Assessment of groundwater extraction in the Tadla irrigated perimeter (Morocco) using the SSEBI remote sensing algorithm

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1 Introduction

The Tadla irrigation perimeter is located on the left and right banks of the Oum Er Rbia river, some 250 km south-east of Rabat, Morocco (Figure 1).

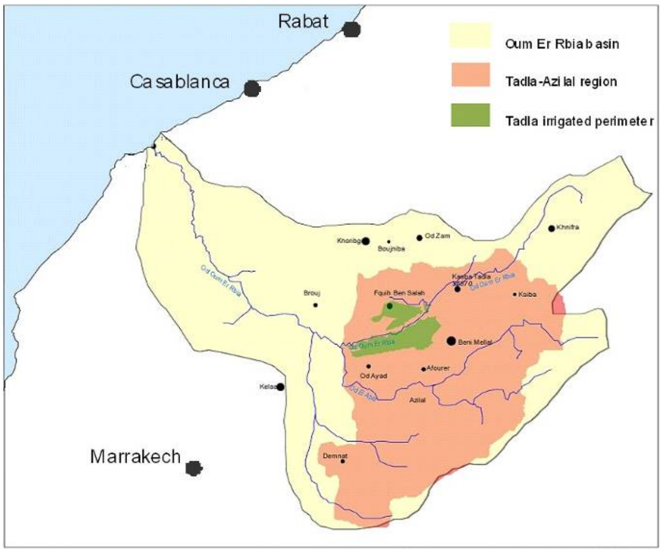

Figure 1 Tadla irrigation perimeter, Morocco

Tadla irrigates more than 100,000 hectares and is one of the most important agricultural areas in Morocco regarding its contribution to the Gross National Product. The perimeter is composed of two sub perimeters which are hydraulically distinct (Figure 2):

- Beni Amir, right bank of river Oum Er-Rbia, 27,500 ha, irrigated from the Ahmed El Hansali dam (670 Mm3);

- Beni Moussa, left bank, 69,600 ha, irrigated from the Bin el Ouidane dam (1.30 Bm3).

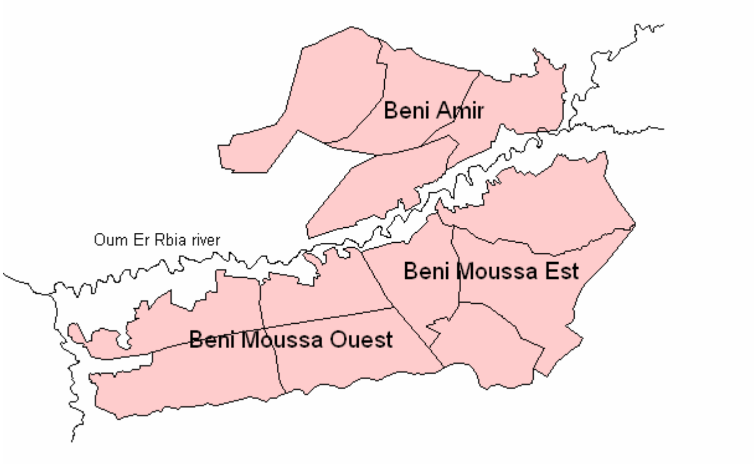

Figure 2 Layout Tadla irrigation perimeter

The area has an arid to semi-arid climate, receiving about 300 mm of rain annually, most of which is received during the winter rainy season from November to March. The temperatures vary widely, being more temperate during the winter, but with peaks in summer reaching at times 45-50 degrees Celsius. The main irrigated crops in the area are fodder crops (alfalfa, maize), wheat, olives, citrus, and vegetables. Livestock production (milk, meat) also plays an important role in Tadla.

The Tadla irrigation perimeter is suffering from water stress. The main problem is the high consumption of irrigation water in combination with groundwater over-exploitation, leading to a lowering of the groundwater table in the area. Approximately 50% of the farms have private wells and about 10,000 wells are used in the schemes (Hammani et al., 2008; Hammani et al., 2009). There has been a regular decline in the level of the shallow aquifer for already 20 years now, and there is no regulation to control withdrawals of groundwater (Hellegers, 2007). Surveys make clear that groundwater is pumped not only from the phreatic aquifer, but also from the deeper eocene aquifer (Hammani, 2004; Hammani et al., 2007; Hammani et al., 2009).

The ORMVAT (Office Régional de la Mise en Valeur Agricole du Tadla), in charge of the management of the irrigation schemes, implemented a monitoring network to keep track of the fluctuations of the water levels in the perimeter. At present the depth of the groundwater table in Beni Amir and Beni Moussa varies between 15 m and 20 m below soil surface, reaching in some places more than 20 meters depth (Kselik et al, 2008). An additional concern is the deteriorating water quality, with increasing amounts of water needed to flush and dilute pollution loads.

2 Material and method

There are no measurements to quantify the extracted volumes, and therefore remote sensing techniques are proposed to estimate the groundwater use. Groundwater extraction is estimated from the rest term of the water balance, where precipitation and irrigation flows are in-situ measured and the actual evapotranspiration is calculated using the SSEBI remote sensing algorithm (Roerink et al., 2000).

MODIS images

For the Tadla case study, evapotranspiration is calculated on a daily basis using MODIS images. A total number of 22 cloudfree MODIS images for 2006 were obtained from the LP DAAC EOS Data Gateway. The Terra MODIS daily surface temperature and surface reflectance products have been used for the study, with resolutions of 1x1 km and 500x500 m respectively.

The SSEBI algorithm

The Simplified Surface Energy Balance Index (SSEBI) algorithm (Roerink et al., 2000) has been developed to solve the surface energy balance with remote sensing techniques on a pixel-by-pixel basis. Over the years it is applied all over the world (Brunner et al., 2008; Sobrino et al., 2007; Gomez et al., 2005; Bauer et al., 2006). The energy balance is given by:

$Rn = G0 + H + \lambda E$ (formula 1)

where:

Rn = net radiation [W m-2]

$G0$ = soil heat flux [W m-2]

H = sensible heat flux [W m-2]

λE = latent heat flux [W m-2]

SSEBI requires scanned spectral radiances under cloudfree conditions in the visible, near-infrared and thermal infrared range to determine its constitutive parameters: Surface reflectance, surface temperature and vegetation index. With this input and some additional meteorological data, the energy budget at the surface can be determined.

First the net radiation term is calculated as the rest term of all incoming and outgoing shortwave and longwave radiation. Secondly the soil heat flux is derived with an empirical relationship of the vegetation and surface characteristics. The sensible and latent heat flux are not calculated as separate parameters, but as the evaporative fraction, Λ, which is determined as:

$\Lambda = \lambda E / (Rn-G0)$ (formula 2)

It has been observed that surface temperature and reflectance of areas with constant atmospheric forcing are correlated and that the relationships can be applied to determine the effective land surface properties (Bastiaanssen et al., 1998; Roerink et al., 2000). By assuming constant global radiation and air temperature, a formal explanation can be given to the observed surface reflectance and temperature.

The SSEBI model is based on the principle that two boundary conditions can be distinguished in the reflectance-temperature relationship; one for completely wet surface conditions and the other for completely dry surface conditions (Figure 3). For completely wet surface conditions all available energy (Rn-G0) goes to the evapotranspiration process (λE) and nothing goes to the heating process of the surface (H). Therefore a constant temperature is expected with increasing reflectance. For completely dry areas all available energy goes to the heating process of the surface and nothing goes to the evapotranspiration process. A decreasing surface temperature with increasing reflectance values is expected, as increasing reflectance values result in decreasing solar radiation values and less energy becomes available for the heating process.

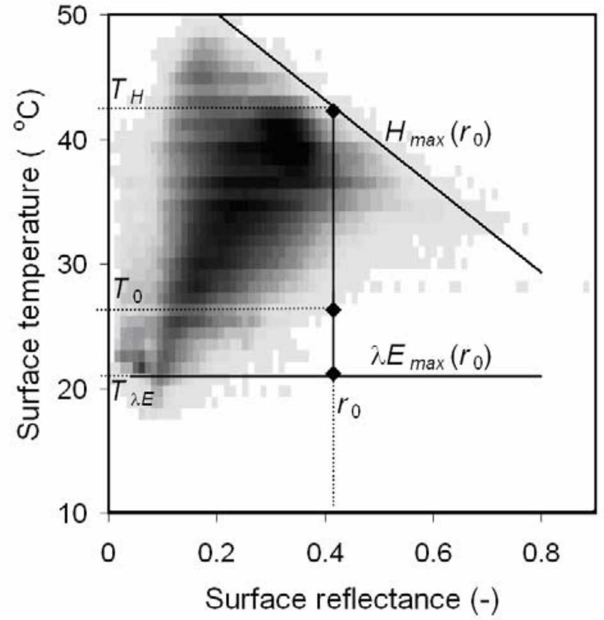

Figure 3 Schematic representation of the relationship between surface reflectance and temperature together with the basic principles of SSEBI.

In the case where the two reflectance-to-temperature relationships for zero evapotranspiration and potential evapotranspiration can be determined, SSEBI then calculates the evaporative fraction as follows: For each pixel the surface reflectance (r0) and surface temperature (T_0) are determined; where temperature is related to soil moisture and thus the fluxes. The evaporative fraction (Λ) is calculated as a temperature ratio:

$$\Lambda = \frac{T_{dry} - T_0}{T_{dry} - T_{wet}} \quad \left(= \frac{\lambda E}{R_n - G_0} \textit{ in energy balance terms} \right) \text{ (formula 3)}$$

The S (of Simplified) in the SSEBI model stands for the case where the extreme temperatures Twet and Tdry can be determined from the image itself. This is only possible when the atmospheric conditions are constant over the image and sufficient wet and dry pixels are present throughout the reflectance spectrum. Note that a different wind speed will change the values of the extreme temperatures Twet and Tdry, but as long as the wet and dry pixels are present the SSEBI method will work.

So far, SSEBI is applied to separate remote sensing images, representing individual days within a season. A method for temporal integration of the images into a constant time series of daily ET maps was lacking. Currently SSEBI developed into a procedure that applies such a temporal integration. First, remote sensing images are used to derive maps of the surface albedo, surface temperature, evaporative fraction and emissivity. Then a daily interpolation of these remote sensing maps is applied, from which the daily evapotranspiration (ETa) is calculated. Since the evaporative fraction behaves constant during the day, ETa is calculated as:

$$ET_a = \Lambda R_n \text{ (formula 4)}$$

where the daily net radiation (R_n) is calculated from remote sensing (albedo, temperature) and standard meteorological measurements (solar radiation).

3 Results

Evapotranspiration

The resulting ETa and ETp maps for the 2006 hydrological year are shown as yearly totals in Figure 4.

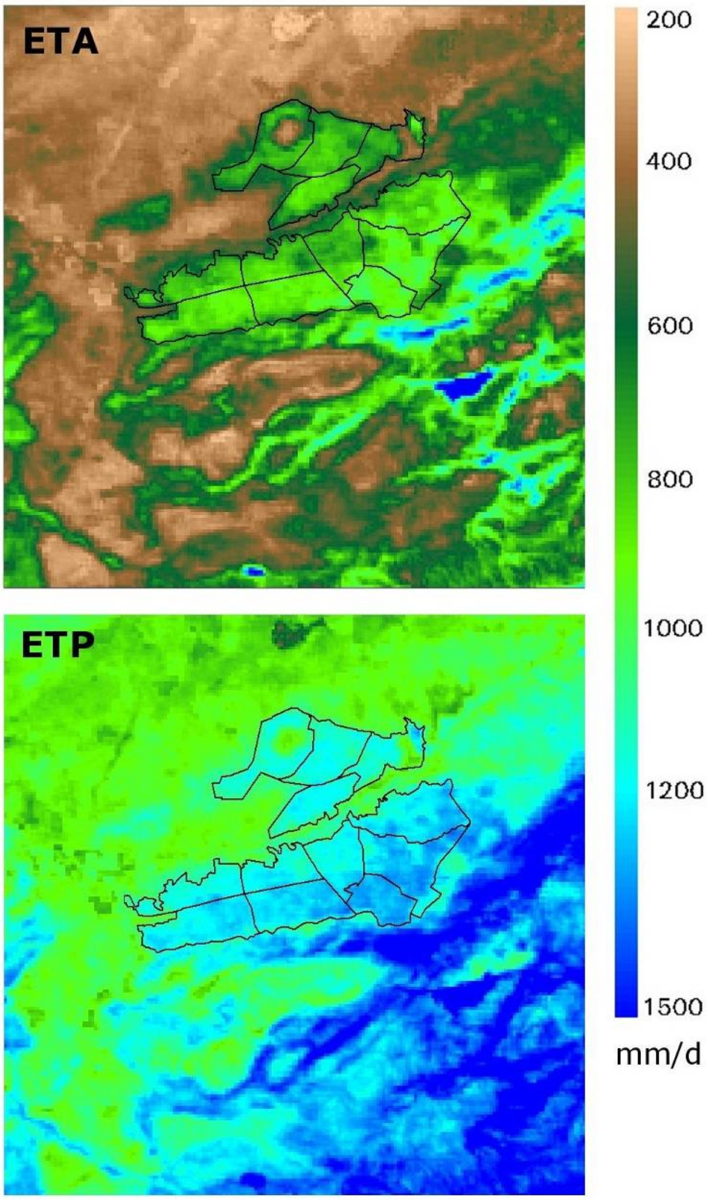

Figure 4 Spatial presentation of yearly ETa and ETp from SSEBI, Tadla 2006

Figure 5 shows a temporal comparison of monthly ETa and ETp values for Beni Amir and Beni Moussa Est. The comparison reveals the occurrence of crop water stress in the Tadla perimeter during the summer months June, July and August. The Beni Amir sub perimeter shows more severe crop stress in summer than the Beni Moussa Est sub perimeter.

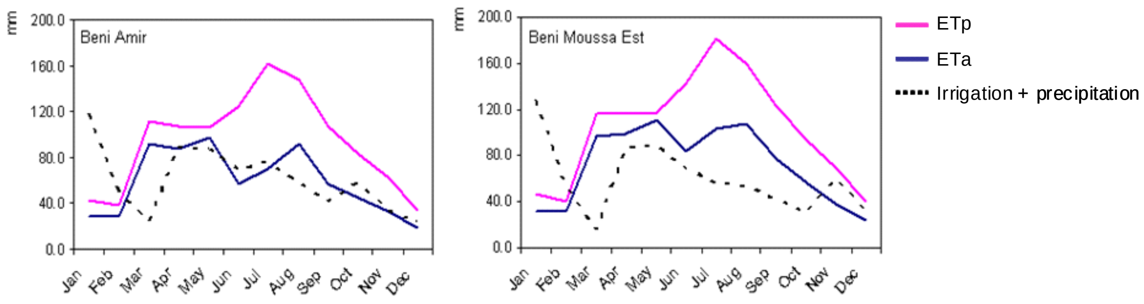

Figure 5 Comparison of ETa and ETp to available water (irrigation and precipitation)

Comparing water consumption to water availability, it is clear that more water is evapotranspired than is available from canal irrigation and precipitation. This makes it evident that groundwater is used for irrigation. Especially in Beni Moussa Est the use of groundwater appears to be substantial. From Figure 5 it can be seen that during the months of July and August, almost twice the amount of water available from irrigation and precipitation was consumed.

Validation

Kselik et al (2008) compared already Potential Evapotranspiration (ETp) values derived from SSEBI to values from an agrohydrological model. Now ETa and ETp values were compared to values from local lysimeters, showing good correlations (Figure 6). As the 3 lysimeters (bare soil, cereals and sugar beet) were watered every decade a more or less potential ET is expected to be derived from the lysimeter data. The steep increase in lysimeter values around decade 7-9 in 2007 is almost equal to the steep increase in the SSEBI ET values. However, the decrease in lysimeter ET around decade 12-14 is not shown in the SSEBI results. As the net radiation in this period is very high the only way to explain the low lysimeter data is trough a water shortage; probably the irrigation regime in the lysimeters failed at that time. Another remarkable difference is the slight underestimation of SSEBI ETp values compared to the lysimeter values in decades 17-25, most probably by energy advection from the surrounding areas towards the irrigated perimeter, which at this moment cannot be modeled in the SSEBI algorithm. The annual ET (decade 2006-25 until 2007-24) from the bare soil lysimeter is 1322 mm. This is also slightly higher than the ETP values for Tadla irrigation units (Table 1), where the average is 1190 mm for 2007.

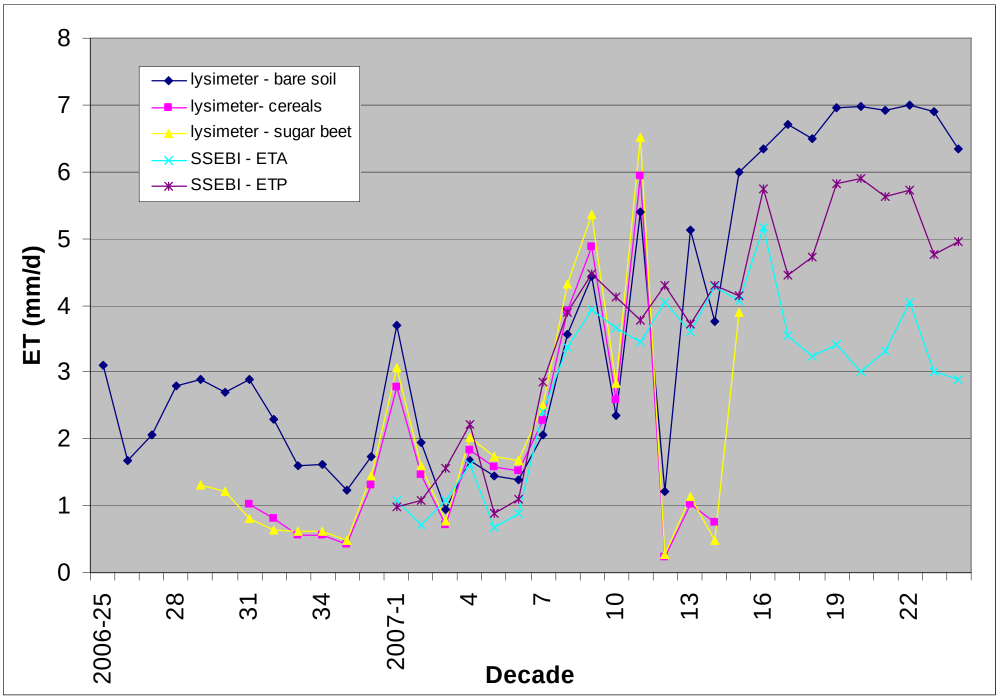

Figure 6 Comparison of evapotranspiration from remote sensing and lysimeter

Estimation of groundwater use

The amount of groundwater used for irrigation is estimated based on the water balance of the irrigated perimeter. When we consider a schematic water balance in an irrigated area, there are three inflows of water: rainfall (P), groundwater inflow from upstream areas and diverted canal water (I). Often groundwater inflow is in the same order as groundwater outflow. Part of the precipitation and diverted river water (P+I) leaves the area as actual evapotranspiration (ETa). The remaining part is stored in the irrigated area or drained. For Tadla, with medium clay soil types, it is estimated that around 20% of the inflow is drained from the irrigation perimeter (surface drainage, seepage). Based on this assumption, groundwater use for irrigation (GW use) can be estimated for the Tadla irrigation units (Table 1).

Table 1 Estimation of groundwater use for Tadla

Sub perimeter	**Irrigation unit**	**ETA mm/year**	**ETP mm/year**	**P mm/year**	**I mm/year**	**GW use mm/year**

Beni Amir	1	645.5	1099.5	253.7	459.8	93.3
Beni Amir	2	751.1	1152.6	253.7	667.2	18.0
Beni Amir	3	653.2	1097.3	253.7	414.4	148.4
Beni Amir	4	774.2	1165.2	253.7	561.7	152.3
Beni Moussa Est	5	932.3	1293.9	283.7	400.0	481.7
Beni Moussa Est	6	785.7	1194.6	283.7	292.5	405.9
Beni Moussa Est	7	880.5	1266.9	283.7	462.3	354.5
Beni Moussa Est	8	836.2	1219.4	283.7	478.2	283.4
Béni-Moussa Ouest	9	777.1	1176.8	222.5	460.1	288.8
Béni-Moussa Ouest	10	763.7	1163.2	222.5	492.8	239.3
Béni-Moussa Ouest	11	870.4	1246.1	222.5	446.2	419.3
Béni-Moussa Ouest	12	831.5	1210.8	222.5	555.7	261.2
Average	-	791.8	1190.5	253.3	474.2	262.2

For the Tadla irrigation perimeter, average groundwater use is estimated at 262 mm/year, which amounts to 55% of the surface irrigation water use on a yearly base. This percentage is close to the value obtained by Hammani et al. (2009) in the Tadla area for the year 2003. Groundwater use is highest is the Beni Moussa Est sub perimeter and amounts to 80% of surface water use.

4 Conclusions

In the Tadla irrigation perimeter, farmers supplement their irrigation supplies with groundwater, leading to water table depletion in the area. An additional concern is the deteriorating water quality in the area. There is no regulation to control withdrawals of groundwater, and no data are available to quantify groundwater use. The paper demonstrates a method based on remote sensing techniques and field observation data to estimate the ground water use for the 2006 hydrological year. Calculations show that for Tadla, average groundwater use amounts to around 55% of the surface irrigation water use. This is substantial, and requires immediate attention. Policy recommendations are needed to control the use of groundwater and to reach an integral management with the canal water. For exact calculations, data on groundwater levels are needed.

Acknowledgements

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