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REGULAR ARTICLE

Effects of land use changes on the hydrological sustainability of mountain oases in northern Oman

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Abstract Traditionally, oasis farmers in hyperarid northern Oman have adapted to the interannual variation of irrigation water supply by dedicating an often sizable proportion of the agricultural area to the production of annual crops and leaving this area uncultivated in drought years. We hypothesized that increases in the share of perennial crops may put long-term hydrological sustainability at risk. To test this hypothesis, we compared agricultural water demand patterns of five oases in the mountain region of Al Jabal al Akhdar for 1978 and 2005. We analyzed land use changes by classifying aerial photographs taken in 2005 and 1978 into five land use types. Water demand in 2005 was estimated based on two GIS-based detailed crop inventories during the hot and cool season and on measurements of temperature, solar radiation and wind speed, from which crop evapotranspiration was calculated using the Penman–Monteith equation. Radiation and wind speed measurements were improved by topographic modeling. Water demand per area was summarized for each land use type and the results used to estimate water demand in 1978. Water supply estimates were based on spring flow measurements. Between 1978 and 2005, agricultural water demand in the study area rose from 218,800 to 256,377 $m^3 a^{-1}$. The most prominent land use changes were the disappearance of non-palm orchards at Masayrat ar Ruwajah and expansions of the area under perennial crops at Al ‘Aqr, Ash Sharayjah and Qasha’ at the expense of field crops. As a consequence, the summer peak of crop water demand decreased at Masayrat ar Ruwajah, where all perennial crops could easily be irrigated with the minimum water supply observed during our study, but this summer peak increased at the other oases. Meeting the water demand of all perennial crops at Qasha’ required average spring flow conditions in 2005, indicating severe water deficiency in drought years. In addition to increased water demand, the oases’ water balance might also be under pressure from reductions in water supply caused by increased extraction of water from the same aquifer by a rapidly growing new town in the area.

Keywords Al Jabal al Akhdar · Evapotranspiration modeling · Falaj · NUATMOS · Penman–Monteith · Transformation process

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Introduction

The climate of northern Oman is hot and hyperarid. Mean annual temperatures range between 18°C in the high mountains and 28°C in the lowlands (Fisher 1994), with maximum values frequently exceeding

40°C in the summer (Dorvlo and Ampratwum 1998). Rainfall is very scarce and erratic, with mean annual precipitation varying between 39 and 312 mm among stations in Oman, and coefficients of variation of the annual rainfall between 48 and 162% (Fisher 1994).

Today most agricultural areas in the country, which total less than 0.3% of the land area (FAO 2007), are irrigated with groundwater pumped up to the surface of the coastal plain. Traditional agricultural systems, however, did not have that option and were thus confined to specific hydrological settings, where water accumulated and was dispensed over longer time spans (Luedeling and Buerkert 2008). Where water surfaced naturally or could be harvested by carving tunnels into storage rock formations, farmers collected it and directed it to the cropping areas through a system of irrigation channels, called aflaj in Arabic (Sing.: falaj) (Costa 1983). On irrigated terraced fields, farmers cultivate date palms (*Phoenix dactylifera* L.) and other tropical and subtropical crops, along with vegetables and fodder for the goats, sheep, camels and cattle that are traditionally kept in the oases (Luedeling et al. 2005).

Several studies have shown that traditional oasis agriculture in Oman is very water-efficient. Estimates of its water use efficiency range between 60 and 98%, for several plots in Wadi Bani Kharus (Norman et al. 1998), while Siebert et al. (2007) computed a water use efficiency of 75% for the oasis of Balad Seet in Wadi Bani Awf. Given the large variation in potential evapotranspiration over the course of a year (Siebert et al. 2007), such high efficiencies cannot be achieved without adaptations to the changes of the seasons. While date palms such as at Balad Seet require irrigation throughout the year, farmers can compensate for the higher water requirements of these perennials during the summer by reducing the area under field crops (Siebert et al. 2007). Such adaptations can be observed in all traditional settlements, except where water is so abundant that there is no shortage during the summer. An example of such a setting with ample year-round water supply is the line of oases along narrow Wadi Tiwi (Korn et al. 2004), where space rather than water is the limiting factor for crop production. While typically most of the oasis area is covered by perennial orchards, there is almost always a sizeable proportion under field crops, which can be adjusted between and within years as a response to falaj flow.

Many of the most remarkable traditional settlements lie in the mountains, where they receive their irrigation water from permanent springs emerging from limestone aquifers (Glennie et al. 1974; Luedeling and Buerkert 2008). While the cropping patterns of most mountain oases differ little from those of the date palm-dominated lowland settlements, several oases in the remote high-altitude region of Al Jabal al Akhdar rely on the production of pomegranates (*Punica granatum* L.), peaches (*Prunus persica* L.), roses (*Rosa damascena* L.) and other crops typically found in temperate and cool subtropical regions (Fig. 1; Scholz 1984; Gebauer et al. 2007). Due to the remoteness of their locations, these oases retained their traditional cropping systems, until political changes in the 1970s led to the rapid modernization of Oman's economy and infrastructure. In recent decades, the high-mountain farmers were connected to the markets of the lowlands by a new access road, leading to increasing imports of basic foodstuffs and exports of high-value agricultural products, such as rose water and fresh fruit. These changes brought about shifts in the spectrum of cultivated crops, leading to an abandonment of cereal production and an expansion of deciduous orchards. Oasis life was further affected by more and more farmers either emigrating to the cities of the lowlands or moving to the new town of Sayh Qatanah, which was constructed in the immediate vicinity of the traditional settlements, satisfying its water needs from the same aquifer that is feeding the agricultural systems. Further land use changes were caused by the spread of Witches' Broom of Lime, a phytoplasma disease (Garnier et al. 1991), which almost eradicated lime trees (*Citrus aurantiifolia* (L.) Swingle) in Oman (Khan and Grosser 2004).

The seemingly fine balance in Omani oases between orchards and field crops, with the orchard area apparently correlating with the long-term minimum water supply that can be relied upon, leads to our hypothesis that the recent and on-going land use changes put the hydrological sustainability of the traditional land use systems at risk. Recently, many farmers of the villages in our study area have complained about water shortages, for which they mostly blamed insufficient rainfall. While reliable rainfall data for the past few years is lacking, several major rainstorms in recent months and measurements of high subsequent spring flows make it unlikely that

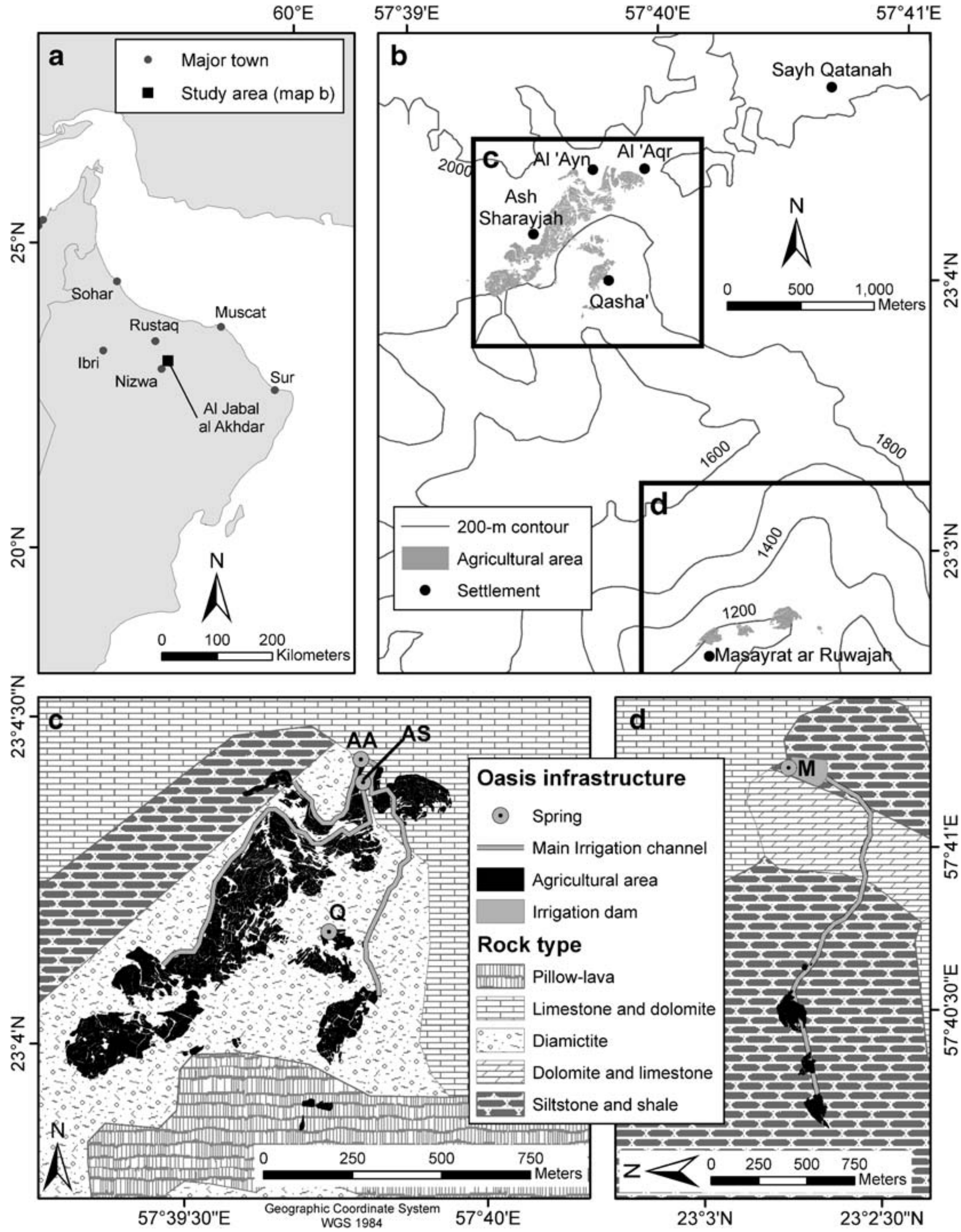

Fig. 1 Location of the study area in Oman (**a**), overview of the oasis sites and their topographic settings (**b**), and geologic settings and oasis infrastructure of the upper oases (**c**) and Masayrat ar Ruwajah (**d**). In maps **c** and **d**, *AA* indicates the location of the spring feeding Al ‘Ayn, Al ‘Aqr and most of Qasha’, *AS* is the spring of Ash Sharayjah, *Q* is the small spring at Qasha’ and *M* indicates the location of the spring and irrigation dam at Masayrat ar Ruwajah

lack of precipitation is the only factor putting the oases’ water balance under pressure. Rainfall records given by Fisher (1994) also indicate that periods of at least two subsequent years of annual rainfall of well under 100 mm, a third of the long-term average, are not uncommon in this region, and there is no historic evidence that in the past oasis systems suffered excessively during such periods. We therefore hypothesized that above all else, the observed land use changes in the oases have led to increased agricultural water demand and to a less favorable seasonal distribution of water use. The objective of this study therefore was to quantify the impact of recent and ongoing land use changes on crop water demand as they affect overall hydrological sustainability of the oases of Al Jabal al Akhdar.

Materials and methods

Study sites

The study was conducted in five mountain oases in Al Jabal al Akhdar, the highest agricultural area in the Sultanate of Oman (Scholz 1984; Gebauer et al. 2007). Three of the oases, the villages of Al 'Aqr (57° 39'58"E, 23°04'22"N, 1,950 m a.s.l.), Al 'Ayn (57° 39'44"E, 23°04'22"N, 1,900 m a.sl.) and Ash Sharayjah (57°39'30"E, 23°04'10"N, 1,900 m a.s.l.) lie at the top of a large eroded basin at the edge of the Sayq Plateau, a large dissected plain at an altitude above about 1,950 m a.s.l. (Fig. 1). The ground surface of the plateau consists of Late Permian to Middle Cretaceous limestones of the Hajar Supergroup, and all important springs of the area emerge from the unconform geologic boundary at the bottom of the lowest formation in this unit (Luedeling and Buerkert 2008). The agricultural areas of the three highest oases of our study are fed by two springs which emerge from this setting. The terraced fields lie directly below the level of the springs, along the slope of the eroded basin (Fig. 1c). The terraced area of Ash Sharayjah amounts to 13.5 ha, Al 'Aqr has 1.7 ha and the farmers of Al 'Ayn cultivate 1.4 ha.

Below this set of oases lies the settlement of Qasha' (57°39'50"E, 23°04'00"N, 1,640 m a.s.l.). Qasha's 2.1 ha of terraced fields obtain their water from one of the springs at Al 'Ayn, from where the water flows through a steep channel down to the oasis. One smaller spring in the valley adds to Qasha's water supply (Fig. 1c).

The lowest oasis, Masayrat ar Ruwajah (57° 40'13"E, 23°02'37"N, 1,030 m a.s.l.), lies about 900 m below the plateau in a deeply incised wadi. Its agriculture is characterized by date palms and other tropical and subtropical crops, corresponding closely to the farming system described by Nagieb et al. (2004) for the oasis of Balad Seet at the upper end of Wadi Bani Awf. The oasis' water supply is ensured by a single spring emerging from a similar setting as in the upper oases. From the inaccessible spring site, the water falls several hundred meters into a dam, from where it is conducted to the fields through a falaj of more than 2 km length (Fig. 1d).

Assessment of current and historic land use

To determine current land use, we took aerial images of the oasis area using a digital camera mounted on a model plane (Buerkert et al. 1996; Schäper 2006). Photographs were taken from flight altitudes ranging from several hundred meters to 1.5 km, providing a complete coverage of the entire oasis area, as well as sufficient detail to map land use on the ground. For georeferencing these photographs, DGPS (Differential Global Positioning System) ground-truthing information was collected using two Trimble Pathfinder Pro XRS receivers (Trimble Navigation Ltd., Sunnyvale CA, USA) as field rover and base station. The photographs were then rectified using ERDAS Imagine 8.5 (Leica Geosystems GIS & Mapping LLC., Norcross, GA, USA).

Based on the maps obtained through this process, a detailed field survey was carried out, during which all terraces of the five oases were visited and all trees were counted and classified by species (Gebauer et al. 2007). Areas covered by field crops were also registered on two occasions, in April and September of 2006, to account for different cropping patterns during the summer and winter season.

In addition to this detailed survey, we classified vegetation of each terrace based on the appearance of the terrace on the aerial photograph. Since for most tree and field crops, the crop species could not be determined on the images, all terraces were assigned one of five classes that could be visually distinguished with sufficient certainty. The resulting land use classes were 'rose gardens', 'date palm orchards', 'other orchards', 'field crops' and 'bare ground'.

Historic aerial images of all oases except Masayrat ar Ruwajah were obtained from an archive of such images set up by Prof. Fred Scholz (Free University of Berlin, Germany), who studied the development of Oman and its oases since the 1970s. All images were taken in 1978 and showed all upper oases in sufficient detail for coarse classification. For Masayrat ar Ruwajah, no such aerial image was available, but since the oasis lies in a deep valley, its whole extent was captured by a panoramic photograph taken by Prof. Scholz during an expedition to the area in 1976. Several photographs from the same and one subsequent expedition, as well as two color plates from a 1981 issue of National Geographic, which featured an article about Oman (Abercrombie 1981), helped in the assessment of historic land use. As described for current land use, we classified vegetation in the oases into the five classes mentioned above.

Evapotranspiration modeling

For modeling crop evapotranspiration (ET_c), we used the Penman–Monteith equation (Penman 1948; Allen et al. 1998), in the standardized version of the American Society of Civil Engineers (ASCE 2005):

$ET_c = k_c \cdot ET_{sz}$, with k_c being a crop-specific coefficient and ET_{sz} being the standardized reference evapotranspiration.

We preferred the Penman–Monteith method over other methods to estimate evapotranspiration, such as the Hargreaves–Samani (Hargreaves and Samani 1982) and Priestley–Taylor (Priestley and Taylor 1972) methods, because it can be adjusted to account for topography-induced differences in solar radiation and wind speed. Due to the rugged topography of Al Jabal al Akhdar, such differences are likely to be of great importance in the study region. Furthermore, crop coefficients for this equation have been determined and published for many crops (Allen et al. 1998), so that little experimental field work was required for modeling water demand. The standardized reference evapotranspiration in the equation can be calculated solely from geographic and climatic parameters. ASCE (2005) gives the basic form of the equation as:

$$ET_{sz} = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{C_n}{T+273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + C_d \cdot u_2)},$$

with

- R_n calculated net radiation at the crop surface (MJ m^{-2} day^{-1}),
- G soil heat flux density at the soil surface (MJ m^{-2} day^{-1}),
- T mean daily temperature at 1.5 to 2.5 m height (°C),
- u_2 mean daily wind speed at 2 m height (m s^{-1}),
- e_s saturation vapor pressure at 1.5 to 2.5 m height (kPa),
- e_a mean actual vapor pressure at 1.5 to 2.5 m height (kPa),
- Δ slope of the saturation vapor pressure–temperature curve (kPa °C^{-1}),
- γ psychrometric constant (kPa °C^{-1}),
- C_n numerator constant (K mm s^3 Mg^{-1} day^{-1}),
- C_d denominator constant (s m^{-1}).

Most of the parameters required by the equation are difficult to measure directly in the field, but according to ASCE (2005), they can be calculated from variables that can easily be assessed. Following these recommendations, R_n was calculated as the difference between net short-wave radiation (R_s) and net outgoing long-wave radiation (R_{nl}), both of which were derived from a range of equations given by ASCE (2005). Determination of R_{ns} required measured net short-wave radiation (R_s) and an albedo constant, which in the standardized procedure is set to 0.23. Calculation of R_{nl} is based on three-dimensional site coordinates (latitude ϕ, longitude δ and elevation z), measured temperatures (minimum temperature T_{min} and maximum temperature T_{max}), time (day D, month M and year Y) and the solar constant of 4.92 MJ m^{-2} h^{-1} (ASCE 2005).

Since evapotranspiration modeling was done for monthly intervals, the soil heat flux density G was computed as $G(T_{month-1}, T_{month+1}) = 0.07 \cdot (T_{month+1} - T_{month-1})$, with $T_{month-1}$ being the mean temperature of the previous month and $T_{month+1}$ the mean temperature of the following month (ASCE 2005).

Rather than computing mean daily temperatures T as the arithmetic mean of all measured temperatures, we follow the recommendations by FAO (Allen et al. 1998) and ASCE (2005), calculating T as

$$T(T_{\min}, T_{\max}) = \frac{T_{\min} + T_{\max}}{2}$$

Saturation vapor pressure e_s was derived from measured temperatures as

$$e_s(T_{\min}, T_{\max}) = 0.5 \cdot \left(0.6108 \cdot e^{\frac{17.27 \cdot T_{\max}}{T_{\max}+237.3}} + 0.6108 \cdot e^{\frac{17.27 \cdot T_{\min}}{T_{\min}+237.3}}\right)$$

(ASCE 2005).

Our estimate of mean actual vapor pressure e_a is based on an estimate of the dew point temperature T_{dew}, for which the daily minimum temperature is reduced by 2°C. Because of the non-standard conditions, with largely barren landscape around our study sites, measured dew points or relative humidity were discarded and the simplified calculation was applied instead (Allen et al. 1998; ASCE 2005). Mean actual vapor pressure was thus calculated as

$$e_a(T_{\min}) = 0.6108 \cdot e^{\frac{17.27 \cdot (T_{\min}-2)}{T_{\min}-2-237.3}}$$

(ASCE 2005).

The slope of the saturation vapor pressure–temperature curve Δ was calculated as

$$\Delta(T) = \frac{2503 \cdot e^{\frac{17.27 \cdot T}{T+237.3}}}{(T+237.3)^2}$$

(ASCE 2005).

For estimating the psychrometric constant γ, we used the following equation:

$$\gamma(z) = 0.00065 \cdot 10.1.3 \cdot \left(\frac{293 - 0.0065 \cdot z}{293}\right)^{5.26}$$

with z = site elevation (ASCE 2005).

From the two reference vegetation types given by ASCE (2005), we chose the tall vegetation type, because vegetation in the oases of Oman resembles much more closely alfalfa than clipped grass in terms of crop height and vigor. Accordingly, the numerator constant C_n was set to 1,600 and the denominator constant C_d to 0.38.

After all of these substitutions the standardized reference evapotranspiration was calculated by a function of 12 variables.

$$ET_{sz} = ET_{sz}(\varphi, \delta, z, D, M, Y, T_{\min}, T_{\max}, T_{month-1}, T_{month+1}, R_s, u_2)$$

Thus, only four climatic variables, T_{min}, T_{max}, R_s and u_2, remained to be determined in the field, with $T_{month-1}$ and $T_{month+1}$ being derived from these measurements.

Crop coefficients k_c

Crop coefficients were assigned to each crop according to the appropriate table of Allen et al. (1998). For the lengths of crop development stages, we also referred to this report, but adapted the growing periods to local conditions as observed in the field. Where crop coefficients for a crop were unavailable, we used k_c values for the crops in the FAO list, for which growth habits corresponded most closely to the crops we encountered. For pomegranates, this required using the growth stages of deciduous orchards and the crop coefficients of the 'Apricot, Peaches, Stone Fruit' category from the FAO table. For roses, we used the same crop coefficient, but accounted for the shorter period of cultivation by using only half the stage length recommended for deciduous orchards. The duration of water use by roses was thus reduced from 240 days to 120 days, which corresponds well to our field observations, according to which these crops are mainly irrigated between January and April. Between May and August/September, roses receive about one irrigation per month to sustain their vegetative growth. We approximated this irrigation regime by setting k_c to 0.3 for June to August and 0.15 for September.

We determined the start and end month of the growing season for each crop by interviewing farmers and observing cultivation patterns in the field. To account for the temporal variation in field cultivation among farmers, we used three different starting dates for each crop. Starting dates were set to the estimated average planting date, and dates for early and late planters set to 2 weeks before and after this date. We assumed that one third of all farmers planted their crops at each of these three points in time. For fodder crops, which are replanted after harvest, each cultivation interval started 5 days after the harvest of the previous crop.

As recommended by Allen et al. (1998), crop coefficients were adjusted to account for crop height and deviations of wind speed and relative humidity from the standard values of 2 m s^{-1} for wind speed and 45% for minimum relative humidity, for which the k_c values given by Allen et al. (1998) have been calibrated. We consequently adjusted $k_{c\ end}$ and $k_{c\ mid}$ as:

$$k_c = k_c(table) + [0.04(u_2 - 2) - 0.004 \cdot (RH_{\min} - 45)] \cdot \left(\frac{h}{3}\right)^3,$$

with u_2 being the mean wind speed of the site, RH_{min} an estimate of the mean daily minimum of relative humidity and h the approximate crop height.

Mean wind speeds for Al 'Ayn, Al 'Aqr, Ash Sharayjah and Qasha' were derived from the wind speed grid described below, from which we calculated the mean wind speed for the entire area of each oasis. Measurements of relative humidity were taken, but yielded monthly minima that often were below 10% and monthly means of between 20 and 70%. Since the minima of relative humidity were mostly lower than the range of RH_{min} allowed as input for the k_c adjustment equation, we decided to substitute our measurements by setting RH_{min} to 20%, corresponding to conditions expected in such an arid area (Allen et al. 1998). Crop height was set to 1 m for field crops, 2 m for roses, 10 m for date palms and 5 m for all other tree crops. Adjustments added to the k_c values for each oasis and crop type are summarized in Table 1.

For all months between December and May, we assigned crop coefficients according to the crop identified during the April survey, and for the remaining months, we used the coefficients corresponding to the crops encountered in September. Crop coefficients were calculated for every day of the year, and averaged for each combination of month, crop and oasis.

Measurement of climatic parameters

Since modeling evapotranspiration requires information about the insolation of a site, we measured solar radiation using a small weather station (Weather Station III, O. Feger, Traunstein, Germany). The station's pyranometer was placed at a well exposed location on the roof of the Agricultural Extension Service station in the town of Sayh Qatanah (57°40’36”E, 23°04’51”N, 2,009 m a.sl.). Data were recorded at 10-min intervals for a period of 1 year between January and December of 2006.

For determining minimum, mean and maximum temperatures, we used HOBO Pro data loggers (Onset Computer Corp., Pocasset, MA, USA), which were installed in the gardens of Al ‘Ayn (57°39’48”E, 23°04’21”N, 1,900 m a.s.l.), Qasha’ (57°39’46”E, 23°04’02”N, 1,640 m a.s.l.) and Masayrat ar Ruwajah (57°40’13”E, 23°02’40”N, 1,030 m a.s.l.). Loggers were placed in standard wooden cases designed for weather stations and positioned 1.5 m above terraces cropped with alfalfa (Al ‘Ayn and Masayrat ar Ruwajah) or annual fodder grasses (Qasha’). Temperatures were recorded at half-hourly intervals between February 2005 and April 2007 at Al ‘Ayn, between March 2005 and May 2007 at Masayrat ar Ruwajah and between April 2005 and April 2007 at Qasha’. Because the logger at Qasha’ disappeared between April and September 2006, data for this time span could not be recorded for this oasis. We therefore chose to consider temperatures between April 2005 and March 2006 as measurements for 1 year. The measurement periods for radiation and temperature thus do not completely match, but due to the homogeneous clear sky conditions that prevail almost throughout the entire year, we consider the monthly averages of our radiation measurements representative of the period, during which temperature was recorded.

Wind speed measurements were taken between April and June of 2007 at a well exposed location in the gardens of Ash Sharayjah (57°39’32”E, 23°04’06”N, 1,853 m a.s.l.) using the anemometer of a WatchDog 2700 Weather Station (Spectrum Technologies Inc., Plainfield, IL, USA). Data recorded on June 5th and June 6th were discarded, because they were affected by the tropical cyclone Gonu, which led

Table 1 Adjustments to the k_c values for crops in Al ‘Aqr, Al ‘Ayn, Ash Sharayjah, Qasha’ and Masayrat ar Ruwajah, Oman, calculated from crop height, mean wind speed and the estimated mean minimum of relative humidity

	Mean wind speed ($m\ s^{-1}$)	Estimated RH_{min} (%)	Adjustments to k_c (crop height)			
			Field crops (1 m)	Roses (2 m)	Trees (5 m)	Date palms (10 m)
Al ‘Aqr	0.59	20	0.03	0.04	0.05	–
Al ‘Ayn	0.71	20	0.03	0.04	0.06	–
Ash Sharayjah	0.72	20	0.04	0.04	0.06	–
Qasha’	0.75	20	0.04	0.04	0.06	–
Masayrat ar Ruwajah	0.68	20	0.03	–	0.06	0.07

Note that relative humidity was estimated, because the range of values measured in the field was unrealistic to wind speeds that were far above what would be measured during a normal year.

Wind speed modeling

To estimate site-specific wind speeds, we used an adapted version of the diagnostic windfield model NUATMOS 5 (Ross et al. 1988), which Bachmann (1998) had adapted for use in combination with the GIS package ARC/INFO (ESRI Inc., Redlands, CA, USA). Since an ARC/INFO license was not available, we modified the model's FORTRAN code to work as a stand-alone application. We also adapted the model to work with larger grids than were allowed in the original version, which appears to have been programmed for computers with much lower processing capacity than today's machines.

As inputs, the NUATMOS model requires a digital elevation model (DEM) and observations of wind speed and wind direction from the area, for which winds are to be modeled. As outputs it produces one grid of wind speeds and another one of wind directions. Bachmann (1998) modified the source code, so that his version of the model works with ASCII grids, which can easily be imported into and created by ArcGIS.

We used the DEM of Luedeling et al. (2007), who filled gaps in the elevation model obtained by the Shuttle Radar Topography Mission (SRTM) using topographic information extracted from Russian military maps. This model was improved using a local high resolution dataset, from which altitude lines were digitized and interpolated to form a 10-m DEM. This model was then merged, using a TIN-based delta surface approach (Luedeling et al. 2007), with the SRTM-based model, which had been resampled from its original resolution of 81 to 10 m. Since high-resolution elevation information had only been mapped for part of our study area, the level of topographic detail in the model varies and is substantially lower for the area around Masayrat ar Ruwajah and Al ‘Aqr.

Since the NUATMOS model only allows calculations of instantaneous windfields rather than average wind speeds over longer time spans, we followed the approach by Bowling and Lettenmaier (1997) and calculated distinct windfields for the main wind patterns encountered in our study area. To determine these patterns, we used SPSS 14.0 (SPSS Inc., Chicago, IL, USA) to perform a two-way cluster analysis on wind speeds and wind directions observed by our anemometer. Using wind direction and wind speed as inputs for this analysis is problematic, because of the difficulty of dealing with the wind direction. Wind direction is given in degrees on a 0 to 360 scale, with directions on the low and high end of this scale being northerly directions. While such directions are very similar, they are certain to be separated by a cluster analysis. Therefore, we converted wind directions and speeds into the wind's easterly (v_E) and northerly (v_N) components by applying the following transformations:

$v_E = v_{wind} \cdot \sin\beta$ and $v_N = v_{wind} \cdot \cos\beta$, with v_{wind} being the wind speed and β the wind direction in degrees.

The number of clusters is automatically determined by the software, delivering the main wind situations encountered in the area. After running the NUATMOS model for each of these settings, we calculated an average wind speed, weighted by the frequency, at which the different wind patterns occurred. One anomaly in the calculated windfield consisted of a sudden peak of wind speeds that were about ten times higher than anywhere else in the study area and partly overlapped with the oasis of Masayrat ar Ruwajah. This area was cut out of the grid and replaced by interpolated values. The cause of this anomaly, which covered about 6 ha, with 1 ha overlapping with the oasis, seemed to be the presence of a very steep slope adjacent to the oasis.

Modeling of solar radiation

Solar radiation was modeled for monthly intervals using the standard tool provided by the Spatial Analyst extension for ArcGIS 9.2 (ESRI Inc., Redlands, CA, USA). The model requires inputs of latitude, sky size, diffuse proportion of the radiation, transmittivity of the atmosphere and a digital elevation model. Furthermore, it requires information on whether or not to incorporate the effects of slope and slope bearing (aspect) on insolation. We modeled radiation based on the elevation model described above using the default settings for the simulation. Since all agricultural production in our study region happens on terraced fields, which have been well leveled for the flood irrigation typically practiced in the oases, we did not differentiate between different slopes or aspects. Variation of radiation is thus mostly due to different levels of shading caused by the surrounding topography.

Rather than modifying the radiation settings in the ArcGIS tool, we adapted the modeled radiation to local conditions using our own measurements of radiation. To this end, we divided the modeled radiation grid by the radiation calculated for the measurement site. This normalized radiation grid was then multiplied by the radiation measured at the site. For some months, measured radiation was higher than modeled radiation (Fig. 2). In these cases, we used only the modeled radiation as input for the Penman–Monteith equation, since higher values would be difficult to explain and are probably caused by reflections from the area surrounding the pyranometer rather than by elevated solar radiation. The output of these calculations was a set of 12 grids containing the site-specific monthly radiation for the entire study area at a resolution of 10 m.

Water availability

Spring flow of all oases was estimated using the methodology described by Nagieb et al. (2004). For the spring feeding the gardens of Al ‘Aqr, Al ‘Ayn and Qasha’, as well as for the separate spring at Qasha’, measurements were based on a volumetric method, in which we determined the time it took to fill containers of known volume. Because of strong spring flow and unsuitable topography for this method, the flow of the aflaj of Masayrat ar Ruwajah and Ash Sharayjah could only be approximated by repeatedly measuring the speed of a floating device on the water surface and multiplying this speed by the diameter of the channel. We estimated the average and minimum falaj flow based on monthly measurements carried out between December of 2006 and August of 2007. The highest flow of each falaj was discarded, because this flow measurement was taken directly after heavy rainfall, so that the flow did not represent normal conditions.

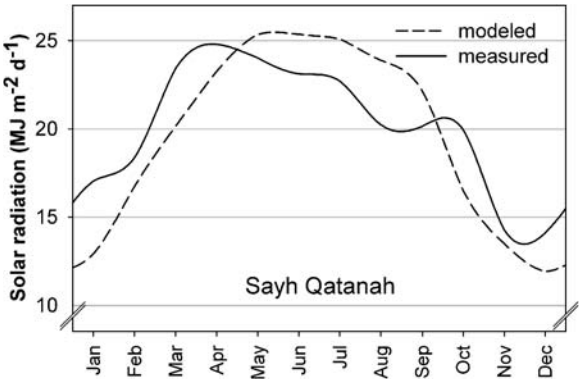

Fig. 2 Measured and modeled radiation for the town of Sayh Qatanah, Oman, between January and December of 2006

Despite the extreme aridity of our study region, occasional heavy rainfalls occur. These are, however, so erratic that direct assessment during the short period of our study would hardly be representative of average conditions. We therefore used a 12-year average calculated by Fisher (1994), who reported mean annual precipitation in this region to be 312 mm. In addition to the spring flow, this water is also available for crop production. We accounted for this source by adding the mean monthly rainfall as derived from this average on top of the average spring flow of the oases for estimating water availability during an average year. Even though the climate diagram presented by Fisher (1994) shows two pronounced rainfall peaks in February and August, we chose to assume an even distribution, because the detailed rainfall records presented in the same study indicate that these peaks are owed to very few exceptionally humid months within the observation period of 12 years. As reference area for estimating the amount of water derived from rainfall, we used at each site the entire oasis area, excluding all areas classified as bare soil. To estimate the minimum water supply of the oases, we extracted the minimum flow from the spring flow dataset and calculated available water based on this flow rate. To this estimate, we did not add any rainfall, because long dry-spells of several months are frequent and, because of the coupling of rainfall with aquifer recharge, not unlikely to coincide with low spring flows.

Implementation of the models

We used ArcGIS 9.2 ModelBuilder (ESRI Inc., Redlands, CA, USA) to calculate a 10-m grid of ET_{sz} for the study area. This allowed the combination of radiation and wind speed data, which are raster datasets, with the numerical modeling required to calculate all other elements of the Penman–Monteith equation. To account for different temperatures measured at different elevations, we ran each calculation separately for each elevation level. For the upper oases, Al ‘Aqr, Al ‘Ayn and Ash Sharayjah, we used the ET_{sz} calculated from the temperatures measured at Al ‘Ayn, whereas for Qasha’ and Masayrat ar Ruwajah, we calculated ET_{sz} based on temperatures measured in the oases themselves.

For each agricultural terrace, we extracted the average ET_{sz} from the resulting raster. Crop coefficients were then transferred into the data table belonging to each terrace, as separate entries for trees and field crops and for each month of the year. For all terraces that had more than one tree or shrub species, we calculated a weighted average of all individual k_c values, weighting each contributing k_c by the proportion of the corresponding species among all trees. Subsequently, multiplying the modeled ET_{sz} for each month with the corresponding crop coefficients yielded ET_c, the crop evapotranspiration per crop type and terrace.

Since not the entire terrace was cropped in all cases, we estimated the proportion of each terrace that was covered by field crops. The product of this proportion and the area of the terrace was accepted as cropped area. For trees, only the numbers were assessed in the field, which had to be converted to areas for use with the Penman–Monteith equation. Therefore, we calculated the crop density per terrace of roses, date palms and other trees and analyzed the density distribution, comparing it with our aerial photographs, to define the density threshold that corresponded to full cover. We set the threshold values for full cover to 400 roses ha^{-1}, 100 date palms ha^{-1} and 200 other trees ha^{-1}. For terraces with densities of roses, date palms and trees below these thresholds, we calculated the area covered by the respective perennials as the product of the number of specimens and the average area per tree according to the threshold density, which was 25 m^2 for roses, 100 m^2 for date palms and 50 m^2 for other trees. All other area was interpreted as bare. This assumption is realistic, because all terraces are divided into so-called jalbas, small irrigation plots that are separated from the rest of the terrace by low ditches. Jalbas that currently have no vegetation are not irrigated and thus do not contribute to evapotranspiration.

The product of the effectively cultivated area and ET_c is the daily volume of water per terrace that evaporates from the soil or is transpired by the plants. Multiplying this value by the number of days in the respective month yielded the monthly evapotranspiration.

Historic water use

To determine historic water use patterns, we calculated the average water consumption per month and ha of each land use type assigned to the 2005 vegetation based on our aerial photographs. For most land use types, whose species composition was assumed to have changed only little over time, this mean water consumption was used to calculate historic water use by multiplying it with the area assigned to the land use type as interpreted from the historic photographs.

Adjustments were necessary for the land use type of field crops in the upper oases, for which historic sources (Abercrombie 1981; Scholz 1984) indicate the presence of large areas of onion and garlic, along with some cereals, mostly wheat. We implemented this adjustment by assuming a full cover of 80% garlic and 20% wheat covering 80% of the area of these terraces. Subsequently, we calculated water use on the terraces as described above, and calculated the average water consumption per month and area. For the mean historic water consumption of the land use type ‘field crops’, we then calculated a weighted average of current and assumed historic water consumption, assigning a weight of 0.2 to the consumption derived from the modern analysis and 0.8 to the water use pattern modeled for exclusive cultivation of garlic and wheat. Multiplying this average with the area under field crops in 1978 yielded the historic water consumption by field crops.

Similarly, the land use type of non-date trees, which no longer exists in Masayrat ar Ruwajah, had to be defined for the historic analysis. Based on the historic aerial photographs, we assumed that this land use type was composed almost exclusively of lime trees, which, according to information obtained from local farmers, was partly intercropped with fodder grasses. In an analysis similar to the one for the field crops of the upper oases, we assumed a vegetative cover of 80% lime and 10% fodder crops, composed of a combination of maize and barley. We assumed the remaining 10% of the area to be bare soil. We followed the above procedure to calculate the oasis’ water consumption per area. Multiplication by the historic tree area at Masayrat ar Ruwajah yielded the water demand by these trees in 1978.

Comparing the modeled water demand patterns in 1978 with those of 2005 allowed detection of changes in the water demand for each land use type. Since the differences in demand between perennial and annual crops is particularly important for the ability of an oasis to endure drought periods, we summarized water demand by roses, palm groves and other orchards as water demand by perennials, while demand by field crops and bare areas was considered as demand by annuals.

For both 1978 and 2005, we estimated irrigation water use efficiency according to Norman et al. (1998) as:

$IWUE = \frac{ET_a - P_e - \Delta S}{I_s}$, where ET_a is the actual evapotranspiration, P_e the effective precipitation, ΔS the change in root zone moisture and I_s the irrigation water supply. We followed the reasoning by Siebert et al. (2007), that on terraced fields in the Omani rainfall regime (short, heavy showers), runoff and evaporation losses are negligible and thus virtually all rainfall is effective. Since all calculations were done at monthly intervals and oasis fields are irrigated frequently, changes in root zone moisture were considered negligible. Since the water supply in 1978 was unknown, we assumed that it equaled the values for 2005, for the calculation of the *IWUE*.

Results

Current and historic land use

The main field crops in the oases were maize (*Zea mays* L.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), garlic (*Allium sativum* L.), alfalfa (*Medicago sativa* L.), sweet potato (*Ipomoea batatas* (L.) Lam.), sorghum (*Sorghum bicolor* (L.) Moench) and potato (*Solanum tuberosum* L.). On areas of less than 100 m^2, we also encountered guinea grass (*Panicum maximum* Jacq.), egg plant (*Solanum melongena* L.), radish (*Raphanus sativus* L.), cucurbits (*Cucurbita pepo* L.), hyacinth bean (*Lablab purpureus* (L.) Sweet), cabbage (*Brassica oleracea* L.), lettuce (*Lactuca sativa* L.), chili (*Capsicum frutescens* L.), parsley (*Petroselinum crispum* (Mill.) Nym.), carrot (*Daucus carota* L.), tomato (*Lycopersicon esculentum* Mill.), faba bean (*Vicia faba* L.) and wheat (*Triticum aestivum* L.) (Table 2).

The most frequent tree or shrub crops in the oases were pomegranate, rose, date palm, lime and peach. In smaller numbers, bananas (*Musa* x *paradisiaca* L.), apricots, grapes (*Vitis vinifera* L.), walnuts (*Juglans regia* L.), pears (*Pyrus communis* L.), plums (*Prunus domestica* L.), apples (*Malus domestica* Borkh.), papayas (*Carica papaya* L.), guavas (*Psidium guajava* L.) and figs (*Ficus carica* L.) were present (Table 2).

The percentage of the area that was covered by field crops in 1978 ranged from 9% at Masayrat ar Ruwajah to 42% at Al ‘Ayn and Qasha’ (Fig. 3, Table 3). Rose gardens made up between 0% of the area at

Table 2 Species composition of the cropping systems of the oases of Al ‘Aqr, Al ‘Ayn, Ash Sharayjah, Qasha’ and Masayrat ar Ruwajah, Oman, during surveys in April (trees and field crops) and September (field crops only)

Species	Al ‘Aqr	Al ‘Ayn	Ash Sharayjah	Qasha’	Masayrat ar Ruwajah
Field crop area recorded in the April/September survey (m^2)					
Alfalfa	106/79	1,029/854	148/129	–/–	703/579
Barley/oats	3,173/38	1,322/10	4,511/165	280/–	1,528/–
Garlic	634/–	988/–	7,422/18	310/–	230/–
Maize	749/2,718	1,515/2,787	2,897/7,301	1,740/1,623	3,945/5,171
Potato	–/–	–/65	20/350	–/38	–/–
Sorghum	9/–	19/–	75/70	–/–	336/291
Sweet potato	–/–	–/9	38/58	122/264	65/409
Others	18/14	13/14	76/–	10/42	–/107
Trees and shrubs (frequency)					
Apricot	11	34	181	21	1
Banana	0	0	11	44	216
Citrus	41	37	481	76	168
Date	0	0	3	3	956
Fig	7	2	12	9	15
Grape	15	8	83	30	30
Tropical fruits	0	27	6	6	35
Peach	57	45	265	178	30
Pear, plum, apple	36	8	44	12	1
Pomegranate	817	265	4,812	776	5
Rose	295	635	1,989	168	0
Walnut	8	11	86	31	0
Others	0	0	9	4	0

Masayrat ar Ruwajah and Al ‘Aqr and 18% at Al ‘Ayn. The proportion of the area covered by trees was highest at 74% at Al ‘Aqr and lowest at 25% at Qasha’. Palm groves were only present at Masayrat ar Ruwajah, where they covered 40% of the area. Bare soil covered 31% at Qasha’, 10% at Ash Sharayjah and below 10% at the other oases. At Masayrat ar Ruwajah, no bare areas were found.

In some respects, land use in 2005 differed substantially from land use in 1978 (Fig. 4). At Al ‘Aqr, rose gardens expanded from 0 to 15% of the area, with much of what was previously under field crops (decline from 23 to 6%) being converted to rose plantations. At Al ‘Ayn, a similar increase in the rose area occurred, from 18 to 31% of the area. Here, the additional area was mainly gained from a reduction in orchard size from 34 to 24% of the area. Some of this decline was due to the building of a new road on the area of a former orchard. At Ash Sharayjah, much of the former field crop area had been abandoned, leading to a decline in field crop area from 29 to 9% and an increase in bare area from 10 to 27%.

The greatest land use changes happened at Qasha’ and Masayrat ar Ruwajah. At Qasha’, the area under temperate and subtropical orchards was expanded from 25 to 61% of the area, at the expense of field crops (42 to 5%) and bare ground (31 to 24%). Masayrat ar Ruwajah lost virtually all of its area under non-palm orchards, which had covered half of the oasis area in 1978. The area previously under this land use type was converted to palm groves (40 to 60%), field crops (9 to 32%) and bare ground (0 to 8%)

Climatic parameters

Temperature

Measured temperatures reflected the different elevations of the sites (Fig. 5). At Al ‘Ayn, mean monthly minimum temperatures (T_{min}) ranged from 6.6°C in January to 22.0°C in July, whereas mean monthly maximum temperatures (T_{max}) were between 15.1 and 30.4°C. At Qasha’, T_{min} ranged between 8.0 and 22.4°C, while T_{max} was between 18.4 and 33.3°C.

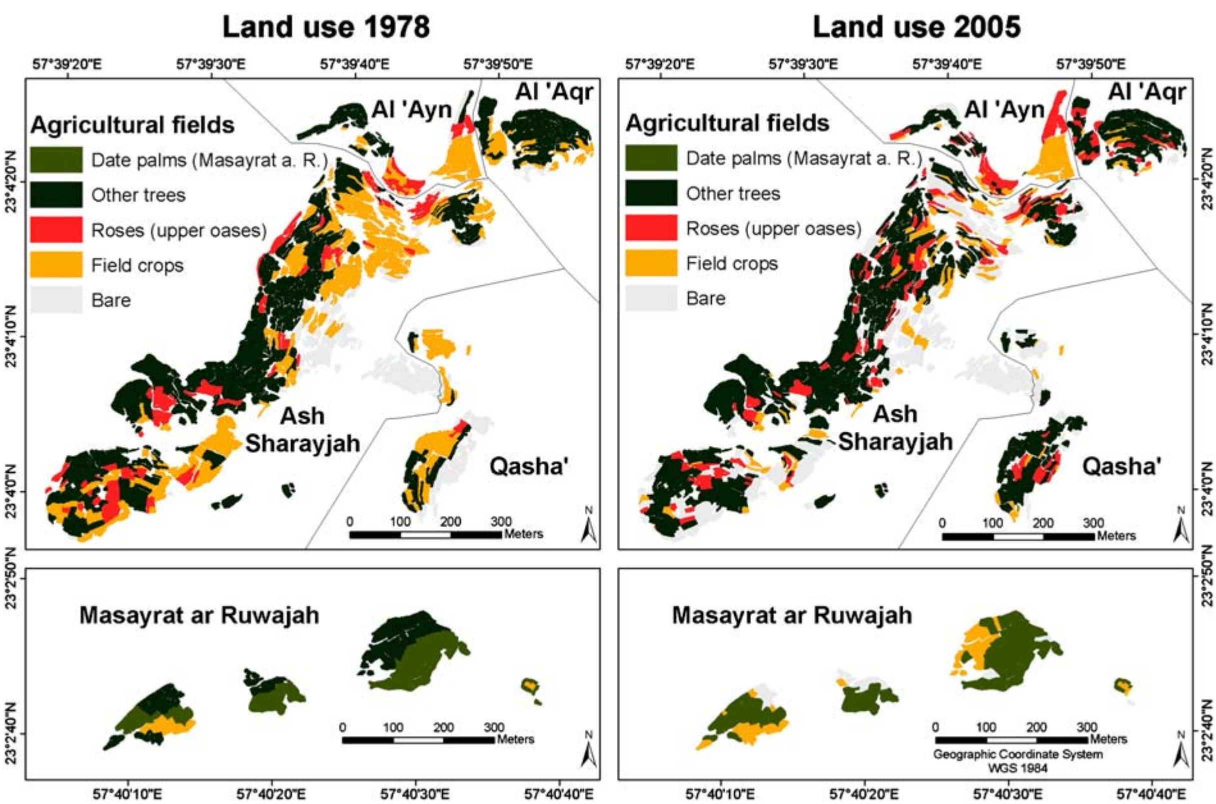

Fig. 3 Land use in the oases of Al ‘Aqr, Al ‘Ayn, Ash Sharayjah, Qasha’ and Masayrat ar Ruwajah, Oman, as mapped from aerial photographs. For better legibility, refer to the color figure in the online version

Table 3 Area covered by rose gardens, date palm orchards, other orchards, field crops and bare ground in the oases of Al ‘Aqr, Al ‘Ayn, Ash Sharayjah, Qasha’ and Masayrat ar Ruwajah as mapped from aerial photographs, and water consumption per area based on water use calculated from modeled evapotranspiration

Name of oasis	Roses	Date palm orchards	Other orchards	Field crops	Bare
Area 1978 (1,000 m^2)					
Al ‘Aqr	–	–	12.6	3.8	0.6
Al ‘Ayn	2.7	–	5.2	6.5	1.0
Ash Sharayjah	16.2	–	68.1	40.8	14.5
Qasha’	0.4	–	5.4	9.0	6.7
Masayrat ar Ruwajah	–	18.2	23.1	4.2	–
Area 2005 (1,000 m^2)					
Al ‘Aqr	2.6	–	12.4	1.0	1.0
Al ‘Ayn	4.8	–	3.7	5.9	0.9
Ash Sharayjah	14.9	–	75.3	12.3	37.1
Qasha’	2.0	–	13.3	1.2	5.2
Masayrat ar Ruwajah	–	27.4	–	14.6	3.4
Water consumption per ha and year (1,000 m^3)					
Al ‘Aqr	14.4	–	13.7	9.9	1.5
Al ‘Ayn	11.3	–	12.0	9.5	0
Ash Sharayjah	11.1	–	11.6	6.1	1.1
Qasha’	10.2	–	12.2	7.4	0.7
Masayrat ar Ruwajah	–	22.5	12.0	12.4	12.7

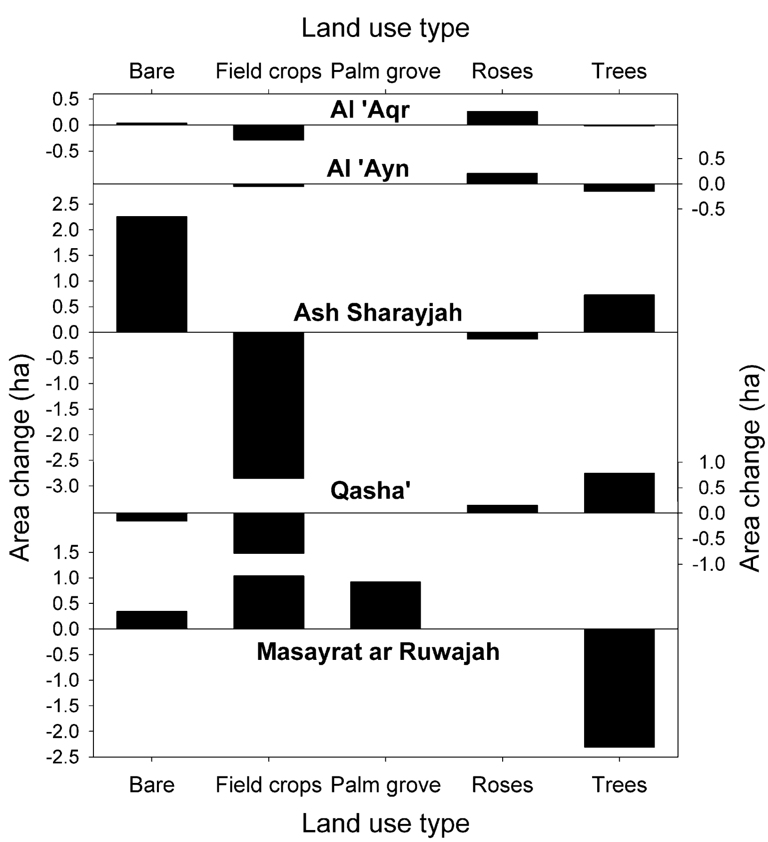

Fig. 4 Changes in the areas dedicated to five land use types in the oases of Al ‘Aqr, Al ‘Ayn, Ash Sharayjah, Qasha’ and Masayrat ar Ruwajah, Oman between 1978 and 2005

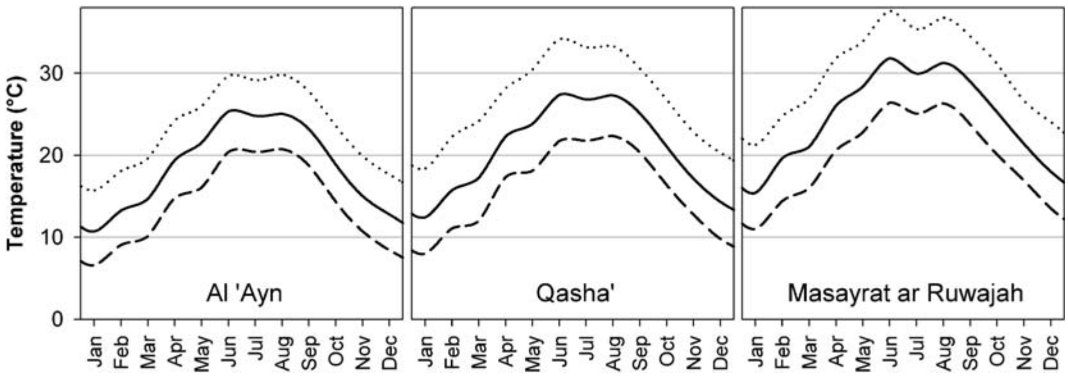

Fig. 5 Mean daily minimum (*dashed*), mean (*solid*) and maximum (*dotted*) temperatures recorded at Al ‘Ayn, Qasha’ and Masayrat ar Ruwajah, Oman, between April 2005 and March 2006. For better illustration of the course of the year, monthly values for January to March 2006 are displayed before April to December of 2005

Masayrat ar Ruwajah was the warmest site, with T_{min} between 11.0 and 26.4°C and T_{max} between 24.1 and 37.6°C. The absolute minimum temperature in this study was measured at Al ‘Ayn with 1.9°C, while the absolute maximum was 42.8°C at Masayrat ar Ruwajah. Mean temperatures were slightly higher than the arithmetic mean of T_{min} and T_{max}, which is recommended for modeling ET_{sz} (Allen et al. 1998; ASCE 2005), on average by 0.13°C at Al ‘Ayn, 0.64°C at Qasha’ and 0.37°C at Masayrat ar Ruwajah.

Measured and modeled radiation

Measured solar radiation at Sayh Qatanah ranged between 14.1 MJ m^{-2} day^{-1} in November and 24.8 MJ m^{-2} day^{-1} in April, whereas modeled radiation had a slightly greater range with 11.9 MJ m^{-2} day^{-1} in December and 25.4 MJ m^{-2} day^{-1} in July (Fig. 2). Because of the shading effect of the surrounding mountains, modeled radiation slightly deviated from the distribution expected for a flat landscape. For all months between September and April, measured radiation was above modeled radiation. As described above, we therefore used the modeled instead of the measured radiation as input for estimating ET_{sz} for these months.

Measured and modeled wind speed

Wind measurements at Ash Sharayjah were only available for a time span of about 6 weeks between early May and mid June due to the weather extremes described above. Based on the half-hourly measurements taken during this time, the cluster analysis detected three major wind patterns, with very low wind (0.27 m s^{-1}) from the north-east occurring 69% of the time, slightly stronger winds (0.80 m s^{-1}) from the south blowing 4% of the time, and moderate southerly winds (2.36 m s^{-1}) occurring 27% of the time.

The weighted average of the respective runs of the NUATMOS model amounted to mean wind speeds for the oases of between 0.59 and 0.75 m s^{-1} (Table 1).

Water availability

The flow rate of the four main springs of our study area was quite variable over time. The spring supplying the gardens of Ash Sharayjah delivered between 15 and 52 m^3 h^{-1}, the spring flow of Masayrat ar Ruwajah was between 10 and 34 m^3 h^{-1}, the flow of the spring delivering the irrigation water of Al ‘Aqr, Al ‘Ayn and the larger proportion of Qasha’s water supply ranged between 6 and 13 m^3 h^{-1} and the small separate spring of Qasha’ varied between 0.2 and 4 m^3 h^{-1}. After excluding the highest flow rate of each spring, which occurred just after a major rainstorm, and distributing the water from the spring at Al ‘Ayn according to the oases’ traditional water rights, the average flow to the oases was thus 89 m^3 day^{-1} to Al ‘Aqr, 96 m^3 day^{-1} to Al ‘Ayn, 88 m^3 day^{-1} to Qasha, 607 m^3 day^{-1} to Ash Sharayjah and 447 m^3 day^{-1} to Masayrat ar Ruwajah.

Adding mean rainfall (Fisher 1994) to these mean values resulted in an average daily water supply of 103 m^3 at Al ‘Aqr, 108 m^3 at Al ‘Ayn, 694 m^3 at Ash Sharayjah, 102 m^3 at Qasha’ and 482 m^3 at Masayrat ar Ruwajah.

For the minimum flow rates of all springs, the water supply of Al ‘Aqr amounted to 53 m^3 day^{-1}, Al ‘Ayn received 57 m^3 day^{-1}, Qasha 42 m^3 day^{-1}, Ash Sharayjah 404 m^3 day^{-1} and the spring of Masayrat ar Ruwajah delivered 231 m^3 day^{-1}.

Evapotranspiration modeling

Reference evapotranspiration varied between 1.9 and 7.2 mm day^{-1} (Fig. 6). In spite of the elevation gradient, which led to different levels of radiation and temperature, mean monthly ET_{sz} was surprisingly similar between the oases, indicating that shading by the surrounding mountains largely offset the influence of higher temperatures on ET_{sz} at Masayrat ar Ruwajah. Mean daily ET_{sz} was lowest at Al ‘Aqr and Ash Sharayjah with 4.43 mm day^{-1} and highest at Masayrat ar Ruwajah with 4.50 mm day^{-1}. Variation of ET_{sz} within one oasis was highest in Ash Sharayjah, reflecting the different levels of shading by surrounding mountains in this large oasis. At Masayrat ar Ruwajah, where all fields lie at the bottom of a valley in very similar topographic settings, modeled ET_{sz} is very similar for all parts of the oasis.

Current and historic water demand

Based on our estimates, the total water requirement of all five oases increased from 218,800 m^3 in 1978 to 256,377 m^3 in 2005. In both investigated periods, water demand followed a strong seasonal pattern. In 1978, overall demand by the five oases amounted to 27,903 m^3 in June, the month of the highest solar radiation, and only 6,218 m^3 in December, when solar radiation was lowest (Fig. 7). In 2005, the water demand in June was at 36,037 m^3 substantially higher than in 1978, while water use in December was much lower at 5,020 m^3. The proportion of the water consumed by field crops was equally variable throughout the year, ranging from 39% in winter to 6% in summer in 1978, and from 35% in winter to 14% in summer in 2005.

Among the oases, water demand patterns were slightly different. Masayrat ar Ruwajah, which lies at much lower altitude than all other settlements, has a temperature regime that is more suitable for year-round cultivation than at the other places. Since the palm trees grown here are irrigated throughout the year, the winter depression in water requirement is less pronounced than in the higher oases (Fig. 8). The disappearance of lime trees and the conversion of much of the orchard area to fodder production have raised the proportion of the water that is consumed by field crops.

Of the upper oases, water demand by field crops was highest at Al ‘Ayn, where they covered 49% of the area in 1978 and 45% in 2005. Here, the proportion of the irrigation water that is consumed by vegetables and fodder crops never dropped below 25% in the summer of 2005, and was thus higher than in 1978, when field crops accounted for only 12% of water use in August. The biggest change at Al ‘Aqr and Ash Sharayjah was an increase in the amount of water required by trees in all months of 2005 compared to 1978. Accordingly, water demand by field crops decreased.

At Qasha’, the orchard area expanded by 162%, causing a 166% rise in water demand by perennial

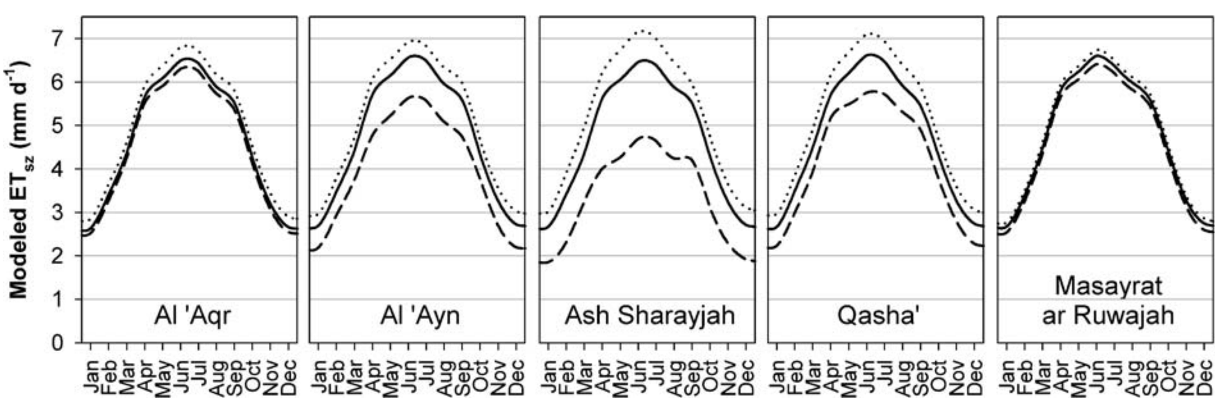

Fig. 6 Minimum (*dashed*), mean (*solid*) and maximum (*dotted*) modeled reference evapotranspiration (*ETsz*) for the fields of Al ‘Aqr, Al ‘Ayn, Ash Sharayjah, Qasha’ and Masayrat ar Ruwajah, Oman, throughout the year of 2006

trees and shrubs. This oasis experienced the strongest increase in overall water requirement, which rose by 93%, compared to 36% at Al ‘Ayn, 18% at Al ‘Aqr, 15% at Masayrat ar Ruwajah and 9% at Ash Sharayjah.

Irrigation water use efficiency in 1978 (Table 4) was lowest at Qasha’ (0.17) and highest at Al ‘Aqr (0.42). By 2005, overall water use efficiency had increased in all oases. The least efficient oasis was now Al ‘Ayn at 0.31, while Al ‘Aqr was still the most efficient, with an irrigation water use efficiency of 0.52.

Discussion

Considering the annual total supply and demand, all oases have sufficient water, with the ratio of available to needed water ranging from 2.0 at Al ‘Aqr to 3.7 at Qasha’ in 1978, and between 1.7 at Al ‘Aqr and 2.2 at Al ‘Ayn in 2005. The resulting irrigation water use efficiencies of between 0.17 and 0.52, which in our model are exclusively explained by changes in water demand, were thus relatively low compared to those found by Norman et al. (1998) and Siebert et al. (2007), which ranged between 0.60 and 0.98. In the arid climate of Oman and in cropping systems that rely to a high degree on perennial crops that need a certain amount of water to stay alive during all seasons, considerations about the annual total water supply and demand are not very meaningful. Because of the higher temperature and radiation levels in the summer, water use by such perennials is much higher in the summer than in the winter, whereas available irrigation water remains more or less the same. Farmers in the oases of Al Jabal al Akhdar have no way of storing the winter’s water surplus for use in the summer months. Consequently, any discussion about the sufficiency of the incoming water should focus on the time of year, when water shortage is most likely to occur. While, for instance, water supply at Ash Sharayjah was 13 times higher than demand in January of 2005, it exceeded the crop requirements by only 20% in June of the same year. Based on average flow conditions and mean rainfall, water excess in June was 53% at Al ‘Ayn, 40% at Masayrat ar Ruwajah and 8% at Qasha’, while Al ‘Aqr had a water deficit of 8%. Irrigation water use efficiency in June thus ranged between 72 and 102%, values which typically indicate a high risk of water shortage. Since spring flow could only be measured close to the springs, inevitable losses during conveyance of water to the fields have not been taken into account and are likely to further aggravate the water deficit. Leaching of water below the root zone, in contrast, should not lead to major water losses during the summer, since it only appears to occur after large irrigation or rainfall events, which provide excessive amounts of water (Luedeling et al. 2005). While major rainfalls can occur at all times of year, excessive summer irrigation is unlikely.

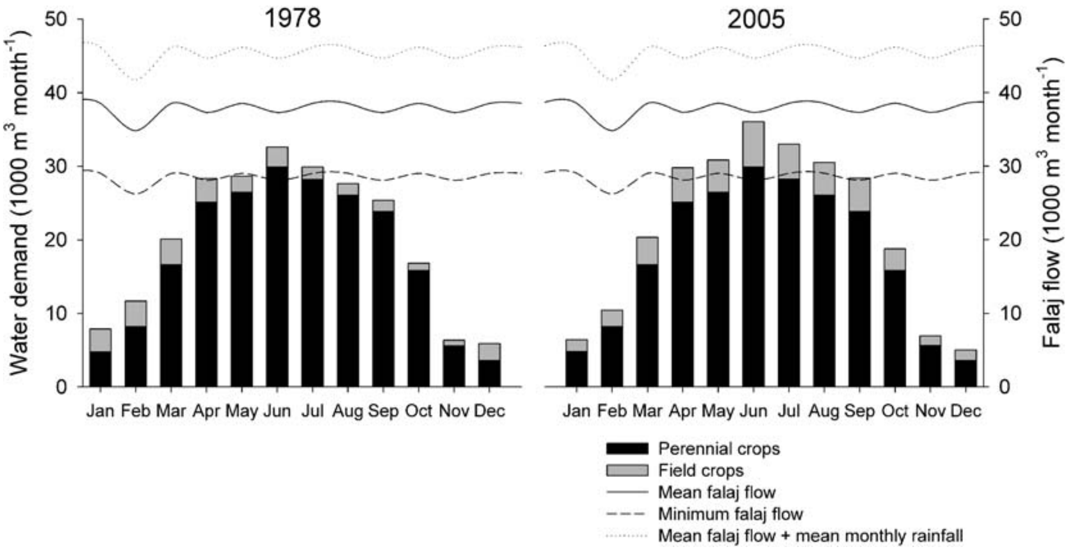

Fig. 7 Monthly water demand of the oases of Al ‘Aqr, Al ‘Ayn, Ash Sharayjah, Qasha’ and Masayrat ar Ruwajah modeled for 1978 and 2005

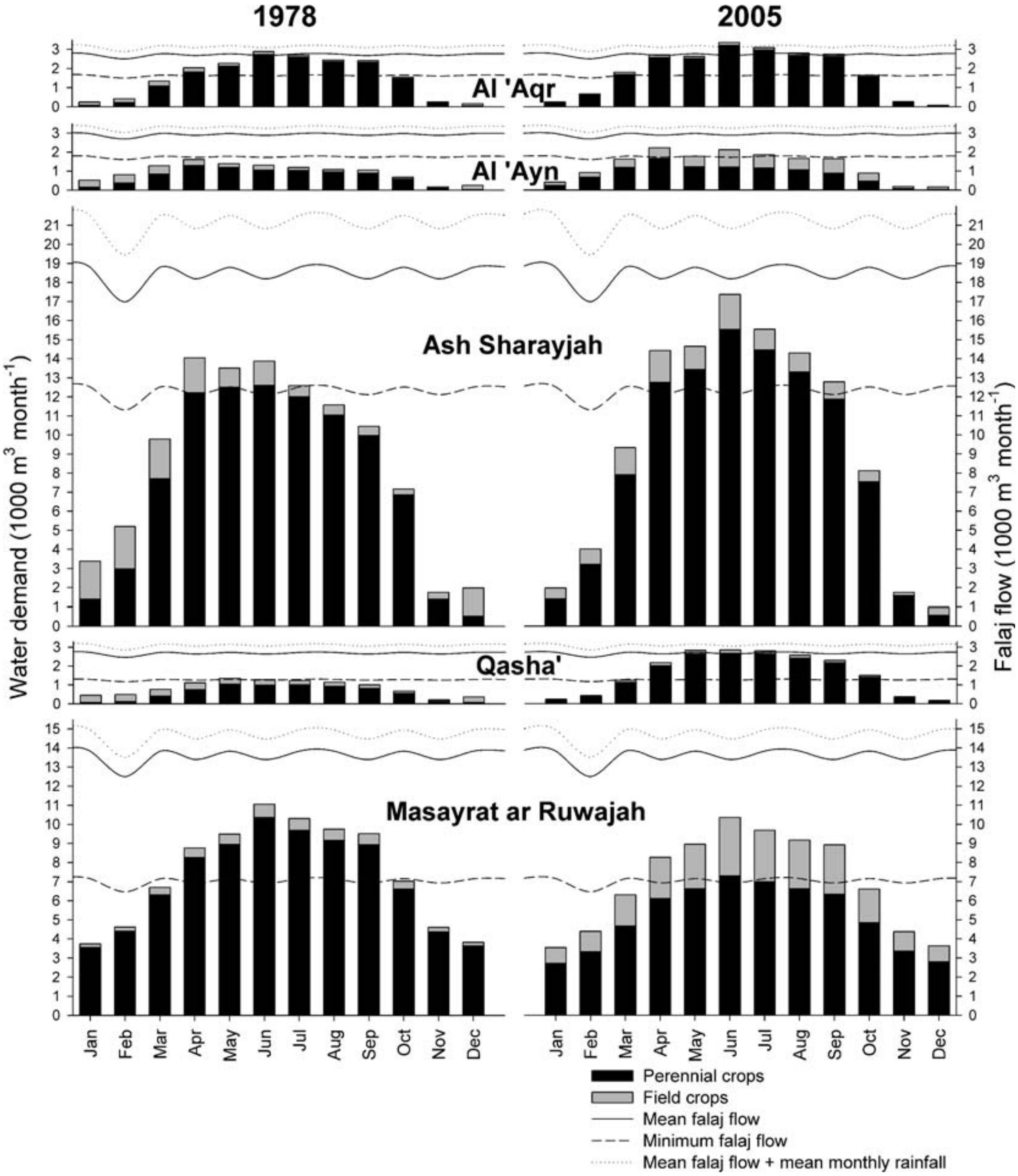

Fig. 8 Modeled monthly water demand in 1978 and 2005 at the oases of Al ‘Aqr, Al ‘Ayn, Ash Sharayjah, Qasha’ and Masayrat ar Ruwajah, Oman, and available water based on calculations of minimum falaj flow, mean falaj flow and mean falaj flow plus mean monthly rainfall, based on falaj flow measurement between December 2006 and August 2007

Based on water supply and demand computed from minimum falaj flow and crop water requirements, the oases of Al Jabal al Akhdar seem very vulnerable to drought years. When the amount of incoming water corresponds to the minimum spring flow during our study period, the oases would be water-deficient between March/April and July/September, with the amount of lacking water reaching a peak of 56% of the crop requirement at Qasha’. In such years, farmers at Masayrat ar Ruwajah could respond by leaving most of their field crop area uncultivated throughout the summer, which would almost eliminate their water deficit. At Ash Sharayjah and Al ‘Ayn, similar adaptations would be possible, but alleviate the water shortage to a lesser degree, because the proportion of the area that is cropped with field crops is much smaller than at Masayrat ar Ruwajah. At Qasha’ and Al ‘Aqr, the possibility to adapt to water shortage by

Table 4 Irrigation water use efficiencies (IWUE) of Al ‘Aqr, Al ‘Ayn, Ash Sharayjah, Qasha’ and Masayrat ar Ruwajah in Al Jabal al Akhdar, Oman, in 1978 and 2005

Name of oasis	IWUE 1978	IWUE 2005
Al ‘Aqr	0.42	0.52
Al ‘Ayn	0.20	0.31
Ash Sharayjah	0.30	0.38
Qasha’	0.17	0.45
Masayrat ar Ruwajah	0.36	0.44
Total	0.31	0.41

not cultivating annual fields is very limited. The area under field crops is so small, that such measures would have no significant effect on the water shortage.

In interpreting the numbers given above, the limitations of the modeling procedure should be kept in mind. Our model is only based on 6 weeks of wind measurements and for part of the year only on modeled solar radiation. Besides, several input parameters, such as the crop coefficients and the durations of the growth stages of many crops, were based on sporadic field observations or assumed to correspond to values taken from published sources. Moreover, the modeled evapotranspiration might be somewhat inaccurate, because the arid climate of the study sites does not correspond to the reference conditions required for the equations. Spring flow measurements by the floating method might also not be very exact, so that the estimates of water use efficiency at Ash Sharayjah and Masayrat ar Ruwajah might not be accurate. However, since all these uncertainties represent systematic influences that would affect water demand in 1978 and 2005 alike, they do not affect the capability of our modeling approach to evaluate the effects of land use changes, which was the primary goal of this study.

To overcome the water shortage in the summer, storage of excess water during the winter in reservoirs and gradual release during the summer months would provide a possibility to alleviate the risk of water shortages. At Masayrat ar Ruwajah, such an irrigation dam has already been constructed. At the other locations, however, this type of construction is precluded by the elevation of the springs, which is directly above the level of the terraces, and by unsuitable terrain.

Between 1978 and 2005, the ability of farmers at most oases to adapt to the seasonal variation in crop water requirement decreased. While at Masayrat ar Ruwajah, the abandonment of large-scale lime production has actually increased the farmers’ flexibility in distributing water use over the year, the expansion of the orchard area at all other oases had less favorable effects. In years of drought, and at Qasha’ and Al ‘Aqr even in years of average spring flow and mean rainfall, farmers face seasonal water shortages in summer. During the hottest months of the year, the water supply is then not sufficient for optimal irrigation of all perennial fruits and shrubs. Especially the conversion of many annual fields at Qasha’ to fruit orchards increased the minimum monthly water need in this oasis to a level that can hardly be met by the flow of the springs during the summer. All oases except Masayrat ar Ruwajah have thus increased their vulnerability to the interannual variation of water supply that is a defining characteristic of Omani oasis agriculture (Siebert et al. 2005).

In considering water use efficiency for an entire oasis, however, it should be taken into account that water is not equally distributed within the oases. The number of households that receive a certain proportion of the overall water according to traditional water rights (Abdel-Rahman and Omezzine 1996) ranges between 11 at Qasha’ and about 25 at Ash Sharayjah. While some of these households, especially those with substantial off-farm income, might cultivate an area that is smaller than in the past, and thus require less than their allotted share of water, others might face severe seasonal water shortage. Some households that have left the oases over the past few decades might even not use their share of water at all. Water rights are therefore traded among farmers (Abdel-Rahman and Omezzine 1996), but farmer interviews revealed that some farmers nevertheless remained short of water.

There is evidence that the manpower available for maintaining the irrigation infrastructure decreased substantially between 1978 and 2005. As already described in 1984 (Scholz 1984), migration to the cities and towns of the lowlands, especially by the younger generation, as well as off-farm employment have decreased available farm labor and elevated the risk of labor shortages. Consequently, the average age of the household heads, who are often the only people permanently employed in agriculture, is fairly high today. According to a survey conducted in 2006, 80% out of 41 interviewed farmers in Masayrat ar Ruwajah, Qasha' and Ash Sharayjah were over 50 years of age, with 68% over 60 (Dickhoefer, unpublished data). So far, the lack of maintenance, along with damage inflicted to the terrace systems during the Jabal War (Scholz 1984), has mainly led to the decay of many terraces formerly cropped with field crops. While this damage to the agricultural infrastructure reduces the ability to make use of the excess water in winter, it does not put the perennial crops at risk. However, as soon as the irrigation infrastructure is affected by lack of maintenance, water shortages will increase.

With the current distribution of annual water use, oases in Al Jabal al Akhdar do not show a particular adaptation of cropped area to the seasonal variation of crop water requirements. A large number of abandoned terraces at Ash Sharayjah still gives testimony of a much better functioning of this mechanism in the past. We assume that after the destructions of the war, the economic incentive of producing field crops was no longer strong enough to warrant rebuilding the terraces. Besides, since these terraces are often far from the main village and require both long walks to and from the fields and the maintenance of long irrigation channels, labor shortages might have precluded continued use of these land resources. Today, the abandoned terraces increasingly fall into disrepair, making a return to cultivation unlikely. Even though we have no evidence on how the agricultural areas were used before the 1950s, we assume that the area under annual crops was much greater than today, ensuring sufficient food production for the then much greater number of inhabitants of the oases.

In the future, it is likely that the water supply of the oases might further recede due to the competition by urban water needs in the new town of Sayh Qatanah. While the town did not exist at all in 1978, the infrastructure has since then grown to 297 buildings, many with irrigated gardens around them, and according to the development plan for the town, the number of houses is projected to rise to 920 within the next few years. In addition to the developments envisioned by this plan, additional housing areas are being built closer to the villages of Al 'Ayn and Ash Sharayjah, and new tourism facilities are expected to arise close to an already existing hotel on the plateau. All of these will extract water, and it is likely that, in the long run, they will compete for water with agricultural production. To what extent this competition has already affected the oases' water supply is unclear, but it is likely that the boreholes supplying Sayh Qatanah have already led to decreasing flow rates of springs that are fed by the same aquifer. It is therefore possible that our assumption of comparable water supplies in 1978 and 2005 is incorrect. If water supply was indeed higher in 1978, irrigation water use efficiencies would be lowered, leading to even better resilience to droughts in the past. According to statistics of the Waterworks on Al Jabal al Akhdar (Ministry of Housing, Electricity and Water, Sultanate of Oman), water extraction from the main well of Sayh Qatanah amounted to 234,410 m^3 in 2004 and 244,360 m^3 in 2005. It thus already equals the water demand of all oases combined, and is likely to substantially exceed it in the near future. While the new town is likely to generate additional employment opportunities for the inhabitants of the oases, which might prevent many from leaving the area, it might on the other hand put pressure on the complex hydrological sustainability of traditional oasis agriculture.

Conclusions

The seasonal distribution of water demand is more unequal in the high-mountain oases of Al Jabal al Akhdar than reported in comparable studies of oases at lower altitudes, and recent land use changes have aggravated this imbalance. It is likely that, in addition to increased water demand, water supply has decreased and is likely to further decrease in the future, because of recent expansions of urban developments in the vicinity of the oases, which compete with agriculture for water. Overall, the hydrological sustainability of all oasis systems in Al Jabal al Akhdar except for Masayrat ar Ruwajah seems to have substantially diminished between 1978 and 2005.

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