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The Role of Modelling in Integrated Water Management (A Case Study in Zayandeh Rud Basin)

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Abstract: In water scarce basins, it is inevitable that changes in water use in one sector or at one level will have a direct impact on water availability and water productivity for other sectors or other users. In looking at these interactions it is useful to have a set of models on hand that enable us to accomplish two objectives: i) understanding current conditions, ii) developing future scenarios that address alternative uses and allocations of water and seeing how they affect water conditions at different scales. Three clear steps including scenario, projection and water management option should be distinguished in process of defining future water management. Current cropping patterns (F0), farmers stop growing rice (F1), farmers improved water management techniques (F2) and deficit irrigation (F3), were selected as farm level options. Three system level options (including current practice (S0), equal (S1) and unequal (S2) water allocation between irrigation systems, with six projections for water availability to agriculture (500, 750, 1000, 1250, 1500 and 1750 MCM) were selected for water management analysis. This four farm level options combined with three system level options gives us 12 management possibilities that need to be analyze for each of the six projections of the water availability. In total 72 combinations will be analyze for this impact assessment. Results shows that because of fixed amount allocated water to non-agricultural sectors, basin inflow is linear to the six defined projections for water to agriculture. In terms of water management options at system level, the equal allocation practice (S1) guarantees that the area can be cropped is maximal. Deficit irrigation (F2) and improved field water management option (F3) result shows the highest water productivity. Stopping rice cultivation will reduce this water productivity substantially, caused by the high price of rice. In terms of system water management options, the current situation (S0) is providing the lowest productivity and allocating water equally between systems (S1) or serve upstream farmers first (S2) appears to be better ways to improve water productivity. Therefore, during dry conditions we can expect deficit irrigation (F3), with a water productivity of about 0.15 \$ m^{-3}, preference to the current practice with a value of about 0.13 \$ m^{-3}

Key words: Modelling • Water management • Basin water productivity • Zayandeh Rud

INTRODUCTION

Integrated water management models have been use to inform decisions about water supplies and water management in complex regional systems. For example, we might advocate changing cropping patterns in one part of a basin in order to improve water productivity and farm level profitability and use a model that determines what the impact of those changes might be for the farmers involved. However, if we restrict our analysis only to that particular domain, i.e. the fields of those farmers making changes in cropping patterns, then we do not know whether those changes have had a positive or adverse affect on other water users.

To understand integrated modeling we need to understand three different concepts: interdependency between different water management systems as a set of nested systems, the effect of scaling up and scaling down when changing the domain of analysis and the spatial and temporal interactions between different water users. Nested systems are characterized by a set of inputs and outputs that form the linkages between the systems [1].

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In the context of water management, the smallest system is that of the soil-plant-water complex. Water inputs come from larger systems (precipitation, surface irrigation and groundwater) and are export from the system in the form of evaporation, transpiration, surface runoff and subsurface drainage. Agricultural outputs and other performance measures also transfer into the next higher system resulting in system and basin level performance indicators. Any change made in inputs into this system inevitably results in a different balance of the outputs from the system. From the perspective of the irrigation system, which incorporates a large number of smaller field level systems, the outputs from the field systems in terms of surface runoff and subsurface drainage become inputs into the water balance of the irrigation system. If changes occur in the field level water balance, then they inevitably affect the hydrology of the irrigation system itself. However, as the domain of analysis changes to irrigation system level, many of the losses at farm level remain internal to the domain and are not lost. Surface runoff may be used as irrigation water elsewhere and water that percolated into the groundwater can be pumped for productive use. Similarly, at basin level, we find that reuse of surface and groundwater, either by irrigated agriculture or another sector, remains within the basin until eventually all remaining water flows to the sea or a sink [2]. This water can not be reused and is a true loss for the basin.

The same principle applies at the basin level. If there are changes in the hydrology of irrigation systems, then these have an impact on basin level hydrology, because demands for irrigation supplies may change. There will then be commensurate changes in the return flows to the river or in groundwater levels that will affect other users of water. Exactly the same line of thought can be applied as we move downwards through the nested system. For example, if a change is made in sector-level water allocations so that agriculture receives less water then this will affect the inflows into the irrigation sub-systems within the basin and therefore h the return flows to the system and the inflows into the field level sub-systems.

Scaling up is not the same as replication. If we model and recommend a change in field level water management practices, we can assume that the physical processes will remain the same if a large number of water users adopt these practices. That is what is involved in replication. Scaling up, however, looks at the impact of widespread adoption of those changed practices at higher levels in a basin by examining what the changes are in the inflows and outflows across sub-system boundaries. An analysis of irrigation system level efficiency, based on replication would treat each irrigation system as an independent entity and not look at their interaction. Scaling up, looks at the interaction between the different irrigation systems at the basin level. If therefore, we find that outflows from one irrigation system become inflows into another system downstream, then the "losses" are transformed into potentially productive inputs in another subsystem. It is the analysis that leads us to a conclusion that basin level water use may be very high even though each sub-system component within the basin may appear to be very inefficient. This is certainly the case in the Zayandeh Rud basin.

It is on this basis that in the Gediz basin in Turkey, irrigation efficiencies were less than 50% for 11 systems, but the total water use in the basin was over 95% of available supply simply because of reuse of surface drainage water and pumping of groundwater that had been recharged by seepage from irrigation systems [3].

Spatial relationships are important in terms of h water quantity and water quality. Irrigation affects downstream users in two ways: returns flows from irrigation systems may augment downstream supplies, but the quality of those return flows may have an adverse impact on those downstream water users. This is particularly true in closed basins such as the Zayandeh Rud because salinity inevitably increases downstream and has a direct impact on the productive potential of those downstream areas.

An important aspect of this concern is that there may be downstream requirements for water quantity and quality that can only be satisfied if there are specific changes in water use and management by upstream water users. We need models to help us understand these upstream interactions as well as the more obvious downstream interactions.

From the temporal perspective, we may find that what appear to be losses in the context of a short-term analysis may turn out to be useful water in the context of a longer-term analysis. In the Zayandeh Rud basin, for example, aquifers close to the river are the only source of water for irrigated agriculture from January to March when no releases are made from Chadegan reservoir. During the summer irrigation season the aquifers are depleted, but recharges after harvest of summer crops is used for winter irrigation.

MATERIALS AND METHODS

Zayandeh Rud Basin: The main irrigated areas in the Zayandeh Rud basin, Esfahan, Iran, 41500 km^2, have been selected to analyze the integrated assessment of water management options at different scales. The main river in

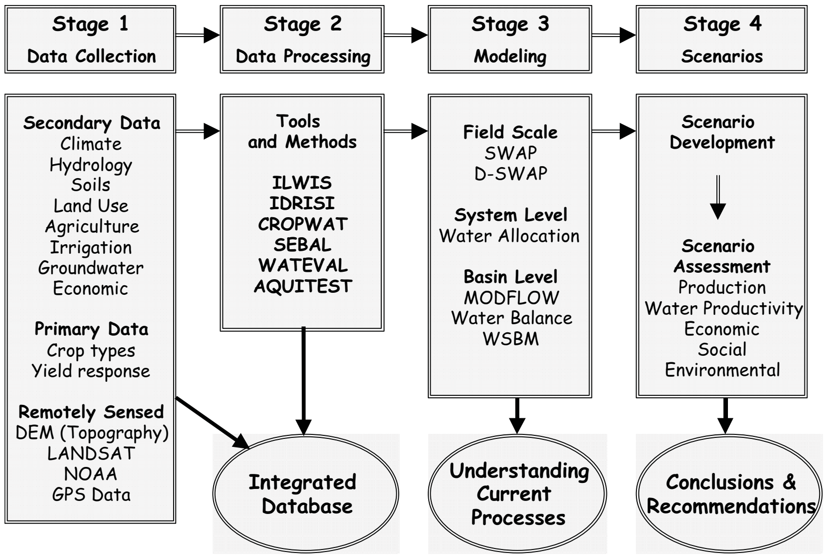

Fig. 1: Sequence of stages required for integrated assessment of water management options at different scales

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°C in July, but are cool in winter dropping to an average minimum temperature of 3°C 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 is 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 catchments 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 [4].

The implementation of a project looking at integrated water management at field, irrigation system and basin scale has four sequential stages:

- Data collection and establishment of a structured database.
- Data processing through use of a wide range of tools.
- Model development and/or application to understand current conditions.
- Scenario development and assessment leading to conclusions and recommendations.

The process is shown in Figure 1, although it must be recognized that there is a lot of overlap during the first three stages. However, Stage 4 cannot be complete until the first three stages have been complete for all different levels of analysis in the basin because it requires all of this information to undertake the scenario assessment process.

Primary data collection was restricted only to essential pieces of information that were required for supplementing secondary data or for providing ground truth for remotely sensed data. The secondary data that we were able to collect covered all of the main areas required for an integrated approach to water management assessment and modeling. It should, however be recognized that there are gaps and compatibility issues arising from the use of data derived from a large number of different organizations and agencies, each of which have their own specific purposes for data collection. We recognize that the data we were able to obtain is not ideal, but it turned out to be sufficient for our modeling purposes. Remotely sensed data is of two types. The Digital Elevation Model from the USGA TOPO30 series was used to delimit basin boundaries and other topographic information. This information is largely preprocessed. Data from various LANDSAT 7 and NOAA satellites were extensively used for base map preparation and a range of crop and water conditions through processing in the second stage of activities. The project has used a number of standard tools for processing the data collected during the initial phases of the project. A brief description of these tools is given below.

The Integrated Land and Water Information System (ILWIS) is a GIS-based package developed by [5], the Netherlands. In this project, ILWIS packages were used to undertake land classification. In order to assess irrigation demand and to link secondary data on canal discharges to estimations of irrigation performance determined using Surface-Energy Balance Algorithm (SEBAL) from h LANDSAT 7 and NOAA images [6, 7].

The wide range of water management issues in the Zayandeh Rud basin and the complexity of interactions mean that it is unrealistic to try to use a single model. With different underlying approaches to modelling it is impossible to have a workable model that combines all aspects. Instead, the philosophy used in this study has been to have a suite of models that are linked in one of two ways. linking was done in a few cases by using outputs from one model as direct inputs into another model. This approach works well as long as the overall range of parameters is similar and there is a simple linkage in the way in which the models fit into the nested structure, but most linking was done by using each model separately to assess a particular scenario, taking care to ensure that the assumptions used in each model were compatible. Eight models used in this study, some based on physical laws, some on water balance or mass balance accounting, together with an indication of the scale at which they were used and the level of physical detail included in the model.

The final stage of the integrated modelling approach is to use the results obtained in assessment of different scenarios for water management. We have not favored any effort to develop a single model that can do this. Rather, we prefer an approach that transfer results from different models into an integrating spreadsheet, which can produce outputs for a set of pre-determined performance indicators.

Three clear steps should be distinguished in the process of defining future water management: scenario, projection and water management option. In order to select the best water management option we should evaluate each option by a set of so-called performance indicators such as water productivity and gross return.

The primary effect of basin level allocation decisions is to modify the total amount of water allocated to the agricultural sector and we can use this as a starting point for scenario analysis at lower levels. We are not really concerned about what other sectors do with their water, only how much we will be allocated for agriculture and when it will be made available to us.

We found that overall water availability for agriculture in the basin could range from a high of 1715 MCM to a low of 1100 MCM under balanced budget scenarios. However, projections should normally look at extreme conditions as well as normal ones. We therefore propose that water availability for agriculture should be divided into a set of projections that reflect different conditions. Water management options can therefore be undertaken for each of these projections and allow us to look at the full range of possible water conditions. Using this approach, we can use six projection values of water availability to agriculture (500, 750, 1000, 1250, 1500, 1750 MCM) for impact assessments that allow us to examine the whole range of conditions from severe drought to abundant water conditions.

At irrigation system level, managers have a limited range of possible actions they can take. Probably the most important relate to allocation between irrigation systems along the Zayandeh Rud. In this respect, we only examine three possible management options. The first option is to allocate water according to the current practice (S0), which is a kind of mixture between preference to upstream irrigation systems and equal allocation. The second option is equal allocation between irrigation systems (S1) based on the designed command area. The third option is unequal allocation among systems (S2), the “first-come, first-served” which progressively satisfies the demand of the headmost systems and allocates remaining water to other systems until all available water is allocated. In water short years this favors head-end systems but in water abundant years almost all systems will get sufficient water. Obviously, there are an infinite number of intermediate conditions between these three, but analysis of these three alone will provide the extreme conditions in terms of impact assessment.

At field level, the options we have selected for analysis reflect a combination of changes we think are likely to occur given current trends and those that are being advocated by different groups, included current cropping patterns (F0), farmers stop growing rice (F1), farmers adopt improved farm level water management techniques (F2) and deficit irrigation (F3). While this is not a selective list we feel it provides sufficient range of options for policy makers and farmers to consider. These four farm level options combined with three system level options gives us a total of 12 management possibilities that need to be analyzed for each of the six projections of values of water availability, a total of 72 combinations which require impact assessment.

Water management options to respond to the different projections at basin and irrigation system level have been analyzed by using the Water and Salinity Basin Model (WSBM), as developed earlier [8]. The model has been generalized and was setup for only one year, using average conditions as occurred during 1989 to 1999. This 11-years period included a wet year (1993) and the first dry year (1999) of the drought, that occurred from 1999-2001. The assumption in the scenarios defined is that water allocation to other sectors has a higher priority than water allocation to agriculture. As agriculture gets only the remainder, we have used the historic period of 11 years to assess the relative flow, in percentage of total water extracted to all the irrigated areas, to each of the main systems. This data is used for the S0 option, where water is allocated according to the current situation.

The S1 option, where water is allocated equally among the systems we use the area of each system to set allocation rules. We have used the irrigable areas as described by [9, 10] to assess the water allocation rules according for option S1. Finally, the last water management option considered at system level is to allocate water unequally, where upstream farmers extract all the water they want and only the remainder and return flows are available for downstream located farmers.

Field scale analysis includes the impact of the irrigation applications and the quality of this water on evapotranspiration, return flows, soil salinity, depleted water and, most importantly crop yields. These analyses were supported by the Soil Water Atmosphere Plant model, SWAP, as described in detail elsewhere [11]. The model was tested and applied for major crops and soil types in irrigation system level [12-14]. The latter study will be used here to assess the different water management options at field scale.

The first water management option at field scale, F1, considers the option where farmers are forced to stop growing rice. The original cropping distribution, based on the historic range over the last 11 years, has been adjusted assuming that the rice farmers convert their fields according to the average cropping system in their command area.

An explorative study on the impact of converting the irrigation systems to pressurized system for the basin has been described [15]. Based on this study it was clear that upstream farmers might benefit somewhat from such a switch, but the impact on downstream users was quite substantially as return flows would be reduced. The third scenario defined here is similar but looks in a more comprehensive way, including different crops, economics and equity, what the impact will be of such a shift from furrow and border to drip irrigation techniques. It was assumed that all crops would be irrigated by drip, which is in practice not likely or possible, but this scenario can be considered in a broader sense as a total package of improved field water management practices.

This water management option (F2), has been implemented in the modelling environment by assuming that the irrigation system return flows would be reduced from the original of 20% to 10%. Although these return flows seems quite low, it should be considered that we look at the overall irrigation system return flows and that water is scarce so farmers will try to use every available drop. The amount of water extracted (not depleted) for one hectare was assumed to be about 80% of the original optimal irrigation depth.

The last water management option (F3), looks at the opportunity to practice deficit irrigation to cope with water shortage. Deficit irrigation takes already place in the area, especially during droughts and by downstream users. What we are exploring here is the option that all farmers in the basin take up deficit irrigation as a management option. Obviously, this will be more difficult to implement for upstream farmers, who are used to get most of the water, than for downstream ones. Also, in the Nekouabad systems rice is grown, which is more susceptible to water deficit conditions than other crops. This option (F3) is implemented in the modelling approach by assuming that water deliveries for irrigation are reduced to 70% of the original ones. At the same time, return flows from systems will, similar as to option F2, also reduce to 10%.

RESULTS

As starting point, we will have a look at allocations between different sectors on a basin scale. As mentioned earlier, we concentrate here on water allocation to agriculture assuming that it is not relevant to farmers whether changes in the amount of water they receive is caused naturally or by policy decision. Obviously, changes caused by policy decisions might be discussed

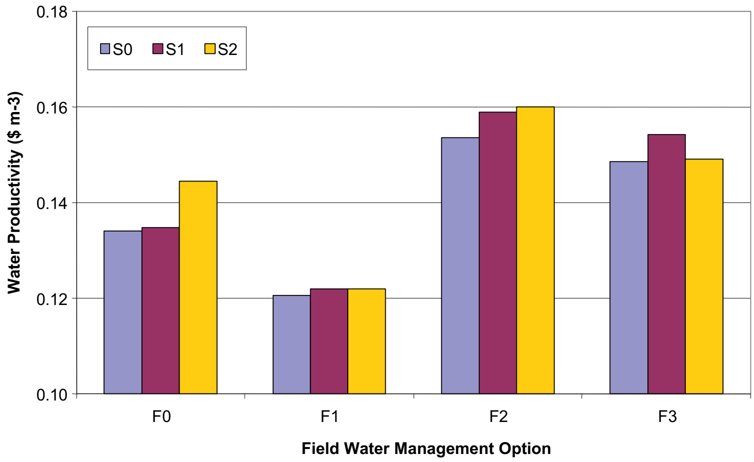

Fig. 2: Average water productivity for the entire basin for Projection 4, average water availability.

and the scenarios presented here might support such a discussion. The main question remains how to respond best on a certain amount of water available to agriculture.

Base on the results, we assume that by 2020 the amount of water depleted for urban and industrial use, evaporation from the river and requirements for the environment is 437 MCM. The remaining inflow in the basin is available to agriculture. Results shows that as a consequence of the fixed amount allocated to non-agricultural sectors, basin inflow is linear to the six defined projections for water to agriculture (500, 750,1000, 1250, 1500, 1750 MCM).

Flow requirements to the downstream located wetland Gavkhouni was set at 70 MCM. At higher basin water supply (P4-P6), this flow to Gavkhouni exceeds this 70 MCM and can go up to about 250 MCM. The reason for this is that at higher levels of water availability return flows are also high and agriculture is unable to capture all of them. It should be noted that even at projection P6, 1750 MCM to agriculture, the full demand by agriculture is still not satisfied by canal irrigation due to design limitations of the main canal system. The gap between the percentage of water extracted and depleted by agriculture is widening at increasing water availabilities. The percentage depleted has a maximum of about 70% and is already reached at average water availabilities (P4, 1250 MCM), while the percentage extracted increases even at the highest projection rate.

In terms of water management options at system level the equal allocation practice (S1) guarantees that the area that can be cropped is maximal. Allocate water by preference to the upstream users first (S2) appears to be the less favorable option in terms of getting the total highest cropped area in the basin.

As land is not the main constraint in Zayandeh Rud Basin but water, it is important to maximize the return per cubic meter of water. The concept of Water Productivity has been developed over the last decade and is finding wide application nowadays. From Figure 2 it is clear that deficit irrigation and improved field water management option result in the highest water productivity figures. Stopping rice cultivation will reduce this water productivity substantially, caused by the high price of rice.

In terms of system water management options the current situation (S0) is providing the lowest productivity. Allocating water equally between systems (S1) or serve upstream farmers first (S2) appears to be better ways to improve water productivity. Which is preferred depends also on the farm water management option adopted.

Estimates for other water availability projections (P1-P3 and P5-P6) show the same trend. This is somewhat unexpectedly as it has been reported that water scarce areas tend to have higher water productivity figures and vice versa. As mentioned earlier, in reality farmers will adopt some form of deficit irrigation during dry periods and will tend to over-irrigate in times of abundance. Therefore, during dry conditions we can expect deficit irrigation option (F3), with a water productivity of about 0.15 $ m^{-3} in preference to the current practice with a value of about 0.13 $ m^{-3}. Overall, water productivity is not much affected by any water management option and expected values are between 0.12 and 0.16 $ m^{-3}. This suggests that under the most favorable management conditions and with current price structures, the maximum productivity improvement is in the order of 30%. It should be recalled that this is a projection for 20 years from now, suggesting that there is little gain over expected population increases in rural areas over the same time period.

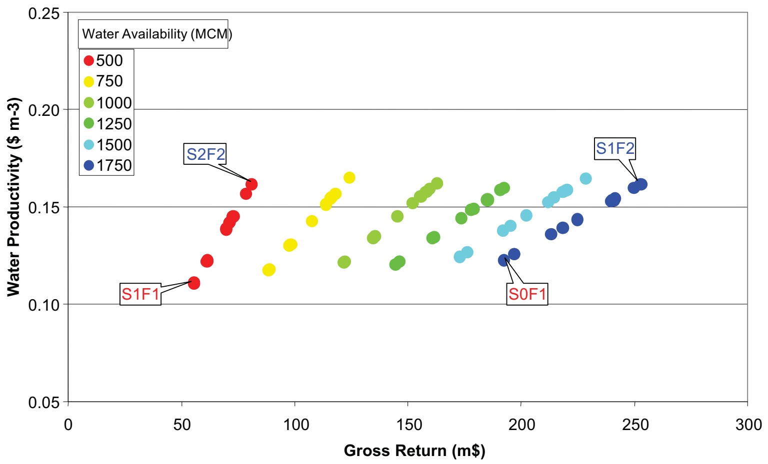

Fig. 3: Water productivity versus gross return for each of the 6 water availability projections and the 12 combinations of system and field water management options.

The assessment of the different water management options should follow a multi-objective approach. Opting only for the highest cropped area does not result necessarily into the highest overall gross return. Similarly, a high gross return might cause an inequity in income not preferable. As an example of such a multi-objective approach the trade-off between gross production and water productivity is plotted in Figure 3 for the six water availability projections. As shown clearly in the graph, management affects gross return and water productivity to a large extent and the best management option differs from one water availability option to another. In this example of gross return versus water productivity the tradeoff between these two is straight forward. Aiming for the highest gross return coincides with the highest water productivity. So there is no conflict between these two objectives. The next example will show that this is often not the case.

At the field level, the options to stop rice cultivation (F1) or to practice deficit irrigation (F3) reduce incomes in especially Nekouabad. Somewhat surprisingly is seems that the option to improve field water management practice (F2), does not increase farm income as such in comparison to current practice. The main reason is most likely that these improved options are mainly aimed at saving some water, which will have an impact on the total cropped area as presented earlier, rather than on individual farm income. Since total water availability is an external factor the question is which management option, is the best given a certain amount of water available for agriculture? In contrast to the tradeoff between gross return and water productivity, as explained earlier, there is no best management practice that satisfies h objectives. The highest gross return does not guarantee the lowest variation in income and vice versa. If we take for example the case where water is abundant (P5) then aiming at the highest equity can be achieved by water management option S1F3: equal water allocation between systems and deficit irrigation. However, if gross production should be maximized the allocation should be upstream systems first and the improved field water management options are preferred (S1F2).

The most interesting result is that while management can influence equity, water availability is the dominant factor in this. It should be considered that farm income wascalculated for all farms, so it includes farms not receiving any water and thus having a zero income.

Figure 4.a- shows nicely how water will be distributed if upstream systems will be served first. At the average water projection (P4, 1250 MCM) full supply is realized to the Nekouabad and to Mahyar and the other systems are not provided with any water, with the exception of Borkhar to a certain extent. Even at the highest water availability, not all systems are served completely and Rudahst and the Abshar systems will receive only 25% of the water they require. It is clear that the basin is scarce and that even at high water projections not all farmers can be served.

At the irrigation system level, the option to adopt deficit irrigation (F3) might be one solution to this basin water deficit. Figure 4.b represents the same situation as Figure 4.a except that deficit irrigation is practiced. It is clear that the Nekoubad and Mahyar systems are already fully supplied when only 750 MCM is available. At the highest water availability projection, most systems are fully supplied, but the downstream ones are still only at a level of 65% relative water supply.

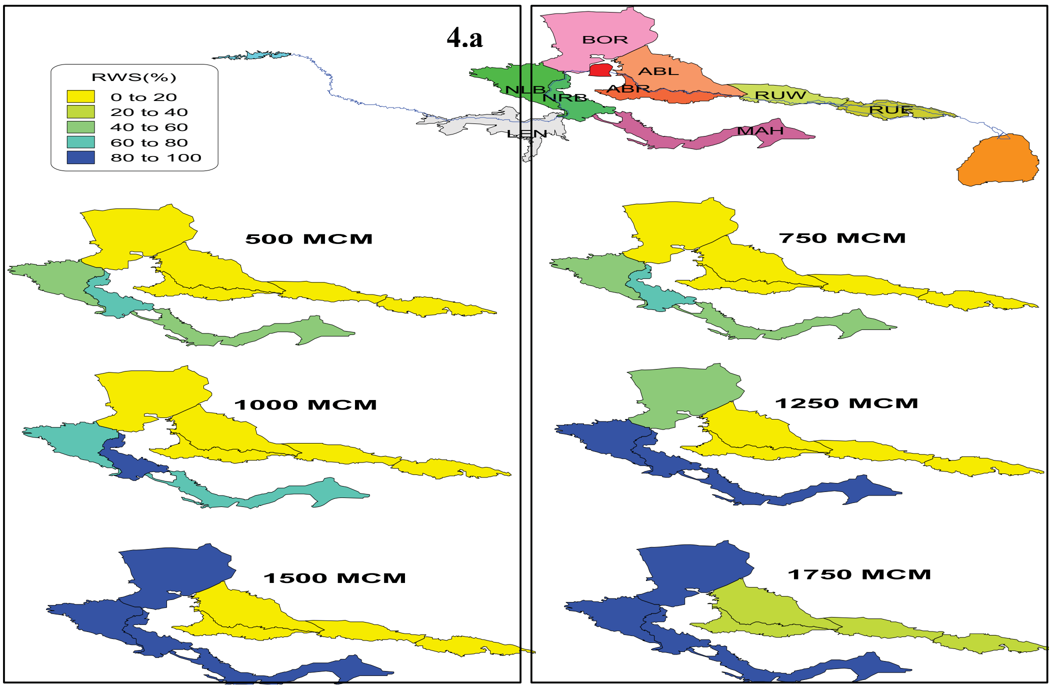

Fig. 4: Water allocations between systems according to system water management option S2, server upstream farmers first for current situation (4.a) and deficit field water management practice (4.b).

CONCLUSION

It is insufficient to have models that look only at the impact within one sector or for one class of water users because the potential benefits identified by using that model may be outweighed by larger costs to other users or sectors. Models also permit us to assess the relative benefit and cost of different water management options in the future on the basis that the processes and relationships hold true over a range of different conditions. This is done through the use of scenario analysis that examines not only the direct changes that result from exercising a different option but also the impact and changes at other levels of water management in the basin. Three clear steps should be distinguished in the process of defining future water management: scenario, projection and water management option. Therefore, we have selected a combination of three water allocation and four water management options with six projection values are likely to occur given current trends and those that are being advocated by different groups, for impact assessments that allow us to examine the whole range of conditions from severe drought to abundant water conditions. We concentrate here on water allocation to agriculture. The results shows that as a consequence of the fixed amount allocated to non-agricultural sectors, basin inflow is linear to the six defined projections for water to agriculture (500, 750, 1000, 1250, 1500, 1750 MCM).

In terms of water management options at system level, the equal allocation practice (S1) guarantees that the area that can be cropped, is maximal. Allocate water by preference to the upstream users first (S2) appears to be the less favorable option in terms of getting the total highest cropped area in the basin. Figure 2 shows clearly that deficit irrigation and improved field water management option result are in the highest water productivity figures. Stopping rice cultivation will reduce this water productivity substantially, caused by the high price of rice. In terms of system water management option, the current situation (S0) is providing the lowest productivity. Allocating water equally between systems (S1) or serve upstream farmers first (S2) appears to be better ways to improve water productivity. Which is preferred depends also on the farm water management option adopted. So, during dry conditions we can expect deficit irrigation, option F3, with a water productivity of about 0.15 \$ m-3 in preference to the current practice with a value of about 0.13 \$ m-3. The option to adopt deficit irrigation (F3) might be one solution to this basin water deficit. Overall, water productivity is not much affected by any water management option and expected values are between 0.12 and 0.16 \$ m-3.

Figure 4.a shows what the impact will be in terms of system water allocation. So Figure 4.b represents the same situation as Figure 4.a except that deficit irrigation is practiced. It is clear that average income in the Nekouabad systems is substantially higher than in Abshar. Reasons for this is a high area under rice in Nekouabad, better soils and better water quality. The options to stop rice cultivation (F1) or to practice deficit irrigation (F3) reduce incomes in especially Nekouabad. Somewhat surprisingly is seems that the option to improve field water management practice (F2), does not increase farm income as such in comparison to current practice.

In contrast to the tradeoff between gross return and water productivity, as explained earlier, there is no best management practice that satisfies h objectives. If gross production should be maximized the allocation should be upstream systems first and the improved field water management options are preferred (S1F2).

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