustainability of the millennia-old mountain oases of northern Oman has recently received considerable attention. However, little is known about crop growth and water use efficiency of these systems. To fill this gap of knowledge evapotranspiration and water use indices were modeled for nine field crops and date palm (*Phoenix dactylifera* L.) at *Balad Seet*, a typical oasis in the northern Omani *Hajar* range, whose agricultural area is composed of 8.8 ha of palm groves with 2690 date palms and 4.6 ha of land under field crops. Climatic data were derived from a weather station located in the oasis. The use of a digital elevation model (DEM) allowed estimating the shading effect of the surrounding mountains on evapotranspiration. When removing the site-specific effects of altitude and shading by surrounding mountains, reference evapotranspiration increased from 1778 mm year^{-1} to 2393 mm year^{-1}. Total crop water requirements of the oasis were modeled at 194,190 m^3 year^{-1} while measured available water resources from spring outflow and precipitation amounted to 245,668 m^3 year^{-1}. An irrigation water use efficiency of 0.75 at the oasis level provides evidence for an efficient use of this yield limiting resource in these ancient land use systems.

1. Introduction

In 2002, the cultivated area in the Sultanate of Oman amounted to only 73,500 ha, representing about 2.4% of the total geographical area of the country. Of these about 42,000 ha produced fruits (mainly dates from *Phoenix dactylifera* L.), while the remaining area was used to grow vegetables, the fodder crops Rhodes grass (*Chloris gayana*) and alfalfa (*Medicago sativa* L.) and a range of other field crops (Ministry of National Economy, 2004). At an average annual rainfall of about 100 mm year^{-1} with extremes of 300 mm year^{-1} in the northern mountains and 55 mm year^{-1} in the central part of Oman (Shahalam, 2001) and a potential evapotranspiration rate of more than 2000 mm year^{-1} (FAO, 2001a) the country's agriculture depends completely on irrigation. Because of the absence of surface water bodies all irrigation occurs with ground water withdrawn from sedimentary aquifers (springs). The large climatic water deficit on agricultural land and the increase of cultivated area from about 20,000 ha in 1961 (FAO, 2005) to over 70,000 ha since the beginning of the 1990s (Ministry of National Economy, 2004) led to an increased consumption of irrigation water which represents about 94% of the total water use of the country (FAO, 1997).

Several authors claim that at the country level water use now exceeds the long-term recharge (Omezzine et al., 1998; Al-Ajmi and Abdel-Rahman, 2001; FAO, 1997). Consequences are a decline of ground water tables and saline water intrusion into aquifers of the *Batinah* and *Salalah* costal plains (Omezzine et al., 1998; Victor and Al-Farsi, 2001; Weyhenmeyer et al., 2002).

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The reported salinity problems, particularly in the intensively cropped *Batinah* coastal plain, and the ongoing rapid development of the country (Peterson, 2004) stimulated scientists and government to study the water sector in more detail, in particular the balance between water availability and consumption to ensure a more sustainable use of the country's water resources (Abdel-Rahman and Abdel-Magid, 1993; Omezzine et al., 1998; Al-Ismaily and Probert, 1998; Al-Ajmi and Abdel-Rahman, 2001). While an increasing part of domestic and industrial water demand can be satisfied by water produced in desalination plants and while treated waste water is widely used to water trees along roads (FAO, 1997), agricultural water use in the *Batinah* district depends on pumping of groundwater from wells (Al-Ismaily and Probert, 1998). Total water consumption in this district was estimated at 766 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$ and thus 190 $\mathrm{Mm}^3\ \mathrm{year}^{-1}$ larger than the groundwater recharge (Ministry of Water Resources, 1993). Ground water recharge could be increased by establishing additional recharge dams, which lower surface runoff after the rare flood events and allow about 75–80% of the captured volume to enter the groundwater body (Al-Ajmi and Abdel-Rahman, 2001). There also still is large potential to increase agricultural water use efficiency (Al-Lawati and Esechie, 2002; Omezzine and Zaibet, 1998). Another option to save water may be to reduce the cultivated area in the *Batinah* plain and to replace the corresponding irrigation water demand by ''virtual water' imported via food trade (Hoekstra and Hung, 2005).

In contrast to modern day's water resources overuse in the coastal plain, land use in traditional Omani mountain oases has been considered sustainable given their millennia-old existence (Nagieb et al., 2004). In mountain oases, only a minor proportion of the water supply comes from wells, whereas the major part is provided by channel systems called *Aflaj* (singular *Falaj*). Three main types of *Aflaj* can be distinguished (Al-Ismaily and Probert, 1998): *Dawudi Aflaj* are fed from a mother well from which tunnels convey the water to the surface and finally to the fields. In the *Ghayli Aflaj* system water is taken from the sediments of a *wadi* (valley), captured in depressions and transported in channels to the point of use. Finally *Ayni Aflaj* are directly fed from springs. Common to these systems is that their water flow is natural and once established, does not need any direct energy input (Shahalam, 2001). The system is thus self-regulating and avoids an overuse of the water body (Al-Ismaily and Probert, 1998). At present over 4000 *Aflaj* exist in the Sultanate of Oman supplying about 33% of the country's water demand (Shahalam, 2001).

The functioning of *Aflaj* systems, its organization and the scheduling of water distribution is well documented (Al-Ghafri et al., 2001; Shahalam, 2001; Al-Marshudi, 2001; Abdel-Rahman and Omezzine, 1996; Wilkinson, 1977). However, little is known about irrigation water use efficiency in traditional mountain oases. The average efficiency of surface irrigation methods as used in the *Aflaj*-driven mountain oases was estimated at 60% by Oman's Ministry of Agriculture and Fisheries (MAF), whereas the efficiency of modern irrigation methods reportedly reaches 85%. Therefore, the ministry supports the conversion of the traditional systems to modern irrigation methods by subsidies (Al-Ajmi and Abdel-Rahman, 2001). However, in their study of irrigation demand/supply ratios of six farm plots under traditional flood irrigation at *Falaj Hageer* in *Wadi Bani Kharus*, Norman et al. (1998) found efficiencies between 60% and 98% with a mean of 79%.

In view of this contrasting information about the water use efficiencies of traditional oasis agriculture in Oman, the objective of this study was to model crop water requirements for a representative oasis of northern Oman and to compute irrigation water use efficiency by comparing modelled crop evapotranspiration to measured water use. To this end the effects of site-specific conditions such as altitude and topography on crop evapotranspiration were to be quantified.

2. Materials and methods

2.1. Study site

The research was carried out in the mountain oasis of *Balad Seet* (23.19°N; 57.39°E; 996 m a.s.l.) situated at the upper end of the *Wadi Bani Awf*, a watershed on the northern side of the *Hajar* range of the *Al Jabal Al Akhdar* mountains. The oasis is situated at the foot of a 1000 m high cliff and surrounded by mountains consisting of highly permeable carbonates (dolomites and limestones of the *Mahi* formation) resting over impermeable, red-greyish-green silt- and clay-stones of the *Muaydin* formation (Fig. 1). The siltstones have very little fracture porosity and act therefore as an aquifuge, whereas the carbonates above are highly fractured and karstic allowing groundwater to be stored, to migrate over long distances and to enter the surface via many different springs located along the boundary of these two rock formations (Nagieb et al., 2004).

The outflow of 12 springs is collected by five *Ayni Aflaj* systems (Luedeling et al., 2005) and is transported to 385 agricultural fields covering 4.6 ha and to 2690 date palms (*P. dactylifera* L.) growing on an additional 8.8 ha of terraced land intercropped with some lime (*Citrus aurantiifolia* [Christm. et Panz.] Swingle) and banana (*Musa* spp.) plants. About 1.9 ha of the palm groves are sown to understory grasses (Buerkert et al., 2005). Fields and palm groves surround the houses of the 650 inhabitants, which are located on a rocky outcrop in the centre of the oasis (Fig. 2). Compared to more marginal oases, in which settlement and fields are more dispersed given the occurrence of smaller and less reliable water bodies, *Balad Seet* can therefore be characterized as a typical core oasis (Nagieb et al., 2004). Cultivated plants are perennial alfalfa (*M. sativa* L.) and annual crops such as traditional wheat landraces (*Triticum aestivum* L. and *Triticum durum*; Al-Maskri et al., 2003), sorghum (*Sorghum bicolor* Moench s. l.), barley (*Hordeum vulgare* L. s. l.), oat (*Avena sativa* L.), maize (*Zea mays* L.), garlic (*Allium sativum* L.), onion (*Allium cepa* L.) and coriander (*Coriandrum sativum* L.). These are planted in complex summer–winter crop rotation systems (Fig. 3). Wheat, garlic, onion and coriander are grown for human consumption and partially sold as cash crops on the market while the other cereals are used to feed up to 200 small ruminants (sheep and goat). Maize, oat and barley are harvested immature, while sorghum is harvested as both grain and green fodder (Nagieb et al., 2004). Barley, oat, onion and garlic are grown during the winter season, whereas sorghum is cultivated only during the hot summer season. Maize and coriander are grown in both summer and winter (Fig. 3; Table 1). The

Fig. 1 – View of the oasis of *Balad Seet* situated at the upper end of the *Wadi Bani Awf* on the northern side of the *Hajar* range of the *Al Jabal Al Akhdar* mountains in Oman.

cultivated area varies over the year as a large portion of the field crop area is left fallow during summer (Table 1).

The agricultural land consists of Irragric Anthrosols (FAO, 2001b) of 0.4–1.3 m depth with 9–14% clay content. These soils are well drained because of a gravel layer below 1.3 m. Plant available water capacity of the topsoil is about 19% compared to 13 and 13.5% at 0.25 and 0.60 m depth. The soil's organic carbon (C_{org}) content is with 3.7% at 0–0.15 m depth and 3% at 0.15–0.45 m depth and on very high (Luedeling et al., 2005). This is a consequence of annual manure applications of up to 12 t ha^{-1} (Buerkert et al., 2005). In general the deeper soils are to be found on cropland whereas palms are growing on more shallow soils (Nagieb et al., 2004).

The predominant part of the oasis water demand is met by the 12 springs. Only a minor part (estimated at 9% annually) is provided by motor pumps from 14 wells that have been dug into the *wadi* sediments. However, during the prolonged drought between 2001 and 2003 most of these wells fell dry (Nagieb et al., 2004). The domestic water demand of the inhabitants is largely met by a well below the terraces while the *Falaj* water is used for basin-based surface irrigation. The average size of the basins is about 1.7 m^2 on cropland and up to 30 m^2 in palm yards. The water collected from the springs is flowing downwards in cement-lined channels and is collected in up to 2 m deep storage basins close to the fields. To irrigate the crops a gate is opened and the water rushes in channels to the fields where the small basins are flooded one after the other. The average length of an irrigation cycle amounts to 18 days during the winter season and to 9 days in summer (Nagieb et al., 2004).

2.2. *Irrigation water use efficiency (IWUE)*

Many indices to assess water use performance have been used and are summarized by Purcell and Currey (2003). These indices describe the conversion of available water resources into crop yield at different stages of plant growth and thus quantify the proportion of productive water use to unproductive losses. In this study irrigation water use efficiency is computed as the ratio of actual water demand and the applied amount of irrigation water (Norman et al., 1998):

$$\mathrm{IWUE} = \frac{\mathrm{ET_a} - P_e - \Delta S}{I_s} \quad (1)$$

where IWUE is the irrigation water use efficiency, $\mathrm{ET_a}$ the actual evapotranspiration (mm), P_e the effective precipitation

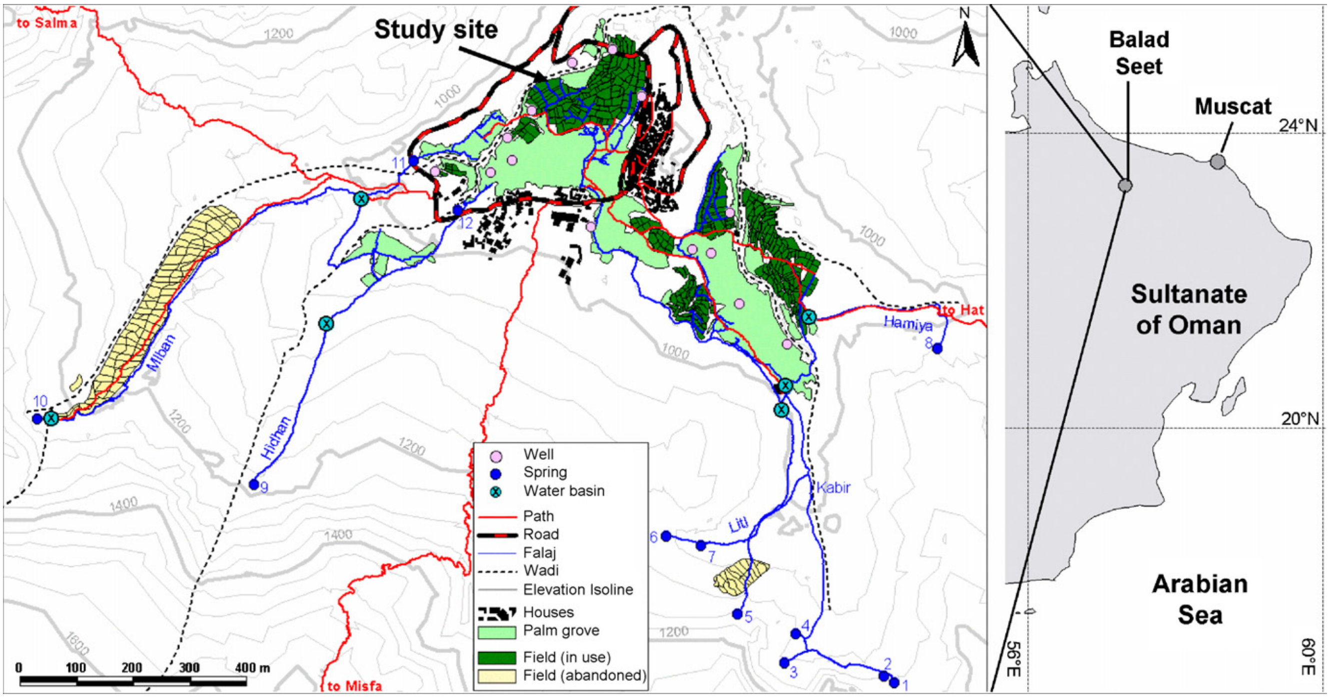

Fig. 2 – GIS-based map with the agricultural features and archaeological sites of the mountain oasis of *Balad Seet*, Oman (Luedeling et al., 2005).

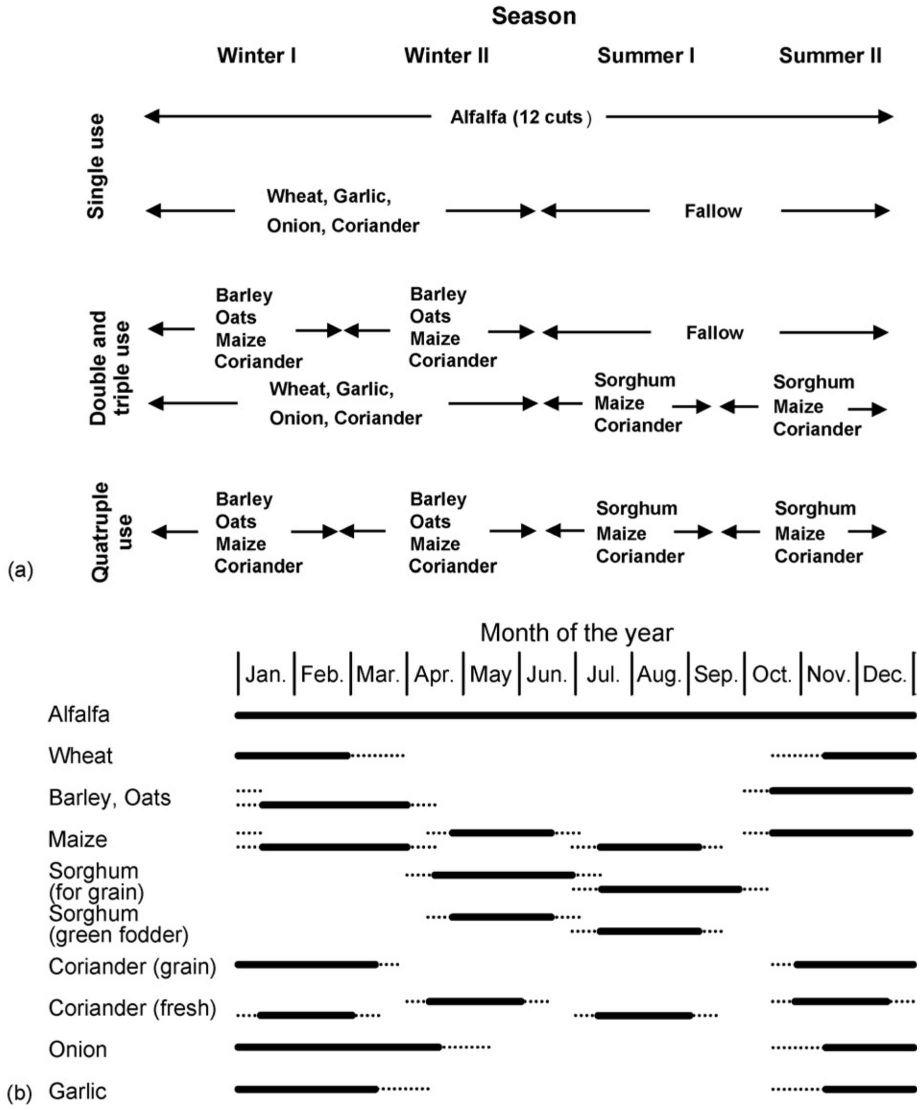

Fig. 3 – Cropping calendar on fields at *Balad Seet* (Oman): (a) cropping pattern and (b) length of growing season, solid line: fields are cropped in general, dotted line: only some fields are cropped.

(mm), ΔS the change in root zone moisture (mm), and I_s is the irrigation water supply (mm).

All presented terms refer to averages for a 2-year measurement period between October 2000 and 2002. Because of the low amount of rain per precipitation event (maximum 40 mm) and because surface runoff is to be excluded given the existence of irrigation basins, it was assumed that all precipitation was effective. Change in root zone moisture (ΔS) was neglected because the calculations were performed for the oasis as a whole over the 2-year period and differences of the soil moisture balance in specific plots were therefore assumed to level out. Irrigation water supply (I_s) was estimated as the sum of water flows in the five *Aflaj* systems. Measurements of *Falaj* flows were taken at monthly intervals with a hand-operated barrel system (Nagieb et al., 2004). Actual evapotranspiration was assumed to be equal to potential crop evapotranspiration (ET_c) in all months with water surplus ($ET_c \leq I_s + P_e$) but reduced to the given water supply ($I_s + P_e$) in months with water deficit ($ET_c > I_s + P_e$). Potential crop evapotranspiration was computed in daily time steps as

$$ET_c = k_c ET_0 \tag{2}$$

where ET_0 is the reference evapotranspiration (mm day^{-1}) and k_c represent crop coefficients that depend on crop type and development stage. Crop coefficient curves for four growth stages (initial stage, crop development, mid-season and late season) were developed according to the single crop coefficient approach (Allen et al., 1998). The crop coefficients (Table 2) were adjusted to match the observed management and climate conditions using the recommendations given by Allen et al. (1998). The length of the four crop development stages (Table 2) was chosen according to site-specific field observations. Within the initial stage, crop coefficients were constant at the level of $k_{c\ ini}$. During crop development, crop coefficients increased at constant daily rates to the level given by $k_{c\ mid}$. In the mid-season period, crop coefficients were

Table 1 – Cropping areas in growing seasons 2000/2001 and 2001/2002 (ha), total cultivated and fallow area (ha) and cropping intensity on fields at *Balad Seet* (Oman)

Crop	Cropping areas in growing season 2000/2001 (ha)				Cropping areas in growing season 2001/2002 (ha)			
	Winter I	Winter II	Summer I	Summer II	Winter I	Winter II	Summer I	Summer II
Alfalfa	0.42	0.42	0.37	0.37	0.33	0.33	0.32	0.35
Barley	0.61	0.52	0.00	0.00	0.62	0.49	0.00	0.00
Coriander	0.22	0.18	0.19	0.16	0.09	0.13	0.17	0.23
Garlic	0.83	0.83	0.00	0.00	0.66	0.66	0.00	0.00
Maize	0.38	0.34	0.14	0.15	0.16	0.10	0.05	0.04
Oat	0.66	0.65	0.00	0.00	0.47	0.42	0.00	0.00
Onion	0.18	0.18	0.00	0.00	0.11	0.11	0.00	0.00
Sorghum	0.00	0.00	1.06	0.99	0.00	0.00	1.11	0.73
Wheat	0.61	0.61	0.00	0.00	0.96	0.96	0.00	0.00
Cultivated	3.91	3.72	1.76	1.67	3.41	3.20	1.65	1.35
Bare	0.72	0.92	2.87	2.97	1.23	1.44	2.98	3.29
Cropping intensity	0.84	0.80	0.38	0.36	0.74	0.69	0.36	0.29

Table 2 – Length of initial growing period (L_{ini}), crop development period (L_{dev}), mid-season period (L_{mid}), late season period (L_{late}) and total length of growing period (L_{tot}) in days, crop coefficients for initial period ($k_{c\ ini}$), mid season ($k_{c\ mid}$), end season ($k_{c\ end}$) and average crop coefficient over the growing season ($k_{c\ avg}$) for crops at *Balad Seet* (Oman)

Crop	Length of growing periods (day)					Crop coefficients			
	L_{ini}	L_{dev}	L_{mid}	L_{late}	L_{tot}	$k_{c\ ini}$	$k_{c\ mid}$	$k_{c\ end}$[a]	$k_{c\ avg}$
Alfalfa	5	10	10	5	30	0.40	1.20	1.15	0.93
Wheat	20	25	60	30	135	0.35	1.15	0.40	0.87
Barley	15	25	50	0	90	0.35	1.15	n.a.	0.91
Oat	15	25	50	0	90	0.35	1.15	n.a.	0.91
Maize (winter)	20	30	40	0	90	0.35	1.15	n.a.	0.84
Maize (summer)	15	30	25	0	70	0.35	1.15	n.a.	0.81
Sorghum (for grain)	15	25	30	20	90	0.35	1.10	0.55	0.81
Sorghum (green fodder)	15	30	25	0	70	0.35	1.10	n.a.	0.78
Coriander (for grain)	15	30	45	45	150	0.50	1.10	0.30	0.75
Coriander (green)	15	25	20	0	60	0.50	1.10	n.a.	0.83
Onion	20	30	90	45	185	0.70	1.05	0.20	0.88
Garlic	20	30	80	20	150	0.70	1.00	0.70	0.91

[a] Late season is not applicable for crops that are harvested immature.

constant at the level of $k_{c\ mid}$ and in the late season stage, crop coefficients were assumed to decrease in constant steps to the value given by $k_{c\ end}$. By using the crop calendar (Fig. 3) and records of the crops grown on the fields in the winter and summer seasons of 2000/2001 and 2001/2002 (Buerkert et al., 2005), the crop coefficient curves were applied to the 385 individual fields. Given their large numbers the start of the growing season (Table 3) could not be recorded for all fields and was therefore defined according to the following criteria:

(a) The start of the growing season was within the observed range given in Table 3.
(b) Farmers who cultivated more than one field should harvest or prepare at the most one field per day to minimize labour peaks.

2.3. *Reference evapotranspiration (ET_0)*

Reference evapotranspiration was computed in daily time steps according to the FAO Penman–Monteith method (Allen et al., 1998) as

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_n - G) + \gamma(900/(T+273))u(e_s - e_a)}{\Delta + \gamma(1 + 0.34u)} \qquad (3)$$

where ET_0 stands for the reference evapotranspiration (mm day^{-1}), R_n the net radiation at the crop surface (MJ m^{-2} day^{-1}), G the soil heat flux density (MJ m^{-2} day^{-1}), T the mean daily air temperature (°C), u the wind speed at 2 m height (m s^{-1}), e_s the saturation vapour pressure (kPa), e_a the actual vapour pressure (kPa), Δ the slope of the vapour

Table 3 – Start of growing seasons for non-perennial crops at *Balad Seet* (Oman)

Crop	Start of growing season
Barley, oat	1 October–16 October and 1 January–15 January
Coriander (for grain)	15 October–29 October
Coriander (green)	15 October–29 October, 1 January–15 January, 1 April–15 April and 30 June–14 July
Garlic, onion, wheat	15 October–14 November
Maize	1 October–16 October, 1 January–15 January, 11 April–25 April and 30 June–14 July
Sorghum (for grain)	1 April–15 April and 30 June–14 July
Sorghum (green fodder)	11 April–25 April and 30 June–14 July

pressure curve (kPa °C^{-1}) and γ is a psychrometric constant (kPa °C^{-1}).

Since the calculations were performed in daily time steps, soil heat flux density (G) was assumed to be negligibly low compared to R_n (Allen et al., 1998) and was therefore set to 0. Net radiation was computed as the difference between incoming net short wave radiation (R_{ns}) and the outgoing net long wave radiation (R_{nl}):

$$R_n = R_{ns} - R_{nl} \tag{4}$$

Net short wave radiation was computed as:

$$R_{ns} = (1-\alpha)R_s \tag{5}$$

where α is a reflection coefficient set to 0.23 and R_s stands for the incoming short wave radiation (MJ m^{-2} day^{-1}). Net outgoing long wave radiation (R_{nl}) was computed as

$$R_{nl} = \sigma\left(\frac{T^4_{\max,K}+T^4_{\min,K}}{2}\right)(0.34-0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{s0}}-0.35\right) \tag{6}$$

where σ stands for the Stefan–Boltzmann constant set to 4.903×10^{-9} MJ K^{-4} m^{-2} day^{-1}, $T_{\max,K}$ the daily maximum temperature (K), $T_{\min,K}$ the daily minimum temperature (K) and R_{s0} is the short wave radiation on a clear-sky day (MJ m^{-2} day^{-1}).

2.4. Climatic data

The calculation of ET_0 according to the FAO Penman–Monteith method requires measurements of air temperature (daily minimum, maximum and average), solar radiation, humidity and wind speed. Air temperature was measured with thermocouples in a cultivated alfalfa field using a combined setup which recorded soil moisture by capacitance probes (Decagon Devices Inc., Pullman, WA, USA) and soil temperature and air temperature by thermocouples. All measurements were collected in 30-min intervals and stored with a Campbell CR10 (Campbell Scientific Inc., Logan, UT, USA) data logger. For each day the minimum and maximum temperature was derived and the average of the 48 values computed. Measurements were taken between October 2002 and 2003 and assumed to be also representative of the previous cropping seasons. Relative humidity and dew point temperature were measured in 10-min intervals using a small weather station (Weather Station III, O. Feger, Traunstein, Germany). An analysis of the data showed that maximum humidity was for many summer days below 70%, which was confirmed by measurements taken with an independent climate logger (Technika, Phoenix, AZ, USA). This indicated a deviation from reference conditions, most probably caused by the aridity of the site and the small size of the oasis. As recommended by Allen et al. (1998) these measurements were therefore discarded and instead actual vapour pressure (e_a) was computed as

$$e_a = 0.6108\exp\left(\frac{17.27T_{dew}}{T_{dew}+237.3}\right) \tag{7}$$

assuming that $T_{dew} = T_{min} - 2$ where T_{dew} stands for the dew point temperature (°C) and T_{min} for the daily minimum temperature (°C).

Based on the fact that there was no or only very light wind on the large majority of days in the oasis, wind speed was assumed to be constant at 1 m s^{-1}. Solar radiation was measured during four selected time periods (25 November 2002–21 December 2002, 4 January 2003–1 May 2003, 18 June 2003–6 July 2003, 18 August 2003–4 October 2003) with a pyranometer in 10-min intervals using the small weather station. The cumulative length of all measurement periods was 211 days. Duration of daily sunshine (in minutes) was recorded by the same weather station using the radiation records and a threshold value of 120 W m^{-2} for bright sunshine. Missing data of global radiation and daily sunshine were modelled using a digital elevation model (DEM) based on digitized Russian military maps (Buerkert et al., 2005). The position of the sun at the sky was computed for each minute in the simulation period according to Szokolay (1996) and Carruthers et al. (1990) as applied by the solar position calculator of Square One research PTY LTD (http://www.squ1.com/index.php?http://www.squ1.com/solar/solar-position.html). The use of the DEM allowed computing the height of the mountains along the horizon as it appears to an observer located near the weather station. Subsequently daily potential sunshine (n_{DEM}) was calculated as the length of the period when the sun was above the mountains. Daily actual sunshine was calculated by applying a coefficient that represents the influence of cloudiness as

$$n_{act} = c_n n_{DEM} \tag{8}$$

where n_{act} is the actual duration of sunshine (min day^{-1}), c_n the cloudiness coefficient, and n_{DEM} is the potential duration of sunshine (length of period when the sun is above the mountains along the horizon in min day^{-1}). The coefficient c_n was computed by linear interpolation between the related coefficients as calculated during the measurement periods (Table 4).

Solar radiation was modelled in a similar way. During the period, when the sun was above the mountains along the horizon, solar radiation on a clear-sky day (R_{s0}) was computed according to Allen (1996) as

$$R_{s0(a)} = \sum_{m=1}^{1440} R_a \exp\left(\frac{-0.0018P}{K_t\sin\phi}\right) \tag{9}$$

where $R_{s0(a)}$ is the short wave radiation on a clear-sky day with the sun above the mountains (MJ m^{-2} day^{-1}) [$R_{s0(a)} = 0$ if the sun is behind the mountains along the horizon, m the minute of the day ($1 \le m \le 1440$)], R_a the extraterrestrial radiation (MJ m^{-2} min^{-1}), P the atmospheric pressure (kPa), ϕ the angle of the sun above the horizon (rad) and K_t is the turbidity coefficient (kPa rad^{-1}) which was set to 1.0 for clean air.

The solar radiation on a clear-sky day for the period when the sun is above the horizon ($\phi > 0$) but behind the mountains ($R_{s0(b)}$) was computed by assuming that the average incoming solar radiation during this period in the early morning and the late afternoon was 25 W m^{-2} and that any increase or decrease of solar radiation was linear during this period (Fig. 4). Total daily incoming solar radiation (R_s) was then computed by applying the coefficient c_s (Table 4) to the sum of both solar radiations computed before as

$$R_s = c_s(R_{s0(a)} + R_{s0(b)}) \tag{10}$$

Table 4 – Average coefficients for cloudiness or turbidity used in calculations of daily sunshine duration (c_n) and incoming solar radiation (c_s) as computed from measurements or interpolated for periods without measurements at *Balad Seet* (Oman)

Month	Number of measurement days	Coefficients as derived from measurements		Coefficients computed for periods without measurements	
		c_n	c_s	c_n	c_s
January	28	1.065	0.958	1.067	0.986
February	28	1.024	0.950	n.a.	n.a.
March	31	0.986	0.882	n.a.	n.a.
April	29	0.975	0.917	0.975	0.921
May	1	0.984	0.984	0.983	0.908
June	13	0.969	0.851	0.976	0.874
July	6	0.981	0.834	0.969	0.847
August	14	0.987	0.848	0.979	0.838
September	30	0.992	0.838	n.a.	n.a.
October	4	1.000	0.961	1.033	0.934
November	6	1.022	1.049	1.053	0.943
December	21	1.102	0.966	1.081	1.011

where c_s represents the influence of cloudiness or turbid air and $R_{s0(b)}$ stands for the short wave radiation on a clear-sky day with the sun above the horizon but behind the mountains (MJ m^{-2} day^{-1}). The radiation and sunshine values recorded or simulated for the period November 2002–2003 were assumed to be also representative for the period October 2000–2002.

Daily precipitation was recorded at *Balad Seet* between July 2001 and 2004, of which monthly averages were used to calculate water use efficiency (Eq. (1)).

2.5. *Crop water use indices*

Crop water use indices were computed for eight field crops and date palms as

$$\mathrm{CWUI} = \frac{Y}{\mathrm{ET_c}} \tag{11}$$

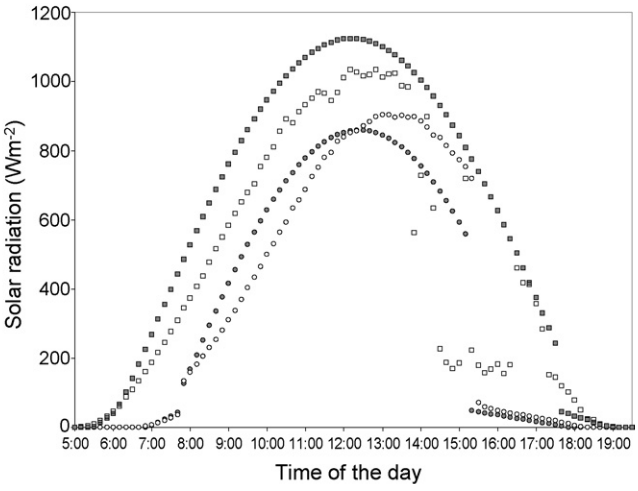

Fig. 4 – Measured solar radiation (unfilled symbols) versus simulated clear-sky solar radiation (filled symbols) on 1 February 2003 (circles) and 20 June 2003 (squares) at *Balad Seet* (Oman).

where CWUI denotes the crop water use index (kg m^{-3}), Y the dry matter economic crop yield (kg) and ET_c is the crop evapotranspiration (m^3). The aboveground dry matter of crops was recorded for the four seasons (winter I and II, summer I and II) and the two growing seasons 2000/2001 and 2001/2002 following the procedure described by Buerkert et al. (2005).

2.6. *Effects of altitude and topography on potential evapotranspiration*

To estimate potential evapotranspiration in a fictive oasis at the same geographical location but without the surrounding mountains and at mean sea level, altitude a.s.l. was set to 0 m and measured average temperatures were increased by 6.5 °C based on an altitudinal temperature gradient of 0.65 °C per 100 m altitude. Average daily maximum temperature was only increased by 2 °C because an increase of 6.5 °C would lead to average maximum temperatures larger than 50 °C that were not reported for any place on the entire Arabian Peninsula. The lower increase of maximum temperatures was balanced out by an increase of average daily minimum temperatures by 11 °C. Daily sunshine duration was set to monthly values as reported by Jervase et al. (2003) for the town of *Rustaq* (23.41°N; 57.42°E; 322 m a.s.l.) which is located just 25 km north of *Balad Seet*. Solar radiation was increased in the months of December–February to averages measured at Seeb International Airport near Muscat to reduce the shadow effect of the mountains. In all other months, solar radiation measured at *Balad Seet* was larger than the values measured at Muscat and was therefore not changed. Wind speed was increased to monthly averages as recorded for July 2004–February 2005 at *Rustaq* (http://www.wunderground.com/global/stations/41253.html). Wind speed for the months March–June was computed by increasing wind speed as measured in February at *Rustaq* each month by 0.1 m s^{-1}. A stepwise increase of wind speed in this season was reported previously for other weather stations in Oman (Sulaiman et al., 2002).

Table 5 – Monthly averages of daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), daily average temperature (T_{avg}), daily sunshine duration (n) and daily solar radiation (R_s), monthly sum of effective precipitation (P_e) at *Balad Seet* (Oman)

Month	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	n (min day^{-1})	R_s (MJ m^{-2} day^{-1})	P_e (mm)
January	26.3	8.8	16.3	436.4	15.1	0.0
February	29.0	12.5	20.4	484.5	18.8	1.2
March	31.0	15.2	23.5	533.6	21.6	12.2
April	35.6	16.4	25.9	585.8	26.2	22.2
May	39.5	19.9	29.9	634.4	28.0	4.2
June	44.0	23.9	33.9	659.1	27.1	0.0
July	40.1	25.8	32.3	643.2	26.1	40.1
August	40.3	23.7	31.8	610.9	24.8	2.3
September	38.2	21.2	29.8	566.1	22.0	8.9
October	36.5	17.1	26.5	515.7	20.4	0.5
November	30.3	14.1	21.1	457.4	16.6	2.9
December	27.2	11.2	17.9	423.6	14.2	0.0
Annual average[a]	34.9	17.5	25.8	546.2	21.7	94.5

[a] In case of precipitation the annual sum is reported.

3. Results

3.1. Climatic data

Average temperature during the 1-year measurement period was 25.8 °C. Average daily maximum temperature was 34.9 °C while the average daily minimum was 17.5 °C. January was the coolest month and June the hottest one (Table 5). Average annual precipitation over the 4-year measurement period was 94.5 mm. Most of the rain fell in July with 40.1 mm, which indicates the influence of the Indian Ocean monsoon (Burns et al., 2002). During winter time (November–February) only very little precipitation was recorded.

A large variation of sunshine duration and solar radiation between summer and winter season was found (Table 5), which reflects the combined effect of site-specific topography and solar geometry. In December the sun was above the mountains along the horizon for about 6 h and for about 11 h in June (Fig. 5). The shading effect of the mountains around *Balad Seet* had a much larger influence on the sunshine duration than on solar radiation (Figs. 6 and 7). The potential sunshine duration at the given latitude was computed to last 640 min day^{-1} in December and 800 min day^{-1} in June while the potential solar radiation on clear-sky days amounted to 17 MJ m^{-2} day^{-1} in December and 32 MJ m^{-2} day^{-1} in June. Including the shading effect of the mountains decreased potential sunshine duration to 380 min day^{-1} in December and to 680 min day^{-1} in June, while potential solar radiation decreased to 14.5 MJ m^{-2} day^{-1} in December and to 31.2 MJ m^{-2} day^{-1} in June (Figs. 6 and 7). The reduction of sunshine and solar radiation by cloudiness, however, seemed to be higher in summer than in winter (see coefficients in Table 4).

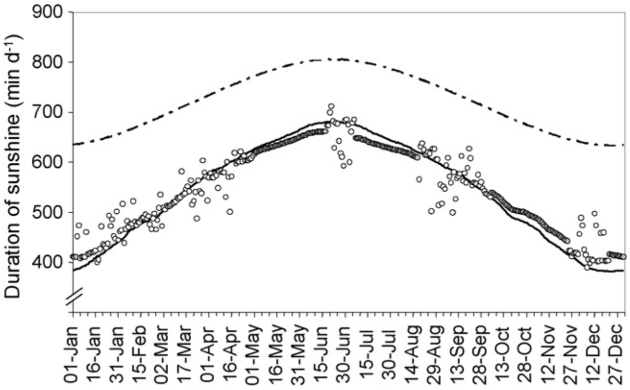

Fig. 6 – Daily duration of sunshine at *Balad Seet* (Oman); dot-dashed line: potential astrological sunshine duration (sun altitude > 0°), solid line: potential local sunshine duration (sun above the mountains along the horizon), unfilled dots: measured sunshine duration, filled dots: sunshine duration interpolated for periods without measurements.

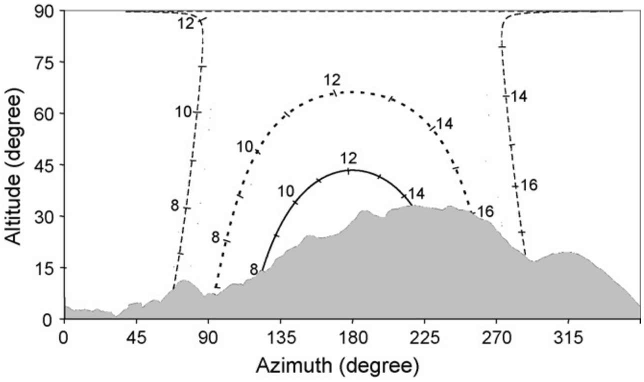

Fig. 5 – Height of the mountains along the horizon and sun path on 20 December (solid line), 20 March (dotted line) and 20 June (dashed line) at *Balad Seet* (Oman), thick marks along the sun paths indicate hours of local time, Azimuth of 0 = North.

3.2. Evapotranspiration

Annual reference evapotranspiration (ET_0) was 1778 mm year^{-1} in the 2 years simulated. Monthly reference evapotranspiration was highest in June with 208 mm while reference evapotranspiration appeared to be lowest in December with 84 mm (Table 6).

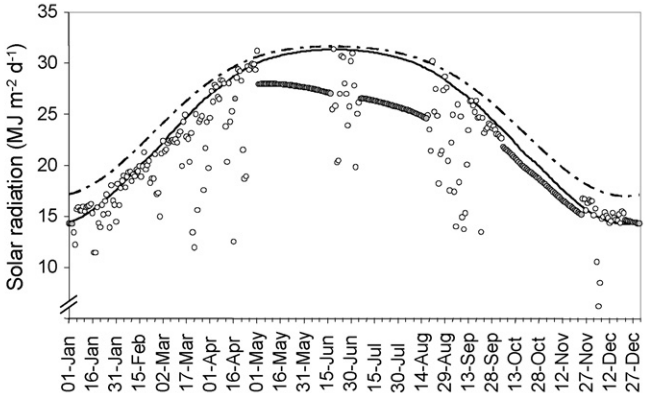

Fig. 7 – Daily incoming solar (short wave) radiation at *Balad Seet* (Oman); dot-dashed line: potential astrological solar radiation on a clear-sky day, solid line: potential local solar radiation on a clear-sky day (shadowing effect of mountains along the horizon considered), unfilled dots: measured solar radiation, filled dots: solar radiation interpolated for periods without measurements.

Total annual crop evapotranspiration in palm groves accounted for about 84% of the total evapotranspiration on agricultural land (Table 6). Because of the perennial cultivation of palm groves, the seasonal variation of crop evapotranspiration was similar to that of the reference evapotranspiration. Therefore, evapotranspiration was largest in the hot summer season (May–August) and lowest in the cooler winter season (November–February).

In contrast to the situation in palm groves, seasonal evapotranspiration is more balanced on cropland (Table 6). So total crop evapotranspiration in winter (October–March) was 17,355 m^3 $year^{-1}$ and was thus even higher than evapotranspiration computed for the period April–September (13,838 m^3 $year^{-1}$). This reflects the higher cropping intensity in the winter compared to the summer season (Table 1). The highest total evapotranspiration was computed for sorghum (8216 m^3 $year^{-1}$) and alfalfa (5939 m^3 $year^{-1}$).

3.3. *Irrigation water use efficiency (IWUE)*

Irrigation water use efficiency for the entire oasis was 0.75 during the 2-year period from October 2000 to September 2002. Actual evapotranspiration (ET_a) was 373,623 m^3 and thus only 4% lower than the potential evapotranspiration of 388,780 m^3. Total precipitation on agricultural land was 25,390 m^3 and irrigation water supply from the *Aflaj* (I_s) was 465,946 m^3 with, however, large seasonal differences. While in the winter season about half of the used irrigation water was not needed by the plants, there was a small water deficit computed for some months in the summer season (Fig. 8).

3.4. *Water use indices*

Crop water use index was 0.92 kg m^{-3} for wheat grain yield, 0.64 kg m^{-3} for sorghum grain and 1.85 kg m^{-3} for garlic bulbs (Table 7). Crop water use indices for total dry matter (TDM) ranged between 1.88 kg m^{-3} for oat and 4.27 kg m^{-3} for maize.

Table 6 – Reference evapotranspiration (ET_0) in mm $month^{-1}$ and crop specific evapotranspiration in m^3 $month^{-1}$ for alfalfa, wheat, barley, oats, maize, sorghum, coriander, onion and garlic, for cropland total, palm groves and total agricultural land as average of the 2-year simulation period at *Balad Seet* (Oman)

Month	ET_0 (mm $month^{-1}$)	Potential evapotranspiration (m^3 $month^{-1}$)									Cropland	Palm-groves	Total
		Alfalfa	Wheat	Barley	Oat	Maize	Sorghum	Coriander	Onion	Garlic			
January	88	316	795	211	230	86	0	150	134	656	2,577	8,097	10,675
February	101	352	653	540	580	207	0	115	154	749	3,350	9,309	12,659
March	137	478	78	783	839	346	0	13	160	432	3,129	12,555	15,684
April	170	536	0	112	97	82	640	111	52	1	1,631	15,609	17,240
May	202	648	0	0	0	171	2096	360	0	0	3,275	18,569	21,843
June	208	664	0	0	0	144	1991	63	0	0	2,862	19,126	21,988
July	200	663	0	0	0	74	778	158	0	0	1,673	18,373	20,046
August	189	639	0	0	0	179	1648	357	0	0	2,823	17,373	20,196
September	157	526	0	0	0	55	974	19	0	0	1,574	14,401	15,975
October	141	479	127	356	313	129	89	28	71	301	1,893	12,939	14,831
November	99	346	458	652	592	246	0	102	119	582	3,097	9,093	12,190
December	84	295	746	581	537	256	0	145	128	622	3,309	7,753	11,062
Annual	1778	5939	2857	3235	3189	1974	8216	1621	818	3344	31,193	163,197	194,390

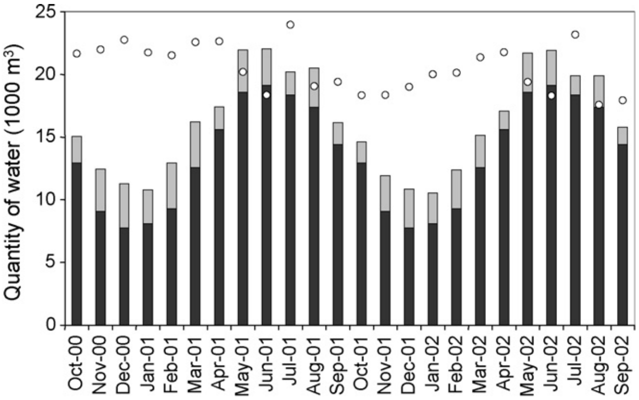

Fig. 8 – Fresh water resources as sum of spring outflow and precipitation (unfilled circles) and crop evapotranspiration in palm groves (black columns) and cropland (gray columns) at *Balad Seet* (Oman).

For wheat and sorghum differences between both types of indices were particularly large (Table 7). The crop water use index in palm groves was 0.17 kg m^{-3} for dates and 2.74 kg m^{-3} for harvested understory fodder.

3.5. *Effect of altitude and topography on potential evapotranspiration*

When simulating climate conditions of the fictive oasis at the same position but at mean sea level and without surrounding mountains, reference evapotranspiration increased by 35% from 1778 mm year^{-1} to 2393 mm year^{-1} (Table 8).

4. Discussion

4.1. *Methodology and data*

The modelling of evapotranspiration, crop water use indices and irrigation water use efficiency as conducted in this study bears several sources of uncertainty. First, the scarcity of data required their combination across different time periods assuming that the measured values were representative to be used across years. It is nevertheless obvious that these climate data do not represent the conditions in any specific year very well. However, it is well known that the interannual variability of climate in this part of the Arabian Peninsula is low since on the large majority of days bright sunshine predominates. A comparison of monthly mean temperatures for the years 2001–2003 at the Muscat airport (http://www.wunderground.com/cgi-bin/findweather/getForecast?-query=23.58,58.28) showed for example a maximal difference of 2.6 K (December 2001 compared to December 2003). The average monthly difference in mean temperature was 0.6 K when comparing year 2001–2002 and 0.9 K when comparing year 2001–2003. Monthly mean temperatures were correlated with an r^2-value of 0.97 (2001–2002), 0.93 (2001–2003) and 0.96 (2002–2003). The annual mean temperature was 27.9 °C in 2001, 28.1 °C in 2002 and 27.8 °C in 2003.

A second source of uncertainty is that radiation and sunshine measurements were not available for a complete year and missing values therefore had to be modelled. Also, it was impossible to compare the measured or modelled values to measurements taken in similar locations, as all the registered long-term measurement stations in the Sultanate of Oman are close to the coastline and at least 100 km away from *Balad Seet*. Nevertheless, a comparison of measured or assumed values for temperature and wind speed at *Balad Seet* to values reported by a newly established weather station at *Rustaq* indicates that the former values are reliable. Radiation measurements were found to be higher than at other weather stations of Oman (FAO, 2001a; Dorvlo and Ampratwum, 1998; Al-Hinai and Al-Alawi, 1995).

A simple sensitivity analysis was carried out to find out how the computed reference evapotranspiration changes as a function of climate input variables. One result of this analysis was that the method used to compute the reference evapotranspiration appeared to be relatively robust against measurement errors of temperature, while the computed evapotranspiration was very sensitive to changes of wind speed (Table 9). Based on the observation that there was no or only light wind on the vast majority of days in the oasis wind speed was set to a low level (constant at 1 m s^{-1}). It seemed unrealistic to reduce it further. In contrast an increase of wind speed would result in a larger evapotranspiration and thus in an even higher water use efficiency of the oasis, which proves

Table 7 – Crop evapotranspiration, dry matter yield and crop water use indices for alfalfa, wheat, barley, oat, maize, sorghum and garlic over the 2-year period at *Balad Seet* (Oman)

Crop	ET$_c$ (m^3)	Total dry matter yield (kg)		Crop water use index (kg m^{-3})	
		Grain[a]	Above-ground dry matter	Grain[a]	Above-ground dry matter
Alfalfa	11,878	[b]	19,750	[b]	1.66
Wheat	5,713	5,264	22,791	0.92	3.99
Barley	6,470	[b]	13,206	[b]	2.04
Oat	6,379	[b]	11,965	[b]	1.88
Maize	1,976	[b]	8,429	[b]	4.27
Sorghum[c]	12,174	7,766	45,265	0.64	3.72
Garlic	6,687	12,390	16,680	1.85	2.49

[a] Dry bulbs in case of garlic.
[b] Only vegetative parts were harvested as animal fodder.
[c] Only sorghum for grain production considered.

Table 8 – Monthly averages of daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), daily average temperature (T_{avg}), daily sunshine duration (n), daily solar radiation (R_s) and daily reference evapotranspiration (ET_0) at *Balad Seet* (Oman) after removing shadowing effects of mountains and surface cooling effect by the high elevation of the site

Month	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	n (h)	R_s (MJ m^2 day^{-1})	u (m s^{-1})	ET_0 (mm day^{-1})
January	32.8	15.3	22.8	8.5	15.3	1.43	3.86
February	35.5	19.0	26.9	8.6	18.8	1.76	4.99
March	37.5	21.7	30.0	9.0	21.6	1.86	5.86
April	42.1	22.9	32.4	9.7	26.1	1.96	7.61
May	46.0	26.4	36.4	10.5	27.9	2.06	8.74
June	50.5	30.4	40.4	10.8	27.0	2.16	9.50
July	46.6	32.3	38.8	10.6	26.1	2.28	8.61
August	46.8	30.2	38.3	10.3	24.8	1.97	8.06
September	44.7	27.7	36.3	10.0	21.9	1.97	7.11
October	43.0	23.6	33.0	9.6	20.3	1.69	6.18
November	36.8	20.6	27.6	9.3	16.9	1.44	4.43
December	33.7	17.7	24.4	8.7	14.6	1.38	3.67
Annual	41.4	24.0	32.3	9.6	21.8	1.83	6.56

Table 9 – Sensitivity of the computed reference evapotranspiration (ET_0) on changes of climate input variables at the oasis of *Balad Seet* (Oman)

Variable	Applied change	Change in annual ET_0 (%)
Temperature	Increase of all measurements by 1 K	+2
Temperature	Decrease of all measurements by 1 K	−1
Wind speed	Increase from 1 m s^{-1} to 2 m s^{-1}	+18
Wind speed	Decrease from 1 m s^{-1} to 0.5 m s^{-1}	−10
Sunshine duration	Use of sunshine duration to compute solar radiation instead of using measured solar radiation	−2
Solar radiation	Increase of all measurements by 10%	+6
Solar radiation	Decrease of all measurements by 10%	−6

one major finding of the study. Changes of measured solar radiation resulted in only moderate changes of evapotranspiration. Changes of sunshine duration did not have any effect on evapotranspiration since this variable was not used in the calculations (the calculation were based on measured solar radiation, see Eq. (6)). However, sunshine duration was used to test to some degree the integrity of the solar radiation measurements. For this purpose expected solar radiation was computed as

$$R_{sc} = \left(a_s + b_s \times \frac{n}{N}\right) R_a \qquad (12)$$

where R_{sc} is the computed solar radiation (MJ m^{-2} day^{-1}), n the sunshine duration (h), N the daylight hours (h), R_a the extraterrestrial radiation (MJ m^{-2} day^{-1}), a_s the fraction of extraterrestrial radiation reaching the earth on overcast days and the sum $a_s + b_s$ was the fraction of extraterrestrial radiation reaching the earth on clear days.

As recommended by Allen et al. (1998) a_s was set to 0.25 and b_s to 0.5. If the so computed solar radiation was used instead of the measured solar radiation annual reference evapotranspiration changed from 1778 mm to 1748 mm which is a decrease by about 1.7%. This difference is acceptable because the coefficients a_s and b_s need usually to be calibrated to fit local conditions.

The differences between astrological and simulated solar radiation (Fig. 7) was much smaller than the difference between astrological and simulated sunshine duration (Fig. 6) because solar radiation was highest at noon when the sun was always visible. In the morning and evening when the sun might be below the ridge solar radiation was much lower. Therefore, the fraction of solar radiation that might be ‘‘lost’’ in the morning and evening was relatively low. In contrast, the fraction of ‘‘lost’’ sunshine duration was equivalent to the fraction of the daytime when the sun was behind the mountains and in particular during winter time this fraction was high (see Fig. 5).

Any straightforward calculation of actual evapotranspiration from potential evapotranspiration (Section 2.2.) represents a very simplified approach. Usually modelling of actual evapotranspiration requires at least measurements of the actual soil water status (Doorenbos and Kassam, 1979) or the measurement of plant parameters like sap flow (Smith and Allen, 1996) or stomatal responses (Jarvis, 1976). However, some observations indicate that for our case the simplified version may be acceptable. First of all, the high nutritional status of the crops at *Balad Seet* (Buerkert et al., 2005) suggests that evapotranspiration might be at its full potential, if enough water was available. As surface runoff on the terraced soils can be excluded, water losses in the fields only occur by drainage into deep soil layers. The first assumption that has to be verified is that $ET_a = ET_0$ in times when more water is available than is usable by plants. This holds generally during winter time (Fig. 8). Assuming an average plant extractable water capacity of 16 vol% (Luedeling et al., 2005), a maximum evapotranspiration of 100 mm month^{-1} during winter time (Table 5) and a length of the irrigation cycle of 18 days, an effective soil depth of 37.5 cm would be needed to store enough water. This soil depth is given almost everywhere in the oasis. The other assumption is that all applied irrigation water is extracted by the plants in periods of water scarcity, which appear to be limited to summer time. Assuming a minimum effective soil depth of 40 cm, about 64 mm of applied water can be stored in the soil. Assuming a water application of maximum 20,000 m^3 per month (Fig. 8), about 10.5 ha cultivated land (8.8 ha palm groves and 1.7 ha cropland) and a length of the irrigation cycle of 9 days during summer time, the mean application rate would be 55.5 mm. Thus the assumption that there are no leaching losses during summer might hold.

The coefficients c_n and c_s used to compute actual sunshine duration (Eq. (8)) or actual solar radiation (Eq. (10)) should be smaller than 1 because potential sunshine duration and potential solar radiation computed when considering the shadow effect of the mountains should be further decreased by effects of cloudiness, fog or dust. However, in wintertime these coefficients were computed to be larger than 1 (Table 4). The measurements taken in this period also showed that measured sunshine duration and radiation (Figs. 6 and 7) were often larger than the respective computed potential values. This indicates problems with the precision of the used digital elevation model. Indeed numerous altitude measurements taken by differential GPS south of *Balad Seet* confirmed differences of up to 100 m between measured elevation and altitude derived from the DEM (Luedeling, unpublished). Therefore, coefficients c_n and c_s not only represent corrections for cloudiness or turbid air but also corrections of the used DEM. As a consequence, these coefficients could not be used to calculate the effects of altitude and topography on evapotranspiration (Section 2.6).

4.2. Assessment of results

The computed annual reference evapotranspiration of 1778 mm $year^{-1}$ was much lower than evapotranspiration computed for other locations in northern Oman. Scientists at FAO computed the reference evapotranspiration for *Muscat* at 2287 mm $year^{-1}$, for *Sohar* at 2604 mm $year^{-1}$ and for *Sur* at 2314 mm $year^{-1}$ (FAO, 2001b). The lower reference evapotranspiration given by our model is clearly an effect of the local climate as driven by the high altitude of the site and the shadow effect of the surrounding mountains. Annual evapotranspiration computed after removing these effects was 2393 mm $year^{-1}$ and thus very close to the values reported for *Muscat* and *Sur*.

The IWUE of 0.75 for the entire oasis was surprisingly close to the IWUE at *Falaj Hageer* reported by Norman et al. (1998). The high values at both locations indicate that water use efficiency in traditional Omani mountain oases might be much higher than previously assumed, although farmers use surface irrigation methods. A high IWUE, the location of the oasis close to the springs and the reduced reference evapotranspiration show the adaptation of the oasis system to the harsh environmental conditions. An important reason why the efficiency in those mountain oases is high might be the small size of the irrigation basins (on average only 1.7 m^2 for field crops). The surface irrigation system described here allows a demand-oriented application of the water which is completely different from systems where the basins are some hectares large (such as in Egypt) and where a significant amount of irrigation water is lost due to drainage in deeper soil layers. The water flows in the aflaj which are all cemented and thus do not have the typical seepage losses of unlined canal systems were measured at the entrance to the storage basins close to the fields so that conveyance losses between the measurement point and the fields should be low.

The results of this study also indicate, that IWUE could be even larger than 0.75 if more cropland was cultivated during winter. The plants needed only about 60% of the available water resources for evapotranspiration (Fig. 8). Numerous abandoned fields at *Balad Seet* and the records of the farmers provide evidence that in the recent past more cropland was in use (Nagieb et al., 2004).

Average annual evapotranspiration in palm groves (18,545 $m^3\,ha^{-1}\,year^{-1}$) was larger than that of cropland (6781 $m^3\,ha^{-1}\,year^{-1}$), because palm groves are growing also in the hot summer season whereas large parts of the cropland areas are left fallow during this period. As Norman et al. (1998) have described, arable cropland is only being used to cultivate non-perennial field crops when there is excess water. Therefore, the use of different portions of the available cropland in different times of the year allows the oasis inhabitants to adapt their use of irrigation water to the available flow of the springs. As a consequence, the ratio of cropland to palm groves could be used as an indicator to quantify the amount and variation of spring flows in other traditional mountain oases. Evapotranspiration computed for palm groves may thus only represent the long-term minimum spring flow, whereas maximum evapotranspiration on total agricultural land would reflect usable spring flow in years of big rains. According to the oral records of the farmers at *Balad Seet* such a strong rain event, which may lead to a profound recharge of the groundwater reservoir occurs on average every 6 years. The last strong rain event was reported for 1997. In a typical drought period spring flow from antecedent precipitation was computed to decline at a rate of about 3% per month (Nagieb et al., 2004). By using the average evapotranspiration for the period June–August the expected minimum spring flow at *Balad Seet* was estimated at 609 $m^3\,day^{-1}$, while the expected maximum usable spring outflow was as high as 843 $m^3\,day^{-1}$. The observed variation in spring outflow between October 2000 and September 2002 ranged from a maximum of 734 $m^3\,day^{-1}$ in December 2000 to 558 $m^3\,day^{-1}$ in September 2002. This means that water supply to the plants would be below the optimum in hot summer months without monsoon-driven precipitation.

Results of other studies performed in *Wadi Tiwi* (Korn et al., 2004) or *Wadi Khabbah* (Siebert et al., 2005) support the hypothesis that a low cropland/palm groves area ratio indicates the existence of water rich oases or oases with stable water flows, whereas a high ratio indicates a large inter-annual variability of given water resources. However, more research is certainly needed to verify this.

The computed crop water use index (CWUI) for wheat grain yield is with 0.92 $kg\,m^{-3}$ lower than the median of 412 experiments collected from 28 different sources all over the world by Zwart and Bastiaanssen (2004), which was reported to be 1.02 $kg\,m^{-3}$. However, the latter values refer to air-dry grain yields, whereas in this study the values refer to total dry matter. At *Balad Seet* CWUI for wheat would be 1.02 kg m^{-3} if it was based on air-dry grain yield.

For forage crops CWUIs were higher than respective values measured by Al-Lawati and Esechie (2002) for maize (2.24 kg m^{-3}) and Rhodes grass (0.91 kg m^{-3}) in the *Batinah* region near Muscat. At *Balad Seet* CWUIs amounted to 4.27 kg m^{-3} for maize, to 1.66 kg m^{-3} for alfalfa, to 1.88 kg m^{-3} for oats and to 2.04 kg m^{-3} for barley which may have several reasons. The trial at the research station near *Muscat* was carried out only during winter as in the *Batinah* region commonly crops are only grown in the winter season to save irrigation water. However, maize and Rhodes grass are C_4-crops and could therefore be more productive during summer season. At *Balad Seet* maize was grown in the winter and in the summer season. Another reason may be that compared to the use of modern short stature varieties in the *Batinah*, farmers at *Balad Seet* used local landraces with a much lower harvest index (see the ratio of grain yield and above-ground biomass harvest for wheat and sorghum in Table 7).

Unfortunately, there are no comparative crop water use indices for sorghum, dates and garlic grown under Omani conditions. However, yields for sorghum and dates at *Balad Seet* are close to the country's averages as reported by FAO (2005) and Omezzine et al. (1998). Due to the lower evapotranspiration at *Balad Seet* compared to the country's average evapotranspiration, it may be expected that CWUI-values for these crops are also higher at *Balad Seet* than for the average of the country.

5. Conclusions

The data indicate that altitude and shading by mountains have a large effect on crop evapotranspiration. Therefore, a combination of high resolution land use data and digital elevation models would be needed to reliably model irrigation water requirements for larger regions or the entire country of Oman.

The measurements of climatic data taken at *Balad Seet* indicate that climate conditions in the interior of Oman differ considerably from values measured by the registered long-term measurement stations along the coastline. To reduce the uncertainty of modelling studies of water use in the interior of the Arabian Peninsula, it would thus be necessary to also establish long-term climate stations in regions distant from the coastline.

The observed high water use efficiency, the apparent sustainability of land and water use, the comparatively little competition for water by other users and the wealth of cultural heritage to be preserved call for a more systematic support of *Aflaj* agriculture in remote mountain oases of Oman. This may require a reassessment of prevailing public policies which focus on the agricultural systems of the country's coastal plain.

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