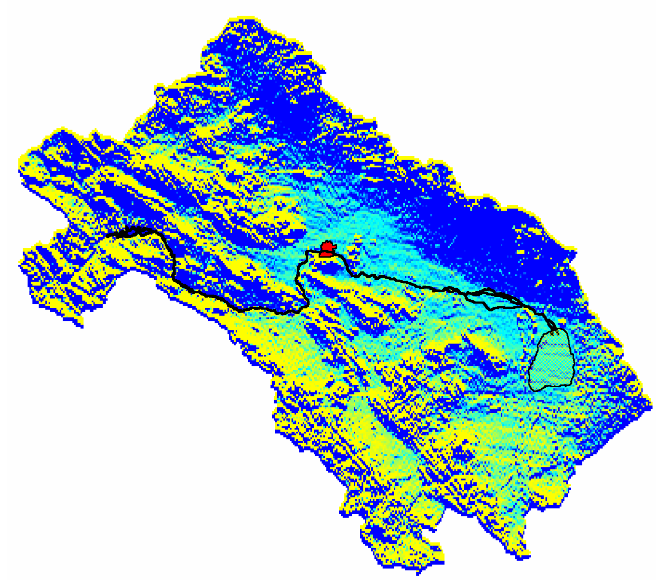
Sustainable Irrigation and Water Management in the Zayandeh Rud Basin, Iran

Exploring Basin Scale Salinity Problems Using a Simplified Water Accounting Model: the Example of Zayandeh Rud Basin, Iran

P. Droogers, H.R. Salemi, A. Mamanpoush



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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:

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P. Droogers, H.R. Salemi, A. Mamanpoush.

Abstract

Water scarcity and salinization are major threats to sustainable irrigation in Iran as well as other parts of the world. Irrigation schemes are part of a basin and as such, irrigation research must be conducted in a basin context. For the Zayandeh Rud basin in central Iran, a simplified Water and Salinity Basin Model (WSBM) was developed for a quick analysis of river basin processes. First the model was calibrated and used for current and past water resources analyses. Despite the simplicity of the model, observed and simulated stream flows were similar, proving that the model could be used for scenario analyses. The first scenario was setup to analyze the effect of more efficient irrigation techniques on the basin water resources. As a consequence of these efficient irrigation practices, return flows will decrease, resulting in less water available for downstream users. It was concluded that the effect on the downstream irrigation schemes was dramatic, with a 22% decrease in yield. A second scenario was defined where the effect of an increase of water extraction for Esfahan was evaluated. In terms of basin scale water quantity aspects this increased extraction is negligible as extractions are relatively low and return flows are high. The last scenario was developed to study the additional releases required from the reservoir to provide sufficient water for expansion of the tail-end Rudasht irrigation scheme. If no restriction is imposed on water quality, additional releases from the reservoir are limited. However, if salinity levels are not to exceed 2 dS m^{-1}, mean annual water release requirements from the reservoir will increase from 52 m^3 s^{-1} to 64 m^3 s^{-1}, and peak requirements during the irrigation season will increase from 85 to 112 m^3 s^{-1}. Finally, it was concluded that the methodology and the model developed were useful for a swift and transparent analysis of past, current and future water and salt resources, and to perform scenario analyses.

Introduction

Water is and will become the major constraining resource for sustainable development of large areas in the world. As irrigated agriculture is the major consumer of water, improvements in basin water management should focus on this. Measures like subsurface irrigation, trickle or micro irrigation have been studied in detail and may result in higher efficiencies than more traditional systems. However, irrigation schemes are not isolated but are part of a river basin with other water users. Water 'savings' at one place are likely to reduce return flows to other users downstream in the basin (Seckler, 1996). An integrated basin approach, considering all water users, is therefore necessary to assess whether water 'saving' actions are real or are only local 'savings'. Besides water quantity problems, many areas around the world encounter water quality problems in terms of industrial – urban pollution or in terms of natural salinity due to high evaporation rates. It is estimated that in Iran about 25 million hectares suffers from salinity or salinity related problems, which is 50% of the irrigable area (Pazira, 1999). As water management includes many aspects and changes upstream in a basin are likely to affect water quantity and quality downstream, a basin scale approach is essential.

Simulation models have proved to be very useful in two ways. First of all, they can be used to fill the data gaps in measurements in terms of spatial and temporal resolution, but also in terms of difficult to measure properties. An example of the latter is the distinction between soil evaporation, considered as a loss in agronomy terms, and crop transpiration. This distinction is difficult to measure, but estimates can be easily made using simulation models (Droogers, 2000). A second application of models are scenario analyses, to answer questions in the form of: what happens if…? An example of this is given by Voogt et al. (2000), where different scenarios were analyzed considering the distribution of surface water between irrigation and a wetland.

Models differ in their complexity, their physically soundness. For detailed analysis of basin hydrology, including rainfall-runoff, land cover, groundwater, and hydraulics, comprehensive models are required (e.g. Kite, 1998). However, input requirements in terms of data, time and knowledge, for these physically based basin models are often lacking. For the Zayandeh Rud basin in Iran a simplified approach was tested. A water balance model, based on a spreadsheet, was developed to study water quantity and salinity problems at a river basin scale. Current and past water resources were analyzed and scenarios were defined and evaluated using the model developed to improve water management. The main water consumer in the Zayandeh Rud is irrigated agriculture and the simulation model will therefore focus on this. A link to field-scale effects, in terms of yield, is also presented. In addition to water used for irrigation, drinking water must be provided for the town of Esfahan (2 million inhabitants) at a reliable rate in terms of quantity and quality.

In summary, this paper explores the application of a simplified basin scale water quantity and salinity model, to evaluate different management decisions and to evaluate the effect of different scenarios on basin scale water and salt balances.

Materials and methods

Study area

The Zayandeh Rud basin, 41,500 km^2, is a closed basin with no outlet to the sea (Figure 1). The main river, 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 most fertile part of the basin are the alluvial deposits flanking the Zayandeh Rud.

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^{o}C in July, but are cool in winter dropping to an average minimum temperature of 3^{o}C in January. Annual potential evapotranspiration is 1500mm, and it is almost impossible to have any economic form of agriculture without reliable irrigation.

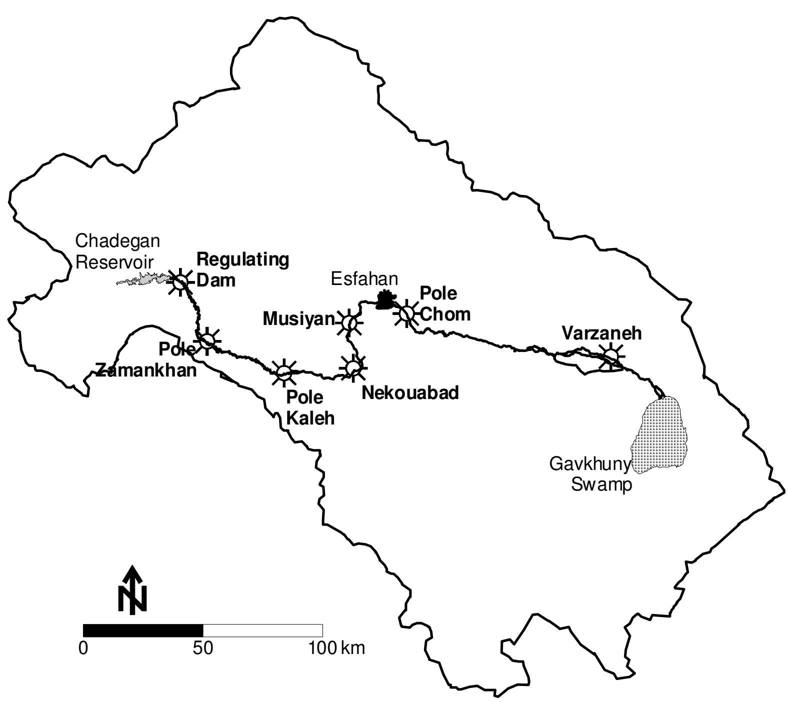

Figure 1. Main regulators in the Zayandeh Rud Basin, Iran.

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.

A more detailed description of the Zayandeh Rud Basin can be found in Salemi et al. (2000).

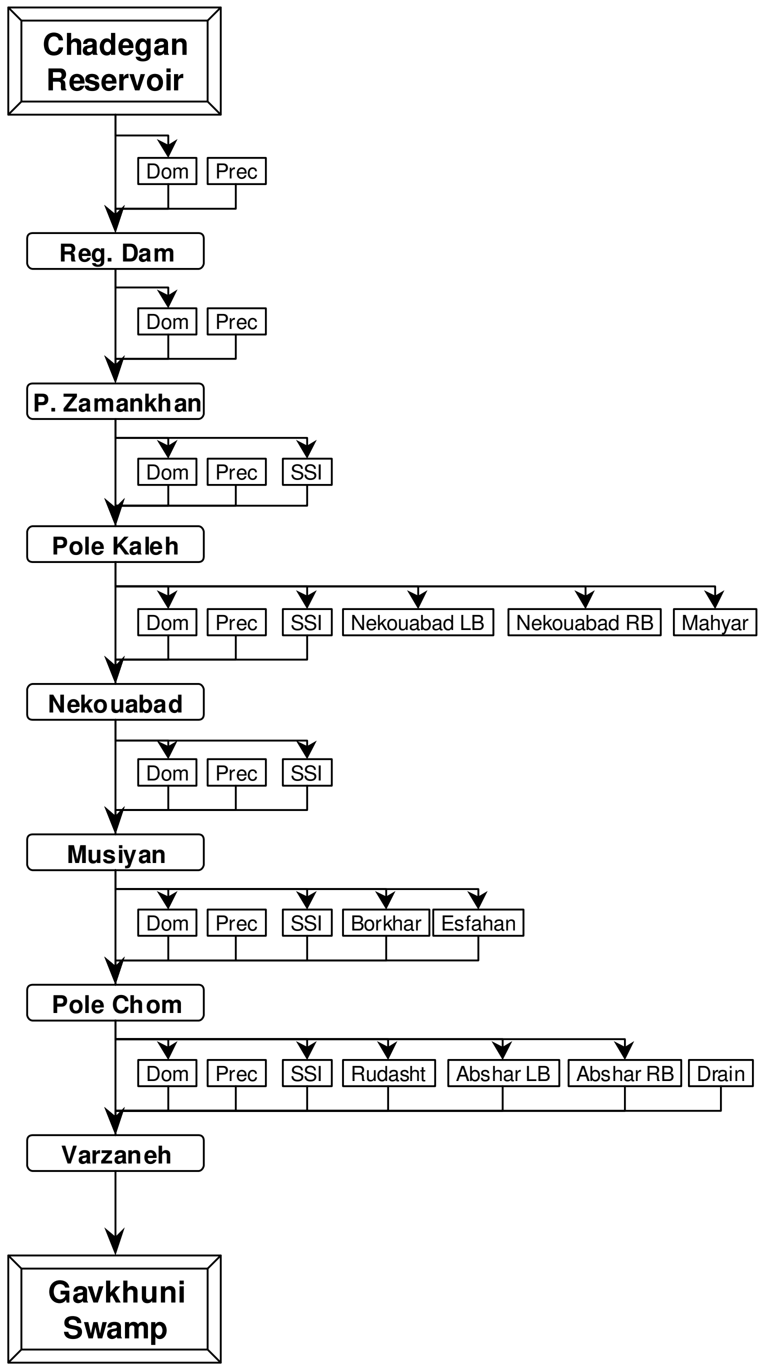

Figure 2. Schematic stream flow network of the Zayandeh Rud. Dom is domestic, Prec is precipitation, and SSI is small-scale irrigation.

Table 1. Nodes defined in the simulation model and observed annual average extractions at reaches. Return flows and salt accumulation are estimated values.

Node	Extraction	Avg. Flow m3/s	Return flows %	Salt Accumulation %
Chadegan reservoir				
	Domestic	1.9	50	0
	Precipitation	0.1	-	-
Regulating dam				
	Domestic	1.9	50	0
	Precipitation	1.2	-	-
Pole Zamankhan				
	Small scale irrigation	1.9	20	10
	Domestic	1.9	50	0
	Precipitation	1.2	-	-
Pole Kaleh				
	Mahyar	1.7	0	10
	Nekouabad LB	16.4	20	10
	Nekouabad RB	6.9	20	10
	Small scale irrigation	4.7	20	10
	Domestic/industrial	1.9	50	0
	Precipitation	1.2	-	-
Nekouabad				
	Small scale irrigation	4.7	20	10
	Domestic/industrial	1.9	50	0
	Precipitation	1.2	-	-
Musiyan				
	Borkhar	1.1	20	10
	Esfahan	4.6	80	10
	Small scale irrigation	4.7	20	10
	Domestic/industrial	1.9	50	0
	Precipitation	1.2	-	-
Pole Chom				
	Abshar LB	7.2	20	10
	Abshar RB	7.0	20	10
	Rudasht	0.4	20	10
	Small scale irrigation	4.7	20	10
	Domestic/industrial	1.9	50	0
	Drain inflow	9.4	-	-
	Precipitation	1.2	-	-
Varzaneh				

Simulation model

The main objective of the simulation model developed, WSBM (Water and Salinity Basin Model), was to create a simple and transparent water and salt accounting model, to be used for quick analyses of river basin processes. The model focuses on extractions for irrigation and the associated return flows from these systems. The model also includes a simplified urban and industrial water extraction component. In order to accomplish this, we decided to create the model in a spreadsheet to ease data input, transparency and flexibility. Moreover, the model was setup in a kind of object oriented style to support this transparency and flexibility.

WSBM assumes that the river is divided into nodes with a reach defined between two successive nodes. Nodes are located at typical points in the river were stream gauges are present or output is required. Water extractions, or supplies, occur only in the reaches. Using this approach water and salt flow along the river can be simulated by subtracting extractions, or adding supplies, from one node to get the value for the next node. As mentioned before, extractions are defined for urban-industrial and irrigation supplies. For both types of extractions the amount of water, the return flow as a percentage of the extraction and the accumulation of salt as percentage of the total inflow, must be specified. Obviously, values can be either real data or hypothetical values to explore the effects of different interactions. The whole model was setup to run with a monthly time-step and it was assumed that the response time of the river was within one month, so no time lag in water and salt flow between months occurs.

Three statistical parameters were used to compare observed and simulated flows. The Root Mean Square Error (RMSE, m^3s^{-1}) is defined as:

$$RMSE = \sqrt{\frac{\sum (Obs - Sim)^2}{n}} \qquad (1)$$

where *Obs* is observed flow (m^3s^{-1}), *Sim* is simulated flow (m^3s^{-1}), and *n* is number of observations. Another statistical parameter used is the correlation coefficient r^2:

$$r^2 = \frac{\left[\sum (X - \overline{X})(Y - \overline{Y})\right]^2}{\sum (X - \overline{X})^2 \sum (Y - \overline{Y})^2} \qquad (2)$$

where *X* and *Y* are observed and simulated flow (m^3s^{-1}), $\overline{X}$ and $\overline{Y}$ are average observed and simulated flow (m^3s^{-1}).

A third parameter, the absolute difference between observed and simulated flow has been used to reveal an under- or overestimation of the model.

Input data

A schematic representation of the stream network can be seen in Figure 2. The Borkhar and Mahyar irrigation scheme started to function in 1997 and 1998, respectively. Table 1 shows the different nodes, and extractions between nodes considered in the model. Data can be divided into data required to run the model (releases from the reservoir and extractions) and data to verify model performance (flows at nodes). As can be seen from Figure 3 some of the required data is missing. Variation in extraction patterns for the irrigation schemes considered was low (Figure 4) and therefore the monthly averages from the other years was used to fill the missing data. Model performance was checked at seven sites along the river (Figure 1) and data availability for these are shown in Figure 5.

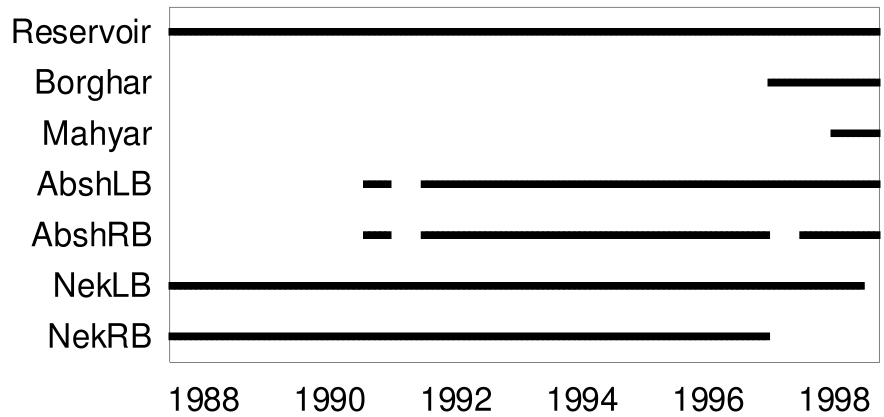

Figure 3. Data availability on extractions to the main irrigation schemes as required input to run the simulation model.

For the main irrigation schemes data availability on extractions is shown in Figure 3. As mentioned before, the Borkhar and Mahyar irrigation scheme started to function in 1997 and 1998, respectively. For the missing data, it was assumed that the extraction for a particular month was equal to the average of the same months from the other years. Furthermore, it is known that a substantial amount of smaller scale water extractions takes place in the basin. In order to account for this, an average annual extraction pattern based on the main schemes was assumed. Using the observed flow data in each node, the extent of this small-scale extractions was fitted.

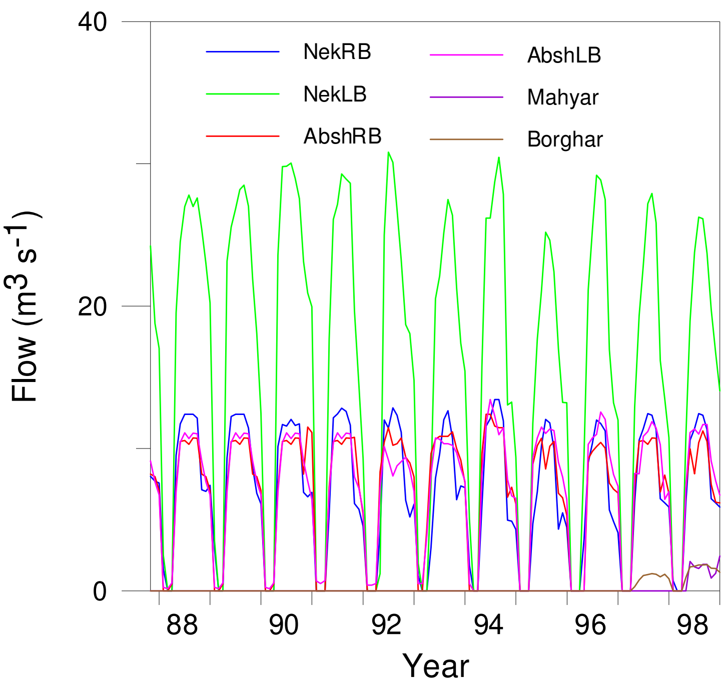

Figure 4. Extraction pattern for the main irrigation schemes.

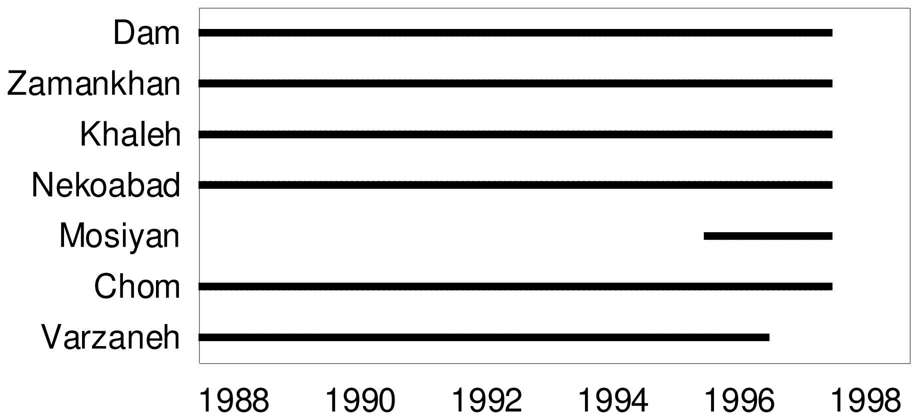

Figure 5. Data availability on streamflows as used to verify the simulation model.

For all the irrigation extractions, a return flow was assumed. Somewhat arbitrary, this was set at 20%. This relatively low value was assumed to be realistic as this is the overall irrigation scheme return flow, so internal return flows within a scheme are not considered. Moreover, water scarce areas tend to have low return flows.

Salt inflow to an irrigation scheme was equal to the amount of water inflow multiplied with the salinity level at the intake node. A fix amount of salt accumulation was assumed, which can be flow to the deep groundwater, some uptake by the crop, and storage in the soil profile. This accumulation was assumed to be 10% of the total salt inflow, so a return flow of 90%. This salt return flow of 90% combined with the water return flow of 20% induces the built up of salinity levels in the river.

For each reach a fixed amount of 1.9 $m^3 s^{-1}$ for urban and industrial use was assumed. Return flows of these extractions are normally high and were set at 50%, while salt accumulation was considered to be negligible. For Esfahan an additional extraction was calculated based on a population of 2 million and a per capita requirement of 200 $l\ d^{-1}$.

Precipitation is very low with annual values of about 130 mm. Observed monthly values were used and a contributing area was defined, which can be considered to represent the area that contributes to the river discharge. This is the so-called effective precipitation in hydrological terminology. As this effective precipitation is so low, this rough approximation was considered to be sufficient accurate.

Generalization

The model was setup for an 11 years period (1988-1998). Missing data were assumed to have the same value as the average ones from the same months, as described before. Recorded flow data were used to adjust some unknown required input data, such as small scale irrigation and domestic/industrial extractions. After the calibration for these data a generalized model was created taking the average simulated flow for each month from the period 1995-1998. This generalized model is used for scenario analyses.

Scenarios

The generalized model, as described above, has been used to explore different alternatives in terms of water resources. From the range of possible scenarios, three have been selected for further analyses: (i) lower return flows from irrigation, (ii) increased water extraction for Esfahan, (iii) additional inter-basin flows to support new irrigation developments in the Rudasht scheme.

With the increase in use of pressurized irrigation systems, it is likely that return flows from irrigation systems will reduce (scenario 1). The already relative low return flows of 20% are assumed to reduce to 10% in this scenario. The second scenario, an increased water demand for Esfahan, is based on the assumption of a growth in population from 2 million towards 3 million, and an increase in per capita use from 200 l d^{-1} to 400 l d^{-1} as a result of a higher standard of living. The last scenario is based on new irrigation developments in the Rudasht area, between Pole Chom and Varzaneh, and the required water quantity and quality for this. It is expected that the irrigation demand will go up from an annual average of 0.4 $m^3 s^{-1}$ to 2 $m^3 s^{-1}$, and a peak demand from 1.7 $m^3 s^{-1}$ to 8.5 $m^3 s^{-1}$ in August. Besides this increase in water quantity, the water quality aspects are set so that salinity levels should never exceed 3.0 dS m^{-1} (scenario 3a) and 2.0 dS m^{-1} (scenario 3b).

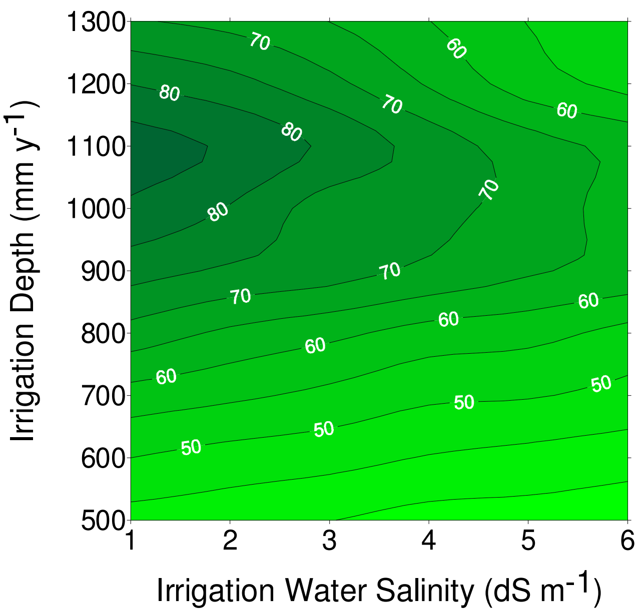

Figure 6. Water quantity/quality yield response figure (adopted from Droogers et al., 2000).

Impact on yields

The impact on production is the key indicator as this integrates all the management effects, in terms of water quantity and quality. A modeling study, based on the well-tested field scale agro-hydrological model SWAP (Van Dam et al., 1997), was performed for the Rudasht area, resulting in a water quantity/quality yield response graph (Figure 6). Details of this study can be found elsewhere (Droogers et al., 2000), and results are used as input here.

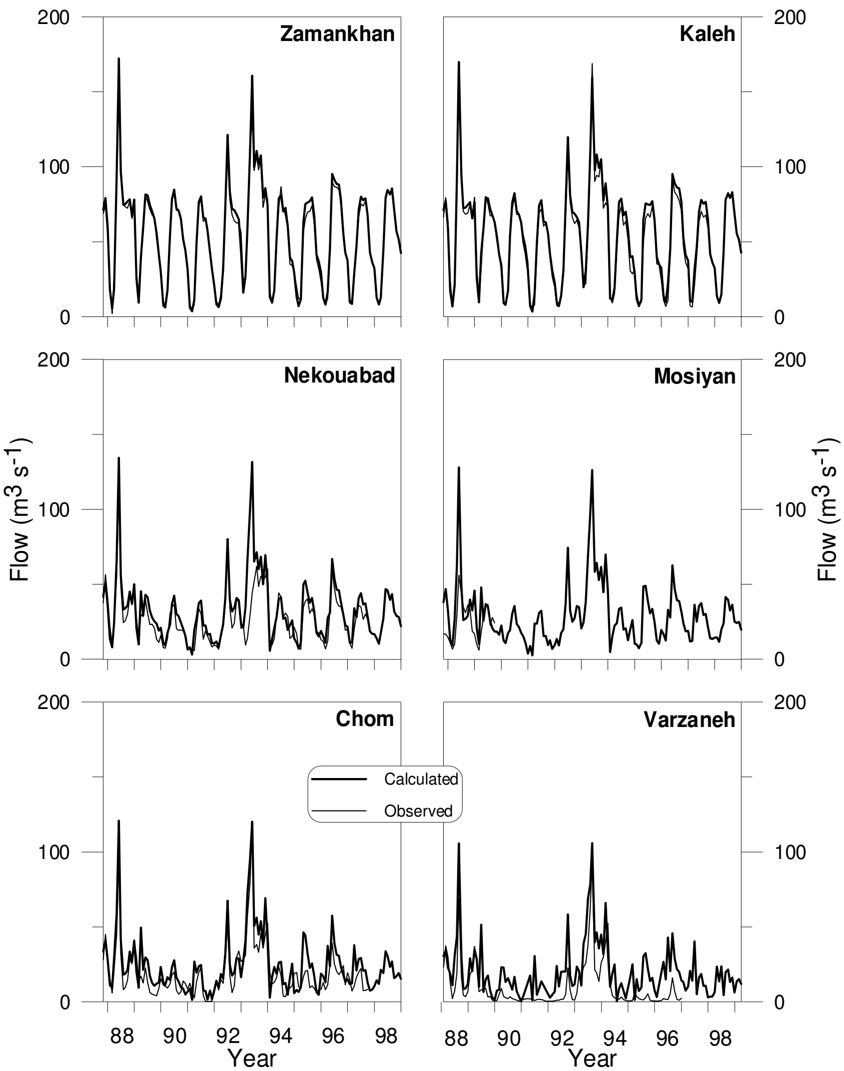

Figure 7. Observed and simulated flow data.

Results

Model performance

After completing the model and including the data, the performance of the model was tested. Some preliminary test runs showed that the performance of the model for the last reach, Chom-Varzaneh, was less accurate, showing much higher estimated flow rates at the Varzaneh node then measured. Increasing the small-scale irrigation extractions resulted in negative values during some months and still high values at other months. The nature of this downstream irrigation is a clear example of water extractions in a water scarce area. As long as water is available, irrigators will use it, and no clear irrigation season can be distinguished. However, if flows are too high, not all the water is extracted and a threshold value of 50 MCM (19 $m^3 s^{-1}$) was assumed.

Including this adaptation in the model, recorded and simulated streamflows were compared for the seven locations along the river. Figure 7 and Table 2 show this comparison and some statistics. Observed and simulated values for the Regulating dam were similar to the Pole Zamankhan ones, and were therefore excluded from Figure 7. Calculated values were close to observed ones, especially for the more upstream nodes. The excellent performance of the model for Regulating Dam, Pole Zamankhan and Pole Kaleh nodes is related to the fact that almost no extractions take place in the upstream part. Between the Kaleh and the Nekouabad a substantial amount of water was extracted (about 20 $m^3 s^{-1}$), but recorded and calculated flows were in reasonable agreement. An exception is the peak flow in spring 1993, where a big deviation between observed and calculated stream flow can be seen. Most likely the peak flow was missed at the Nekouabad station, as it was observed more downstream in Pole Chom and Varzaneh. In general, calculated flows were somewhat higher then observed ones and model performance was better for the upstream nodes than for the downstream nodes.

Table 2. Comparison between observed and calculated monthly streamflows.

Node	RMSE $m^3 s^{-1}$	r^2	Absolute Difference $m^3 s^{-1}$
Regulating dam	3.87	0.99	0.67
Zamankhan	5.09	0.98	1.63
Kaleh	5.63	0.98	3.17
Nekouabad*	13.43	0.69	5.63
Musiyan	7.48	0.71	2.85
Chom	10.65	0.81	5.78
Varzaneh	15.48	0.67	10.18

**Values ignoring the apparent measurement errors in spring 1993 are: 6.90, 0.89, 3.56.*

The calculated salinity levels in terms of EC are displayed in Figure 8. For the upstream part of the basin salinity levels are around 1 dS m^{-1}, and not much fluctuation occurs. For the middle-part of the basin, levels have increased to about 2-3 dS m^{-1}, with some peaks reaching levels up to 8 dS m^{-1}. Hugh fluctuations occur at the tail end of the basin, with very high salinity values if water levels are low, such as at the end of 1991 for Pole Chom and at the beginning of 1991 for Varzaneh. Average calculated values, excluding peak values are about 2.5 and 6.5 dS m^{-1}, for respectively Pole Chom and Varzaneh.

Scenarios

Average monthly model results from the last four years, 1995-1998, were used to generate a standard model, the baseline, to evaluate the effects of the different scenarios. These four years were selected as no extremes occurred during this period.

The first scenario, a smaller amount of return flows due to a higher water use efficiency, has almost no impact on the upstream part of the basin, as the number of irrigation extractions is low. Effects can be seen from the Nekouabad node and further downstream (Figure 9). At Pole Chom, average flows during the irrigation season, April to October, reduces by 20% from 25 $m^3\ s^{-1}$ down to 20 $m^3\ s^{-1}$. Moreover, salinity levels will increase substantially, with average values in the growing season going up from 2.9 to 4.0 dS m^{-1}. The implications for irrigation downstream of Pole Chom and for expected yield reductions can be estimated using Figure 6. Assuming a total irrigation application of 1000 mm with a salinity level of 2.9 dS m^{-1} for the base scenario expected yields are 74% from potential. Using the scenario results, expected yields will drop to 58% from potential, for 800 mm of irrigation with a salinity level of 4 dS m^{-1}. This means a drop of 22%. Further research, including an economic analysis, should reveal whether this loss of production at the downstream areas will be compensated by expected higher yields in the upstream part of the basin.

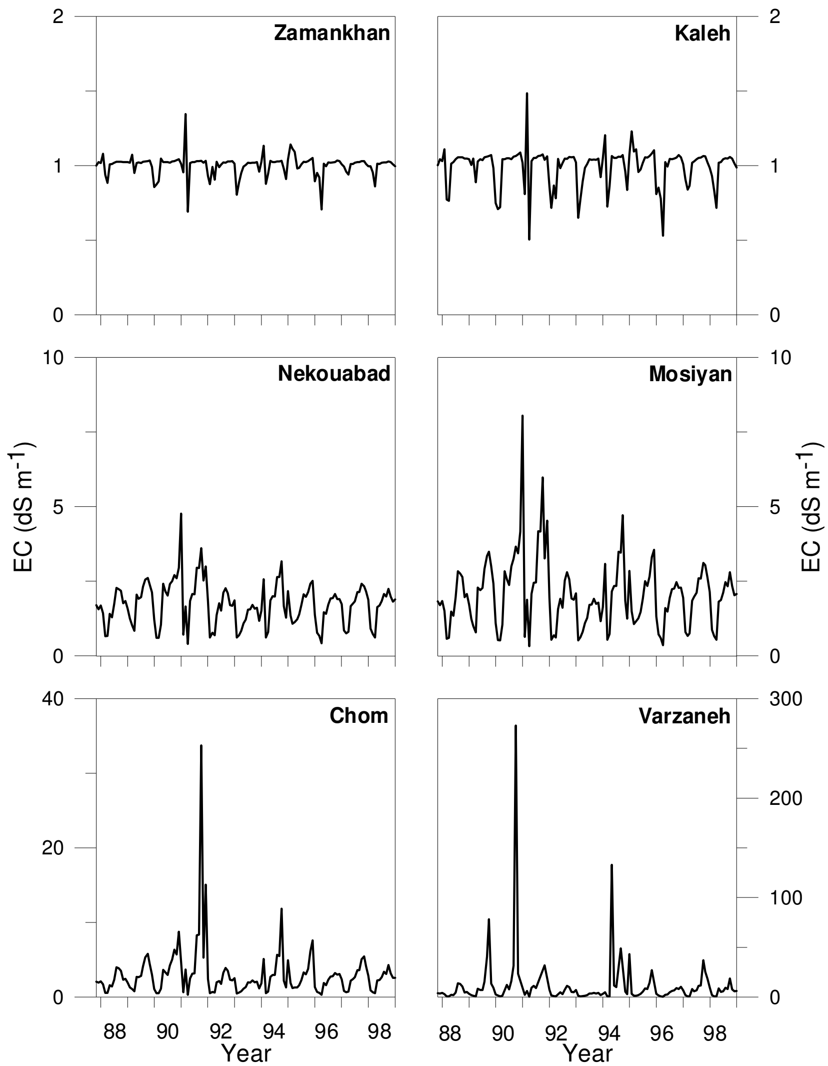

Figure 8. Simulated EC values along the river. Note: Y-axes scales are different.

The increase in water extractions for Esfahan, scenario 2, has almost no effect on the flow in the Zayandeh river. Average extractions went up from 4.6 $m^3\ s^{-1}$ to 13.9 $m^3\ s^{-1}$, but as return flows were assumed to be constant at a 80% level, net extractions went only up by about 2 $m^3\ s^{-1}$. A point not considered here is that the increased return flows from the town will certainly reduce the water quality of the river, with all the likely negative impact on agriculture downstream.

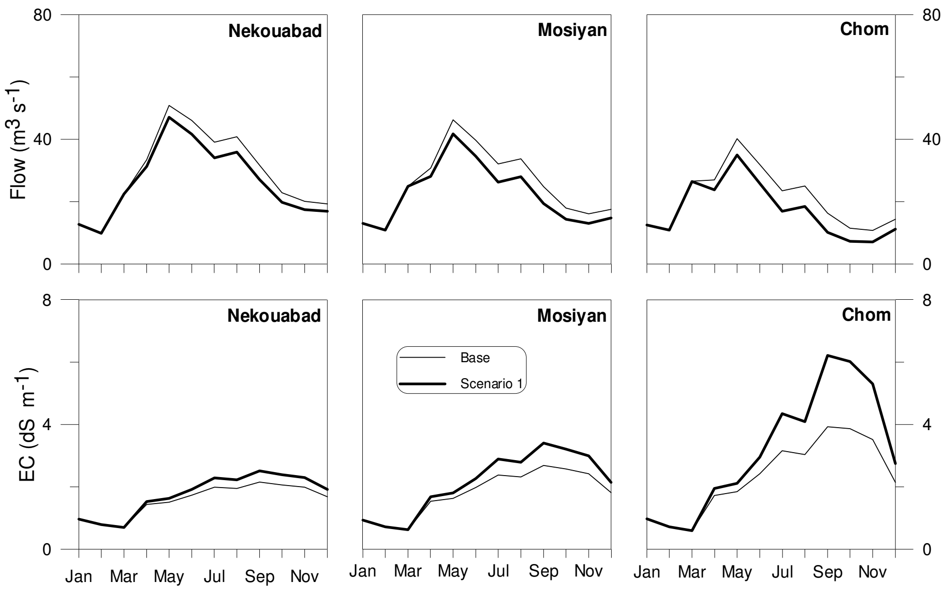

Figure 9. Effect of lower return flows from irrigation, scenario 1, on flows and salinity levels as compared to the baseline.

The last scenario, inter-basin flow to support new irrigation development in the Rudasht area, affects the whole basin. The amount of water required can be divided into water needed to fulfill the additional irrigation demand of the new area, and water needed to reduce salinity levels to the maximum specified value of 3.0 dS m^{-1}. Analyses show that mean annual water release requirements from the reservoir will increase from 52 m^3s^{-1} to 54 m^3s^{-1}, and peak requirements during the irrigation season will increase from 85 to 88 m^3 s^{-1} (Figure 10). If the criterion for the water quality was set more strict to a maximum level of 2.0 dS m^{-1}, average annual flows should be 64 m^3 s^{-1}, and peak requirements are going up to 112 m^3 s^{-1} in August.

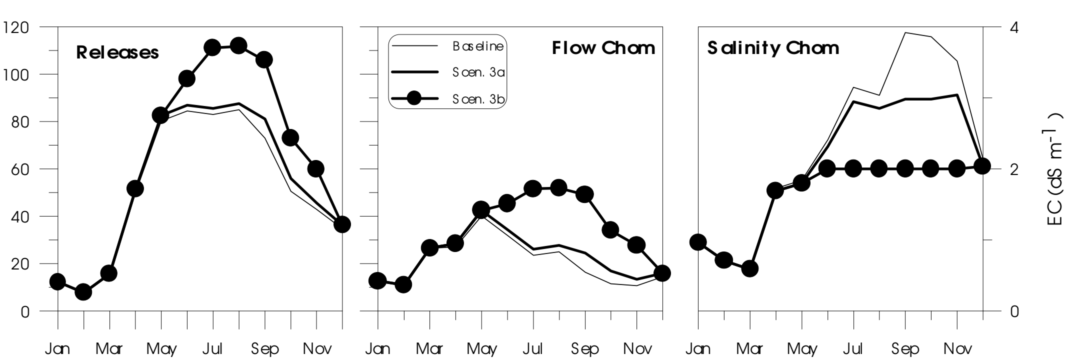

Figure 10. Additional required releases to supply sufficient water for the Rudasht area, including salinity threshold values of 3 dS m^{-1} (scen. 3a) and 2 dS m^{-1} (scen. b).

Conclusions

The model developed for this study is an example how basin scale water quantity and quality analyses can be performed in a clear, transparent and swift mode. Four steps can be distinguished in this study (i) the development of the model, (ii) verifying and calibrating the model, (iii) generalizing the model, and (iv) scenario analyses based on the generalized model. The model itself was developed in a spreadsheet using an object orient mode, which makes the inclusion of additional components in the river layout fairly simple. Moreover, data entry, analysis of results, and plotting, can be all done in the same spreadsheet environment. The verification and calibration of the model was done by a combination of adjusting some of the unknown extractions and inflows. This was fairly easy, as the basin layout was not complicated and no sophisticated rainfall-runoff processes should be considered as precipitation is very low. For the Zayandeh Rud the model can produce reliable results as compared with observed data. The generalized model, developed by combining simulated results over the last 4 years, is a transparent and easy to use tool for scenario analyses. This generalized model can be considered to be reliable as not much variation within years was observed. The advantage of such a simplified model is that an unlimited number of scenarios can be analyzed in a very short time frame.

The scenarios defined here are selected to demonstrate the application of the model, but additional scenarios can be developed and evaluated using the model. The increased efficiency scenario showed that an apparent water saving methodology, has a negative impact on the downstream area of the basin. A basin scale evaluation is therefore essential before expensive efficient irrigation techniques are introduced. A point not considered here is that efficient irrigation techniques can reduce non-beneficial evaporation. On the other hand, leaching will be lower with a higher risk of salt accumulation in the soil. A detailed field scale soil-water-crop analyses can reveal these complex interactions (e.g. Droogers et al., 2000).

The increased water demand for urban water supply has only a minor effect on the water balance of the basin. The two main reasons are that these extractions are relatively low in comparison to agricultural demands and that return flow from urban extractions are high. Not considered in this study is that these return flows can be heavily polluted, resulting in a diminishing of the water quality (Safavi, 1995).

The last scenario considered here, an increase in water demand for the development of new irrigation schemes in the Rudasht area, shows clearly the relationship between water quantity and quality. In terms of water quantity, the required additional releases from the reservoir are low. Including a threshold value for the salinity level, increases the demand for releases drastically.

Some general conclusions can be drawn from this study. The flow to the Gavkhuni Swamp is very small and the quality of this water is so poor that it is unsuitable for any further use. At the tail end water is fully committed even while salinity levels are too high for a sustainable irrigation practices. A further expansion of agriculture can only be accomplished by increasing the inter-basin transfer of water, or a higher productivity in terms of kg produced per cubic meter of water used. Increased field scale management, more productive crops, and decreased non-beneficial evaporation are ways to achieve this higher agricultural productivity.

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