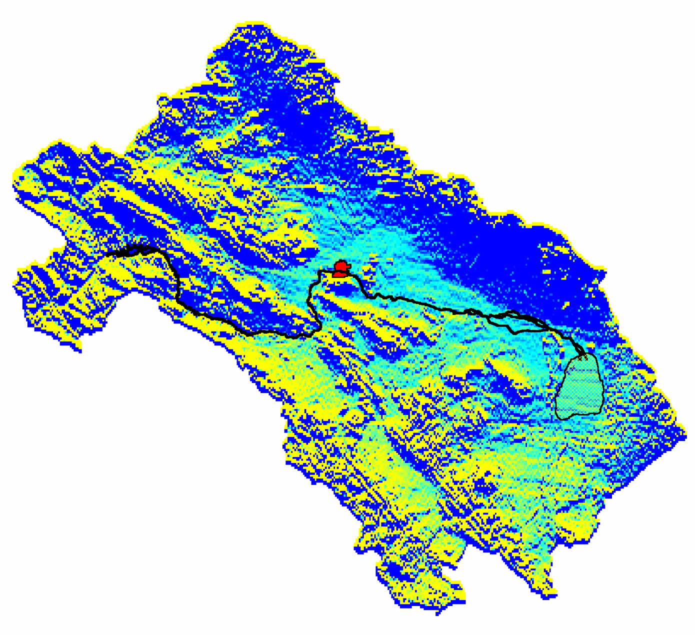
Sustainable Irrigation and Water Management in the Zayandeh Rud Basin, Iran

Field scale scenarios for water and salinity management by simulation modeling

P. Droogers, M. Torabi



Research Report No. 12

Iranian **A**gricultural **E**ngineering **R**esearch **I**nstitute
Esfahan **A**gricultural **R**esearch **C**enter
International **W**ater **M**anagement **I**nstitute

IAERI EARC IWMI

Droogers, P. and M. Torabi. 2002. Field scale scenarios for water and salinity management by simulation modeling. IAERI-IWMI Research Reports 12.

Keywords: Water Productivity, salinity, simulation model, Iran, agro-hydrology, irrigation

Peter Droogers, International Water Management Institute
Manuchehr Torabi, Esfahan Agricultural Research Center

The IAERI-EARC-IWMI collaborative project is a multi-year program of research, training and information dissemination fully funded by the Government of the Islamic Republic of Iran that commenced in 1998. The main purpose of the project is to foster integrated approaches to managing water resources at basin, irrigation system and farm levels, and thereby contribute to promoting and sustaining agriculture in the country. The project is currently using the Zayendeh Rud basin in Esfahan province as a pilot study site. This research report series is intended as a means of sharing the results and findings of the project with a view to obtaining critical feedback and suggestions that will lead to strengthening the project outputs. Comments should be addressed to:

Iranian Agricultural Engineering Research Institute (IAERI)
PO Box 31585-845, Karaj, Iran.
Phone: +98-261-241116, fax: +98-261-226277
e-mail: maryam.sal@neda.net

Esfahan Agricultural Research Center (EARC)
PO Box 81785-19, Esfahan, Iran
Phone: +98-31-757201-2, fax: +98-31-759007
e-mail: agresor@cc.iut.ac.ir

International Water Management Institute (IWMI)
PO Box 2075, Colombo, Sri Lanka
Phone: +94-1-867404, fax +94-1-866854
e-mail: iwmi@cgiar.org

Field scale scenarios for water and salinity management by simulation modeling

P. Droogers, M. Torabi

Abstract

Water scarcity and salinization are the main problems irrigated agriculture in arid and semi-arid regions are facing. For the Zayandeh Rud basin in Iran options for changes iin field scale water and salt management has been studied iusing the physically based model SWAP. A link with basin scale water resources was made, as changes in these basin scale water resources will affect the field scale and vice versa. Four major crops on the three main soils have been simulated with the SWAP model for different irrigation applications and salinity levels, resulting in yields, water balance components, water producitivy and gross and net returns. Eight generalized scenarios were studied based on limitations or non-limitations in land, water quanity and water quality. Contour plots generated from the SWAP output were used to analyze these scenarios and give options for improved water and salt field scale practices. Rice appeared to be the far-most profitable crop but at the same time it has a major impact on basin scale water resources, especially affecting downstream farmers. Proposed inter-basin transfer could be used to fulfil demands for expansion in rice area or can be used to supply additional water to all users in the basin having substantial impact on income for many farmers. Finally it was concluded that results presented in the contour graphs can be used for basin scale scenario studies to give the necessary link to the field scale level.

Introduction

Irrigated agriculture is the primary water consumer in Zayandeh Rud. Any attempt to increase the productivity of water should therefore originate from changes in agricultural practices, including irrigation system management, crop selection, soil management, field scale water management, salinity control, among others. Obviously, changes in water allocation between different sectors might change basin-wide productivity as well. The latter is however more a socio-economic and political factor, rather than a managerial one, where in general priorities between different sectors are set to: (i) water for domestic use, (ii) water for industry, (iii) water for agriculture, and (iv) water for nature. The last two priorities are often in reversed order in the developing world.

Simulation models have proven to be indispensable tools to explore options for future water management, including impacts of exogenous factors such as climate change, climate variability, economic growth and population increase. These models can differ in their spatial scale they are intended to be used for and the amount of physics included. Obviously, the coarser the spatial resolution, the lower the amount of physics included in the model. On the contrary, field scale analysis does not require automatically fully physically based models. The amount of detail included in the model to be applied depends mainly on which question to be addressed and some other factors as: data accessibility, level of expertise, and time available.

Agriculture in Zayandeh Rud is only possible by irrigation and as a consequence of the limited rainfall, the main threat is water scarcity and salinity. The appropriate model to select should therefore have a strong emphasis on salt-water-soil-crop interactions. The SWAP model is specific equipped to deal with these processes and was therefore selected as a tool to explore options for field scale management. A comparison of SWAP with the regular used crop growth models DSAT (ref) showed that SWAP was not only superior in water and salt processes, but that even the crop growth module in SWAP was as good as the one used in DSAT (Ines and Droogers, 2001).

For the Rudasht Area in Zayandeh Rud SWAP was used to explore salinity processes for one soil type and one crop (Droogers et al., 2001). That study focused on using the model as a tool to understand processes rather than as a tool for scenario analysis. In the current study a similar setup has been used, but focus is here on the entire agricultural area in Zayandeh Rud, including major crops and soil types, and on the exploration of options for improved field scale water management.

Since farming in Zayandeh Rud is moving beyond the level of subsistence farming, not only obtained yields but economic benefits should be taken into consideration. A simplified approach will be followed in this study based on gross returns and fixed costs per kg product and per hectare. Since land is in many cases not the limiting factor in Zayandeh Rud, but water, it would be better to express productivity not in terms of kg per hectare or dollar per hectare, but in terms of kg per m^{-3} or dollar per m^{-3} water used. This concept is know as Water Productivity (WP) and will be discussed more in detail later.

As irrigated agriculture should be considered from a basin perspective, these field scale analyses should consider the quantity and quality of water as boundary condition originating from basin scale analysis. Similarly, outflow of water from a field by drainage, percolation or runoff should also be linked to basin water analysis. The basin scale analysis has been discussed elsewhere for Zayandeh Rud (ref).

In summary, the objectives of this study are to provide for the main crops at major soil types in Zayandeh Rud: (i) yield functions (ii) net returns, (iii) water productivity figures, and use this information to perform scenario analysis for improved farm management practices given a certain set of limitations. Also links scale up to the basin level will be provided.

Methods and Materials

Zayandeh Rud Basin

The main river in the Zayandeh Rud Basin, the Zayandeh Rud, runs for some 350 km roughly west-east from the Zagros mountains to the Gavkhuni Swamp. The majority of the basin is a typical arid and semi-arid desert. The basin has an arid or semi-arid climate. Rainfall in Esfahan, which is situated at an elevation of 1800 m, averages only 130 mm per year, most of the rainfall occurring in the winter months from December to April. During the summer there is no notable rainfall. Temperatures are hot in summer, reaching an average of 30^oC in July, but are cool in winter dropping to an average minimum temperature of 3^oC in January. Annual potential evapotranspiration is 1500 mm, and it is almost impossible to have any economic form of agriculture without reliable irrigation. The most fertile part of the basin are the alluvial deposits flanking the Zayandeh Rud.

The primary source of water in the basin is the upper catchment of the Zayandeh Rud. Other perennial streams have little regional importance and do not reach into the main part of the basin. The Chadegan reservoir allows the natural peak flows from April to June to be regulated to promote more effective irrigation. Some of these excess flows in April and May are stored and released gradually throughout the remainder of the year.

About 180,000 ha of the basin is under irrigation with main crops are rice, wheat, alfalfa, sugarbeet, and vegetables. Most irrigation takes place in nine major irrigation systems along the river. During the last years a major drought occurred in the catchment area resulting in very low and even no surface water available for irrigation during several years. The only source for irrigation during these years was groundwater resulting in major drops in levels. Further details can be found in Salemi et al. (2001).

SWAP simulation model

The SWAP model (Van Dam et al. 1997) is a one-dimensional detailed agro-hydrological model that is capable of simulating the relationships of the soil, weather, water and plants with high physical basis. The core of the model is the Richards' equation where the transport of soil water is based on head differences in space and time. The Mualem-Van Genuchten equations describe the soil hydraulic functions. The water balance is solved by considering two boundary conditions, the top and bottom boundaries. These could be either flux or head controlled. Evapotranspiration is estimated using the Penman-

Monteith equation. SWAP calculates the actual ET in a two-step approach. First, potential ET is calculated using the minimum value of canopy resistance and the actual air resistance, and then actual ET is calculated using the root water uptake reduction due to water and/or salinity stress based on the method of Feddes (1978) and Maas and Hoffman (1977), the compounded effect is assumed as multiplicative. Field and regional drainage system can be also modeled. The model is also capable to handle the transport of solute in the soil profile. Crop growth can be studied using the production model of Doorenbos and Kassam (1979) and a detailed crop growth model WOFOST (Supit et al. 1994). The simplified crop model was used in this study as no detailed crop parameters were available.

Several water management scenarios can be modeled in SWAP. Irrigation scheduling can be considered as fixed time or according to number of criteria or combination of both. The ratios of T_a/T_p were used as irrigation scheduling criteria with a fixed irrigation depth of 100 mm.

The model has been applied successfully in many studies over different conditions. For Zayandeh Rud the model has been applied earlier (Droogers et al., 2001). A detailed description can be found in Van Dam et al. 1997.

Data

Soils

The objective of this study was to produce general applicable outcome and it was therefore decided to use only the main three soil types found in the irrigation systems in the Basin. Figure 1 shows the major soil texture classes in the basin and for the irrigation systems. Clearly the irrigation systems are dominated by clay soils. To solve Richards' equation as used in SWAP the hydraulic functions, water retention and hydraukic conductivity, are required. The so-called pedo-transfer function approach was used, where texture, bulk-density and organic matter content data are used to obtain these soil hydraulic functions. Figure 2 shows the derived curves.

Crops

Four of the most common crops in the area have been selected for further analysis: alfalfa, rice, sugarbeet, and wheat. Some general information on crops as well as more detailed data required for the modeling is provided in Table 1. Data is originating from a variety of field experiments carried out in the basin combined with some general data from different sources.

Table 1. Main crop characteristics as used in the SWAP model.

	wheat	rice	alfalfa	sugerbeet
Planting date	2 Nov	15 May	1 Jan	20 Mar
Harvesting date	1 Jul	20 Oct	31 Dec	22 Nov
Max. crop height	100	70	55	45
Max. rooting depth (cm)	100	70	100	70

Yield response	0.2-0.6-0.5	1.2-2.3-0.3	0.9	0.8
HLIM1 (cm)	-10	100	-10	-10
HLIM2L (cm)	-10	100	-10	-10
HLIM3H (cm)	-500	-500	-1500	-400
HLIM4 (cm)	-16000	-1000	-8000	-16000
ECMAX (dS m)	6	3	2	7
ECSLOP (dS m)	7.1	12	7.3	5.9
Potential yield (kg/ha)	6000	7000	15000	45000

Climate

Climate conditions are similar over the irrigated systems in Zayandeh Rud with a small trend of precipitations rates ranging from about 150 mm yr^{-1} in Nekoubad to about 50 mm yr^{-1} in Rudasht. Other climatological parameters are very similar and it was therefore decided to use the average data from Kaboutharabad station for an average year (1991). SWAP simulates on a daily base, but only monthly data were available and for each month the day with highest precipitation. This information was used to generate daily climate data.

Economics

A simple economic analysis was used based on three factors: price per kg crop, costs per kg crop, and fixed costs per hectare. Price of water is very low in the basin (about \$ 0.002 m^{-3}) and it was considered to be included in the fixed costs. Prices for crop were obtained from statistical data, but costs per kg and costs per hectare were estimated. Table 2 shows values used.

Table 2. Prices and costs as applied to calculate net return and water productiviy.

	Alfalfa	Rice	Sugarbeet	Wheat
Price (\$ kg^{-1})	0.13	0.77	0.03	0.12
Fixed Costs (\$ ha^{-1})	300	300	300	300
Variable Costs (\$ ha^{-1})	0.02	0.10	0.005	0.02

Model Setup

The SWAP model has been setup for each soil-crop combination and for different salinity levels of irrigation water at different irrigation depths. The salinity levels considered are 0, 1, 2, 4, 6, 8, and 10 dS m^{-1}, according to levels found in the basin. Irrigation depths applied currently are in the range from 500-1500 mm, depending on water availability, soil and crop type. In principle the sole source of irrigation water is from canals as rainfall is limited to about 100 mm yr^{-1}. However, a substantial amount of farmers rely also on groundwater as irrigation water source, especially as backup system in case canal water delivery stops unexpectedly. It is important to keep in mind that, due to the low amount of rainfall, most of this groundwater originates also from canal water through seepage losses and percolation.

The SWAP model provides the option to specify fixed irrigation applications, but using this option will not guarantee that this is done at the optimum timing. Alternatively, irrigation scheduling can be defined where the ratio actual over potential transpiration is used for optimized scheduling. By running the SWAP model for 20 combinations of Tact over Tpot (0.5, 0.10, …, 1.0), irrigation depths ranging from about 200-2000 mm are realized at the most optimum timing. Obviously, farmers have also not always the option to irrigate at the right time, but since we are in this study mainly interested in differences in crop, soil, irrigation depth and salinity levels we assume this optimum timing. Interesting is that many farmers in the basin has also access to groundwater, which enables them much more to irrigate at the optimum time.

Results

Results will be first presented in detail for one combination of soil and crop (wheat on clay) and later expanded to all the soil-crop combinations. It should be made very clear that results presented are the outcome from simulation modeling and might therefore differ from actual values. Data used was also not specific for one location but represent general conditions for the basin. At the same time, the SWAP model has been successfully tested, validated and applied for many cases and many conditions. As a final point it should be considered that reliability in terms of relative differences in general higher is then absolute values, making simulation models suited for scenario analysis.

3D Representation

One of the main output figures for this study is the relationship between irrigation application, salinity level and expected (simulated) yields. Such a relationship can be presented in a contour map, where directly the impact of changes in water quantity and quality on crop yield can be examined (Droogers et al., 2001). These contour maps are created by spatial interpolation, or gridding, of the known values to get a smooth surface. It is well-known that the gridding method applied can have significant impact on the final contour map and should therefore be carefully selected. For irregular spaced data, such as groundwater observation wells, it was demonstrated that different gridding methods can result in very different maps (Droogers, 2002). Since we are dealing here with data in a regular grid (EC and irrigation application at fixed intervals), different conclusions are likely.

Figure 3 shows for the wheat-clay combination the results of different gridding methods. Gridding and mapping were done using the Golden Software Surfer 8 package (Golden Software, 2001). The top-left figure shows the data points resulting from the SWAP runs. Since for the irrigation scheduling the transpiration deficit ratio was used, no irrigation depths were simulated above the level of maximum yield. For example the scenario where irrigation water was completely fresh, this maximum irrigation application is 1000 mm. The simplest representation is provided by dots with different colors related to the estimated yield for each combination of water quantity and quality. Although most reliable since no interpolation has been used, the figure is not very useful in practical terms.

From the presented gridding methods two are not able to extrapolate outside the observed values: Natural Neighbor and Triangulation with Linear Interpolation. Although this is very secure since extrapolation is error sensitive, some extrapolation of results is required. The danger of extrapolation is clearly shown by some methods that suggested that more irrigation with freshwater will reduce crop yields (e.g. Kriging, Nearest Neighbor). In reality this is a phenomena as water logging occurs, but in this case it is a clear example of extrapolation since no data points are available for these regions. The method best suited for this data set appears to be the Local Polynomial with the options Power=3 and Polynomial Order=1, which leads to:

$$F(X,Y) = a + bX + cY$$

where X and Y are locations and a, b, and c are fitting parameters obtained from known data points. Note that a, b, and c are not fixed for the entire grid, but are recalculated for each grid point and depends on the neighbors.

Gridding methods shown can be divided into two general categories: exact interpolators and smoothing interpolators. Exact interpolators honor data points exactly with the gridded data, while smoothing interpolation reduces the effects of small-scale variability between neighboring data points. The Local Polynomial is a weak smoothing gridding method, so only extreme values are smoothed.

Considering these points it was decided that for this data set the Local Polynomial gridding method is the best and will be used for all the 3D figures in this publications.

Water Balance

The output of the SWAP runs can be used to get all the terms of the water balance as function of irrigation application and salinity level. Figure 4 shows the most relevant terms.

The yield as estimated by the SWAP model shows the general trend that above 1000 mm of irrigation the incremental benefit from additional irrigation water is limited. Yields from fields receiving water of 5 dS m^{-1} are about 75% of the ones receiving fresh water, and yields higher then 5,000 kg ha^{-1} are impossible for these farmers. If a yield of 4,000 kg should be obtained 600 mm of fresh water is sufficient, while about 1000 mm is required to obtain the same yield if salinity levels are 6 dS m^{-1}. These examples show that the figure presented is very useful in translating the somewhat complex SWAP output in a simple and transparent graph.

Percolation of water from the unsaturated zone to the deep groundwater follows a linear trend where more irrigation induces more percolation. Even at very low irrigation rates percolation is unavoidable, but some might originate from winter rains. Interesting is that if irrigation water is more saline percolation rates are higher. Main reason is that saline water is more difficult to take up by roots, so transpiration rates are lower and more water remains in the soil profile, which will eventually percolate.

Transpiration is the most important process, since this is the only use of water that is beneficial. All other water uses are non-beneficial or reusable. Transpiration at high irrigation applications is more affected by salinity levels then at lower irrigation rates. If water is too saline roots have difficulty in taking up sufficient water. From all the water applied by irrigation only a fraction is used for transpiration, for freshwater and low irrigation applications this is close to 90%. At higher application rates and high salinity levels this fraction reduces to a merely 25%.

Soil and ponded water evaporation is quite constant at about 200-250 mm and is not affected by salinity and only slightly by the irrigation application. Consequently evapotranspiration follows a similar trend as transpiration, but at a level about 200 mm higher.

The salinity level of percolated water is calculated as this is a dominant factor influencing reuse of percolated water. At irrigation levels between 1000 mm (fresh water) and 500 mm (saline water) percolated water is at the poorest level. If less irrigation is applied leaching is lower, if more water is applied dilution of percolated water occurs. The figure shows that irrigation with water of a salinity level of 2 dS m^{-1} generates percolation water between 5 and 10 dS m^{-1}. Obviously, this will have tremendous impact on the reuse aspects of water by downstream farmers.

Finally, from the yield figures the net return can be calculated using average figures for crop prices and costs as defined in Table 2. It is clear that salinity levels are the dominant factor in this net return, especially if irrigation applications are higher then about 800 mm. Some interesting facts can be read from the graph. For example, a farmer receiving freshwater can earn \$250 ha^{-1} by receiving 700 mm of water, while a farmer receiving more saline water (4 dS m^{-1}) needs 1250 mm of water to get the same net return.

Water Productivity

Traditionally, productivity in agriculture has been expressed in kg yield per hectare or cash (dollars) per hectare. However, increasing water scarcity has lead to the development of the concept of Water Productivity (WP) expressed in kg or cash per cubic meter. Obviously, if land is the main limiting factor the traditional approach is still preferable and challenges are to maximize output in dollar per hectare. The Water Productivity approach is sometimes somewhat blurred as it should specify clearly to which water it relates to: applied irrigation at farm level, applied irrigation at system level, water used by evapotranspiration, etc. Here we will use the concept of real water used, as reuse of water is very common in Zayandeh Rud. This is best demonstrated by the fact that almost no water flows to the Gavkony swamp.

WP for downstream users should be different defined then for upstream ones. Percolation, drainage and runoff are factors not to be considered as water consumed for upstream users, since these flows are reused (if water quality permits). For downstream users these factors should be considered as real losses. In summary, water used for upstream farmers is crop transpiration and soil evaporation. For downstream users percolation, drainage and runoff should be added to this.

For the wheat crop on clay the WP values, expressed per kilogram and per dollar, for downstream and upstream areas, are displayed in Figure 5. All upstream values are higher then downstream ones, since different terms for water consumed are applied as explained in the previous section. The implication of this is that upstream farmers can maximize their WP by just applying the maximal amount of water they can get, since any outflow from their field is assumed to be reused. The fact that water is so cheap that we considered it here as a fixed amount included in the costs per hectare and per kg crop, is also reflected in these result.

Another consideration is that outflow from fields is often saline and not applicable by downstream users. To include this fact we have derived a generalized WP where outflow water from a field is considered to be reusable as salinity level is lower then 4 dS m^{-1}. Salinity levels higher then 10 dS m^{-1} are considered to be not useful any more and levels between 4 and 10 dS m^{-1} are partly reusable assuming dilution with fresh water can be achieved: a normal practise in the basin. Between 4 and 10 dS m^{-1} a linear decline in reusable was assumed. This approach is considered as general applicable and used in this study.

The obtained WP values in terms of kg ha^{-1} can be classified as average, but very low as expressed in \$ ha^{-1}, mainly caused by the low price of wheat, \$0.12 kg^{-1}. The fixed costs per hectare and per kg make the shape of the WP_kg graph different from the WP_\$ one. Figures also show that highest WP_kg can be obtained at application rates of 800 mm for freshwater cases, but at low irrigation applications for saline water. Obviously, farmers are more interested in WP_\$, where the optimum is around 1000 mm for freshwater and higher with increasing salinity levels.

Scenarios for wheat on clay

The often recommended "optimal irrigation application" should be used with care and depends on several factors, where the most important one is whether land or water is limiting, quality of water and costs of water and land. In terms of limitations included in defining optimal farm management the following options will be explored:

- land unlimited/limited
- water availability unlimited/limited
- water quality unlimited/limited

Combining these factors result in a matrix with 8 options to be explored as shown in Table 3. For the moment we will only consider one crop, but this will be discussed later to include the treat offs between different crops. Obviously, farmers are not interested in yield optimization but in income generation. A simplified economic approach will be followed here with in brackets the values used for the wheat crop:

- gross return (\$0.12 kg^{-1})
- fixed operational costs per kg yield (\$0.02 ha^{-1})
- fixed costs per hectare (\$300 / ha^{-1})

For the moment we consider that the price of water is included in the fixed operational costs per kg yield. This can be justified by the fact that water costs are marginal (20 Rial

m^{-3} = \$0.002). Further discussions about water pricing for Zayandeh Rud can be found in Perry (2001).

Table 3. Scenarios defined to explore options for field scale water and land management.

	water quantity			
	unlimited		limited	
	water quality		water quality	
	unlimited	limited	unlimited	limited
land unlimited	Lu_Qu_Cu	Lu_Qu_Cl	Lu_Ql_Cu	Lu_Ql_Cl
land limited	Ll_Qu_Cu	Ll_Qu_Cl	Ll_Ql_Cu	Ll_Ql_Cl

In order to perform the analysis it would be convenient to have the relationship between irrigation application, salinity level and expected (simulated) yields described by an equation rather than the 3D figure as displayed in Figure 4. Earlier explorations of these yield functions recommended the following equation to be used (Droogers et al.):

$$Yield = a + b \cdot EC + c \cdot Irr + d \cdot EC^2 + e \cdot Irr^2 + f \cdot EC \cdot Irr$$

The constants *a* to *f* were fitted using the outcome of the SWAP model resulting in (R^2 = 0.97:

a	8.498E-01
b	-1.795E-01
c	6.507E-03
d	1.302E-02
e	-1.322E-06
f	-2.694E-04

Scenario Lu_Qu_Cu

This is the most straightforward scenario where no limitations at all occur. From Figure 4 it is clear that the recommended irrigation application is about 1000 mm. Although any supplemental irrigation will generate still more yield, the incremental benefits are limited.

Scenario Lu_Qu_Cl

The scenario where only water quality is limited is also straightforward. Analogous to the previous scenario Figure 4 can be used indicating that about 1000 mm of irrigation would be advisable, as any additional water will increase yields only slightly. At the same time it is very clear that increasing irrigation from 500 to 600 mm has much more affect for low saline water then for high saline water. In other words, any attempt to increase yield will require much more water if water is from poor quality.

Scenario Lu_Ql_Cu

The previous two scenarios are somewhat hypothetical since in Zayandeh Rud water is a limiting factor. This scenario describes the case for upstream irrigation systems where water is still of good quality, but at the same time land is not limiting. The Borkhar system is an example of this scenario. In practical terms this scenario can be explained by a farmer having 100 units of fresh water and whether to distribute this over a limited area or distribute equally over the entire farm. Using the results from Figure 4 and the optimization function in Excel give an estimate about this optimal distribution of water given a certain amount of fresh water delivered to a farmer.

From Table 4 it is clear that the optimal area to distribute water delivered is to have an irrigation application of 1275 mm. This means that if a farmer gets only 2000 m^3, he should not crop this entire hectare but only about 0.16 ha. Contrary, if a farmer gets 1500 m^{-3} it is better to distribute this over about 1.2 ha.

This distribution of water is linked to the gross return, and fixed costs. A further analysis was done to estimate the optimal distribution of water as function of these gross returns and costs (Table 5). This Table shows that if prices for wheat are going up (or costs per kg down) it is more profitable to spread the limited water over bigger areas. The theoretical limit for wheat on clay for the highest price per kg and the lowest fixed costs per hectare, is even to spread over an unlimited area. At the same time as fixed prices per hectare are increasing it is better to limit deficit irrigation. The Table can be used as a first indication when deficit irrigation and in what extent is profitable.

In fact, this scenario is somewhat similar as the previous described concept of Water Productivity where the highest amount of cash per m^{-3} water is the optimal amount of irrigation application. However, in the definition used for WP we assumed that outflow from a field can be used downstream as quality is in certain ranges. Here we look only from a individual farmer's perspective who is less interested in what downstream happens.

Table 4. Optimized cropping area for wheat on a clay soil given a certain amount of fresh water delivered. Gross return \$0.12 kg^{-1}, fixed costs \$0.02 kg^{-1} and \$300 ha^{-1}.

Water Delivered m^3	Area ha	Irrigation mm	Yield 1000 kg	Net Return $
2000	0.16	1275	1.1	63
5000	0.39	1275	2.7	157
7500	0.59	1275	4.1	235
10000	0.78	1275	5.5	314
12000	0.94	1275	6.6	376
15000	1.18	1275	8.2	470

Table 5. Optimal irrigation application given benefits and costs for wheat on a clay soil.

Gross return – fixed costs \$ kg^{-1}	Fixed Costs \$ ha^{-1}	Optimal Irrigation mm
0.05	100	933

0.10	100	337
0.15	100	~
0.05	200	1544
0.10	200	933
0.15	200	605
0.05	300	1974
0.10	300	1275
0.15	300	933

Scenario Lu_Ql_Cl

Limited water availability and at the same time high salinity levels are the characteristics of this scenario. Land is still abundant. These conditions can be found in Rudasth. As demonstrated in the previous scenario, an optimal irrigation depth exists given certain benefits and costs. In this scenario the complicated factor is the salinity level of water delivered. Using the same approach as the previous scenario the optimal irrigation depth is calculated for the case with gross return \$0.12 kg^{-1}, fixed costs \$0.02 kg^{-1} and \$300 ha^{-1}.

The well-known concept that if water is more saline more water should be applied is well demonstrated in Table 6. Interesting is that water quality has a substantial impact on farmers income. A farmer receiving 10000 m^{-3} of freshwater can get a net return of about \$314, while a farmer receiving the same amount of water with is saline (4 dS m^{-1}) receives only half of this. about \$200 less. Farmers in Rudasht with salinity levels of 6 to 8 dS m^{-1} will see a substantial reduction in comparison to earnings of upstream farmers with the same amount of water.

Interesting is also that upstream where land availability is limited farmers would benefit from spreading water over bigger areas. On the contrary, downstream where land is abundant farmers could better concentrate the amount of water they have over smaller areas.

Table 6. Optimal area to irrigate given a total amount of 10,000 m^{3} of water available for different salinity levels. Optimization is based on gross return \$0.12 kg^{-1}, fixed costs \$0.02 kg^{-1} and \$300 ha^{-1}, for the wheat on clay.

EC dS m^{-1}	Area ha	Irrigation mm	Yield 1000 kg ha^{-1}	Net Return \$
0	0.78	1275	5.5	314
1	0.76	1324	5.0	274
2	0.73	1363	4.6	236
4	0.70	1419	3.8	168
6	0.69	1445	3.1	107
8	0.69	1443	2.6	54
10	0.71	1414	2.2	7

Scenario Ll_Qu_Cu

This scenario where fresh water is plentiful and only land is limited can be found in the valleys upstream in Zayandeh Rud. Although water seems abundant it should be considered that every drop used here, will have impact on the downstream irrigation systems. Nevertheless, farmers have the tendency to extract water as required, but are facing land problems since the valleys are small. In practice this scenario can be treated as the first one (Lu_Qu_Cu) and farmers should apply about 1000 mm of irrigation.

Scenario Ll_Qu_Cl

Similar as the previous scenario, the best practice is comparable as the same scenario without land limitations. Figure 4 can be used and irrigation applications should be around 1000 mm for all salinity levels. However, since land is also a limitation, farmers will try to maximize their income, which is only possible by increasing yields. This can be achieved by applying more then 1000 mm, but, as mentioned before, the incremental benefits of this are limited.

Scenario Ll_Ql_Cu

The Nekoubad systems are clear examples of this scenario where land is limited, water is somewhat limited, but quality of water is still good. Farmers are facing challenges as what to do if they have 2 ha and get 10,000 m^{-3} of water. Spread this over one hectare to get an application of 1000 mm which will lead to optimal yield (see scenario Lu_Qu_Cu), or use the 2 ha and apply 500 mm.

The methodology developed under Lu_Ql_Cu can be applied here but somewhat modified to the land limitation. Given the economic conditions as set before, an irrigation application of 1275 mm is the most profitable. Depending on the amount of water provided and the size of the farm, the most profitable area to be irrigated was calculated (Table 7).

Results show clearly that the best practice is to irrigate the entire farm as long as the amount of water delivered is enough to irrigate each field with at least 1275 mm. If water is not sufficient only part of the land should be irrigated. For example, a farmer having 1 ha of land will irrigate his entire holding if he gets 20,000 m^3, but will reduce his cropped area if he receives 10,000 m^{-3} or less.

Table 7. Optimized area to be irrigated for wheat on a clay soil given a certain amount of fresh water delivered and a limited amount of area available. Gross return \$0.12 kg^{-1}, fixed costs \$0.02 kg^{-1} and \$300 ha^{-1}.

Water Delivered m^3	Farm ha	Optimal Area ha	Irrigation mm	Net Return \$
5000	0.5	0.4	1275	157
5000	1.0	0.4	1275	157
10000	0.5	0.5	2000	279
10000	1.0	0.8	1275	314
20000	0.5	0.5	4000	137
20000	1.0	1.0	2000	558

Scenario Ll_Ql_Cl

The last scenario is the strictest one where land, water quantity as well as water quality are limited. For the Zayandeh Rud these conditions can be more or less found in the

Abshar systems. Combining scenario Lu_Ql_Cl and Ll_Ql_Cu will lead to recommendations for farmer practices for this case.

Table 8 indicates, given a certain land area and EC value, what the threshold value in water delivery is to crop the entire farm. If less water is delivered, part of his holding should be irrigated to a level indicated in the "irrigation" column. If more water is delivered, it would be more beneficial to distribute over larger area, but since land is limiting this is no option. In this case the additional water should be distributed over the farm and will still generate more income.

Some interesting conclusions can be drawn from Table 8. The threshold value in water delivered when farmers should consider not to irrigate their entire limited land, is not so much a determined by the salinity level of the delivered water. At the same time is this salinity level of paramount importance for the net return. A farmer with 1 ha and receiving water with a salinity level of 2 dS m^{-1} can make as much money as his colleague with 2 ha, but receiving more saline water. The latter should use the double amount of water as well.

Table 8. Threshold value in water delivery when a farmer should irrigate his entire holding. If less water is delivered he should then the threshold value, he should reduce his cropped area.

Farm ha	EC dS m^{-1}	Threshold Delivery m^{-3}	Irrigation mm	Net Return $
0.5	0	6,375	1275	200
1.0	0	12,750	1275	400
2.0	0	25,500	1275	800
0.5	2	6,815	1363	161
1.0	2	13,630	1363	322
2.0	2	27,260	1363	644
0.5	6	7,225	1445	77
1.0	6	14,450	1445	155
2.0	6	28,900	1445	310

All crop-soil combinations

After these detailed analysis for wheat on clay to demonstrate the methodology and to show the potential of using the SWAP results in a innovative manner, we will here present the results for all the soil-crop combinations. Rice was only simulated for clay, because clay-loam and loam are considered as unsuitable since no puddling layer preventing high percolation can be made in these soils.

Figure 6 shows the yields as function of water applied by irrigation and water quality. The three soil types does not affect yield substantially, and especially the clay and clay-loam generate similar yields. Yields from the loamy soil are around 25% lower then from clay and clay-loam. The general pattern that more irrigation water and lower salinity levels generate more crop can be observed. Remarkable is the pattern for rice where at salinity levels higher then 5 dS m^{-1} no crop can grow and that at least 600 mm of irrigation is required. The well-known fact that rice is also very sensitive to water stress is demonstrated clearly where in the range from 1000-1500 mm each 100 mm difference in application rates induces a yield difference of 1000 kg ha^{-1}. Graphs can be used to assess directly the impact of changes in water application or salinity levels on crop yield, as demonstrated in the detailed wheat-clay description previously.

The net return graphs as shown in Figure 7 indicates why rice is the preferred crop by farmers. Net return can be very high providing sufficient water of high quality is available. Rice used to be a common crop in the basin, but nowadays, due to water shortage and associated salinization, it is only found in the upstream irrigation systems such as Nekouabad. Remarkable is also the high returns on sugarbeet. However, since sugarbeet on clay soils has other limitations then water alone such as tillage and especially harvesting problems, it would be mostly grown on the loamy soils where returns are not as high.

These net return graphs can be used to assess the best water management practices, and not surprisingly, the more water and the better the quality of this water the higher the net return. To translate this conclusion in recommendations is not very useful as in reality water is limited in quantity as well as quality. As explained before, in Zayandeh Rud land is generally not the limiting factor but water, so instead of looking at the highest net return per ha, we should consider the highest net return per m^{-3} of water. Figure 8 shows that the Water Productivity for alfalfa and wheat are very low and reach maximum values of about \$0.02 m^{-3}. Values for sugarbeet are somewhat higher but are also limited to about \$0.06 m^{-3}. Obviously, these low values are associated with low net return. If we calculate the values taking the gross return (ignoring the fixed costs of \$300 ha^{-1} and \$0.02 kg^{-1}) values for alfalfa and wheat will be about \$0.12 and \$0.29, respectively, for 1000 mm of irrigation with freshwater.

Interesting it the potential conflict between individual farmers and water managers. A farmer is interested in obtaining the highest net return and can maximize this by applying as much water as possible. In other words he prefers to use the Figure 7 with net returns. If water is limited, and not land, he will try to maximize his returns on water as displayed in Figure 8. At this point the farmer has the same interest as the water manager. Farmers in the upstream irrigation systems in Zayandeh Rud basin consider that, during normal years, water is not limiting and will try to maximize there kg ha^{-1}. Here the task of the water managers is to think from a basin perspective and maximizing the WP_\$. Downstream farmers at for example Rudasht feel almost every year that water is limiting, especially good quality water, and will therefore try to maximize their WP_\$.

Farmers in Nekouabad having access to sufficient water of good quality would be best off to grow rice. However, this will only provide sufficient income if they can have minimal 1000 mm of water, at the appropriate time. In the figures no water for seedbed preparation was included, which will add another 200 mm to the requirements. From a basin perspective, see hereafter, it should be considered that extensive rice cultivation this will have a big impact on water availability on downstream users.

In the Abshar systems water quantity is not the dominant limitation, but reliability and to some extent salinity makes rice cultivation less attractive. Vegetables (not analyzed here), sugarbeet and wheat are the main crops, where net returns for wheat on clay and sugarbeet on loam are somewhat similar for salinity levels of 1 dS m^{-1} and 800 mm of irrigation.

The downstream Rudahst area is facing salinity problems as well as water shortage. Risk avoiding strategies is therefore the recommended strategy and crop selection is one of the components of this. Rice is impossible since water quality is to poor, quantity low and supply unreliable.

Link to Basin Scale

The results from the SWAP runs as presented in the graphs can be used to assess the impact of changes at basin scale water allocation on crop yields and farmers' income. Average annual releases from the reservoir are about 1600 MCM and irrigated area about 180,000 ha. Assuming that 80% of the water is available for irrigation leads to the conclusion that 700 mm of water per hectare can be used for irrigation. At the same, time a huge amount of salt enters the basin with this 1600 MCM. Average salinity level of water released from the reservoir is 0.35 dS m^{-1}. Converting this to total annual loads leads to $350 \cdot 10^6$ kg of salts flowing from Chadegan reservoir to the irrigation systems every year: 1 million kg per day! The main challenge in basin water management is therefore how to allocate water, including these salts, in such a way that farmers can optimal use the resource to produce food for society and income for themselves.

Similar to the detailed analysis described previously for wheat on clay, basin scale issues can be analyzed as well. The most salient conclusions will be drawn here, while the graphs as presented in Figures 6 to 8 can be used for further analysis. Here we will concentrate on average annual conditions, while monthly and yearly variations can be studied in more detail using the basin scale model developed for the Zayandeh Rud (Droogers et al., 2001) and link this to the yield functions as presented here.

It is very clear that rice is the most profitable crop in terms of \$ ha^{-1} as well as \$ m^{-3}, assuming enough water of good quality can be provided. The latter one is only the case for the Nekouabad systems. Average rice area in Nekouabad is 15,000 ha, which is about 8% of total irrigated area in all the main systems. This rice requires about 1300 mm of irrigation water, which is almost 200 MCM. In other words: rice irrigation uses about 16% of the total annual flow while grown on only 8% of the area. However, on average this generates a very high income for farmers and a very high WP, as can be observed from the graphs. An increase in area appears therefore attractive but will have major impact on other water users in the basin. If we consider the extreme event that the rice area will be doubled to 30,000 ha, this is half of the land in Nekouabad, then on average only 590 mm of water will remain available for the rest of the irrigated areas. As can be observed from the graphs, this means literally that almost no profitable farming in the basin can take place, unless major parts of the systems will be abandoned.

The proposed inter-basin transfer by the tunnel from Kurang will add 280 MCM to the basin. This would give the opportunity to double indeed this rice area, but would not solve the current problems of water shortage in Rudasht, neither would it help to provide water to the extended Borkhar system. Assuming that this 280 MCM would be distributed equally over the current cropped area would increase the average irrigation availability over the entire basin with 150 mm. Using again the graphs provided in Figure 6 this can give a major increase in crop yields for the entire basin. Alfalfa yields, for example, will go up with about 1000 kg ha^{-1}, and sugarbeet with about 5000 kg.

The option to save water by changing to pressurized irrigation techniques is worth evaluating. Transpiration from a field is beneficial and should not be minimized as this will lead to yield reduction. From the other outflow terms only soil and open water evaporation should be minimized, as reducing percolation and drainage would have a very adverse effect on the necessary leaching of salts from the soil profile. Where open water and soil evaporation is highest, on rice fields, pressurized systems are not possible. For some other crops this might be possible at very high costs. The low PW_$ for alfalfa, sugarbeet, and wheat will not motivate farmers to make such an investment. Some higher value crops not considered in this study such as vegetables could change to drip systems, but the actual water saved will not be large. Soil evaporation is about 200 mm, and if we consider that drip will reduce this by 50% and we take the actual are under vegetables (18,000 ha), then we come up with a real saving of 18 MCM. This is 10 mm if distributed over the entire area, which will hardly increase basin wide productivity. The argument that more fresh water will remain in the river is somewhat wishful thinking, as no farmer will accept the fact to get less water after making a huge investment.

Conclusions

Water scarcity and salinity problems require proper field scale management practices taking into consideration overall basin water resources. The methodology developed during this study can be used to assess the impact of changes in water quantity and quality on yields, gross and net return and water productivity. At the same time, the impact of changes at field scale practices on basin water resources, in terms of water quantity as well as salinity issues, can be evaluated too with the results presented here.

The SWAP model has proven to be able to produce a wide range of scenarios to study expected yields for different crops, soil types, irrigation depths and salinity levels. Plot experiments would in principle be able to generate the same data, but from a practical point of view this would be impossible considering the numerous combinations to be studied. Moreover, SWAP generates not only yields, but all the terms of the water and salt balance enables a more realistic assessment, such as real water used versus water applied, salinity levels of percolation water, beneficial versus non-beneficial depletion, etc.

At the same time, we have to realize that outputs presented are model results with their specific limitations. First of all, results produced are based on generalized soil and crop characteristics and average climatic conditions. Secondly, the SWAP model has not been validated for the specific case in Zayandeh Rud. However, SWAP has been validated and applied in more then 20 countries for many cases and many conditions, including similar ones as found in Zayandeh Rud. It should also be considered that reliability in terms of relative differences is in general higher then absolute values, making simulation models suited for scenario analysis.

The results clearly show that rice has a major impact on basin scale water resources, but at the same time that rice is a very profitable crop and an extension of the area under rice is likely. The main task of basin water managers is to show the impact of these changes on downstream farmers, but it is more a policy makers and planners decision whether expected changes are acceptable.

Sufficient water has been shown to be certainly not the only factor to farmers' income. Water salinity levels play a paramount role and proper salt management is therefore one of the major factors to successful basin water management. Sufficient water for leaching and a proper diversion of fresh water, high quality drainage water and low quality drainage water are essential.

Finally, results presented in the graphs can be used for further scenario analyses, especially in combination with basin scale modeling and scenario studies.

References

Ines, A. and P. Droogers. 2002. Crop growth and soil water balance modeling to explore water management options. IWMI Working Paper 22.

Droogers, P., H.R. Salemi, A. Mamanpoush. **2001**. Exploring basin scale salinity problems using a simplified water accounting model: the example of Zayandeh Rud Basin, Iran. Irrigation and Drainage 50: 335-348.

Droogers, P., M. Akbari, M. Torabi. **2001.** Exploring field scale salinity using simulation modeling, example for Rodasht, Iran. Irrigation and Drainage 50: 77-90.

Droogers, P., and M. Miranzadeh. 2002. Spatial Analysis of Groundwater Trends: example for Zayandeh Rud Basin, Iran. IAERI-IWMI Research Reports 9.

Feddes R.A., Kowalik P.J. & Zarandy H. 1978. Simulation of field water use and crop yield. Simulation Monographs. Pudoc. Wageningen, The Netherlands.

Golden Software, 2001. Surface Mapping System, Surfer version 8. Golden Software, Inc. http://www.goldensoftware.com

Maas E.V. & Hoffman G.J. 1977. Crop salt tolerance-current assessment. Journal of Irrigation and Drainage Division. ASCE 103:115-134.

Salemi H.R., A. Mamanpoush, M. Miranzadhe, M. Akbari, M. Torabi, N. Toomanian, H. Murray-Rust, P. Droogers, H. Sally, A. Gieske. 2000. Water Management for Sustainable Irrigated Agriculture in the Zayandeh Rud basin, Esfahan Province, Iran. IAERI-IWMI Research Reports 1.

Supit I., Hooyer A.A. & Van Diepen C.A. (Eds.). 1994. System description of the WOFOST 6.0 crop simulation model implemented in the CGMS Vol. 1: Theory and algorithms. EUR publication 15956. Agricult. Series. Luxemberg. 146 p.

Van Dam J.C., Huygen J., Wesseling J.G., Feddes R.A., Kabat P., Van Waslum P.E.V., Groenendjik P. & Van Diepen C.A. 1997. Theory of SWAP version 2.0: Simulation of water flow and plant growth in the Soil-Water-Atmosphere-Plant environment. Tech. Doc. 45. WAU and DLO-WSC. The Netherlands.

Figures

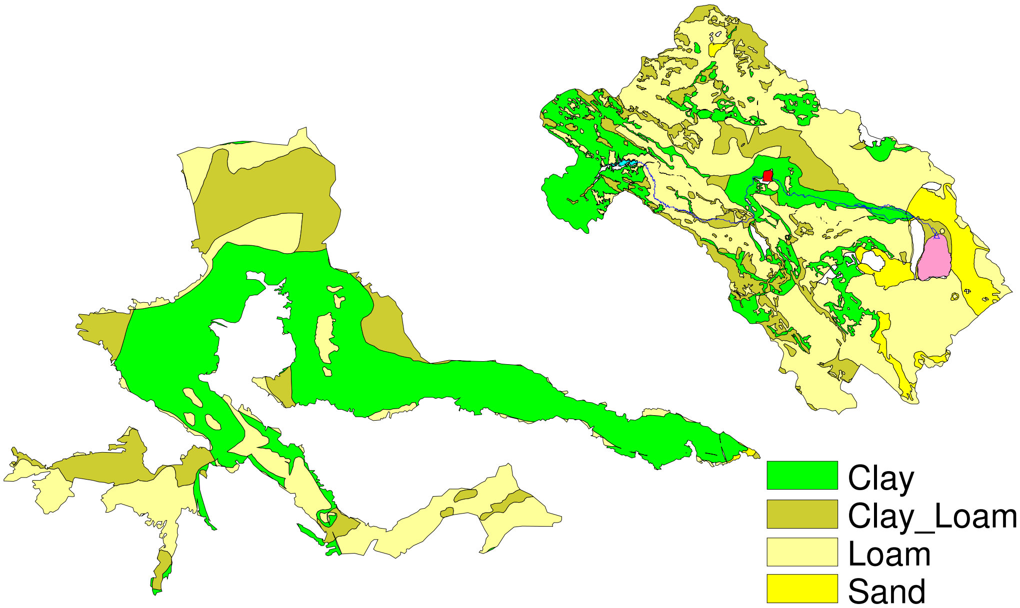


Figure 1. Generalized soil map of Zayandeh Rud basin and irrigation systems.

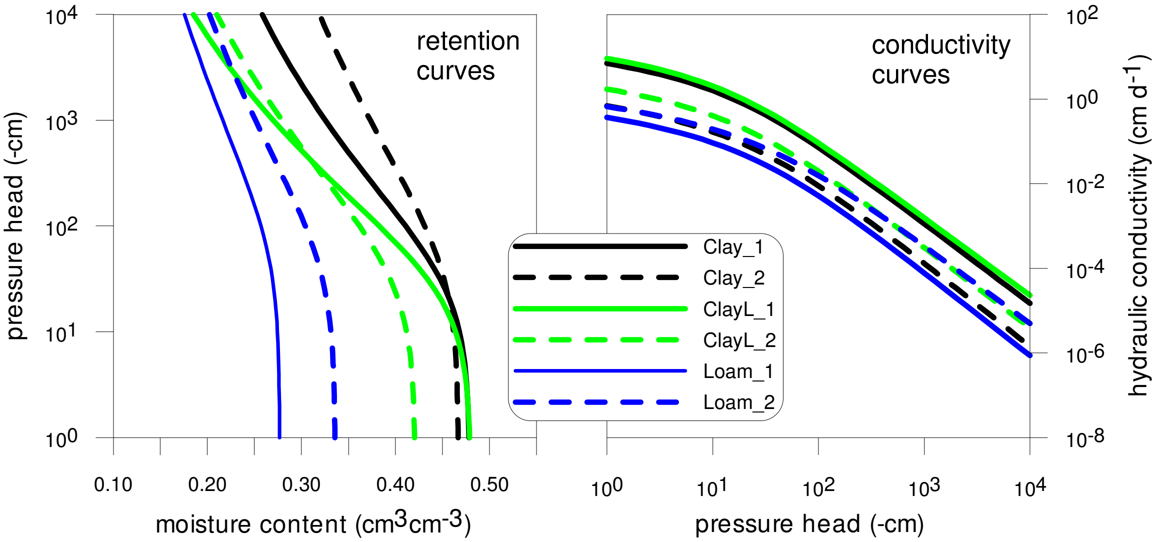


Figure 2. Soil hydraulic functions for the major soil types considered in this study.

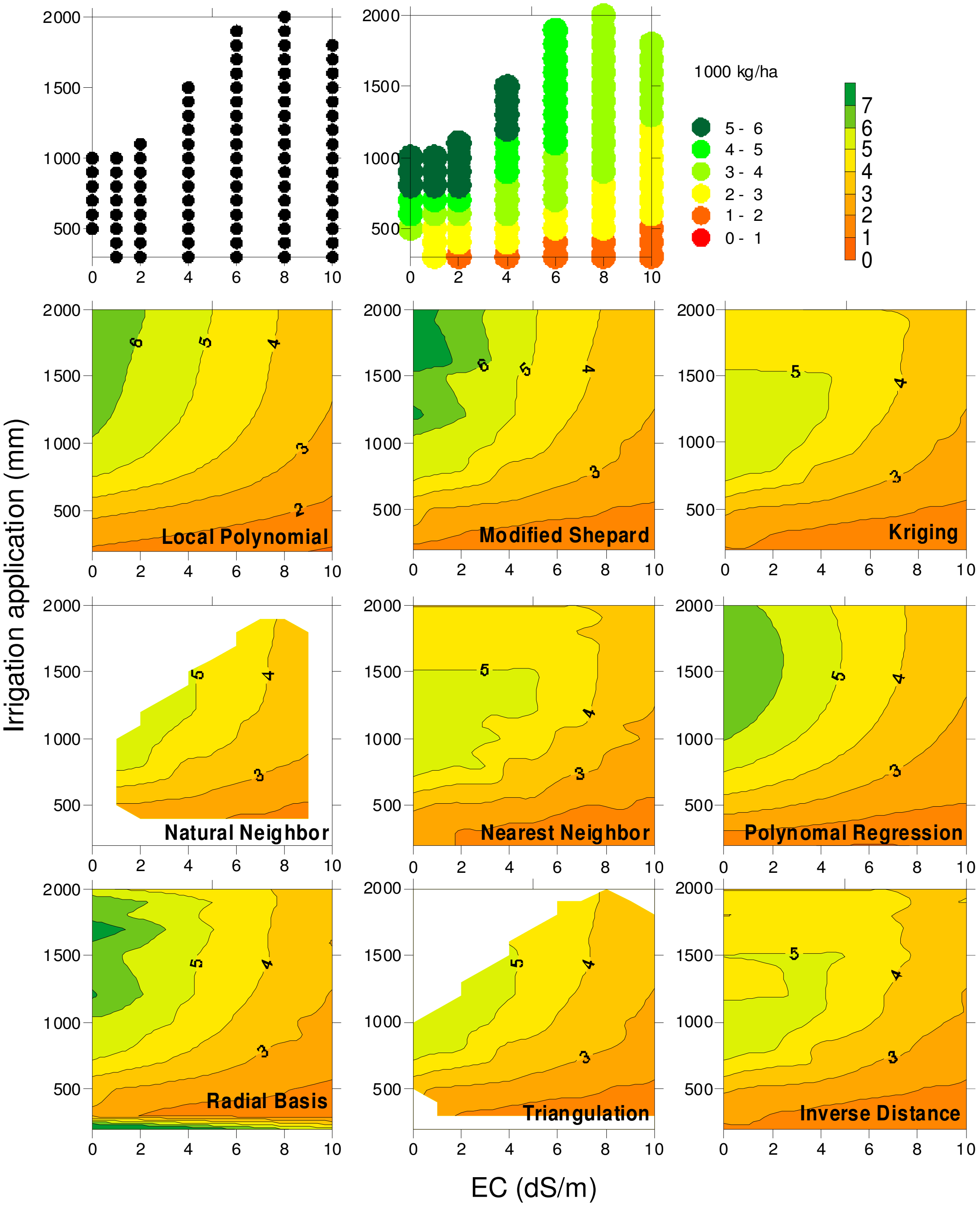


Figure 3. Impact of different gridding methods as applied for wheat on clay.

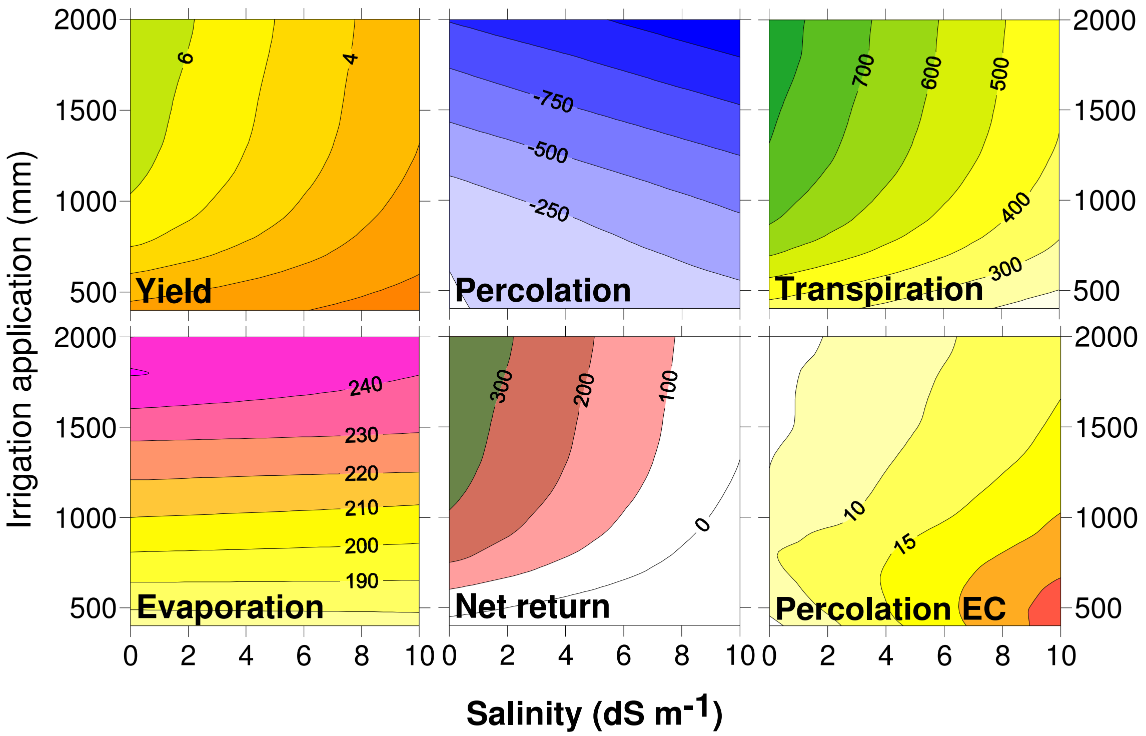


Figure 4. Output from the SWAP model for wheat on clay. Water balance terms are expressed in mm yr^{-1}, yield in 1000 kg ha^{-1}, net return in dollars and salinity of percolation water in dS m^{-1}.

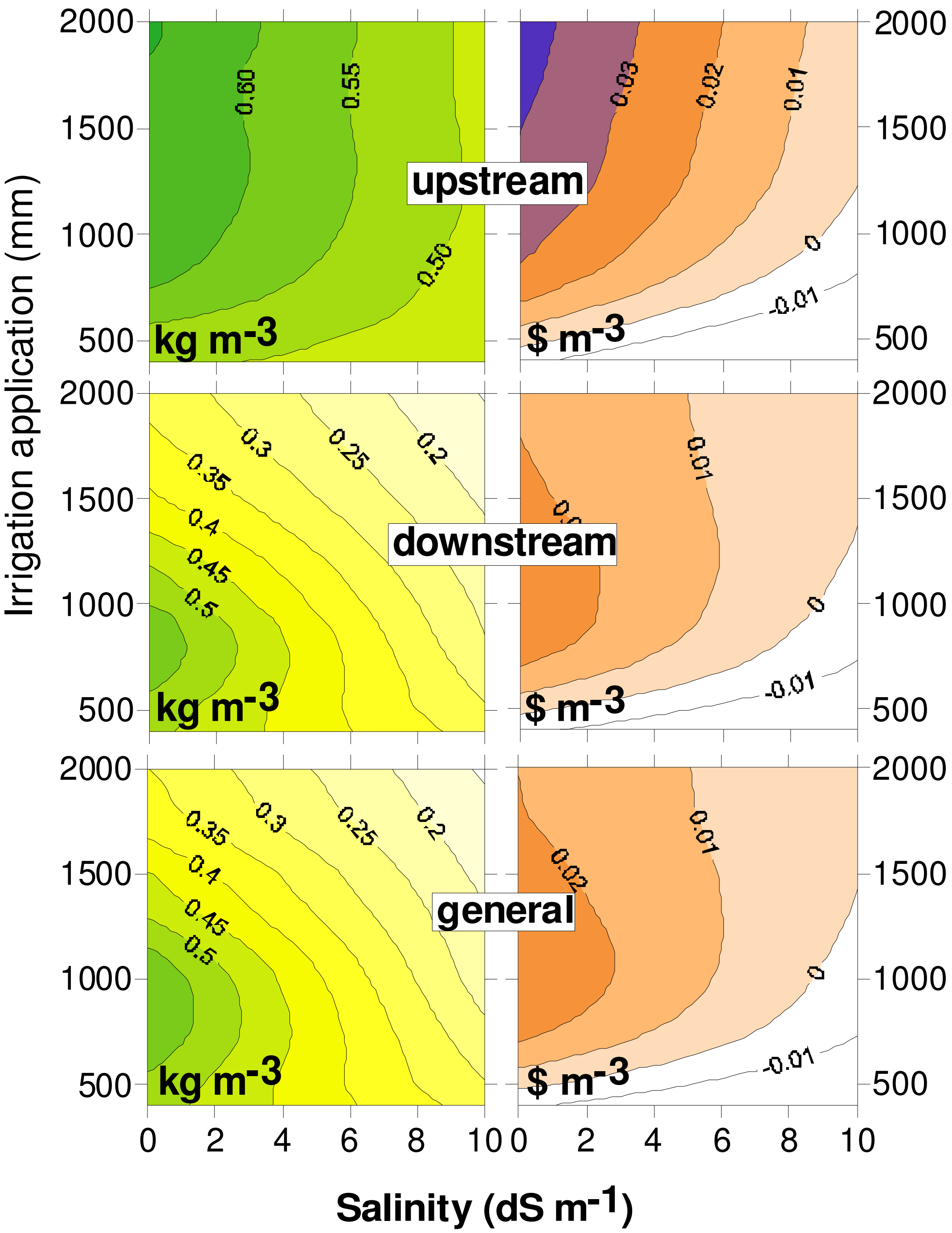


Figure 5. Water producitivy expressed in kg m^{-3} and \$ m^{-3} for upstream and downstream users for wheat on clay. *General* relates to water reuse taking into account the salinity level of outflow water.

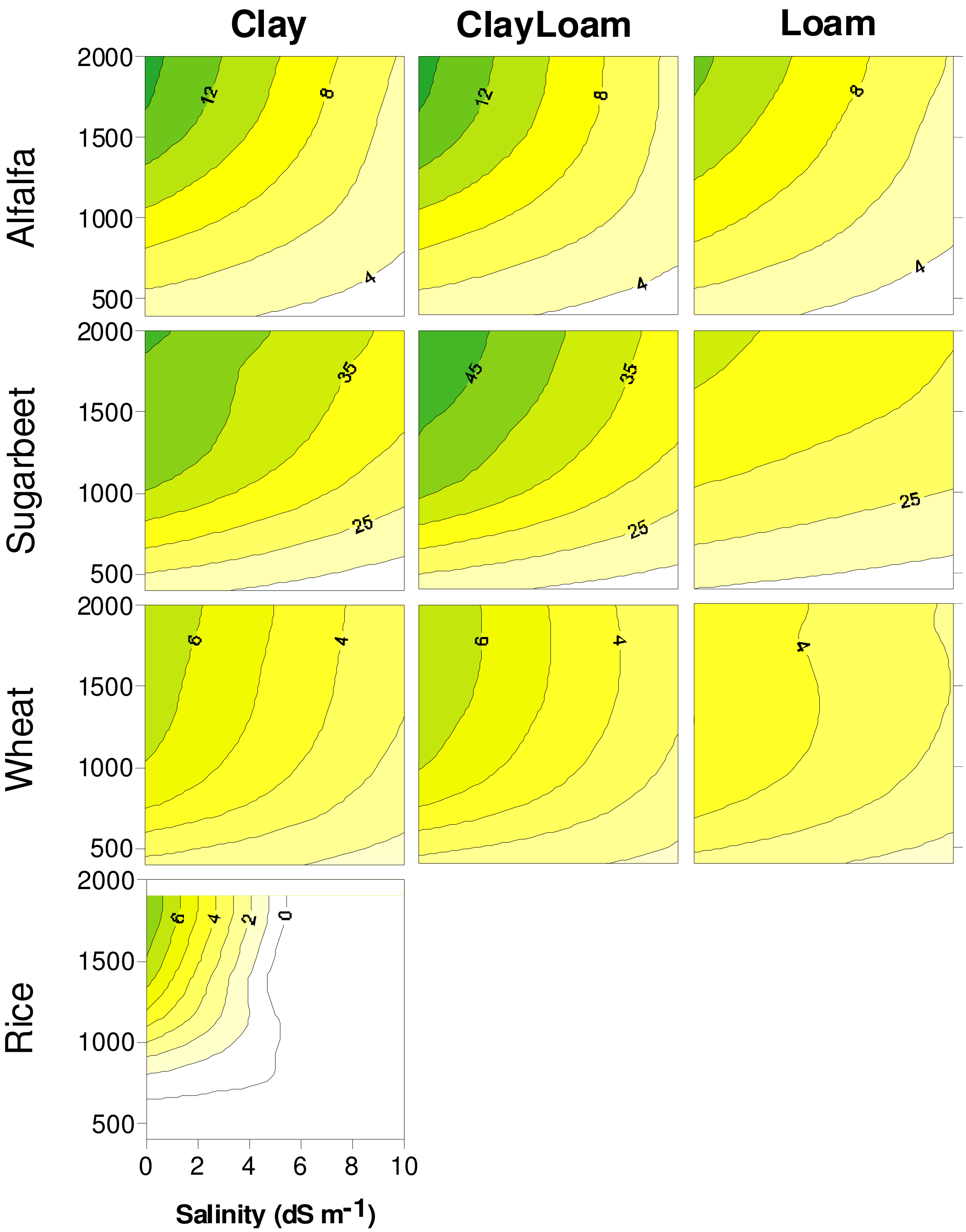


Figure 6. Simulated yields in 1000 kg ha^{-1} resulting from SWAP runs for the main soils and crops in Zayandeh Rud basin.

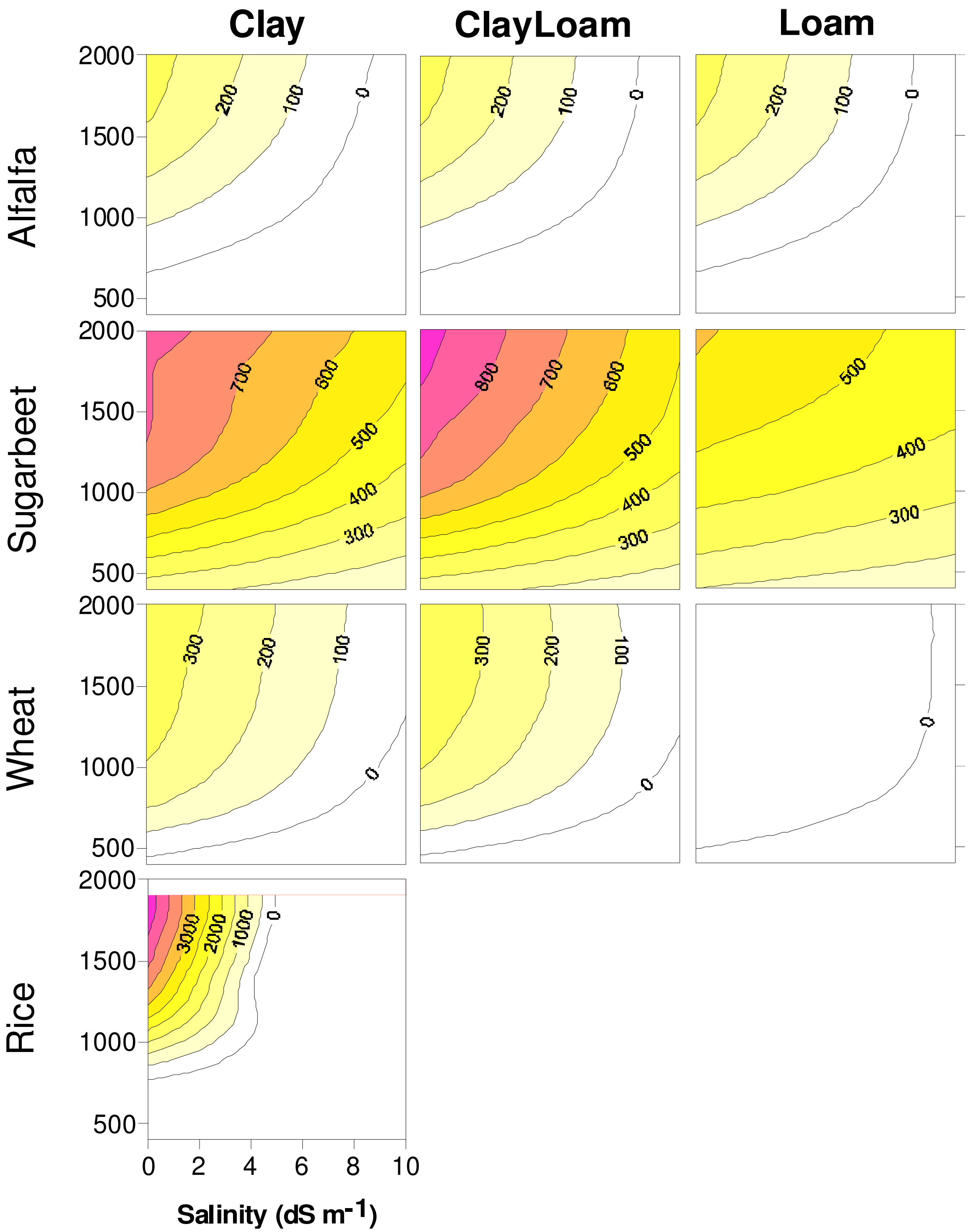


Figure 7. Net return calculated from prices and costs specified in Table 2.

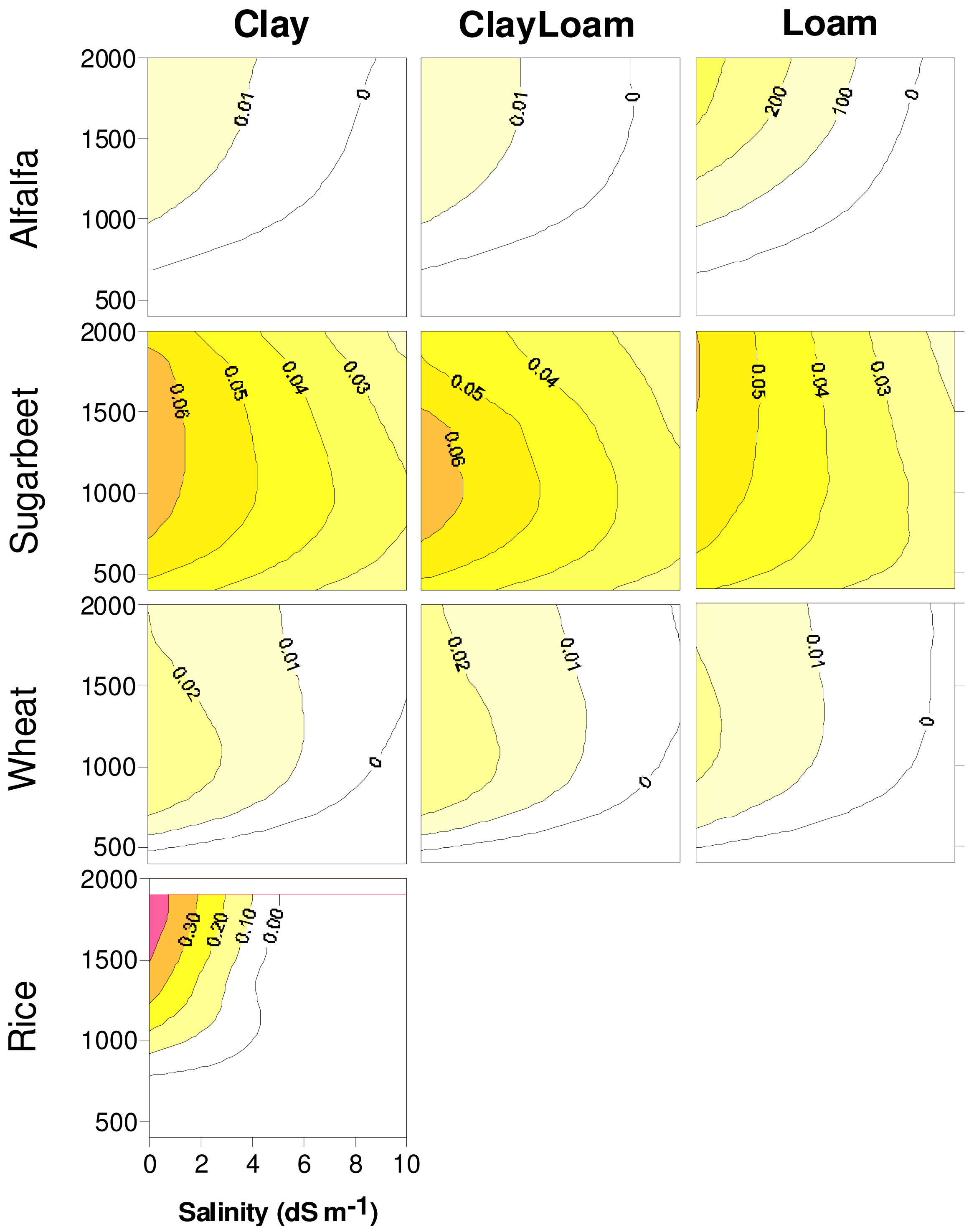


Figure 8. Water Productiviy expressed as $ return per m^{-3} of water used, expressed as the amount of water consumed by evapotranspiration plus the amount of unusable return flows due to salinity. Values are based on net returns.

The following reports have been published in the IAERI-IWMI Research Report series.

1. **Water Management for Sustainable Irrigated Agriculture in the Zayandeh Rud Basin, Esfahan Province, Iran.** (2000) H.R. Salemi, A. Mamanpoush, M. Miranzadeh, M. Akbari, M. Torabi, N. Toomanian, H. Murray-Rust, P. Droogers, H. Sally, A. Gieske.
2. **Exploring field scale salinity using simulation modeling, example for Rudasht area, Esfahan Province, Iran.** (2000) P. Droogers, M. Akbari, M. Torabi, E. Pazira.
3. **An overview of the hydrology of the Zayandeh Rud Basin.** (2000) H. Murray-Rust, H. Sally, H.R. Salemi, A. Mamanpoush.
4. **Groundwater chemistry of the Lenjanat District, Esfahan Province, Iran.** (2000) A. Gieske, M. Miranzadeh, A. Mamanpoush.
5. **Exploring basin scale salinity problems using a simplified water accounting model: the example of Zayandeh Rud Basin, Iran.** (2000) P. Droogers, H.R. Salemi, A. Mamanpoush.
6. **Sustainable irrigation and water management in the Zayandeh Rud Basin. Proceedings of Workshop in Esfahan, Iran, 19-21 November 2000.** (2001) Anonymous.
7. **Assessment of irrigation performance using NOAA satellite imagery.** (2001) P. Droogers, P., W.G.M. Bastiaanssen, A. Gieske, N. Toomanian, M. Akbari.
8. **Water supply and demand in four major irrigation systems in the Zayandeh Rud Basin, Iran.** (2001) H. Sally, H. Murray-Rust, A.R. Mamanpoush, M. Akbari.
9. **Spatial analysis of groundwater trends: example for Zayandeh Rud Basin, Iran.** (2001) P. Droogers, M. Miranzadeh.
10. **Irrigated area by NOAA-Landsat upscaling techniques: Zayandeh Rud Basin, Iran.** (2002) A. Gieske, N. Toomanian, M. Akbari.
11. **Crop and land cover classification by LANDSAT 7 ETM (July 2000) for the Zayandeh Rud basin.** (2002). A.Gieske, A.R. Mamanpoush, M. Akbari, M. Miranzadeh.
12. **Field scale scenarios for water and salinity management by simulation modeling.** (2002) P. Droogers and M. Torabi.
13. **Water Supply and Demand Forecasting for the Zayandeh Rud.** (2002). H.R. Salemi and H. Murray-Rust.
14. **Water Resources Development and Water Utilization in the Zayandeh Rud Basin, Iran.** (2002). H. Murray-Rust, H.R. Salemi and P. Droogers.
15. **Groundwater resources modeling of the Lenjanat aquifer system.** (2002). A. Gieske and M. Miranzadeh.