Considering salinity effects on crop yields in hydro-economic modelling – the case of a semi arid river basin in Morocco

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Abstract

Agricultural production, especially date palm cultivation, is the major food and income source for people in the Drâa basin in Southern Morocco. However, the semi-arid river basin faces very low rainfalls and has suffered from a continuing drought over the last years. River water, as the principal source for irrigation, has been increasingly substituted by groundwater mining. This has led to an unsustainable downing of the groundwater table, increased salinisation problems, and has posed further constrains on the agricultural production potential. Without targeted water resources management, water available for irrigation will soon be depleted or too saline to be used for most crops. Consequently, farmers will not be able to maintain their production levels, and subsequently lose an important source of family income. The relationship between water use and agricultural production is represented using an integrated hydro-agro-economic simulation model with a spatial water distribution network of in- and outflows, balances and constraints. The model results are driven by profit-maximising water use by agricultural producers which are primarily constrained by both water availability and quality. Crop yields are influenced by quantitative irrigation water application deficits and by the salinity of irrigation water. Results show considerable differences depending on whether salinity is incorporated or not. When salinity is considered, yields tend to be much lower despite increased irrigation water needs to enable a reduction of soil salinity through leaching.
Keywords: nonlinear programming, water allocation, water quality, salinity.

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1 Introduction

The Drâa river basin is located in South-East Morocco at the edge to the Saharan desert. The area faces pre-Saharan climatic conditions with naturally low rainfalls. The precarious water situation has been aggravated by subsequent droughts and due to increasing salinity of both ground- and surface water in recent decades. Water salinity adversely affects the yet poor agricultural production potential. During the last years the salt content of irrigation water has further increased, [1] leading to very low agricultural output levels and the need for the farm households to identify additional sources of income. Hence, a holistic water management should take into consideration the impact of salinity on agricultural yields.

Since 1972 a centrally managed reservoir, the Mansour Eddahbi reservoir, supplies a belt of six oases along the middle Drâa River basin with irrigation water. Due to increasing surface water scarcity, farmers progressively established wells with motor pumps and are using groundwater instead of river water for irrigation. However, groundwater use has the drawback of very high salt contents especially in the two most southern oases, Ktaoua and Mhamid. The average values for salt content are shown in table 1. It should be noted that groundwater salinity is markedly higher than that of surface water.

Table 1: Salt content of ground and surface water in the Drâa basin.

Oasis	*Groundwater (g/l)*	*River water (g/l)*
Mezguita	1.5	0.64
Tinzouline	2.2	0.79
Ternata	2.5	1.04
Fezouata	4.0	1.04
Ktaoua	5.0	1.32
Mhamid	5.0	1.32

Source: Bouidida, A. 1990, Ministère du Commerce, de l'Industrie, des Mines et de la Marine Marchande, 1977.

For the Drâa basin irrigation water salinity is tremendously high (locally sometimes up to 10 milliohms/cm in the South), but so far seems not to have been sufficiently considered in water management in the region.

Water quality, especially salinity, has been addressed in various simulation models dealing with irrigated agriculture. Lee and Howitt [2] use a Coob-Douglas production function according to Dinar and Letey [3] to account for water salinity in a nonlinear programming model. Also, Cai et al. [4] use a production function taking the water deficit, salinity rates, and technology levels for yield formation into account. By contrast, the integration of water quality aspects in the hydro-economic model MIVAD (Modèle integrée du Valée du Drâa) presented in this article is formulated as a yield function containing factors reflecting both seasonal water deficits and salinity levels.

2 The role of salinity in the Drâa basin model

The hydro-economic river basin model MIVAD is a nonlinear water allocation model that consists of a node-link network representing the six oases along the Drâa River. MIVAD is similar to the class of river basin models as designed by Rosegrant et al. [5]. The spatial structure of the model is presented in figure 2 where the interconnection between supply and demand is represented with arrows. The objective of the model is to maximize agricultural profits taking into account various constraints and balances. In MIVAD, farmers can make choices in cropping on two levels: the absolute area to be cultivated with a certain crop mix that is kept constant, and the yield levels for the different crops which depend on water application of different quantity and quality (i.e. salt content).

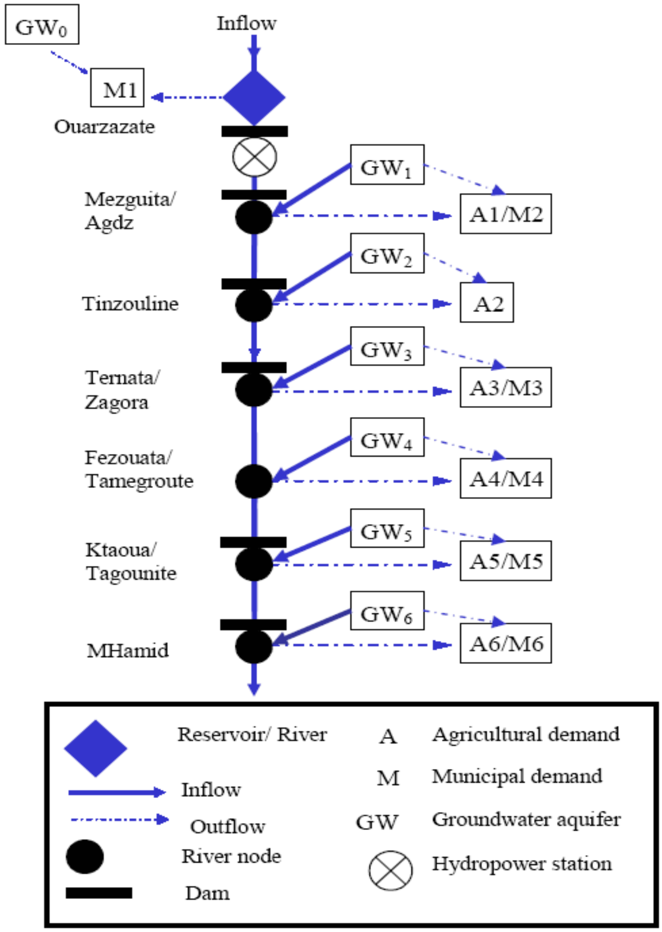

Figure 1: Spatial structure of the MIVAD model (Source: Kuhn et al. [6]).

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More precisely, actual yields are calculated by reducing the maximum yield of a crop by a water deficit factor and a salinity reduction factor. This has been applied by Dinar and Letey [3] to a seasonal crop water production model. It is assumed that there is a maximum crop yield *pmaxyield* to be achieved with average technology (seed variety, fertiliser use, chemicals, seedbed preparation etc.). The actual yield in a certain year may be lower than the maximum due to insufficient water supply to the crop and salinity response. The yield function is based on the following relation:

$$vcropyiel_{dma,crop} = pmaxyield_{crop} \cdot vdef\_maxi_{dma,crop} \cdot vyie\_sali_{dma,crop} \tag{1}$$

with *pmaxyield*, maximum yield for the different crops (per ha), *vdef_maxi*, yield reduction factor due to periodically or generally, insufficient water application (crop water deficit), *vyie_sali,* yield reduction factor due to salinity.

In MIVAD it is assumed that water application to crops is a decision that is made by farmers for the entire cropping season based on a-priori information on the amount of irrigation water available. The yield reduction factor due to crop water deficit (*vdef_maxi*) is calculated as a non-smooth approximation of the seasonal water deficit *vdef_seas*.

$$vdef\_maxi_{dma,crop} = \left(1 + \exp\left(\alpha \cdot \left(-vdef\_seas_{dma,crop} + \beta\right)\right)\right)^{-1} \tag{2}$$

with *vdef_seas* being the seasonal water deficit as calculated by using seasonal ky-values (FAO 1986 [7]), α a slope coefficient of the approximation curve, and β a coefficient determining the position of the curve.

Monthly evapotranspiration consists of two components: total irrigation water applied to a crop (*v__w_a_cr*, which the farmer can choose to take from surface or groundwater sources) reduced by a leaching factor (to be explained later on), and the effective rainfall in the area.

$$\begin{aligned} & veta\_stag_{dma,crop,pd} = \\ & v\_\_w\_a\_cr_{dma,crop,pd} \cdot vleachfct_{dma,crop} \\ & \quad + vcroparea_{dma,crop} \cdot peff\_rain_{dma,pd} \end{aligned} \tag{3}$$

with *v__w_a_cr i*rrigation water available to a crop both from surface water and groundwater, *vleachfct* leaching factor, *peff_rain* effective rainfall in mm, where the leaching factor (see formula 8) is calculated according to Ayers and Westcot [8] as:

$$vleachfct_{dma,crop} = 0.01 \cdot \exp\left(\delta \cdot vet\_ratio_{dma,crop}\right) + pirr\_effy \tag{4}$$

with *vet_ratio* actual evapotranspiration (ETa) divided by maximum evapotranspiration (ETm), *pirr_effy* irrigation efficiency factor (constant).

The leaching factor not only determines the amount of irrigation water which percolates into deeper soil layers, but also plays an important role for the level of soil salinity. Salt concentration in the soil is a result of the fact that evaporation of irrigation water leads to an accumulation of salt in the topsoil. This is especially the case in the most southern oases, Ktaoua and Mhamid, as evapotranspiration in the area is high and insufficient leaching leads to an accumulation of salt on the surface. During and after irrigation days, leaching into deeper soil layers might occur and help to keep soil salinity in check, while during the rest of the time plants may still suffer from irrigation water deficit. This is why the leaching factor used in MIVAD contains a constant additive component (*pirr_effy*) reflecting the leaching losses of furrow irrigation.

The salt content of water consumed by crops (salinity) is another important factor for yield formation. The yield reduction factor due to salinity is calculated on the basis of a modified discount function (Steppuhn et al. [9]). The salinity of soil water (*vyie_sali*) is calculated as:

$$vyie\_sali_{dma,crop} = \left(1 + \left(vsoilsali_{dma,crop} \big/ psal\_thre_{crop}{}^{psal\_slop_{crop}}\right)\right)^{-1} \quad (5)$$

with *vsoilsali* being the salinity level of the soil water consumed by crops, *psal_thre* the crop-specific salinity level at which the yield is depressed by 50%, and *psal_slop* a slope parameter. The effect of the slope parameter is displayed in figure 3.

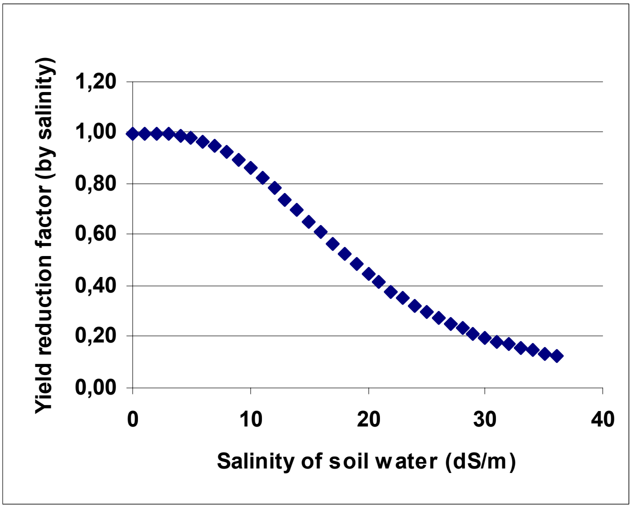

Figure 2: Effect of salt reduction factor on yields.

The soil water salinity level can be derived from the salinity level of the irrigation water multiplied by a concentration factor specific for each crop and oasis.

$$vsoilsali_{dma,crop} = vsalinity_{dma} \cdot vcon\_fact_{dma,crop} \qquad (6)$$

with *vsalinity* being the salinity level of irrigation water and *vcon_fact* the concentration factor. Salinity of irrigation water is the average of the salinity levels of surface (= river) and groundwater used for irrigation, respectively.

The concentration factor describes the ratio of salinity in irrigation water to the salinity of soil water and can be calculated as a function of the variable 'leaching factor' (*vleachfct*) that has already been mentioned in equation 5. On the basis of results from Ayers and Westcot [8], the leaching concentration factor VCON_FACT is calculated as:

$$vcon\_fact_{dma,crop} = \left(\beta \cdot vleachfct_{dma,crop}\right)^{-\rho} \qquad (7)$$

with β a level parameter, and ρ a slope parameter .

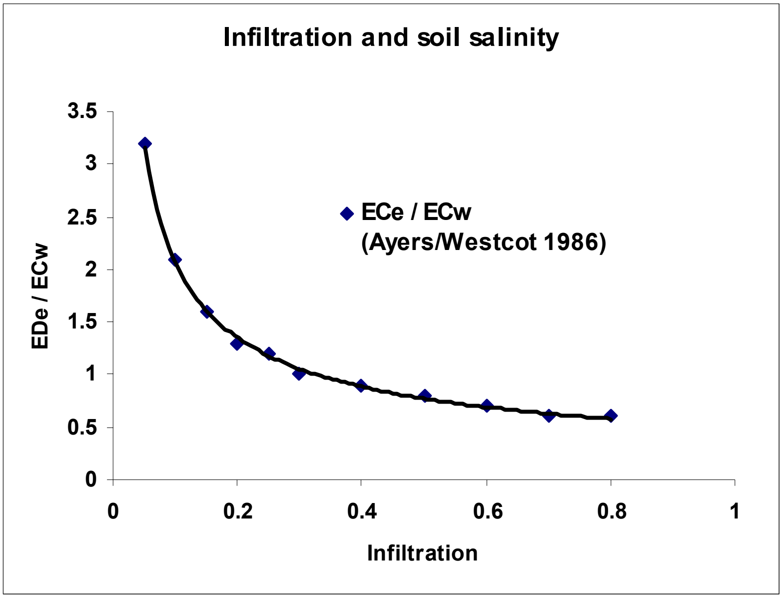

Figure 3: Soil salinity as a nonlinear function of the leaching factor.

3 Results of simulations involving salinity

To evaluate the effect of salinity on crop yields and agricultural profits, comparisons with and without a salinity effects on crop yields have been carried out for three different water supply scenarios. Table 2 summarises simulation results for different levels of surface water availability for the whole Drâa basin: a normal year, a medium and a dry year. The normal year relates to an average of inflows into the surface water network of the basin from 1972 to 2002, the dry year presents the average of the ten driest years over the same period (23% of the water amount of a normal year), and the intermediate year is an average of the other two (62%, respectively). If salinity is not considered, surface water for irrigation is more and more substituted by groundwater the more surface water becomes scarce. As total water use is nevertheless decreasing, agricultural profits are decreasing as well, primarily because the total cultivated area is decreasing, but also because yield levels are lowered, as is shown in table 3.

Table 2: Basin-wide simulation results for normal, medium and low water availability without and including salinity effects.

	Without salinity			*With salinity*		
	Normal	*Medium*	*Low*	*Normal*	*Medium*	*Low*
Ag. river water use (mio cbm)	165.3	89.4	16.9	188.8	118.4	17.9
Ag. groundwater use (mio cbm)	63.3	92.0	76.7	23.9	14.0	6.5
Total ag. water use (mio cbm)	228.6	181.4	93.5	212.7	132.4	24.4
Total water use (mio cbm)	233.8	186.6	98.7	218.0	137.6	29.6
Use of available crop area (%)	63.9	50.7	26.0	47.7	32.0	6.1
Agric. profits total (mio DH)	260.4	189.6	79.6	171.0	119.4	20.5

Results look completely different when the yield-decreasing effect of salinity is considered. As surface water is free of charge for farmers and less saline than groundwater, surface water is strongly preferred for irrigation of agricultural crops. However, when surface water becomes scarcer, for example in the intermediate and dry water supply scenarios, it would be increasingly substituted by groundwater, even though groundwater pumping is costly for the farmers. This is not the case when salinity is considered: groundwater is by far not used as extensively particularly in the dry year due to the fact that its use would not contribute to keep yields per hectare at profitable levels. This ultimately leads to a far more pronounced decrease in crop areas to only 6% of the maximum area available to farmers.

When water scarcity alone is taken into account, farmers will probably decrease crop areas, but also crop yields to a minor extent to deal with the scarcity situation. But in a situation which combines water scarcity and high salinity of the water available, farmers face a more complicated dilemma, as a reduction of the amount of irrigation water per hectare as in the scenario without

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salinity would swiftly increase soil salinity and depress yields by far more. The reason this is that the leaching effect of irrigation would decrease by more than the pure water reduction, an effect which is explained by the non-linear relation between water application and leaching as shown above.

A closer look at the individual effects of water scarcity and salinity reveals that salinity effects are indeed much higher than the impact of water scarcity (see tables 3 and 4). The scarcer the water gets, the more intense are the effects of salinity, as more groundwater is used, and as leaching to keep soil salinity down becomes more expensive. It is no surprise that crops that have both a high drought and salinity tolerance (see table 4, first column) such as wheat, barley or date palms suffer the smallest yield reduction effects as compared to the scenario without salinity (see table 3).

Table 3: Yield levels (in % of maximum yield levels) for normal, medium and low water availability.

	Without salinity effects			*With salinity effects*		
	Normal	*Medium*	*Low*	*Normal*	*Medium*	*Low*
Wheat	95.9	94.1	92.5	96.2	92.7	91.6
Barley	82.5	68.2	66.3	87.6	74.4	74.9
Pulses	97.9	97.2	95.3	91.0	83.3	75.5
Vegetables	98.5	99.1	99.7	58.8	64.4	69.2
Henna	80.2	85.4	86.1	67.3	72.8	72.3
Date palms	77.5	82.2	83.9	70.5	75.6	77.5
Alfalfa	71.1	77.3	78.9	37.8	39.5	38.7

Table 4 decomposes the yield reduction effect under salinity into the water deficit and the salinity effect which together constitute the yield function (see equation (1)). Moreover, the sensitivity of the different crops with respect to water deficit and salinity as used in the model are reported in the first column. Water needs of crops (and implicitly the sensitivity to water stress) are expressed as the evapotranspiration at the maximum yield level under local climate conditions in millimetres per annum. The higher the water need of a crop, the higher the crop is assumed to be prone to water stress. The sensitivity regarding salinity is expressed as an index calculated by dividing the level parameter *psal_thre* by the slope parameter *psal_slop* (see equation (5)). The lower the index, the more sensitive is the crop to the salt content in the soil water.

Table 4 shows that for most crops yield reduction originates from salinity (the reduction factors are much smaller) and not from the 'pure' irrigation water deficit. Moreover, it is difficult to predict the yield reduction on the basis of the sensitivity to water stress and salinity alone. The profitability of crops might still justify a high water input level, which is exemplified by vegetables: the overall salt content of irrigation water does hardly allow yield levels above 70% of the maximum yield. Nevertheless, vegetables are heavily leached in order to allow reasonable yields. Alfalfa yields, by contrast, are allowed to drop, as this crop generates less profit than vegetables.

Table 4: Decomposing the yield reduction under salinity into a water deficit and a salinity effect (figures denote the share of the maximum yield).

	Sensitivity of crops to yield-reducing factors	*Normal*	*Medium*	*Low*
Water deficit effect	*Max. water need*			
Wheat	513	1.00	0.99	0.97
Barley	509	0.96	0.88	0.83
Pulses	431	1.00	1.00	1.00
Vegetables	659	1.00	1.00	1.00
Henna	1848	0.90	0.92	0.93
Date palms	1786	0.83	0.87	0.88
Alfalfa	1848	0.77	0.76	0.76
All crops		0.92	0.92	0.91
Salinity effect	*Salinity tolerance*			
Wheat	6.35	0.96	0.94	0.95
Barley	4.61	0.95	0.93	0.95
Pulses	1.80	0.89	0.82	0.78
Vegetables	2.03	0.57	0.63	0.70
Henna	3.78	0.72	0.79	0.77
Date palms	6.70	0.85	0.87	0.88
Alfalfa	3.30	0.50	0.51	0.51
All crops		0.78	0.78	0.79

4 Discussion

Accounting for salinity in yield formation and production models has enormous effects on simulation results regarding resource use, which is highly relevant for basin-wide water management decisions. Most importantly, the on-farm effects (water use from different sources, cropping choice, yield levels) become more difficult to predict when salinity comes into play. The decision situation facing the farmers is indeed highly complex, even when simulated in a deterministic setting with perfect foresight as in this article. Moreover, if the salinity of irrigation water were to further increase in the coming years, the trend towards using groundwater for irrigation could perhaps be reversed. This effect could be demonstrated in more detail by employing a salt flow balance, which so far has not been addressed due to a lack of empirical data. As to resource management aspects, both groundwater availability and salinity should be considered when deciding on the optimal allocation and distribution of surface water among the oases, as far as it this in the domain of a central water distribution agency.

Furthermore, the cropping mix cultivated is likely to shift to more salt-resistant crops with increasing salinity. The model version on which the results in this article are based is keeping the crop mix fixed and only adapts total cropping area and crop yields. A suitable calibration method allowing for a more flexible cropping mix needs to be further refined.

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