Assessment of sustainable agriculture in the irrigated perimeter of Tadla, Morocco using the CRIWAR strategy module

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Abstract: The CRIWAR computer model for the calculation of crop water requirements was extended with a new strategy module. It is designed to follow two sub-strategies in an irrigated command area. The first one is based on (irrigation) water requirements of the irrigable area and the second one on the water balance of the gross command area for a sustainable water balance. With this extension of the model, the present cropping pattern and irrigation water use in the command area can be evaluated for a stable water balance and for crop production. The strategy component uses the depleted fraction, defined as the ratio of ET_{actual} over total inflow (P + Vc), the parameters of the water balance in an irrigated area. When the depleted fraction is plotted versus the change of the groundwater table, if gives information on the rate of change with which water is stored in the area. In the Tadla plain, thousands of wells are used for the conjunctive water supply with groundwater from the phreatic aquifer, as well as from the Eocene aquifer. The CRIWAR strategy component was applied in the Beni Amir irrigated perimeter to estimate the volume of groundwater being pumped from the Eocene aquifer.

Introduction

The Tadla irrigated perimeter is situated 200 km south of Rabat in the Oum Er Rbia river basin at an altitude of 400 m + mean sea level (Figure 1). With more than 100 000 ha of irrigated land, it is one of the most important large-scale irrigation schemes in Morocco. Its development already started in the nineteen forties.

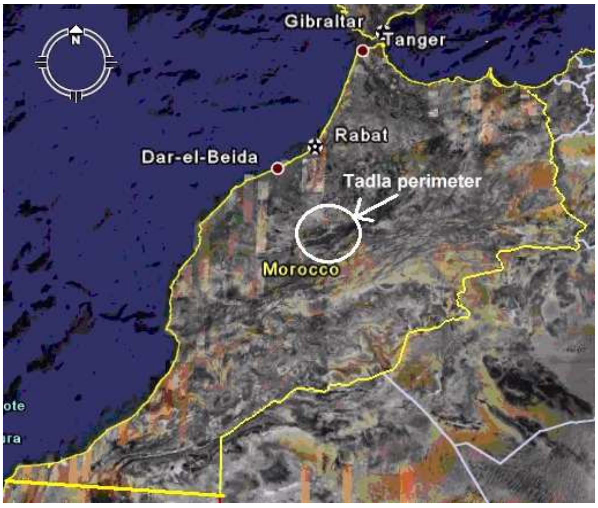

Figure 1. Location of the Tadla irrigated perimeter in Morocco

The Oum Er Rbia, which is the second large river of Morocco, flows from east-north-east to west-south-west through the Tadla plain. It divides the irrigated perimeter into two asymmetrical areas, each having different hydrological and hydro-geological characteristics (Hammani, 2004).

The two irrigated areas receive water by gravity from two dams by separate networks of lined open canals:

- Beni Amir with an irrigated area of about 35 000 ha is located on the right bank of the Oum Er Rbia river. It is irrigated from the Mohamed El-Hansali dam which has a capacity of 740 Mm3.
- Beni Moussa lies on the left river bank and has an irrigated area of about 69 500 ha. Beni Moussa is sub-divided into Beni Moussa East and Beni Moussa West. The area receives irrigation water from the Bin El Quidane dam, which has a capacity of 1300 Mm3. (Figure 2)

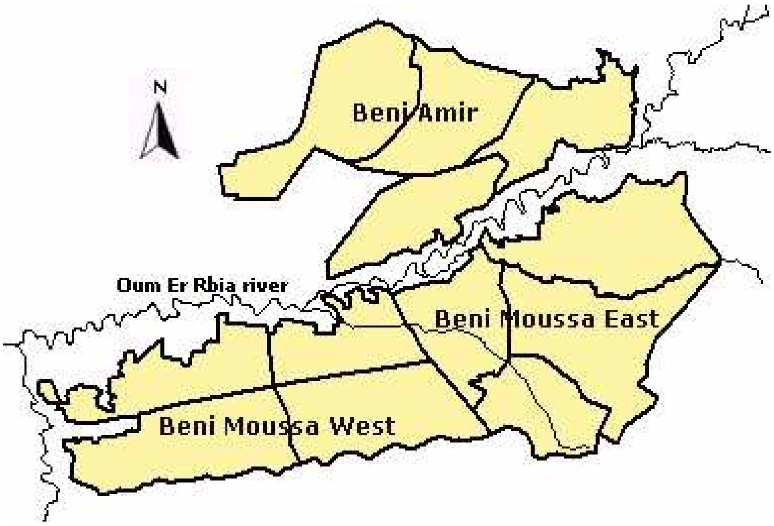

Figure 2. The irrigated perimeter of Tadla

The climate in the irrigated perimeter of Tadla is Mediterranean, being arid to semi-arid. The average annual temperature is 19°C. The average rainfall in the period 1997-2006 was about 260 mm/year. The lowest yearly rainfall in this period was 155 mm/year and the highest 450 mm/year.
Most of the rain falls in the months October - April. There is a tendency that the amount of rainfall becomes less when going from the foothills of the Atlas in the east to the plain in the west. The annual calculated potential evapotranspiration in the period 1997 – 2006 was in the order of 1400 mm.

According to the initial project design, Beni Amir should receive 420 Mm^3 of water annually and Beni Moussa should receive 720 Mm^3 (Hellegers, 2007). Before 1980, groundwater tables in the phreatic aquifer rose due to seepage of irrigation water as a result of low efficiency. This caused soil deterioration and the need for an artificial drainage system. After a large drought between 1981 and 1984, and the decrease of the annual rainfall since 1992, less surface water became available for the Tadla irrigated perimeter. The available volume dropped from 840 Mm^3 in 1979 to 340 Mm^3 in 2002. After the droughts of the eighties, the farmers started to exploit groundwater on a large scale (Hammani, 2004). In the beginning water was pumped from the phreatic aquifer by wells of up to 35 m deep, which had large diameters of 1 to 3 m. After 1992 the groundwater level dropped and the quality of the phreatic groundwater deteriorated. Farmers started to deepen their wells to enhance the discharge by drilling bore holes at the bottom of the wells. These wells could go as deep as 117 m to the bottom of the aquifer. At present, even deeper wells with a small diameter are drilled up to 160 m deep into the Eocene. Since the installation costs of wells went down drastically, many farmers have installed deep wells. The deep wells can take water from the

Eocene aquifer which lies directly below the phreatic aquifer (Figure 3). At some locations wells are installed in the Turonian aquifer. Measurements in the Eocene layer have revealed that water levels have also dropped in this aquifer. A detailed inventory in the perimeter in 2006 counted about 8300 wells, deep wells and boreholes. The volume of groundwater pumped from the Eocene layer is now estimated to be 110 Mm^3 for agricultural purposes (Hammani, 2007). The Eocene layer is also an important aquifer for drink water for several cities and industries. Interviews with farmers showed that alfalfa is the priority crop for pumping groundwater, followed by cereals.

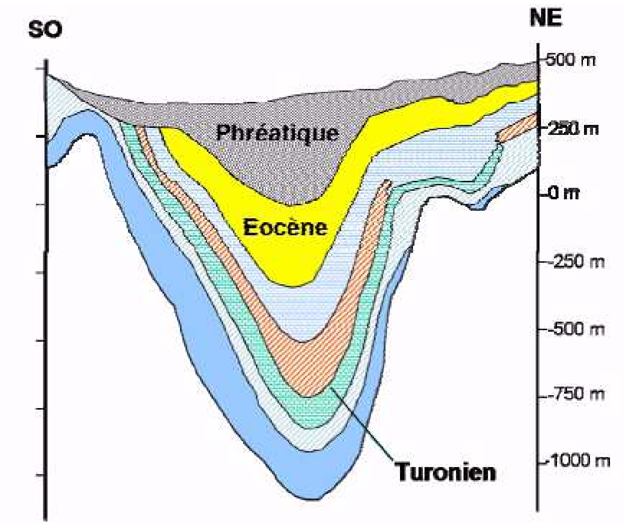

Figure 3. South–west north-east (SO – NE) cross section through the Tadla aquifer system (Hammani, 2007)

The ORMVAT (Office Régional de la Mise en Valeur Agricole du Tadla), in charge of the management of the irrigation schemes (design, operation & maintenance, fees) implemented a monitoring network to keep track of the fluctuations of the water levels in the whole 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, but large fluctuations of several meters during a year are not uncommon in the perimeter. The traditional method of irrigation in the area, the “robta” system, which is the periodically flooding of level basins, is still common practice in Tadla. The “robta” system applies more water to the parcels than the crops actually need. The efficiency of the “robta” system is about 50%. Hence, the non-consumed part (the other 50%) recharges the shallow aquifer. Besides this, the cropping patterns have intensified over the last decades following liberalization of the government controlled cropping patterns. Crop rotation is now a regular practice, where two crops are grown on the same parcels in one year. The cultivation of more water consuming crops like alfalfa, often grown as cattle fodder, has largely increased the crop water demands in the perimeter. Excess water from inefficient irrigation recharges the phreatic groundwater, where it goes into storage until it is pumped up again at a later stage. Besides pumping water from the phreatic aquifer, water is subtracted also from the deeper layers to supplement the need for water. How much water exactly is withdrawn from the aquifers is not known, but over the year, rising and falling water tables can be monitored in the irrigated perimeter, sometimes varying several meters.

To ensure sustainable agriculture in an irrigated area, the conditions under which crops grow, should remain stable over a prolonged period. For crops production, actual evapotranspiration should be close to the potential evapotranspiration. At the same time degradation of the soil (salt accumulation), mining of the groundwater aquifer and the negative influence of drainage water on the downstream environment should be avoided. Water management therefore should balance the need of water for agriculture and the need for a sustainable environment.

This paper describes the CRIWAR hydrological model and the usefulness of its strategy module to evaluate surface and groundwater use in an irrigated command area. The model was applied in the Beni Amir part of the Tadla irrigated perimeter

Description of the CRIWAR model

The CRIWAR 3.0 model consists of two parts, the water requirement part and the strategy part. The strategy module is a new extension to the older CRIWAR 2.0 version (Bos et al., 1996)

The water requirement module

This part of the model calculates the irrigation water requirements of a cropping pattern in an irrigated area throughout the crops' growing season. The crop irrigation water requirements consist of the potential evapotranspiration, ET_p, minus the effective rainfall, P_e. The potential evapotranspiration is the maximum amount of water that plants can evapotranspire when they are not short of water during their growth. First the reference evapotranspiration (ETref) is calculated on a daily basis from meteorological and geographical data. In CRIWAR, three methods are available to calculate the ET_{ref}, preferably the Penman-Monteith method. The reference evapotranspiration is then multiplied with a crop coefficient to obtain the ET_p. Crop coefficients depend on the type of crop and its growth stage. These coefficients are known from field research and from literature.

Effective rainfall is that part of the total precipitation on the cropped area, during a specific time period, which is available to meet the evapotranspiration in the cropped area. Subtraction this value from the ET_p gives the crop irrigation water requirements.
Note that these calculated crop irrigation water requirements do not incorporate losses that occur during distribution, conveyance or field application (Bos, 1996).

The strategy module

When we consider a schematic water balance in an irrigated area, there are three inflows of water: rainfall (P), groundwater from upstream and diverted river water (V_c). Often groundwater inflow is in the same order as groundwater outflow. Part of the precipitation and diverted river water ($P+V_c$) leaves the area as actual evapotranspiration (ET_a). The remaining part is stored in the irrigated area or drained. The depleted fraction DF compares the three components of the water balance in an irrigated area. It relates the actual evapotranspiration to the sum of the precipitation and the inflow of irrigation water. The depleted fraction, DF, is defined as (Molden 1997, Bastiaanssen et al 2001):

$$DF = ET_{actual} / (P+V_c)$$

The depleted fraction can be used as an indicator to assess irrigation water use. When ET_a and rainfall are known, the depleted fraction can be influenced by means of the diverted irrigation water V_c.
Spatial variation of the actual evapotranspiration (ET_a) of an area can be calculated from satellite images. Low resolution images (NOAA or MODIS) are adequate to calculate monthly values. In practice ET_a and rainfall are not calculated for the irrigated area only, but for the gross command area ($ET_{a,gross}$). The $ET_{a,gross}$ is composed of the ET_a from the irrigated (cropped), from the irrigable fallow (non-cropped) area and from the permanently non-irrigated part of the command area.

The value of the depleted fraction influences the volume of water stored within the irrigated area. When the depleted fraction is low, water is stored in the area and the water table will rise. When the depleted fraction is high, water leaves the area and the water table will drop. For a certain depleted fraction, the volume of water stored in the area is stable ($DF_{sustainable}$). This value depends on the natural drainage of the irrigated area and often is about 0.6 (Bos, 2004). This can be visualized when the monthly change of the groundwater table is plotted as function of the depleted fraction (Figure 4). For semi-arid and arid regions the straight line in intersects the x-axes at a depleted fraction between 0.5 and 0.7. For areas with a poor natural drainage the $DF_{sustainable}$ will be around 0.7 (clay, flat areas) and around 0.5 for well-drained areas (sandy, sloping).

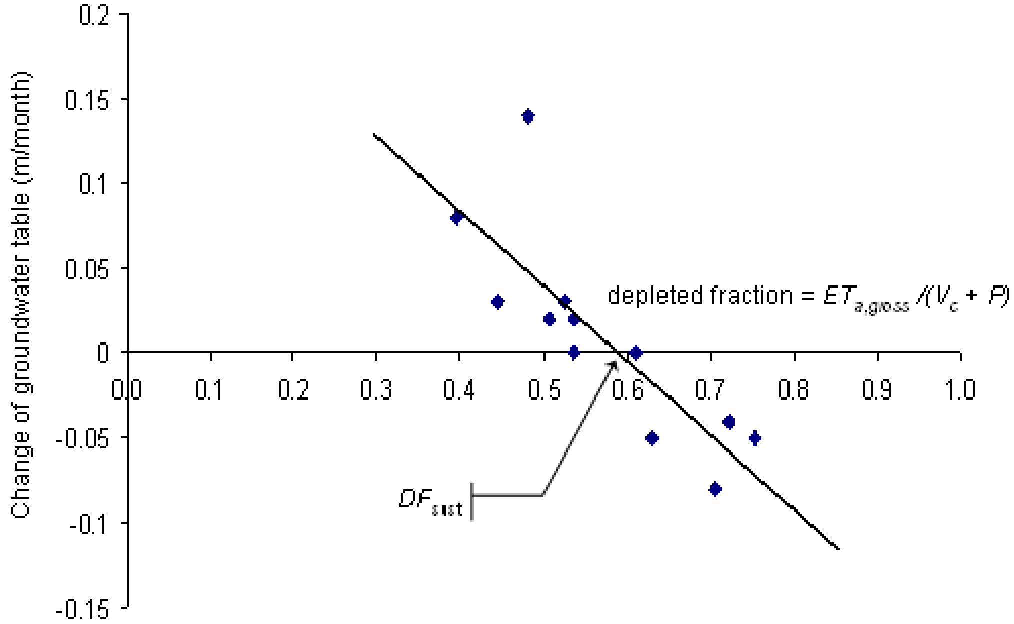

Figure 4. Monthly change of the groundwater table as a function of the depleted fraction. (Example from Brazil, Bos 2004)

If the depleted fraction is 0.6, while $ET_{a,gross}$ is less than about 0.6(P + V_c), a portion of the available water goes into storage causing the groundwater table to rise. Storage of groundwater decreases if $ET_{a,gross}$ is greater than 0.6(P + V_c). Apparently, the natural drainage from command areas in arid and semi-arid regions has a capacity that is sufficient to discharge about 0.4(P + V_c). Thus, the depleted fraction can be used as a performance indicator on irrigation water use. The volume of water diverted into the irrigated area can be reduced during months with a low depleted fraction. If this non-diverted water remains in a storage reservoir, which often is the case in arid and semi-arid regions, this water can be diverted during warmer months (Bos, 2004).

The parameters V_c and $ET_{a,gross}$ in the definition of the depleted fraction are not entirely independent of each other. As long as there is sufficient irrigation water, the $ET_{a \text{ from the}}$ cropped irrigated area will be near its potential value. However, if V_c is reduced in order to increase the depleted fraction, less water will be available for irrigation and ET_a will decrease. The evaporative fraction, ET_a/ET_p for the irrigated area remains about unity if the depleted fraction is less than 0.6. During part of the year such a high evaporative fraction is needed to leach accumulated salts, etc. from the root zone of the crop. For higher values the depleted fraction the value of ET_a/ET_p decreases by about 20 percent. Due to the shape of the yield versus ET curve of most crops a decrease within this range results to a higher yield per cubic meter water. However, crop yield per hectare will decrease (Bos et al.,2005). To sustain agriculture on the one hand (leaching of the root zone is needed) and to attain a high productivity in terms of yield per cubic meter of water on the other hand, the monthly values of the depleted fraction should range between 0.4 and 0.9 while the annual average should be near the established intersection point for the irrigated area. The value of the depleted fraction at this intersection point between the straight line and the x-axes is the value for a sustainable groundwater balance.

The CRIWAR strategy module brings two methods (tracks) to calculate the irrigation water requirements of a command area together. The two tracks can be considered as two sorts of "water flows" that should be managed in such a way that crops can be grown in the irrigable area:

- The classical flow of irrigation water from the surface water source (river diversion or reservoir) through the conveyance and distribution system to the fields. This track considers the “crop water requirements” ($ET_p – P_e$) which subsequently is transferred into “irrigation water requirements” for the irrigated crops (ET-track). In this track, the strategy is to decide on a monthly allowable ratio of ET_a/ET_p for crop production.
- The less visible (and often ignored) vertical flows of water seeping from the canals and fields to the groundwater basin and the “return” flow through pumping and capillary rise. This track considers the water balance of the gross command area. It uses the depleted fraction (DF) as discussed above to attain a sustainable irrigation environment (the DF-track).

The strategy model of CRIWAR takes the user through the two different tracks to calculate irrigation water requirements. It gives the user support to the analysis of the results of these tracks and it compares the results. The results of the calculations are presented as monthly volumes of irrigation water to be applied to the irrigated area. If the results of the two calculations are equal or close, the proposed or present cropping pattern in the study area can be considered sustainable.

Application of CRIWAR in Beni Amir

The CRIWAR model was applied in Beni Amir for the year 2006, which is an average year with 255 mm of rainfall. Meteorological data, irrigation volumes, groundwater levels, soil type and cropping patterns were provided by ORMVAT. Crop coefficients were interpreted from the FAO drainage paper 56 (Allan, 1998) and “Besoins en eau des cultures dans le perimetre du Tadla” (Belabbes, 2004). Calculations of the potential evapotranspiration were done with CRIWAR on a daily base using the Penman-Monteith method. To apply the strategy module, actual evapotranspiration data are needed to calculate the depleted fraction.
The SSEBI-2 algorithm was applied to derive the actual and potential evapotranspiration of the area (Roerink et al, 2000). SSEBI-2 is developed to estimate surface fluxes from remote sensing images. The SSEBI-2 approach allows a quick temporal and spatial assessment of seasonal water consumption for large river basins or irrigation systems, with a minimum amount of input data required. A total of 26 low resolution (500 x 500 m) MODIS images of 2006 were used to derive evaporative fraction maps. These maps were subsequently integrated in equal intervals (days, decades, months), after which the net radiation flux is calculated on the basis of standard meteorological data, combined with remote sensing input. Finally actual and potential evapotranspiration on a daily basis was calculated. For validation, surface flux measurements from the area were used.

The total cropped area of Beni Amir in 2006 was 31850 ha out of 36900 ha for the gross command area. The cropping pattern consisted of Alfalfa (40%), Maize (25%), Olives (17%), Wheat (13%) and Sugar beet and Vegetables (5%). Wheat and sugar beet were grown during the winter. Half of the maize area was also in rotation with the wheat.
For this cropping pattern the potential evapotranspiration was calculated with CRIWAR on a monthly base and compared with the calculations from the satellite image. Over the whole year, the calculations of CRIWAR are about 90 mm lower (1040 mm) than the remote sensing calculations (1130 mm). Only during the months May – July, the calculated values of CRIWAR are somewhat higher (Figure 5). Since both methods are subject to error, this difference of less than 10% is acceptable.

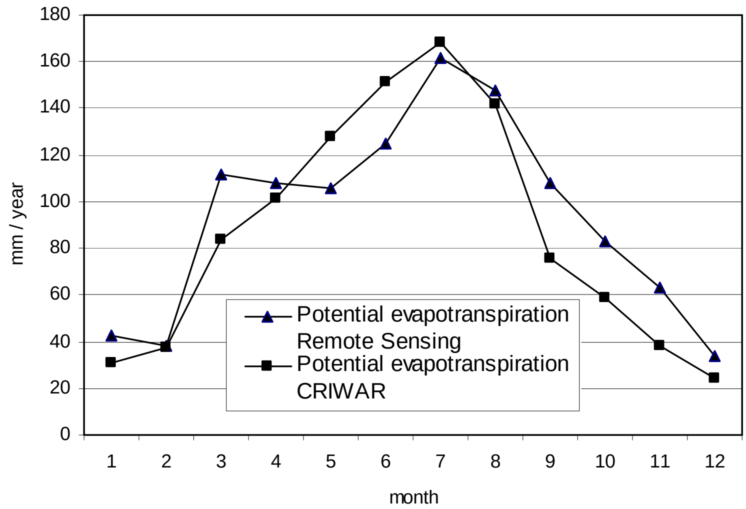

Figure 5. Potential evapotranspiration for 2006, calculated from satellite data and with CRIWAR

Implementation of the strategy module

The strategy module in CRIWAR is designed to compare two strategies in an irrigated command area. The first one is based upon (irrigation) water requirements of the irrigable area and the second one on the water balance of the gross command area. Its purpose is to evaluate the present cropping pattern and irrigation water use in the command area for sustainability and crop production and to inform irrigation managers on the required volumes of water to divert into the area. We applied the strategy module in Beni Amir with a different objective, i.e. the estimation of the volume of groundwater extractions from the deeper non-phreatic aquifer(s).

In Beni Amir, the depleted fraction (DF) could be calculated on a monthly basis from field data and satellite images, i.e. the rainfall (P), the volume of diverted irrigation water (V_c) and the actual evapotranspiration (ET_a) (Table 1).

Table 1. Field data and calculated depleted fraction in Beni Amir in, 2006.

Month	P mm/month	V_c Mm3/month	ET_a m3/month	DF -
J	118	0	29	0.25
F	49	0	29	0.59
M	4	8	92	3.99
A	9	32	87	1.03
M	31	24	97	1.08
J	3	27	57	0.84
J	0	30	71	0.99
A	0	23	93	1.68
S	0	16	57	1.46
O	18	15	45	0.81
N	13	8	32	0.96
D	9	6	19	0.8
Total	255	191	708	

To calculate the depleted fraction, CRIWAR converts the volumes of diverted irrigation water into mm water depth on the gross command area. Table 1 shows that the calculated depleted fraction becomes higher than 1 during certain months of the year. When the depleted fraction is higher then 1, it means that the actual evapotranspiration is higher in the area than the volume received from rainfall or diverted irrigation water. Considering the relation between the depleted fraction and the change of the groundwater table, in which return flow by pumping from the phreatic aquifer or capillary rise is already incorporated, the conclusion is that water must be imported into the command area from other sources. Surveys made clear that groundwater is subtracted for agricultural purposes from aquifers other than the phreatic aquifer (Hammani, 2004, Hammani, 2007). When the relation between the depleted fraction and the change of the groundwater table is known and the knowledge that the sustainable depleted fraction of irrigated areas varies between 0.5 and 0.7, depending on the type of soil, a rough estimate can be made of the volume of imported groundwater.

ORMVAT has about 40 wells in the Beni Amir area where the fluctuation of the groundwater is measured. The depth of the water table was about 10 to 15 meters below soil surface. Measurements are done on a quarterly base only, which gives just a rough estimate of the monthly change of the groundwater table. For this study, a number of wells were selected, that showed a similar change of the groundwater table over the year 2006. In these wells, the position of the groundwater table in January 2007 was at the same depth as in January 2006 (Figure 6), groundwater storage after one year was the same as the year before. The graph shows a rising groundwater level during the rainy season from October through March and a falling groundwater table during the summer months.

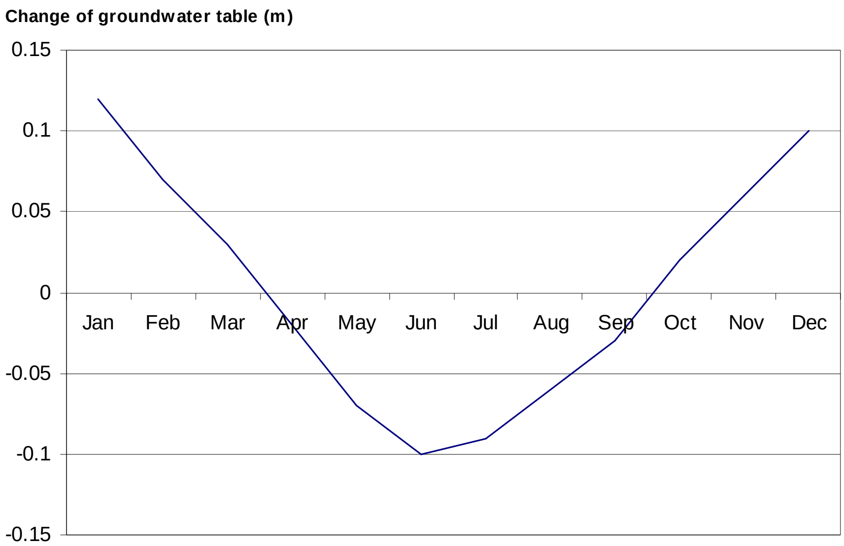

Figure 6. Monthly change of the groundwater table in 2006 in selected wells in Beni Amir

The calculated depleted fractions were plotted versus the change of the groundwater table. For the months where the depleted fractions were higher than 1, the irrigated volumes of water were adjusted by adding water to bring the depleted fractions down to acceptable values. In this process, which is done with CRIWAR, a sustainable depleted fraction (DF_{sust}) of about 0.7 was taken as an acceptable value, since the soil type in Beni Amir is a medium clay (Information by ORMVAT).

Figure 7 shows the result from the CRIWAR strategy module. To adjust the depleted fractions, a total of 117 Mm^3 of water was added to arrive at these results, which we assume is water imported into the area by groundwater abstractions. This is about 45% of the total water requirement of 254 Mm^3 water that CRIWAR calculated as potential evapotranspiration for the present cropping pattern and about 60% of the 191 Mm^3 of surface irrigation water. The total volume of surface and groundwater thus would be 308 Mm^3.

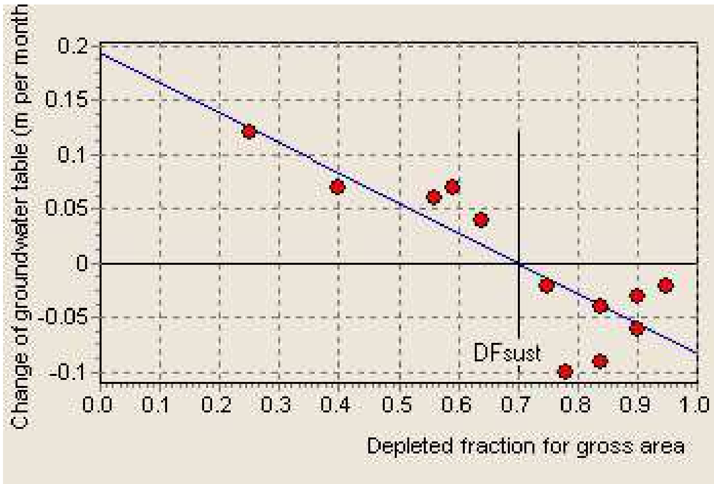

Figure 7. The depleted fraction for Beni Amir plotted vs. the change of the groundwater table in 2006 for selected wells.

Discussion and recommendations

The above water balance calculations show that CRIWAR can be used to estimate the volume of water which is imported into the area through groundwater abstraction from the Eocene aquifer. For Beni Amir, we calculated of about 100 Mm^3/ year. The calculations are based on the monthly fluctuation of the groundwater level, plotted versus the depleted fraction. In the above example, the fluctuation of the groundwater table is only about 0.25 m. At present, the fluctuations of the groundwater are measured with a 3-monthly interval, which is not accurate enough to produce a smooth graph of the groundwater fluctuation. What happens to the fluctuation of the groundwater table in the three-month period is unknown. Depending on the growth stage of the crops, farmers may decide to pump groundwater during critical stages in the development of their crops when there is not enough surface water to meet the crops demand. In our calculations we assumed a more or less linear relation between the 3 monthly values. For a more accurate estimate of the fluctuation it is recommended to measure the groundwater levels at least on a monthly basis.

Surveys in the irrigated perimeter showed that there are more than 8300 locations where water is pumped from the aquifers. Also in the zone outside the irrigated perimeter there are more than 4500 pumping locations, of which more than 1300 wells pump from the Eocene aquifer (Hammani, 2007). Besides for agriculture, the Eocene aquifer provides water to several cities and for industrial use. If future abstractions continue to grow, the competition with these sectors will increase. The sustainability of the present groundwater allocation can only be assessed through a thorough geo-hydrological survey of the aquifers. Such an assessment is recommended to quantify the available resources in the aquifer in combination with measurement of the abstractions by the thousands of wells. It is also recommended to improve the measurements of the pumped groundwater. This could be established by installation of water meters on the wells.

The agricultural sector can play an important role in reducing its demand for water. It could shift from high water demanding crops like alfalfa to low water demanding crops like wheat, possibly in combination with other less water demanding crops. A study on the productivity of water is recommended.

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