Water for the Future – Linking Irrigation and Water Allocation in the Zayandeh Rud Basin, Iran

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Contents

The Iran-IWMI Collaborative Research Report ................................................................. 1
The Zayandeh Rud Basin ................................................................................................... 7
The Role of Integrated Modeling in Understanding Water Management ......................... 25
Research Results from the Zayandeh Rud Study .............................................................. 41
Water Management Options for the Future in the Zayandeh Rud Basin ......................... 117
Conclusions and Recommendations .............................................................................. 141
Literature Cited ................................................................................................................. 167
Chapter 1

The Iran-IWMI Collaborative Research Project

1.1. Background to the Iran-IWMI collaborative research project

The Zayandeh Rud is the most important river in Esfahan Province in central Iran. For many centuries, it has provided the basis for a rich and prosperous region based around the ancient city of Esfahan, the former capital of the Persian Kingdom, which remains the cultural center of modern Iran. The very meaning of the words Zayandeh Rud, “the river that renews itself”, indicates the presence of a substantial perennial river that flows out of the Zagros Mountains into the arid inland basin of central Iran.

*Figure 1.1. Location of Zayandeh Rud basin, Iran.*

During the second half of the 20th century, the age-long balance between economic growth and the water resources available to support that growth has dramatically changed. Expansion of the irrigated area through major investments in modern irrigation systems, the establishment of large-scale industries which require significant volumes of water, and
the continuing rapid growth of Esfahan with a current population over 2 million people, have all depended on the fragile water resources of the Zayandeh Rud. Despite continuing efforts to augment water supplies by reservoir construction and transbasin diversions, the basin is in water deficit, and shows all of the symptoms of a basin where water is insufficient:

- Competition for water between different sectors
- High vulnerability to small water deficits
- Irrigation systems are short of water
- Groundwater levels are declining
- Surface water and groundwater quality are deteriorating
- Water quality along the river is declining due to salinity, rural and urban sewage disposal and industrial pollution
- Little water now reaches the Gavkhouni swamp at the tail end of the river

There are serious concerns that it will be extremely difficult, if not impossible, to meet expected demands for water for Isfahan and neighboring cities over the next 25 years, and this has grave implications for economic growth in the basin, particularly for agriculture which remains the main user of water.

It is within this context that the Ministry of Jihad-e-Agriculture of the Islamic Republic of Iran approached the International Water Management Institute (IWMI) in 1996 to undertake a study of water management within the Zayandeh Rud basin. The overall intention was to use an integrated approach to water management that would enable planners and policy makers to determine suitable strategies for irrigated agriculture in the basin within the context of overall water resources availability. The project has had six primary objectives, listed in table 1.1.

Table 1.1. Objectives of the Iran-IWMI collaborative research program.

<table>
<thead>
<tr>
<th>Objective 1:</th>
<th>Specify present and future (5-, 10-, 25-year) basin level, water level and use scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective 2:</td>
<td>Identify and characterize agricultural water management zones in the major irrigated areas of the basin</td>
</tr>
<tr>
<td>Objective 3:</td>
<td>Identify and characterize pollution sources in the basin (e.g., factories, conurbations, agriculture, pollution type, intensity, importance).</td>
</tr>
<tr>
<td>Objective 4:</td>
<td>Undertake local modeling studies of crop- and soil-water relationships for the specified water management zones</td>
</tr>
<tr>
<td>Objective 5:</td>
<td>Specify present and future farm-level approaches to salt and water management</td>
</tr>
<tr>
<td>Objective 6:</td>
<td>Identify strategies, technologies and policies applicable to salt/water management problems in identified management zones in projects in the basin</td>
</tr>
</tbody>
</table>
The collaborative research project started in early 1998 and closed at the end of 2002. It has been a 5-year collaboration between the Agricultural Research and Education Organization (AREO) of the Ministry of Agriculture, the Iranian Agricultural Engineering Research Institute (IAERI), the Department of Agricultural Engineering of the Esfahan Agricultural Research Center, and IWMI.

1.2. IWMI approach to integrated water management for agriculture.

As a consequence of widening its mandate and changing its name to the International Water Management Institute, IWMI has developed an approach to integrated water management for agriculture that has several important features:

- The use of an integrated approach to basin-irrigation system-field level studies, referred to as the IWMI water-resources paradigm (Perry 1999), that looks not only at problems at different levels in a river basin but also examines the interactions between them. The scope of the study ranges from operation and management of water resources at basin level through irrigation system management to farm-level irrigated agricultural practices. In water-short basins, this approach is essential because the actions of any one water user will automatically and irrevocably affect all other water users in the basin (Seckler 1996).

- Integrated modeling and the use of modern information technology to understand the dynamics within each level, as well as the inter-relationships between them. Several different model approaches are being adopted:
  - Hydrologic modeling that assesses basin-level water availability and hydrology as affected by extractions of water for different uses;
  - Water-allocation modeling of the priorities used in the allocation of water between sectors under different water availability conditions, and allocation within sectors in response to these priorities;
  - Groundwater modeling to determine the changes in water table levels, the deterioration of groundwater quality over time, and the impacts of groundwater-based irrigation on water availability and quality;
  - Irrigation system performance assessment to determine current levels of achievement and the opportunity for improved performance;
  - Soil-water-atmosphere-plant modeling to assess water and salt balance at field level, determine the productivity of water at field level and to examine causes of yield gaps;
• Use of integrating mechanisms to understand the interactions between the different levels, and adoption of this understanding in the development and assessment of a range of scenarios for future water availability and water use;

• The application of a wide range of tested performance indicators covering crop production, productivity, incomes, and environmental impact, all applied at basin, irrigation system and field level.

• The extensive use of already existing information and remotely sensed data rather than reliance on a time-consuming and complex field data collection program. IWMI researchers have already demonstrated that basin modeling can be successfully performed using publicly available data sets (Lacroix et al. 2000) and remote sensing data (Droogers and Kite 2000b).

At the end of the project, a series of possible remedial actions have been proposed whose adoption can help provide a sustainable basis for irrigated agriculture in the Zayandeh Rud basin.

1.3. Structure of this report

This publication provides the overall results and assessments of the project. This report is divided into six chapters. After this introductory chapter, Chapter 2 provides a summary description of the physical characteristics of the Zayandeh Rud basin, water resources development and changing demand, the role of irrigated agriculture in the basin, an examination of the threats to sustainable irrigated agriculture, and possible ways to move towards a more sustainable use of water in the basin.

Chapter 3 focuses on the approach used in the collaborative research activities. Following a combination of data collection and data analysis resulting in an integrated database, much of the research focused on the role and application of models and allied techniques that enable the effects of changes in water management at one level to be assessed in the context of both higher and lower levels. The models themselves have a two-fold purpose:

➤ They enable us to better understand the physical processes occurring within the basin under a wide range of water conditions

➤ They enable us to develop and test scenarios that may develop in the future

Chapter 4 summarizes the main research findings in fourteen different studies. These studies are loosely grouped into field level, irrigation-system level and basin-level issues, allowing that in many studies there is a direct overlap between scales.

• At field scale, results are presented on modeling to assess crop yields and water productivity for a wide range of crops, soils and irrigation regimes and water quality within the basin. The results apply to any given combination of conditions a farmer may face, and indicate what strategies may be adopted at field level to
maximize one or more of a range of different performance indicators. These indicators are not restricted to crop yields; they include water productivity per cubic meter of water applied, gross and net income per hectare, salinity of soils and groundwater, and likely levels of stabilization of these indicators over time.

- Irrigation system level results include irrigation supply and demand modeling to understand how systems are currently managed, and how they respond to water shortages and change in demand, the use of remote sensing for irrigation performance, crop and land cover classification, and determination of actually irrigated area between and within irrigation seasons.

- At basin level there is a variety of research results reported. They include an assessment of water resources development since 1945, basin level hydrology, spatial and temporal variations in groundwater, use of geochemistry to determine the source of groundwater, modeling of groundwater trends over the past 10 years, understanding basin level water and salt balances, assessment of the role of water pricing to modify agricultural water consumption, and forecasting of basin level water availability and allocation up to the year 2020.

Chapter 5 focuses on scenarios for water management in the Zayandeh Rud basin. Based on the results presented in Chapter 4, a representative range of water availability classes has been identified, each representing a specific water availability scenario. These levels are based on the estimation of changes in basin-level water availability due to exogenous factors such as climatic change and land-use change, development of additional water resources in the basin, and changing demand for water due to economic growth.

For each water availability scenario, management responses are identified at basin, irrigation system and field level, the responses based on a combination of current practices and anticipated changes in policy. They include reallocation of water between irrigation systems, and adoption of different farm level crop choices and technologies.

Final conclusions and recommendations are presented in Chapter 6. They are grouped into three main types:

- Technical conclusions and recommendations at field, irrigation system and basin levels

- Policy conclusions and recommendations that include changing water allocation priorities, establishing a central database on water resources and their management, institutional changes that lead towards establishing a strong basin level water management authority, improved regulation, and training requirements

- Areas for further research where we feel there is insufficient information to make a definitive recommendation. These include such aspects as water pricing, crop pricing, water rights and water trading, and the prospects for a more agro-industrial orientation to agricultural water use in the basin
Chapter 2

The Zayandeh Rud Basin

The Zayandeh Rud, which has been the lifeblood of Central Iran for centuries, is focused around the ancient city of Esfahan. In 1600 AD Esfahan was one of the ten largest cities in the world, sustained by irrigated agriculture using the waters of the Zayandeh Rud. The city was the capital of the ancient Persian kingdoms and remains the cultural heart of Iran. In this chapter we provide an overview of the basin that helps put more detailed information into perspective. For more detailed information, the interested reader can refer to Mousavi and Karamooz (1995) where there are several papers dealing with conditions in the Zayandeh Rud basin.

2.1. Physical Characteristics

2.1.1. Topography and geomorphology

Central Iran is a typical arid and semi-arid desert. Rugged mountains of limestone and siltstone, devoid of vegetation, rise sharply from their surrounding alluvial fans built up by seasonal torrents. The majority of the area has thin soils overlying the stony alluvial fans, providing little basis for economic enterprise other than rough grazing on the xerophytic vegetation.

In a few places, natural springs and traditional “qanat” systems—tunnels dug horizontally into alluvial fans to tap groundwater close to the mountain edge—provide modest water supplies to irrigate fruit and vegetable gardens that support small communities tucked into mountain valleys or along the fringes of the mountains.

Cutting across this monotonous landscape is the fertile valley of the Zayandeh Rud (figure 2.1.). The river rises in the bleak and craggy Zagros Mountains that reach over 4,500 m, traverses the foothills in a narrow and steep valley, and then bursts forth onto the plains at an altitude of some 1,800 m. However, the splendor of the river is short-lived. Reduced towards the east by natural seepage losses, evaporation and more recent extractions for irrigation, urban and domestic uses, the river eventually dies out in the Gavkhouni swamp, a vast playa of white salt that forms the bottom end of the basin, lying at an altitude of over 1,466 m. Naturally a closed basin, the flows reaching the playa are now much reduced discharges compared to natural conditions, and there are extended periods when no water flows in the tail reach of the river.

The total length of the river is some 350 km, but it is the central 150 km of the floodplain to the east and west of Esfahan that provides the basis for intensive agriculture and large settlements. Along this strip, soils are deep and fertile—predominately silts and clay loams—and slopes are gentle, ideal for the culture of irrigated agriculture built up over many centuries. The river indeed forms an oasis in the desert.
2.1.2. Climate

The basin has a predominantly arid or semi-arid desert climate. Rainfall in Esfahan, which is situated at an elevation of 1,500 m, averages only 120 mm per year, most of the rainfall occurring in the winter months from November to April (figure 2.2.). During the summer there is no effective 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 1,400 mm, and it is almost impossible to have any economic form of agriculture without reliable irrigation.

The climatic conditions in the mountains are markedly different, as shown by data from Kuhrang, which lies just to the west of the Zayandeh Rud catchment (figure 2.2.). Situated at an elevation of almost 2,300 m, precipitation averages 1,500 mm—much of it in the form of snow—which remains on the ground throughout the winter, only melting when temperatures warm up from April onwards. Winter temperatures are normally below freezing for weeks at a time, although summers are pleasant with average maximum temperatures of 22°C in July (figure 2.3.).
Figure 2.2. Average monthly rainfall: Esfahan and Kuhrang, 1988-1999.

Figure 2.3. Mean monthly temperature at Esfahan and Kuhrang.
2.1.3. Hydrology

The primary source of water in the basin is the upper catchment of the Zayandeh Rud. Other streams are mostly non-perennial, have little regional importance and do not reach into the main part of the basin except during winter months and following rare flash floods.

The natural hydrologic regime of the upper parts of the river reflects the climatic conditions of the Zagros Mountains. Data from the Chadegan Reservoir, constructed just above the point where the Zayandeh Rud enters the flatter parts of the basin, show a marked seasonal pattern. From September until February, inflows average between 50 and 75 x 10^6 m³ month⁻¹ (20-30 m³ sec⁻¹) reflecting both the dry conditions of summer and then the cold conditions dominated by accumulation of snow in the upper parts of the basin (figure 2.4.). Only in December is there a slight increase in discharge, caused by early winter rains that occur before temperatures settle down below freezing.

Figure 2.4. Average monthly inflows and releases from Chadegan reservoir, 1988-1998.

From March onwards snowmelt increases and discharges normally peak in April or May, with average flows of 125-150 m³ sec⁻¹. In June and July the discharge slowly declines to the low flow conditions. The peak flows from April to June provided the basis for widespread downstream irrigation using simple diversion structures to make productive use of floodwaters with one crop per year until more modern development of water resources started in 1952.
2.2. Water Resources Developments in the Zayandeh Rud Basin

In 1954, the first of a sequence of major water resources developments was commissioned. A transbasin diversion tunnel from the Kuhrang River immediately to the west of the Zayandeh Rud watershed was completed, bringing an estimated 300 million cubic meters (MCM) per year into the basin. Although this tunnel enhanced natural flows from the Zayandeh Rud watershed, it did not significantly change the hydrology of the river because the Kuhrang River has an almost identical hydrological regime to the Zayandeh Rud. The primary cropping pattern did not change much as a result of augmentation, being dominated by winter wheat and barley, and orchards in more favored locations.

The completion in 1970 of the approximately 1,400 MCM capacity Chadegan reservoir allowed these natural flows to be regulated to promote more effective irrigation. Excess flows in March, April and May are stored and released gradually throughout the remainder of the year. This means that longer season crops can be irrigated successfully, double cropping is possible in many areas, and that orchards and other perennial crops can be grown with little risk of drought-induced stress.

The third major development was the opening of a second transbasin tunnel from the Kuhrang River in 1985. Somewhat smaller than the original, the designed water transfer to Zayandeh Rud transfer is 250 MCM. These flows reach a maximum during the spring and can therefore assist in augmenting storage in the Chadegan reservoir.

A final phase of water resources development is currently underway. By 2010, an additional 280 MCM will be made available through the third Kuhrang tunnel, and an additional 150 MCM will be developed from a series of local springs throughout the karstic portions of the basin.

There is no significant year-to-year carryover storage in the Chadegan Reservoir because almost all of the floodwater entering the reservoir is released prior to the next flood season (figure 2.5). Although this maximizes yearly production from irrigated agriculture, it also makes the basin susceptible to prolonged precipitation deficits. Average annual releases in the 11-year period from 1988 to 1998 were about 1,750 MCM, which included the contributions from the two Kuhrang tunnels as well as the natural flows from the upper catchment of the Zayandeh Rud.

When the flood control issues in April, May and June are not taken into account, the "normal" annual release volume is about 1,500 MCM, roughly 900 MCM from the Zayandeh Rud catchment and 600 MCM from Kuhrang. During the same period, the average inflow was 1,710 MCM per year with the lowest recorded annual inflow being 1,134 MCM (in 1991). If two such years of low inflow occurred in succession, the reservoir would be unable to meet normal release requirements. It was precisely this sequence of dry years that led to the severe water shortages of 2000 and 2001 when no water was released for surface irrigation in either year.

The progressive reduction in river flows downstream of the Chadegan Reservoir is shown in figure 2.6. For most part of the year, discharges at the Nekouabad regulator are roughly half those released from the reservoir. At Chom Bridge, just downstream of Esfahan, discharges have been halved again, and at Varzaneh, just upstream of the outflow into Gavkhouni Swamp, the discharge is only a few percent of the original releases. Needless to

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1 1,460 MCM capacity at elevation of 2,063 amsl and 120 MCM at elevation of 2,059 amsl.
say, the quality of water by the time it reaches Varzaneh is very poor indeed, being subject not only to agricultural return flows containing large volumes of salt, but also the chemical and biological pollutants coming from rural, urban and industrial sources.

Figure 2.5. Time series of storage and releases, Chadegan Reservoir, Oct 1987-Sept 1998.

Figure 2.6. Average monthly flow volumes along the Zayandeh Rud, 1988-1998.
2.3. Irrigated agriculture in the Zayandeh Rud basin

The pattern of reliable floodwaters emerging from the mountains onto flat, alluvial plains during the warm spring months creates an ideal environment for irrigated agriculture. It is little wonder that irrigation has for centuries provided the basis for productive and, at least until recently, sustainable irrigated agriculture. In all respects, Esfahan was one of the classic oases of the world, and still today the city is full of parks, gardens and orchards that provide relief from the intense heat of mid-summer, all irrigated by diversions from the Zayandeh Rud.

2.3.1. Traditional irrigation

The original irrigation developments relied on three different technologies: diversions, lifting and tunneling. The waters of the Zayandeh Rud were diverted through stone and wood weirs into a complex series of canals ("madies") that roughly paralleled the course of the river.

For several centuries, there were well-established and complex rules for the diversion of water from the Zayandeh Rud. Scrolls dating from 1544 in the reign of Sheikh Bahai, spell out water rights for different parts of the river: 10 shares for Lenjan and Alenjan (Lenjanat and Nekouabad), 10 shares for Marbin and Gey (around Esfahan), 7 shares for Baraan and Kerag (Abshar), and 6 shares for Rudasht. Almost all of these areas, irrigating several tens of thousands of hectares, remained more or less unchanged until the advent of the modern irrigation era in 1970.

In the alluvial flood plains close to the river, water could be lifted using animal-driven Persian wells that lift water through buckets into small farms.

Away from the main river, qanat development in alluvial fans could support small isolated irrigation systems that were sufficient to support a few families and supplement the income produced from the grazing of goats and camels. Larger springs could support villages and small towns. Typically, crops were grains, fruit trees and nut trees.

Few of these traditional technologies remain. Modern irrigation, either in the form of large-scale gravity irrigation systems fed by large regulating weirs or electric or diesel-powered tubewells, now accounts for almost all irrigation. Traditional canals have been absorbed into the large-scale systems, while many qanats have either fallen into disrepair or have been dried up by adjacent drilling of deep boreholes. Only along the bottom of the narrow valley between Chadegan and Lenjanat are older diversion systems still found, with a continuous strip of traditionally irrigated land along the Zayandeh Rud with fruit trees, nut trees, rice, wheat and barley. These systems are entirely under control of local communities and may total as much as 40,000 ha.

2.3.2. Modern Irrigation

Modern surface irrigation started with the construction in 1970 of major diversion weirs at Nekouabad and Abshar, each diversion weir controlling both a Left Bank and Right Bank Main Canal (figure 2.7.). These weirs were designed and built by the same companies involved in the construction of the reservoir, thereby creating a coordinated approach to water control and management in the basin. These four systems have provided the bulk of irrigated agriculture for the past 30 years.
However, one large-scale traditional gravity system still survives, at Rudasht, the most
downstream of the irrigation diversions. Even this is in its last years of operation as a new
diversion weir has already been constructed and will replace the traditional weir as soon as
new irrigation canals are completed (table 2.1.).

All of the gravity irrigation systems are based on modern design concepts brought to
Esfahan by French engineers. The main canals have been designed for automatic upstream
control, so that canal water levels are maintained at a constant level irrespective of actual
demand. NEYRIPC modules, allowing for a high level of accuracy in discharges, control
secondary canals. Larger tertiary canals have similar modules. Only small secondaries and
tertaries rely on simpler vertical sliding gates.

The irrigation season commences on 1 April in all years, and reservoir releases remain
more or less constant in May, June, July and August. It is only in the latter part of the irrigation
season that discharges are reduced as demand drops (table 2.2.).

As a result of the conveyance limits, many farmers rely on tubewells to supplement
surface irrigation flows. In large measure these boreholes are relatively shallow, although
deeper boreholes are found in the Nekouabad area.

Typically, there is a two-season cropping pattern in all of the irrigation systems in the
Zayandeh Rud basin. Summer crops include potatoes, rice, onion, and vegetables while winter
crops are dominated by wheat, barley and vegetables. In addition, there are some annual
and perennial crops, including alfalfa and orchards.
Table 2.1. Basic information on irrigation systems in Zayandeh Rud basin.

<table>
<thead>
<tr>
<th>Name of System</th>
<th>Date of Construction</th>
<th>Command Area (ha)</th>
<th>Design Discharge (m³/sec)</th>
<th>Length of Main Canal (km)</th>
<th>Length of Secondary Canals (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Old Systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nekouabak Right Bank</td>
<td>1970</td>
<td>13,183</td>
<td>13</td>
<td>35.30</td>
<td>45.0</td>
</tr>
<tr>
<td>Nekouabak Left Bank</td>
<td>1970</td>
<td>26,872</td>
<td>45</td>
<td>59.35</td>
<td>76.6</td>
</tr>
<tr>
<td>Abshar Right Bank</td>
<td>1970</td>
<td>12,570</td>
<td>15</td>
<td>33.50</td>
<td>38.0</td>
</tr>
<tr>
<td>Abshar Left Bank</td>
<td>1970</td>
<td>23,000</td>
<td>15</td>
<td>36.00</td>
<td>33.0</td>
</tr>
<tr>
<td>b) New Systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borkhar</td>
<td>1997</td>
<td>18,500</td>
<td></td>
<td>29.00</td>
<td>Not finished</td>
</tr>
<tr>
<td>Rudasht Left &amp; Right</td>
<td>(a)</td>
<td>47,000</td>
<td></td>
<td>209.20</td>
<td>Not finished</td>
</tr>
<tr>
<td>Mahyar</td>
<td>In progress</td>
<td>24,000</td>
<td></td>
<td>120.00</td>
<td>Not finished</td>
</tr>
<tr>
<td>c) Traditional Systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: (a) Rudasht is an ancient system being replaced with a new system
All new systems have conjunctive use of surface water and groundwater

Table 2.2. Average monthly releases for irrigation and water supply from Chadegan reservoir, 1988-1998.

<table>
<thead>
<tr>
<th>Month</th>
<th>Average</th>
<th>Std. Dev.</th>
<th>Coef. Variation</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>150.95</td>
<td>40.0</td>
<td>0.26</td>
<td>210.8</td>
<td>99.5</td>
</tr>
<tr>
<td>November</td>
<td>134.84</td>
<td>48.9</td>
<td>0.36</td>
<td>213.1</td>
<td>85.5</td>
</tr>
<tr>
<td>December</td>
<td>109.77</td>
<td>53.9</td>
<td>0.49</td>
<td>206.8</td>
<td>50.8</td>
</tr>
<tr>
<td>January</td>
<td>33.22</td>
<td>16.1</td>
<td>0.49</td>
<td>66.7</td>
<td>14.7</td>
</tr>
<tr>
<td>February</td>
<td>22.45</td>
<td>13.7</td>
<td>0.61</td>
<td>62.0</td>
<td>12.8</td>
</tr>
<tr>
<td>March</td>
<td>53.20</td>
<td>37.7</td>
<td>0.71</td>
<td>144.6</td>
<td>20.4</td>
</tr>
<tr>
<td>April</td>
<td>154.42</td>
<td>57.9</td>
<td>0.37</td>
<td>281.0</td>
<td>83.9</td>
</tr>
<tr>
<td>May</td>
<td>248.13</td>
<td>94.0</td>
<td>0.38</td>
<td>451.5</td>
<td>187.3</td>
</tr>
<tr>
<td>June</td>
<td>234.27</td>
<td>33.8</td>
<td>0.14</td>
<td>316.6</td>
<td>199.0</td>
</tr>
<tr>
<td>July</td>
<td>211.10</td>
<td>31.3</td>
<td>0.15</td>
<td>291.7</td>
<td>175.6</td>
</tr>
<tr>
<td>August</td>
<td>207.45</td>
<td>27.0</td>
<td>0.13</td>
<td>268.7</td>
<td>174.5</td>
</tr>
<tr>
<td>September</td>
<td>190.83</td>
<td>34.7</td>
<td>0.18</td>
<td>283.5</td>
<td>154.8</td>
</tr>
<tr>
<td>Annual</td>
<td>1,747.63</td>
<td>335.9</td>
<td>0.19</td>
<td>2,483.8</td>
<td>1,440.7</td>
</tr>
</tbody>
</table>

Source: Ministry of Energy, Isfahan Province
The two upstream modern systems at Nekouabad, have no significant waterlogging or salinity problems and apart from a few locations where gypsum deposits create difficulties, there are few constraints to productive agriculture. Annual cropping intensity is about 170 percent, with slightly more land cultivated in winter than summer. The main crops in summer are rice, potatoes and vegetables while in the winter, barley and wheat dominate. There are substantial areas of perennial orchards.

In Abshar—the middle reach of the modern irrigated areas—cropping intensities are lower, just over 100 percent, with only 32 percent of the area cultivated in summer. Constraints to good agricultural production are problems of drainage towards the tail-end reaches near the Zayandeh Rud, and there are some saline and gypsiferous soils. Rice is not grown extensively and there are no orchards. Summer crops are mostly corn and vegetables, while winter is dominated by wheat. Annual crops are mostly sugarbeet and alfalfa. Groundwater quality appears to be declining, and there is significant lowering of the groundwater table away from the Zayandeh Rud.

In Rudasht, there is moderate to severe salinity and water tables are close to the surface. Cropping intensities are lower than Abshar, falling to 95 percent for the year and 28 percent in summer. This is in an area where significant volumes of groundwater are pumped but the water is low quality. Typically, crops are wheat and barley in winter, some cotton and maize in the summer and the annual sugarbeet and alfalfa.

The impact of the development of the four major irrigation networks at the same time as the construction of Chadegan Reservoir can be seen in figure 2.8., which compares gross irrigated area in 1965 and 2000, as well as the shift in crop types. Before new irrigation networks were constructed, cropping was dominated by wheat (62 percent) and barley (9 percent). No other crop exceeded 10 percent of the total irrigated area. These cropping patterns are typical of current practices still found in the lower parts of Abshar and throughout Rudasht. By 2000, the pattern had changed significantly in Nekouabad and upper parts of Abshar, so that now their basin cropping pattern is as follows: wheat has dropped to 43 percent of the cropped area (although total hectares under wheat had increased from 25,000 to 68,000 ha) while fodder (12 percent), vegetables (11 percent) and rice (10 percent) have greatly increased. Other crops did not change significantly in percentage terms.

These cropping pattern changes reflect precisely what would have been expected when more water was made available for irrigation and when more water could be delivered in the hotter summer months. Spring floods ideal for grain crops could be stored and delivered for fodder, rice and vegetables, all of which command much higher market prices.

The provision of more water with timing better suited to the needs of higher value crops has clearly been highly beneficial and productive at basin level and for the upper portions of the irrigation systems. But it has had severe effects on the groundwater problems in the tail part of the system, and this has led to greatly increased inequity in production and incomes between head- and tail-end parts of the basin. Head-end farmers are perceived—perhaps incorrectly—as profligate water users, at the expense of tail-end areas.
2.3.3. Recent Irrigation Developments

In the past few years, there has been a large increase in the gravity irrigation network. Two large systems have been constructed at Mahyar and Borkhar, while the Rudasht network has been modernized and a new weir constructed. The Mahyar system takes off directly from the Zayandeh Rud above Nekouabad, while the Borkhar system is essentially an extension of the Nekouabad Left Bank irrigation system.

The Mahyar and Borkhar systems provide surface water to areas where there has been substantial groundwater irrigation for several years. In both areas, the water table has been dropping, and in Mahyar it is of particularly poor quality. The design intention is that the surface supplies would be delivered when the annual water availability at Chadegan reservoir is at or above normal levels, so that in these less water scarce times farmers can use surface water and thereby protect their groundwater resources.

Whether this happens or not remains to be seen. Farmers will clearly value good quality fresh water supplies more than their lower quality groundwater, and may try to augment groundwater supplies rather than switch backwards and forwards from groundwater to surface water depending on canal availability.

The risk in these areas is that if additional areas under irrigation are established because of additional fresh water supplies, it might result in a greater extraction of groundwater in
dry years to compensate for the lack of surface water supplies. At present, cropping patterns
in both areas tend to be rather low water consuming crops: grapes, sunflower, wheat, melons
and millet. But it is possible that fresh water will encourage a switch to high-value crops,
which have higher water consumption such as rice and alfalfa.

A second type of irrigation development has been expanding very recently in the reach
of the Zayandeh Rud between the Chadegan Reservoir and Lenjanat. Traditionally, irrigation
was restricted to gravity in these areas because of the deep valley in which the river runs.
However, modern technology has allowed the development of larger areas of fruit and nut
trees to be established by installing large diesel pumps along the river, and pumping up the
hillsides into terraces provided with drip irrigation. Initially, the pumping was perhaps 20-
30 m up from the river, but now huge pumps are installed that pump water right up from
the valley to the plains on either side. The current area may be in the order of 10,000 ha and
is rapidly expanding. No doubt this type of irrigation development is and will be profitable
because fuel is cheap and the crops grown are high value. However, the impact on downstream
water users cannot be discounted.

It seems somewhat contradictory that while large scale irrigation systems established
30 years ago — let alone the traditional systems that go back hundreds of years — are struggling
to get sufficient water, new irrigation developments continue apace in the basin.

2.4. Threats to sustainable agriculture

If agriculture were the only significant water user in the basin it would be comparatively
easy to develop a systematic and implementable plan of development, allocation and
management that would lead to sustainable agriculture. But the basin water resources serve
several functions, and it is no longer possible to plan individual water development projects
without looking at overall water utilization in the basin.

The primary threats to sustainable irrigated agriculture are: (a) reductions in water for
agriculture because of competition from other sectors, (b) declining water quality in both
groundwater and surface water resources, and (c) soil salinization.

2.4.1. Competition for water between different sectors

Agriculture remains the largest single user of water in Iran (93 percent) and in the Zayandeh
Rud, despite increased demands from other water uses. The data on extractions show that in a
normal year as much as 90 percent of water released from Chadegan reservoir is diverted into
irrigation systems (Zahabsanei 2000). It is estimated that some 20 percent of diverted water
returns to the river downstream of the irrigation networks, albeit of increasingly poorer quality.

Two main competitors for water are present in the basin: domestic water supply, and
industrial water supply.

*Domestic Water Demand*

The Zayandeh Rud has seen dramatic population increase in the past 45 years. In the 1956
census, there were some 420,000 people in the basin, while in 2000, it is estimated that the
total population was 2,380,000. This is an annual growth rate of 5.9 percent. Figure 2.9 shows population growth in the basin and Esfahan since 1956, projected to 2020 with a 2 percent annual growth rate from 1996 onwards.

Growth has not been uniform. The fastest growth was between 1956 and 1986, averaging close to 7 percent a year, but in the past 15 years the growth rate has slowed to between 2-2.5 percent a year. Initially, the population of Esfahan City grew faster than the rest of the basin, but now this is no longer true: Esfahan growth rates are close to 2 percent, while outside the city they have risen to 2.5-3 percent a year.

Efforts by the government to try to limit urban growth appear to have been reasonably successful, but even with modest growth rates of 2 percent, the urban population will reach as much as 3.6 million by 2020.

\[\text{Figure 2.9. Population Growth Rates in Zayandeh Rud Basin, 1956-2020.}\]

Some urban communities do not have sophisticated water supply systems, and the government is trying to improve this situation as well as maintain supplies to the larger urban centers. Current allocations to the domestic sector are estimated at just over 200 MCM per year. Expansion of existing well fields for Esfahan and provision of supplies for other cities will total 340 MCM by 2020, although there is a return flow to the river through wastewater. This is estimated at 50 percent of total supply, rather lower than in cooler climates.

\[\text{Industrial water demand}\]

The Zayandeh Rud basin was the focus of specific government policies in the 1970s to increase industrial production outside of Tehran. Esfahan was seen as a prime location, particularly
as the Chadegan Reservoir had just been completed and it was assumed water supplies would be readily available. Between 1975 and 1977, four major industries were developed, (defense industries, Mobarakhe Steel Mill, Esfahan oil refinery and Sepahan cement factory), with a total annual demand of 60 MCM. A polyacrylic factory was added in 1980 with a demand of an additional 5 MCM. The war with Iraq halted industrial development, but from 1988 to 1991, four more industrial enterprises were established with a total demand of 39 MCM. Total industrial demand, (at least for major industries), is therefore at least 104 MCM. The growth of industrial demand for water is shown in figure 2.10.

Not included in these figures are water requirements for a host of smaller industrial concerns. Some use boreholes, others may use urban water supply. There are few accurate data available, but these small units when added together represent a major consumer, which will not forgo water in a drought period.

Figure 2.10. Cumulative demands for industrial water consumption, 1975-1991.

The drought of 2001 highlighted competing sectoral allocation priorities. Urban and industrial supplies were not affected as the 500 MCM released from Chadegan met their requirements and left a modest amount of less than 100 MCM for agriculture.

On this basis, we can be sure that in the future, if basin level water supplies are in deficit, either due to drought or merely because demand has increased even further, there will be less and less water for agriculture because it takes a lower priority compared with urban and industrial requirements.
2.4.2. Declining groundwater resources and deteriorating water quality

A typical measure of stress in a basin is the rapid increase in the exploitation of groundwater and deterioration of water quality. Water users turn to as many different water sources as possible to compensate for deficit supplies through their regular source, and less and less water is left in the river to act as a dilution mechanism to deal with pollutants. The Zayandehe Rud basin is no exception to this pattern.

Increased pressure on groundwater resources

In Iran, the relatively low price of diesel fuel, (approximately $0.01 per liter in 2002), means that the cost of pumping is not a major factor in input costs for farmers. Once the capital investment has been covered, pumped water is not expensive.

Following the construction of the Chagian Reservoir, it appears that water table levels rose in many areas, particularly in tail–end areas around Rudasht. However, data over the past 5-7 years indicate that groundwater levels are dropping in all parts of the irrigated areas of the basin, and in some areas they are dropping dramatically. In Najafabad, just west of Esfahan, fruit trees planted 10-15 years ago based on groundwater irrigation are dying due to rapidly declining groundwater. It has also led to older wells drying up. Installation of larger, deeper wells for urban and industrial water supplies, has significantly lowered the regional groundwater levels.

Within the irrigation systems, the decline has been more or less constant in the past 6 years. In Nekouabad Left Bank the average decline has been 2.5 m yr\(^{-1}\), and in Nekouabad Right Bank by 1.5 m yr\(^{-1}\), almost certainly exacerbated by domestic and industrial well installation. In Abshar it has declined by some 0.4-0.6 m yr\(^{-1}\), in Borkhar by 0.8 m yr\(^{-1}\), and even in Rudasht, where water quality is poor, groundwater tables have dropped by 0.25 m yr\(^{-1}\). This suggests that somewhere in the order of 250-600 mm yr\(^{-1}\) is being pumped for agriculture and is not being recharged.

While the drought of 1999-2001 certainly put additional pressure on groundwater resources, there is sufficient evidence of a more long-term depletion that is consistent with the view that canal supplies are less than potential demand, relatively cheap pumping costs favoring private or public groundwater exploitation, and an increased demand for crops such as rice, fodder and vegetables that currently command high market prices.

Deteriorating water quality along the Zayandehe Rud

As the river flows downstream, an increasing proportion is being used for irrigation. The solute content of the irrigation return flow into the aquifers and river, combined with urban and industrial effluents, is much higher than that of the water flowing in the river. The mixing leads to progressively increasing levels of salinity (EC) and total dissolved solids (TDS) along the Zayandehe Rud.

Figure 2.11. illustrates this increase in EC values for a 1996 data set, a typical year before the drought. At the regulating dam, EC values are in the order of 0.3 dS m\(^{-1}\). Significant increase occurs as the water passes through Esfahan, 180 km downstream, with values going up to 2.5 dS m\(^{-1}\). As the river receives return flow from the Abshar irrigation scheme at the 230 km mark, the values further climb to 4 dS m\(^{-1}\). With the inflow of water from the main northern
drain after Ejiyeh at 240 km, the EC reaches a maximum of 16 dS m⁻¹, after which the EC slowly goes down to 12 dS m⁻¹ because of mixing with less saline return flows. Finally, after 280 km, the remaining river water spills into the Gavkhouni Swamp. For the last 30 km, the water is too saline for most agricultural use, and the river can be considered merely a drain.

The pattern is similar for non-agricultural pollution. The increase in concentration of the major cations and anions follows the same trend of increasing downstream, with the exception of HCO₃⁻, which remains at a constant concentration of about 4 meq l⁻¹. The concentration of heavy metals (Pb, Ni, Cd) increases tenfold as the river passes through Esfahan to levels of 0.1 mg l⁻¹ for Pb, 0.07 mg l⁻¹ for Ni and 0.02 mg l⁻¹ for Cd. The results of a 7-year study (from 1988 to 1994) of N, P, pH and EC fluctuations in the Zayandeh Rud river have also been presented by Kalbasi and Mousavi (1995).

Data for dissolved oxygen (DO), chemical oxygen demand (COD) and biological oxygen demand (BOD) were available from a set of 24 shallow wells near the Zayandeh Rud, sampled in 1996. The values of these parameters are also rising as the river passes through Esfahan, but they also point to pollution at Zarinsahr, derived largely from the Moharakeh Steel Mill (figure 2.12.).

Exactly what values of in-flow discharges are required to dilute these contaminants to acceptable levels is not known. An overall estimate of 70 MCM for annual discharges to Gavkhouni swamp are cited, but a more detailed breakdown into monthly requirements is not available. What is certain is that as long as discharges below Pol-e-Chom are negligible, the concentration of pollutants will be in excess of standards, and will pose serious health threats to downstream populations.

Figure 2.11. EC values along the Zayandeh Rud.
2.4.3. Land and Water Degradation

It is estimated that about 23.5 million hectares (or 14.2 percent of the total area of the country) are salt-affected, which is equivalent to about 50 percent of Iran’s irrigated potential (Pazira 1999). Salinization therefore poses a serious threat to the sustainability of irrigated agriculture in Iran.

Salinity levels of water used for irrigation in Zayandeh Rud vary substantially from values of less than 1 dS m⁻¹ upstream up to around 6 dS m⁻¹ at the downstream located Rudasht irrigation scheme. As salts will not leave the system by evaporation, salt accumulation will occur if no surplus water is applied to leach the salts to the groundwater.

Due to this salt accumulation in soils, soil salinity levels can be higher than the irrigation water salinity levels. A dramatic example of this can be seen in the Rudasht area where the soil salinity is reported to be about 14 dS m⁻¹, while irrigation water salinity levels are about 6 dS m⁻¹. Both are increasing.

Obviously, these high soil salinity levels have a severe negative impact on crop yields, as evidenced by the big gap between actual and potential yields obtained from some field experiments in the Rudasht irrigation system as shown in figure 2.13. This gap will widen if salinity levels increase and, with relatively high water tables, it is hard for farmers to apply additional water for leaching even if it were available.
Two hazards are likely to occur if no proper water management is practiced, with little or no leaching applied to reduce soil salinization. First of all, irrigation applications are too low, causing a salt accumulation in the soil. In an attempt to reduce this salt accumulation, a surplus of irrigation water will be supplied to leach these salts from the root zone. This leads in many cases to a second problem—water logging due to rising groundwater.

Often, this groundwater is also very saline and will increase the salinity level of the root zone substantially. So, irrigation applications must be high enough to minimize salt accumulation in the root zone and low enough to limit the hazard of water logging. Obviously, problems related to water logging can also be diminished by an adequate drainage system.

Several measures have been adopted over the past couple of decades to help alleviate these problems, including installation of drains and augmenting water supplies through transbasin diversions. However, these structural measures require proper management for them to be effective; merely adding more water and adding more drains will not automatically overcome the threats to sustainable agriculture. Should drains fail, for example, there will be increased threats to agriculture as watertables will rise and salinity will increase.

The hydrochemical analysis of groundwater from borcholes along the Zayandeh Rud River reveals the same pattern, which is not surprising as the aquifers are recharged both by the river water and return flow and leakage from the irrigation schemes. A detailed hydrochemical study of a small sub-catchment (Lenjanat), along the Zayandeh Rud upstream of Esfahan over a 10-year period, has shown that the groundwater composition is subject to long-term trends (Gieske et al. 2000). In some parts of the aquifer, salts are slowly being flushed out, whereas in other parts, concentrations are rising. It appears that the groundwater composition is slowly changing in response to expanding or variable cultivation practices.

Faced with these threats to irrigated agriculture, it is essential that water at basin, irrigation system and field levels, is managed so that agricultural productivity can be stabilized within the context of wider basin level water availability. It is precisely this objective that forms the basis for the project. The next chapter discusses the approach adopted to meet this overall objective.

Figure 2.13. Yield gap for selected crops, Rudasht irrigation system.
Chapter 3

The Role of Integrated Modeling in Understanding Water Management

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 quality 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 (Droogers et al. 2000c):

a) Understanding current conditions and processes so that we feel confident in knowing how different water uses interact under present management practices

b) Developing future scenarios that address alternative uses and allocations of water and seeing how they affect water conditions at different scales

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. 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.

3.1. Concepts of Integrated Modeling

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.

3.1.1. Nested systems

Nested systems are characterized by a set of inputs and outputs that form the linkages between the systems (Small and Svendsen 1990). 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 exported 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.

Figure 3.1. Nested systems, inflows and outflows.

Figure 3.1. shows how the level of analysis affects the understanding of losses and water availability. At the farm level, the analysis considers inputs such as canal water (C) and tubewell water (T) and treats outflows such as surface runoff (R) or deep percolation (P) as losses. 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 (Molden 1997). This water cannot be reused and is a true loss to 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, it will affect the inflows into the irrigation sub-systems within the basin, and therefore both the return flows to the system and the inflows into the field level sub-systems.

*Scaling Up and Scaling Down, with reference to Water Savings*

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 the 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.

A particular area of interest for water management that needs careful analysis through scaling up is the effect of introduction of technologies that claim to save water. The assumption is that if the adoption of a new technology (e.g., pressurized irrigation, land leveling or raised beds) means that farmers can use less water per hectare, then this leads to water savings. This is quite often an incorrect assertion.

It is true that the adoption of these technologies uses less water per hectare, leading to an increase in water productivity on those fields. But to determine whether water was saved or not, we have to examine what happened to the water that was not used. If it is used by the same farmer on another piece of the same farm, then there is no net change in water use by that farmer—water productivity increases, but there is no overall water saving.

Table 3.1. indicates a number of different potential outcomes from the adoption of water conserving technologies at farm level. If water is used within the same domain (response 1), then there cannot be any overall water saving because the inflow and outflow from the farm domain are the same. However, water productivity increases because the same volume of water is used for a wider area. Response 2 is identical, except increased production is on another farm. Response 3 results in storing water as groundwater for use at a later time. It is likely

<table>
<thead>
<tr>
<th>Management Response to Adoption of Water Conserving Technologies</th>
<th>Impact on Water Productivity</th>
<th>Impact on Water Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Water used elsewhere on the same farm</td>
<td>Increased</td>
<td>No water saved</td>
</tr>
<tr>
<td>2. Water given/sold to neighbor</td>
<td>Increased</td>
<td>No water saved</td>
</tr>
<tr>
<td>3. Less water pumped from groundwater</td>
<td>Increased</td>
<td>Water stored</td>
</tr>
<tr>
<td>4. Secondary canal flow reduced</td>
<td>Potential increase</td>
<td>Water diverted</td>
</tr>
<tr>
<td>5. Main canal flow reduced</td>
<td>Potential increase</td>
<td>Water diverted</td>
</tr>
<tr>
<td>6. Reservoir flows reduced</td>
<td>Potential increase</td>
<td>Water saved</td>
</tr>
</tbody>
</table>

27
that there is no overall saving in terms of water use, but the timing of use is deferred. Responses 4, 5 and 6 require action further upstream, at the level of the irrigation system domain. Whether water productivity and savings occur depend on what happens to the water diverted to another location. If it merely goes to a sink or to the sea, then there is no increase in water productivity and no water is saved. But if it can be captured and reused to grow crops in another location, then there is no net water saving but an increase in water. If water can be stored in the reservoir, i.e., a response at the basin level, then indeed we can see real water savings.

A similar argument holds true at the irrigation system level. Conventional wisdom holds that irrigation systems are generally inefficient, resulting in large amounts of wasted water. The argument goes further: if only irrigation efficiency can be improved then a large amount of water that was wasted can now be saved. But this argument fails to account for the importance of scaling up.

At the level of a single irrigation system, it is true that in many cases a lot of water delivered into the system is not used productively (indeed, that is the concept of efficiency as applied to irrigation). However, in limiting the domain of analysis to the boundaries of the irrigation system, the water that flows out of the system is assumed to be a loss. In reality, these “losses” are frequently used productively, and particularly in water-short basins.

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 this 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.

This is shown diagrammatically in figure 3.2. In the classical view, each system is treated independently, receives 100 units of water and uses 50 units for crop production. The other 50 units are considered lost and system level efficiency is assumed to be 50 percent. However, if surface drainage can be reused and half of the assumed losses are recaptured, then 50 units of water are available for use downstream in the next irrigation system. The total efficiency of the three systems rises to 60 percent. If there is also groundwater flows from one system to the next, then 100 units are available for downstream use and the efficiency of the three systems rises to 75 percent without any actual change in management practice at field level.

It is on this basis that in the Gediz basin study in Turkey, irrigation efficiencies were less than 50 percent for 11 systems, but the total water use in the basin was over 95 percent of available supply simply because of reuse of surface drainage water and pumping of groundwater that had been recharged by seepage from irrigation systems (GDRS and IWMF 2000).

Spatial and Temporal Interactions between different water users

Different water users within a basin are affected not only by the flow of water as inputs and outputs of the different sub-systems but also by the spatial and temporal relationships between the users.
Spatial relationships are important in terms of both 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

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29
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. Groundwater is of particular importance in this respect: aquifers act as reservoirs that capture seepage and percolation from rivers and irrigated areas. Although the supplies may not be immediately useful, they can be tapped at a later stage when other supplies may no longer be available. 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 the Chadegan Reservoir. During the summer irrigation season, the aquifers are depleted but recharge after the harvest of summer crops is used for winter irrigation.

3.2. Using tools and models for multi-scale scenario analysis

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

Diagrammatically, the process is shown in figure 3.3., although it must be recognized that there is a lot of overlap during the first three stages. However, stage 4 cannot be completed until the first three stages have been completed for all different levels of analysis in the basin, because it requires all of this information to undertake the scenario assessment process.

3.2.1. Data Collection

From the outset the project had as a specific objective the utilization of as much secondary data as possible, and to support this with the extensive use of remotely sensed data. A real advantage of working in arid and semi-arid areas is that remotely sensed data is available with little cloud cover for extended periods. 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. Table 3.2. shows the main types of data we were able to compile and use in the project, together with an indication, where relevant, of the time period covered and the source of the data themselves.
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 USGS GTOPO 30 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.

Primary data collection focused on two areas. There has been a small amount of field based observation of crop response to water, soil, agricultural inputs and climate in Kabutarabad Research Station AREO (east of Isfahan) to verify some of the assumptions used in the SWAP model. Field studies were required to identify representative crops in large fields, locate these fields precisely using a GPS system, and use the results for ground truthing of LANDSAT images.

The large amount of data collected for the study required the development of a database to store and manage all of the information. Given the wide range of data available in a wide range of formats, no efforts were made to make this into a unified database with a common format. Instead, the individual data files are linked through a viewer that classifies the information in a nested set of directories. The viewer was developed using Arc Explorer.
This database is stored on a set of CDs for easy reference. The majority of files are in standard applications—Microsoft Excel, Microsoft Access and Microsoft Word—so that they can be used by a wide variety of other software.

### Table 3.2. Data Used in the Zayandeh Rud Study.

<table>
<thead>
<tr>
<th>Subject Area</th>
<th>Type of Data</th>
<th>Dates</th>
</tr>
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<tbody>
<tr>
<td>Hydrologic</td>
<td>Chadegan Reservoir inflows and outflows</td>
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</tr>
<tr>
<td></td>
<td>7 gauging stations: monthly discharges and quality</td>
<td>1990-2000</td>
</tr>
<tr>
<td>Climatic</td>
<td>7 synoptic stations</td>
<td>1980-2000</td>
</tr>
<tr>
<td></td>
<td>24 rainfall stations</td>
<td>1990-2000</td>
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<tr>
<td>Soils</td>
<td>Digital Soil Map of the World (FAO 1995)</td>
<td></td>
</tr>
<tr>
<td>Agricultural</td>
<td>Crop patterns and yields by district</td>
<td>1990-2000</td>
</tr>
<tr>
<td></td>
<td>Sample crop patterns at village level</td>
<td></td>
</tr>
<tr>
<td>Irrigation</td>
<td>Designed command areas</td>
<td>2001</td>
</tr>
<tr>
<td></td>
<td>Deliveries to main and secondary canalsCanal</td>
<td>1990-2000</td>
</tr>
<tr>
<td></td>
<td>layout maps</td>
<td></td>
</tr>
<tr>
<td>Groundwater</td>
<td>Water table twice, twice annually, 717 wells</td>
<td>1990-2000</td>
</tr>
<tr>
<td></td>
<td>Water quality data, twice annually, 717 wells</td>
<td>1990-2000</td>
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<tr>
<td></td>
<td>Detailed information on all groundwater</td>
<td></td>
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<tr>
<td></td>
<td>extractions in Lenjanat District</td>
<td></td>
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<tr>
<td>Economic</td>
<td>Prices for major crops in Esfahan District</td>
<td>1990-1999</td>
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<tr>
<td></td>
<td>Industrial Water Extractions</td>
<td></td>
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<tr>
<td></td>
<td>Urban Water Extractions</td>
<td></td>
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<tr>
<td></td>
<td>Population</td>
<td></td>
</tr>
<tr>
<td>Administrative</td>
<td>District boundaries</td>
<td></td>
</tr>
<tr>
<td>Sensed Data</td>
<td>NOAA (monthly composites)</td>
<td>1995</td>
</tr>
</tbody>
</table>

#### 3.2.2. Using Tools and Methodologies to Process Data

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.

**ILWIS**

The Integrated Land and Water Information System (ILWIS) is a GIS-based package developed by ITC, the Netherlands in 1997. For this project, version 2.1 of ILWIS was used although there is now a version 3.0 for Windows.

The package has a large number of in-built modules that allow spatially referenced data to be analyzed. In this project, ILWIS packages were used to undertake land classification
of LANDSAT 7 images in order to assess irrigation demand, to determine spatial variation in groundwater chemistry so as to determine the likely source of groundwater, and to link secondary data on canal discharges to estimations of irrigation performance determined using SEBAL algorithms from both LANDSAT 7 and NOAA images.

IDRISI

IDRISI (Clark Labs 2002) is a raster-based GIS package that provides similar capability to ILWIS but contains some additional modules that are superior in remote sensing analysis. The modules allow for a full range of GIS applications, together with a number of decision-support modules aimed at geographic and environmental users. Like ILWIS, it was originally a DOS-based modular program but has been translated into a Windows version. The data transfer capacity enables inputs from ILWIS and outputs to ILWIS, making it convenient to adopt whichever GIS package is best suited for a particular task.

In this project, IDRISI was used primarily for assessment of land cover types and soil conditions to develop land classification maps.

CROPWAT

CROPWAT (FAO 1999) is a program that allows users to calculate reference evapotranspiration, crop water requirements and crop irrigation requirements. With these outputs, it is then possible to develop irrigation schedules, scheme water supply, estimate the effect of drought on rainfed agriculture and make assessment of field level irrigation efficiency. It requires input of meteorological data but has a database (CLIMWAT) that contains basin climatic data from a wide range of countries, and crop coefficients for almost all crops.

The program was developed by the Land and Water Development Division of the Food and Agriculture Organization of the United Nations. The version used in this project was CROPWAT 5.7, but there is also an updated version 7.0 that can be downloaded from the FAO website.

Based on the Penman-Montith equation, it determines reference evapotranspiration based on locally derived climatic data and then modifies these results based on crop growth stages and their duration.

The primary utility of CROPWAT is to estimate the potential crop water demand from different crops, and can be converted into total water demand for a farm or irrigation system. Because it is not able to incorporate soil moisture information, which will determine whether the crop actually has sufficient water to meet potential demand, it is best suited as a planning tool for irrigation system design or water scheduling rather than for actual performance studies.

SEBAL

SEBAL (Surface-Energy Balance Algorithm) (Bastiaanssen et al. 1998) has been developed to enable remotely sensed data to be used in determining water balance. It is based on
observations of incoming solar radiation, radiation reflected from vegetation, and temperature of vegetation cover, and estimates sensible heat fluxes from vegetation.

By applying the model to remotely sensed images, it is possible to make estimates of actual evapotranspiration (as opposed to potential evapotranspiration which is what a crop would use if water was freely available), biomass growth, soil moisture content in the root zone, and an approximation of yields for crops which are grown over sufficiently wide areas.

It can be used with a variety of images. In the Zayandeh Rud study, it has been used on both NOAA and LANDSAT 7 images.

WATEVAL

WATEVAL (Hounslow 1995) is a program that allows the origin of groundwater to be estimated by its chemical composition. By measuring the dissolved anions and cations in groundwater and comparing the ratios of particular elements present, it is possible to determine the type or types of source rocks and sediments through which water has passed. It is particularly useful when there is groundwater that is recharged directly from underground sources, as it can clearly distinguish different bedrock types as well as aquifers recharged from rivers and other surface sources.

In this project, it was used in the Lenjanat area to determine the extent of recharge from the Zayandeh Rud in the Lenjanat aquifers.

AQUITEST

Aquifer Test Analysis (Waterloo Hydrogeologic 2002) with Windows™ Software, by William C. Walton, presents a comprehensive aquifer test analysis package for the practicing groundwater hydrologist. It expands the types of well-hydraulics models that are typically supported by including not only those models based on analytical Laplace transform solutions, but also those based on numerical inversion of Laplace transforms. The inclusion of numerical Laplace transforms allows AQUITEST to handle more complicated aquifer systems and well hydraulic problems than other commercially available aquifer test software.

The types of well hydraulic problems that can be analyzed using AQUITEST include: constant-discharge tests for confined, leaky confined, unconfined, and dual-porosity systems; variable-discharge tests for confined systems; partial penetration, well bore storage, confining-bed storage, delayed gravity drainage and stream infiltration; barrier and recharge boundaries and source beds; and slug tests for confined and unconfined systems.

In this project, it was used to assess rates of groundwater recharge by estimating transmissivity and storage capacity of the Lenjanat aquifer system.

3.2.3. Modeling

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 modeling, 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.

Figure 3.4. shows the 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.

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**Figure 3.4. Models and related applications used in the Zayandeh Rud study.**

**SWAP MODEL**

The SWAP model—Soil-Water-Atmosphere-Plant Model—(Van Dam et al. 1997) is a two-dimensional model developed at Wageningen Agricultural University. It is a one-dimensional, physically based model for heat, water and solute transport in the saturated and unsaturated zones. SWAP includes modules for simulating irrigation practices at field level, so that different combinations of irrigation depth and application dates can be tested. It also allows
for different levels of water salinity to be incorporated into the calculations. The water transport module is based on Richard’s Equation, which is a combination of Darcy’s Law and the continuity equation. Crop yields are estimated in two ways: a simple growth algorithm based on the FAO 33 procedure, or a detailed crop growth module using carbohydrate partitioning at different stages of plant growth (WOFOST). Actual soil evaporation and crop transpiration are simulated based on the potential evapotranspiration and leaf area index development, combined with the amount of soil moisture in the top layer or root zone. A schematic diagram of the main components of the SWAP model is presented in figure 3.5.

Figure 3.5. Main components of the SWAP model.

SWAP has the added advantage that it can calculate the values of several pertinent output performance indicators: yield per hectare, yield per cubic meter of water applied, actual transpiration, soil evaporation, and biomass growth. These can then be used with data on prices to produce performance in terms of gross and net income.

D-SWAP

SWAP has been modified into a distributed form (D-SWAP) (Droogers et al. 2000a) that enables a water balance to be estimated for each combination of soils and water conditions. For the Zayandeh Rud, these aggregated areas are irrigation systems, or those parts of irrigation systems that have unique combinations of soil and crop type. Different values of water application depths and water salinity are then applied to each soil-crop combination and distributed to simulate the outputs from each irrigation system. This means that the outputs from D-SWAP can be directly linked to basin-level models by aggregating system level simulation outputs.
Irrigation System Water Allocation Model

At the irrigation system level, a simple model was developed that determines the distribution of water between different irrigation systems in the basin according to overall water availability. It is based on the analysis of the available data of releases from the Chahdeleg Reservoir since 1972, the water deliveries to different irrigation systems, and estimations of extractions for urban and industrial demand.

MODFLOW

MODFLOW (McDonald and Harbaugh 1998) is a three-dimensional finite-difference groundwater flow model. It has a modular structure that allows it to be easily modified to adapt the code for a particular application. MODFLOW simulates steady and non-steady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or simulated as a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal direction aligned with the grid axes with the anisotropy ratio between horizontal coordinate directions fixed in any one layer), and the storage coefficient may be heterogeneous.

Water Salt Balance Model

The Water-Salt Balance Model (WSBM) (Droogers et al. 2001a) is a spreadsheet-based model developed specifically for the Zayandeh Rud for this project. Because the Zayandeh Rud is a completely controlled river below the Chahdeleg Reservoir (except in periods of relatively infrequent large floods in the winter), it is possible to use a simple accounting approach to water and salt balance, working at a monthly time step.

The water balance is estimated using data from each of the main gauging stations along the river, many of which are associated with major control structures for the diversion of water to irrigation canals. By using existing data on monthly diversions for irrigation, it is possible to estimate the return flow from each irrigation system into the river before the next gauging station.

The salt balance is handled in a similar way. Because salt is conservative, the total amount of salt in the basin at any time is a constant, and so it can be routed downstream and a concentration estimated by linking the salt routing to the water routing module of the model.

The model was developed and tested using 12 years of monthly data provided by the Ministry of Energy, Esfahan Regional Water Authority. This time period included both high-flow and low-flow conditions. This means that the overall level of confidence in the model to deal with extreme conditions is high.
3.2.4. Scenario Development and Assessment

The final stage of the integrated modeling approach is to use the results obtained in the 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 transfers results from different models into an integrating spreadsheet, which can produce outputs for a set of pre-determined performance indicators.

The manner in which scenarios are developed is discussed in the last part of chapter 4 and in chapter 5. We aim to predict what the likely consequences of different scenarios will be on water availability at basin level. However, rather than using the exact value generated of basin water level, we have developed a set of six classes of water availability ranging from abundant to severe drought. The great advantage of this approach is that the results of different models can then be applied to one of the six water availability classes, and there is no need to have to repeatedly run models for every possible scenario. As is seen in chapter 5, we have come up with a total of 72 possible combinations of water availability and management options. To have to run all models for each of these 72 options would be laborious; and if we did not adopt this type of approach then even more model runs would be required.

An important consideration here is how results from different models can be transferred into the integrating spreadsheet. For the SWAP model, for various combinations of crops, soils, water availability and water quality, we derive a set of polynomial surfaces that will determine yield, water productivity, gross and net income, and salinity of percolating water. These polynomial surfaces can then be transformed into a set of equations with specified values for the different coefficients. These equations are included in the integrating spreadsheet.

For other model outputs, the results may be expressed in the form of simpler tables that are used as references within the spreadsheet. Thus, for example, once basin level water availability is known, we can allocate water deliveries to each irrigation system in the basin according to whatever management options we specify. This process is depicted diagrammatically in figure 3.6. Inputs into models are from the overall database, and become outputs in the form of polynomial functions or reference tables. These then become inputs into the second part of the process, and are transformed into calculations of appropriate performance indicators.

The use of polynomial equations and reference tables makes the integrating spreadsheet comparatively simple. Admittedly, it has to be modified for each basin but this is a relatively simple procedure and saves a great deal of time compared to the creation of a more universal model that requires a larger number of parameters.

The integrating spreadsheet has outputs in terms of numerical tables as well as graphs. Output can quickly be transferred into a GIS program for spatial representation of certain variables.
Figure 3.6. Integration through combining outputs from different models.
Chapter 4

Research Results from the Zayandeh Rud Study

This section describes the main research results, with an emphasis on those results that describe current processes and conditions within the Zayandeh Rud basin and their application for creating effective models. The chapter is divided into 14 sections, each of which represents a separate research focus of the project and which have been or will shortly be published in the Iran-IWMI Research Report series, some of which have also been published internationally.

Readers who wish to obtain more information on any of the 14 sections should refer to the full list of publications given in Appendix 1.

The research results reported in this chapter are loosely grouped into the three levels of analysis, starting at field level, moving to system level, and finally describing basin level conditions.

Table 4.1. List of Research Activities included in this chapter.

<table>
<thead>
<tr>
<th>Level</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Level</td>
<td>4.1. Crop yield modeling in the Zayandeh Rud using the SWAP model</td>
</tr>
<tr>
<td></td>
<td>4.2. Field level salinity modeling</td>
</tr>
<tr>
<td>Irrigation System Level</td>
<td>4.3. Irrigation supply and demand modeling</td>
</tr>
<tr>
<td></td>
<td>4.4. Satellite assessment of irrigation performance</td>
</tr>
<tr>
<td></td>
<td>4.5. Crop and land cover classification by Landsat 7, and determination</td>
</tr>
<tr>
<td></td>
<td>of irrigated areas</td>
</tr>
<tr>
<td></td>
<td>4.6. Irrigated area by NOAA-Landsat upscaling techniques</td>
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<td></td>
<td>4.8. Hydrologic assessment of the Zayandeh Rud</td>
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<td></td>
<td>4.9. Variations in groundwater chemistry to identify source of</td>
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<tr>
<td></td>
<td>groundwater</td>
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<tr>
<td></td>
<td>4.10. Spatial and temporal analysis of groundwater in Zayandeh Rud</td>
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<tr>
<td></td>
<td>basin</td>
</tr>
<tr>
<td></td>
<td>4.11. Modeling of groundwater trends</td>
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<tr>
<td></td>
<td>4.13. Water Pricing</td>
</tr>
</tbody>
</table>
4.1 Crop yield modeling in Zayandeh Rud using the SWAP Model
P. Droogers and M. Torabi

The SWAP model described in chapter 3 is the mainstay for estimating crop yields under different soil, irrigation and climatic conditions (Van Dam et al. 1997). In addition, it is possible to estimate productivity in terms of both kg m\(^{-3}\) and $ m\(^{-3}\) for different crops. These results can be aggregated to irrigation system and basin level if there is reliable information on cropping patterns in different portions of the basin. Four of the most common crops in the area have been selected for further analysis: alfalfa, rice, sugarbeet, and wheat.

4.1.1. Data Used

Data have been collected from a variety of field experiments carried out in the basin combined with some general data from different sources.

Climate conditions are similar over the irrigated systems in Zayandeh Rud with a small trend of precipitation rates ranging from about 150 mm yr\(^{-1}\) in Nekouabad 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 Kaboutarabad station for an average year (1991). SWAP simulates at a daily time-step, but only monthly data were available and for each month, the day with highest precipitation. This information was used to generate daily climate data.

Irrigation inputs according to normal practice in the area range from 500-1,500 mm yr\(^{-1}\) depending on crop and soil type, and water availability. The SWAP model allows irrigation scheduling to be simulated by using the value of the ratio of actual to potential evapotranspiration, and forcing an irrigation application when this ratio reaches a specific value. For Zayandeh Rud, different runs of the models were used for values of the ratio of actual transpiration (Tact) to potential transpiration (Tpot) from 0.5 to 1.0 in 0.05 increments.

Salinity of irrigation water was also varied for different runs. Values selected were 0, 1, 2, 4, 6, 8 and 10 dS m\(^{-1}\), a total of seven different water qualities that reflect the range of actual values measured in the basin.

A simple economic analysis was used based on three factors: price per kg crop, costs per kg crop, and fixed costs per hectare. The price of water is very low in the basin (about $ 0.002 m\(^{-3}\)) and it is therefore included in the fixed costs. Prices for crops were obtained from statistical data, while costs per kg and costs per hectare were estimated. Table 4.2 shows the values used.

<table>
<thead>
<tr>
<th></th>
<th>Alfalfa</th>
<th>Rice</th>
<th>Sugarbeet</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price ($ kg(^{-1}))</td>
<td>0.13</td>
<td>0.77</td>
<td>0.03</td>
<td>0.12</td>
</tr>
<tr>
<td>Fixed Costs ($ ha(^{-1}))</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Variable Costs ($ kg(^{-1}))</td>
<td>0.02</td>
<td>0.10</td>
<td>0.005</td>
<td>0.02</td>
</tr>
</tbody>
</table>

\(^1\) M. Torabi is a scientific board member of AERI, Esfahan.
One of the main outputs of this study is a series of figures that illustrates the relationships between irrigation application, salinity level and expected (simulated) yields. Such a relationship can be presented in a contour map, where the impact of changes in water quantity and quality on crop yield can be examined directly (Droogers et al 2001b). For this study, local polynomial gridding methods appeared to provide the best outputs.

4.1.2. Detailed Results for Wheat on Clay Soils

Figure 4.1. shows the main outputs for a series of SWAP model runs for wheat grown on clay for the six most important output parameters.

Figure 4.1. Estimated variations of performance indicators for wheat on clay soil at different irrigation application rates and varying water quality.

The yields estimated by the SWAP model show the general trend that, above 1,000 mm of irrigation, the incremental benefit from additional irrigation water is limited irrespective of water quality. Farmers with high quality water can exceed 6,000 kg ha\(^{-1}\) but yields from fields receiving water of 5 dS m\(^{-1}\) are about 75 percent of the ones receiving fresh water, and will not exceed 5,000 kg ha\(^{-1}\). To get a yield of 4,000 kg, 600 mm of fresh water is sufficient, while about 1,000 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. If irrigation water is more saline, percolation rates are higher because saline water is more difficult to take up by roots, so transpiration rates are lower and more water remains in the soil profile and will eventually percolate.
Transpiration is the most important process, since this is the only use of water that is beneficial—trends are almost identical to yield trends. Above 1,000 mm of irrigation, transpiration is largely controlled by salinity, while below 1,000 mm, total available water is more important. 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 percent. At higher application rates and high salinity levels this fraction reduces to merely 25 percent. Evaporation is not greatly influenced by salinity, and increases as more irrigation water is applied.

The salinity level of percolated water is highest when less water is applied and as the salinity of irrigation water increases (Maas and Hoffman 1977). 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, and is an important parameter in understanding sustainability of the irrigated agriculture system.

Finally, from the yield figures the net return can be calculated using average figures for crop prices and costs as defined in table 4.2. It is clear that salinity levels are the dominant factor in this net return, especially if irrigation applications are higher than about 800 mm. Some interesting facts can be read from the graph. For example, a farmer receiving freshwater can earn $250 ha\(^{-1}\) using 700 mm of water, while a farmer receiving more saline water (4 dS m\(^{-1}\)) needs 1,250 mm of water to get the same net return.

### 4.1.3 Water Productivity Analysis

Traditionally, productivity in agriculture has been expressed in kg yield per hectare or cash (dollars) per hectare. However, increasing water scarcity has led to the development of the concept of Water Productivity (WP) expressed in kg or income 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. In this analysis, water productivity is calculated with reference to water actually used. In the upstream part of the basin, this is transpiration and evaporation but for downstream users whose effluents cannot be reused, water used must also include percolation, drainage and runoff.

For the wheat crop on clay the WP values, expressed in kilogram and dollars per cubic meter, for downstream and upstream areas, are displayed in figure 4.2. 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. Because water is so cheap, we considered it as a component of the fixed costs per hectare and per kg for each crop. Generally, the results show a) low values for water productivity in terms of income due to the low price for wheat and b) that salinity affects tail-end farmers disproportionately.

These results can be further analyzed to determine what the optimal farm practices should be under different limitations of land, water and water quality. Details of this analysis for wheat on clay are given in Droogers et al.(2002). Where there are few limitations, farmers will get optimal returns from irrigation applications around 1,000 mm per season. As quality decreases, however, increased applications will be beneficial because they require more water of lower quality to produce the same income. The SWAP model assumes that all other inputs
Figure 4.2. Calculated water productivity values for wheat on clay soil under different irrigation application rates and varying water quality.
(fertilizer, management etc.) are optimal, and therefore the figures given represent the upper end of likely outcomes and not the average actual condition.

If the amount of available water is limited, a farmer cannot increase his water supply and salinity of water plays the major role in determining water productivity in terms of both yield and income per cubic meter applied. A farmer is better advised to concentrate most of the water on part of the farm so as to overcome the negative impacts of salinity.

4.1.4. Modeling of all crop-soil combinations

All other crop and soil combinations were simulated (figure 4.3.), except for rice, which is restricted to clay soils, where a puddled layer can be built up. Other soils are not suitable for rice. Soil type does not affect yield substantially in the basin and clays and clay-loams generate similar yields. Yields from the loamy soil are around 25 percent lower than from clay and clay-loam. The general pattern that more irrigation water and lower salinity levels generate more crops is obvious, and particularly in the case of rice which requires water less than 5 dS m\(^{-1}\) and at least 600 mm of irrigation water to produce worthwhile yields.

Net returns (gross income less costs of cultivation) show that if soils are favorable, if water is not limiting and if salinity levels are low, rice far outstrips all other crops in terms of income per hectare, with values exceeding US$3000 ha\(^{-1}\). This is because the domestic price is considerably higher than the prevailing world value. Sugar beet is the next most profitable choice, obtaining up to US$700 ha\(^{-1}\), and it has the advantage of being less sensitive to salinity than either wheat or alfalfa. These last two crops show high sensitivity to salinity and rarely provide a net return over US$200 ha\(^{-1}\).

The water productivity graphs shown in figure 4.3 indicate why rice is the preferred crop by farmers when water is limiting. The price structure means that rice realizes high income per cubic meter, reaching over US$0.35 m\(^{-1}\) with abundant water of high quality. Sugar beet is the next best crop, with returns up to US$0.06 m\(^{-1}\). Alfalfa and wheat show returns as low as US$0.02 m\(^{-1}\). If water is limiting, then farmers will clearly go for rice rather than any other crop as long as the soils are favorable. Rice is the most profitable crop in terms of US$ ha\(^{-1}\) as well as US$ m\(^{-3}\), assuming enough water of good quality can be provided in late spring and summer. At present, rice irrigation uses about 16 percent of the total annual flow while grown on only 8 percent of the area. However, rice generates a very high income for farmers and contributes about 30 percent of total basin income.
Figure 4.3. Net income per cubic meter of water for different crops with varying irrigation application rates and water quality.
4.2. Field level salinity modeling
M. Akbari, P. Droogers, M. Torabi and E. Pazira

This study focused on the impact of using different volumes of water on the development of soil salinity in the Rudasht area, the tail-most irrigation system in the Zayandeh Rud basin. The area suffers from high water tables and increasing salinity due to low quality irrigation water in the Zayandeh Rud itself, and increasing use of groundwater that has fostered secondary salinization in the area.

The Rudasht area is dry. Winter rains average about 100 mm per year, with only about 15 mm in the summer. Winter temperatures average 8-10°C, rising to over 35°C in the summer. Soils are fine textured alluvial deposits, silts and clay loams, with a moisture holding capacity in the upper 50 cm of roughly 0.21 cm³/cm³, decreasing to 0.13 cm³/cm³ at depth.

The purpose of the research was to develop a methodology that can be applied to any particular combination of crop and soil to see the extent to which salinity builds up under different irrigation scenarios. Cotton was selected for this research study as it is an important commercial crop, and one widely grown in areas affected by salinity.

4.2.1. Simulation of current practices: The baseline condition

In the baseline condition, actual irrigation application data were used to understand the current water and salt dynamics. A typical farmer in this area applies about 900 mm of irrigation water during the cotton growing season, and it was assumed that there were 10 irrigation applications, each of 90 mm, using water with a quality of 4.0 dS m⁻¹. Although the application of 900 mm season⁻¹ almost matches the potential evapo-transpiration demand of 922 mm season⁻¹, in reality the crop cannot use all of the water available. Some is lost through evaporation, some through deep percolation, and in some periods salinity is sufficiently high to inhibit plant growth and transpiration.

The daily changes in precipitation, irrigation, percolation to groundwater, groundwater fluctuations, crop transpiration and soil evaporation for a complete year are shown in figure 4.4. However, a 1-year simulation does not indicate anything about overall sustainability of the water balance and salinity, so a series of runs simulating 10 years were made to determine whether any of the factors reached stability within this time frame.

The water balance appears to stabilize after 5 successive years of irrigation of cotton, with a winter watertable depth of some 240 cm. There are a couple of periods when the groundwater table almost reaches the surface, associated either with winter rainfall or summer irrigation, but the watertable declines shortly afterwards due to drainage and use of groundwater by the crop. Similarly, topsoil salinity levels also stabilized within 5 years at about 20 dS m⁻¹. Groundwater salinity levels did not stabilize so rapidly, taking the full 10 years to stabilize at about 27 dS m⁻¹.

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²The co-author is a Scientific board member of AERI, Karaj.
³E. Pazira is a Scientific board member of Azad University.
Figure 4.4. Daily fluctuations in water balance for a full year, cotton crop, Rudasht area.

From the perspective of production, yields also stabilized at about 66 percent of their potential. In other words, if there was no water or salt stress on the plant, yields would equal their potential, but under the irrigation regime currently experienced where there is an overall deficit of water, and where water is moderately saline, it is impossible to achieve more than two-thirds of the potential yield. Actual yields are even lower as farmers do not use the optimal level of other inputs under these adverse conditions.
4.2.2. Simulating alternative irrigation and salinity conditions

In anticipation of the development of different scenarios, a series of additional simulations were run which varied both the quantity of irrigation water applied and the quality of that water. This approach provides a complete matrix of different results that can then be applied to any given scenario once the water and salinity conditions are known.

Water applications were varied from 300 mm per year to as high as 1,500 mm/year, the lower and upper limits of likely water availability under any scenario. Irrigation deliveries less than 300 mm would not be sufficient to grow any cotton crop, while it seems unlikely that there will ever be enough water at basin level to deliver 1,500 mm to the Rudasht area.

Salinity of irrigation water was varied from 1.0 dS m\(^{-1}\) to 6.0 dS m\(^{-1}\). The lower figure is an estimate of the best water quality likely to be available in the Rudasht area given the upstream abstractions and return flows. The higher figure is arbitrary; but above that figure, we can anticipate very large reductions in actual yields of cotton.

The results of a complete set of simulations of every combination of irrigation depth and water quality are summarized in a set of two-dimensional graphs that allow us to understand the impact of any particular combination of water and salt condition. This is shown in figure 4.6.
Figure 4.6. Effect of different irrigation regimes and water quality on crop yield, soil salinity and water balance, cotton crop, Rudasht area.

In terms of yield, we see an expected pattern: the relative yield (the percentage of the maximum yield likely to be obtained when there is no water or salt stress) is highest when irrigation deliveries meet potential transpiration and when salinity is low. For Rudasht, this combination of circumstances is a total irrigation of 1,100 mm with irrigation water of 1.0 dS m⁻¹. As water application decreases, relative yields decline due to water stress, and even if water applications increase, relative yields still decline due to waterlogging. Increases in salinity invariably result in decreased relative yield irrespective of the volume of water applied.

As would be expected, soil salinity trends show a similar pattern. Increasing salinity of irrigation water results in higher soil salinity, the same trend occurring when irrigation deliveries drop below 1,100 mm. When more water is applied than required, leaching helps to decrease soil salinity, although this is also limited due to high water table levels.

The impact of salt on the water balance is also very clear. Below 1,000 mm there is little or no surface runoff when water is of reasonable quality, but as salinity increases beyond 4.0 dS m⁻¹ runoff occurs when irrigation applications are as low as 800 mm. Similarly, percolation rates are much higher when salinity is higher, even when irrigation application rates are lower because plant roots cannot take up all the water they need due to high salt content.
4.2.3. Implications of results

For the Rudasht area studied here, it can be concluded that given the current practice of about 900 mm of irrigation with an average water salinity level of 4 dS m\(^{-1}\), crop yields for cotton are expected to be around 66 percent of the yield potential of 5,000 kg ha\(^{-1}\). Given the current water quality level, changes in the amount of irrigation applied will not substantially change crop yields and the current practice of 900 mm is recommended for cotton. The main gains will only come from using water of significantly higher quality than 4 dS m\(^{-1}\), and this requires substantial change in water management practices upstream.

If water quality improves due to changes in water management upstream of Rudasht to 2 dS m\(^{-1}\) or even 1 dS m\(^{-1}\), yields can increase to 73 percent and 77 percent, respectively, of the potential value, with the same annual irrigation application of 900 mm. A further increase is possible if, along with an improvement in water quality, more water becomes available for irrigation. Expected yields can increase to 87 percent and 95 percent for respectively 2 and 1 dS m\(^{-1}\), if an annual application rate of 1,100 mm is practiced.

A further salinization of irrigation water to 6 dS m\(^{-1}\), will decrease the crop yield for cotton to 51 percent of potential obtainable. Under current conditions in the basin this seems a more likely possibility—many farmers in the Rudasht area use shallow groundwater to supplement meager surface water supplies, and groundwater quality is significantly lower than canal water.

Data on cropping intensities from 1995 and 1999 suggest that agriculture is more or less stagnant in the Rudasht area, and cropping intensities are significantly lower than in other areas. The modeling of salt dynamics in this research indicates why farmers get poor levels of production and are unwilling to invest in other inputs when water quantity and quality conditions are adverse. Unlike much of the rest of the basin, groundwater is also fairly saline making it difficult for farmers to increase water supplies by resorting to pumping.
4.3. Irrigation supply and demand modeling
H. Sally, H. Murray-Rust, A.R. Mamanpoush and M. Akbari

In this paper, attention is focused on the performance of 4 irrigation schemes, namely Nekouabad Right and Left, and Abshar Right and Left, which have been in operation since the 1970s. The Borkhar, Mahyar and Rudasht (East and West) systems, parts of which are still under development and have only just begun to benefit from Zayandeh Rud surface irrigation water, have not been included in this analysis.

4.3.1. Estimating supply to irrigation systems

From the supply side, the calculations are based on the releases made from the Chadegan Reservoir into each of the main irrigation systems. The overall pattern of water deliveries to each system is shown in figure 4.7, from which it can be seen that apart from recent drought years, there is little overall variation in water deliveries from year to year. This is consistent with the overall basin level management that reservoir releases are directly linked to irrigation and other demands based on storage at the end of March, and only in flood years such as 1992-1993 are releases significantly different from average.

Figure 4.7. Releases from the Chadegan Reservoir and issues to four major irrigation systems, Zayandeh Rud basin, 1991-2000.
4.3.2. Estimating demand for irrigation water

Estimating demand is much more difficult because cropping data is reported by district level only, and these do not coincide with irrigation system boundaries. Attempts to use detailed village cropping data were abandoned because it requires a large amount of data processing and transformation, and a trial effort resulted in major data inconsistencies.

Transforming district level data to irrigation system level data was undertaken on the basis that essentially all cropped areas would be irrigated, and that there is little significant variation in cropping patterns within a district. There are eight districts in the irrigated part of the basin, and by assigning irrigated areas on a proportional basis, the overall cropped area for each basin was developed, as shown in Table 4.3.

Table 4.3. Summary of annual crop areas obtained from district-level statistics.

<table>
<thead>
<tr>
<th>Year</th>
<th>Nek LB</th>
<th>Nek RB</th>
<th>Abs LB</th>
<th>Abs RB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991-1992</td>
<td>37,395</td>
<td>14,931</td>
<td>28,360</td>
<td>12,199</td>
</tr>
<tr>
<td>1992-1993</td>
<td>39,029</td>
<td>14,948</td>
<td>31,596</td>
<td>13,591</td>
</tr>
<tr>
<td>1993-1994</td>
<td>39,765</td>
<td>15,270</td>
<td>27,647</td>
<td>11,892</td>
</tr>
<tr>
<td>1995-1996</td>
<td>39,828</td>
<td>15,002</td>
<td>28,023</td>
<td>12,054</td>
</tr>
<tr>
<td>1996-1997</td>
<td>38,694</td>
<td>14,619</td>
<td>29,677</td>
<td>12,766</td>
</tr>
<tr>
<td>1997-1998</td>
<td>28,699</td>
<td>14,685</td>
<td>29,612</td>
<td>12,737</td>
</tr>
<tr>
<td>1998-1999</td>
<td>27,268</td>
<td>13,956</td>
<td>26,550</td>
<td>11,420</td>
</tr>
<tr>
<td>1999-2000</td>
<td>21,669</td>
<td>11,376</td>
<td>21,612</td>
<td>9,296</td>
</tr>
<tr>
<td>Average</td>
<td>34,721</td>
<td>14,443</td>
<td>27,805</td>
<td>11,960</td>
</tr>
<tr>
<td>C.V. (%)</td>
<td>20.0</td>
<td>8.4</td>
<td>10.0</td>
<td>10.0</td>
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<tr>
<td>Crop Intensity</td>
<td>0.72</td>
<td>1.07</td>
<td>1.85</td>
<td>0.80</td>
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</tbody>
</table>

The district level data identify in excess of 40 crops. To simplify calculations, major crops were identified, together with their normal growth period so that overall estimation of demand could be determined on a monthly basis. From this, a typical cropping calendar for the Zayandeh Rud has been developed, shown in figure 4.8.

The potential evapotranspiration of the 10 crops chosen to be representative of the more than 40 grown in the basin, were estimated using the FAO-CROPWAT program. The data records for the Kabutarabad meteorological station were used for this purpose. The crop water requirements thus obtained were then applied to the estimated crop areas and cropping patterns to determine the water demands of each of the 4 irrigation systems for the 9 years being studied.
Figure 4.8. Typical crop calendars, Zayandeh Rud basin.

<table>
<thead>
<tr>
<th>CROP</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
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<th>Mar</th>
<th>Apr</th>
<th>May</th>
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<td><strong>Winter</strong></td>
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Figure 4.9. Annual surplus or deficit in irrigation water deliveries, 1991-2000.

This approach enables a direct comparison to be made between the overall supply in terms of canal irrigation and the potential demand for water. If there are shortfalls in water supply, actual evapotranspiration will clearly be less because crops cannot transpire at their full potential.

Comparison of supply and demand can be done either on an annual or a monthly basis. On an annual basis, it appears that there is a very consistent pattern over the past 9 years (figure 4.9). Three of the four systems show an overall surplus of water delivery over supply, while the Abshar Left Bank shows a consistent annual deficit.

55
Overall, the entire basin has been more or less in balance for the four systems. Only in the drought starting in 1999-2000 did all systems show an overall water deficit, but before that there were 5 years when deliveries exceeded overall demand, and 3 years when deliveries were less than total demand. On average, there has been a slight over-delivery of water into each system but it does not seem to be very high, and indicates that at least on an annual basis, supply and demand are relatively well matched. Annual calculations, however, mask the pattern of monthly deliveries, which require a more detailed analysis.

To demonstrate the importance of monthly deliveries, 2 years have been selected as examples: 1991-1992 as a normal year, and 1999-2000 as a drought year (figure 4.10). The monthly estimates of supply and demand show that large differences occur within a year. In the typical year of 1991-1992, water deliveries are in deficit for the period February–April, reflecting the closure of the Chadegan Reservoir from January to March each year. The deficits are significant in both March and April as temperatures increase after the winter, and farmers must either rely on stored soil moisture or resort to groundwater pumping to get crops established. From May onwards, however, supplies increase and there is surplus in all systems except Abshar Left Bank up until the end of August. From September until January, all systems receive more water than is required.

By contrast, the situation in the drought year of 1999-2000 shows a deficit from January through September. In order to get any form of yield, farmers had to resort to intense groundwater pumping and this was instrumental in leading to a marked decline in groundwater levels during this period. The situation must have been made worse in 2000-2001 when no releases were made for irrigation, and all agriculture depended entirely on groundwater.

From these results, we can conclude that there may well be opportunities for fine tuning irrigation deliveries during crop seasons in order to avoid excessive surpluses and deficits between different parts of the system. Changing the rule curves for dam operation to store more water into late spring and summer may help, but system operators also need far more knowledge of groundwater-use within systems than they currently appear to have.
Figure 4.10. Monthly water surplus and deficit in four irrigation systems under normal and drought conditions.


4.4. Satellite assessment of irrigation performance

P. Droogers, W.G.M. Bastiaanssen, A. Gieske, N. Toomanian and M. Akbari

Traditionally, performance of irrigated agriculture has been expressed in terms of efficiencies based on observed flows in different points in the water distribution system, such as reservoir releases, main, secondary and tertiary canal, field, and plant. For example, the ratio of total water received at the field by farmers over the releases of a reservoir is defined as the system efficiency. The main objective of irrigation engineering has always been to increase those efficiencies. However, if a significant proportion of these “losses” are actually re-used elsewhere downstream, then improving efficiency may have counter-intuitive results, such as depriving established users of their water supply. In such a situation, improving efficiency upstream would require new flows to be made available to existing downstream users.

To overcome these problems with efficiencies, Molden and Sakthivadivel (1999) described a conceptual framework for water accounting, based on inflows and outflows. The framework includes the assessment of system performance in terms of the Productivity of Water (PW), defined as the amount of water used to produce 1 kg of crop. Here we apply only PW process depletion\(^4\), which refers to the amount of water transpired and evaporated to produce 1 kg of crop.

Recently, new technologies based on remote sensing (RS) have been introduced to monitor several components of the water balance. The main advantage of this approach is that large areas are covered, and that data is easily obtainable without extensive monitoring networks in the field. The SEBAL (Surface Energy Balance Algorithm for Land) algorithm (Bastiaanssen et al. 1998) estimates the energy balance based on remotely sensed images and estimates in actual evapotranspiration. The algorithm includes additional features to estimate crop production and soil moisture contents. For the four main irrigation systems in the Zayandeh Rud Basin, Iran, the SEBAL algorithm was applied, using NOAA images, and results were used to assess the performance of these systems.

Twelve images were selected for 1995, to represent a year in which water conditions were normal and likely to produce typical cropping conditions, and for each image the SEBAL algorithm was applied. SEBAL, the Surface Energy Balance equation, estimates the sensible heat flux from plants and this is used as the basis for estimating instantaneous evapotranspiration. Combined with maps of vegetated area determined using NDVI results, it is then possible to identify both the overall irrigated area and the degree of evapotranspiration.

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\(^4\)N. Toomanian is a Scientific board member of AERI, Esfahan. 
\(^4\)Process depletion is that water actually transpired or evaporated at the field in the course of crop production.
4.4.1. Estimation of Irrigated Areas

Based on NDVI data alone it is possible to estimate irrigated area. These results are presented in table 4.4.

Table 4.4. Irrigated areas measured from maps and estimated from NOAA satellite images.

<table>
<thead>
<tr>
<th>System</th>
<th>Designed Command Area (ha)</th>
<th>Measured Command Area (ha)</th>
<th>NOAA Estimated Area (ha)</th>
<th>Estimated Cropping Intensity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nekouabad Right Bank</td>
<td>13,500</td>
<td>20,532</td>
<td>16,631</td>
<td>81</td>
</tr>
<tr>
<td>Nekouabad Left Bank</td>
<td>48,000</td>
<td>38,863</td>
<td>30,313</td>
<td>78</td>
</tr>
<tr>
<td>Absar Left Bank</td>
<td>15,000</td>
<td>52,370</td>
<td>38,754</td>
<td>74</td>
</tr>
<tr>
<td>Absar Right Bank</td>
<td>15,000</td>
<td>22,565</td>
<td>16,247</td>
<td>72</td>
</tr>
</tbody>
</table>

With the exception of the Nekouabad Left Bank, gross cropped area reported as irrigated and the estimates from NOAA indicate cropped areas are larger than designed, because there is significant groundwater use that increases the area that can be irrigated. For this reason, the use of secondary data alone is insufficient to estimate the actual productivity of the areas, and SEBAL analyses are required to interpret data available from satellites.

Figure 4.11 shows an example of the results from SEBAL for April 1995. April represents a transition month with tail-end areas still having winter crops such as wheat and barley, and head-end areas beginning to have summer crops such as rice, fodder and maize. Irrigated areas can be clearly distinguished from the NDVI map with values of 0.20 and higher. High intensities can be found for the Absar systems, reflecting the dominant cropping pattern with mainly winter crops. Interesting are also the relatively high intensities for the Rudasht-East system, indicating that during spring, a reasonable amount of water is reaching this downstream area.

The estimated crop productions can be considered as the integrating parameter of water and crop management. The Absar system is clearly the most productive system in April, with daily biomass production values for some areas of 100 kg ha\(^{-1}\) d\(^{-1}\). For a crop with an active growing period of 120 days, this translates into 12,000 kg ha\(^{-1}\) biomass. The conversion factors from biomass to harvested product depends on crop, variety, and plant physiological condition, and values range from 10-30 percent, resulting in an actual yield of 1,200-3,600 kg ha\(^{-1}\).

Finally, the estimated soil moisture contents show that most soils are reasonably wet, even soils without any crop (low NDVI). Also areas with an intensive cropping pattern (high NDVI) but moderate soil moisture content can be observed, indicating that irrigation is required for these areas at the time of image acquisition.

\(^7\) This value of NDVI for crops is rather low, and can be explained by low cropping intensity, with a high degree of fallow within an individual pixel at the time of image acquisition.
Figure 4.11. Result of the SEBAL analyses for April 1995.
4.4.2. Monthly Variations in Irrigation Performance

Monthly NDVI values for the four main systems are shown in figure 4.12. The dual cropping pattern can be observed with “high” NDVI values from March to May and from August to October. Lower values in June and July are the result of the end of the growing season for spring crops (wheat) and the start of the summer crops (rice). For Abshar-Right, and especially Abshar-Left, the peak for summer crops is lower as a result of the smaller area cultivated with rice.

Potential evapotranspiration (ET$_{pot}$) shows a similar pattern for all systems (figure 4.12.), with peak values for mid-summer of around 8 mm d$^{-1}$. ET$_{pot}$ reflects again clearly the difference between the Nekouabad and the Abshar systems, with the latter having a cropping pattern existing mainly out of winter crops harvested in June, while Nekouabad systems have sufficient water to allow good crop growth throughout the summer.

Crop growth peaks in May, when climatic conditions in terms of radiation are optimal and sufficient water is available from precipitation, soil moisture storage, and irrigation. Soil moisture storage fluctuations show high values in May as a result of precipitation and irrigation. Low values can be seen for Abshar during the period July-October as a result of water extractions by crops and lack of sufficient irrigation water to replenish soil moisture.

4.4.3. Annual variations in Irrigation Performance

The results for four irrigation systems were aggregated to annual total crop areas (table 4.5) by taking the maximum NDVI value for each pixel in April and September and assuming that all values higher than 0.2 were cropped.

Releases for irrigation differ substantially from system to system. Figures presented here relate to the whole system area, rather than the areas served by surface irrigation. Converting these values to the official command areas leads to application rates between 1,000 and 1,500 mm ha$^{-1}$. Precipitation was considered to be similar for all areas, as the distance between systems was limited. Because precipitation is low throughout the area, it has relatively little impact on annual water balance.

The overall water balances for the systems are not closed (table 4.5) and three of the four systems show a water deficit. The apparent water surplus for Nekouabad Left Bank can be explained by the new intake canal from Nekouabad Left Bank main canal to the new Borkhar system. It is unclear how much water was actually delivered to Borkhar, so the water supply to Nekouabad Left Bank only could not be determined.

The main question for the three water deficit systems is, “where is this other water coming from?” Two sources can be identified. First of all, a certain amount of water is extracted directly from the river, which is not included in the water balance. Second, groundwater irrigation is extensively applied in the area. Quantitative information about these two additional inputs in the systems is lacking, but can be estimated as the missing term in the water balance.
Figure 4.12. Monthly values of NDVI, $ET_{pet}$, $ET_{act}$, biomass production, and soil moisture contents, for the four systems.
<table>
<thead>
<tr>
<th>System</th>
<th>Etact</th>
<th>Releases</th>
<th>Precipitation</th>
<th>Balance</th>
<th>Biomass</th>
<th>PW(_{\text{epl}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCM</td>
<td>mm</td>
<td>MCM</td>
<td>MCM mm</td>
<td>M kg</td>
<td>kg ha(^{-1})</td>
<td>kg m(^3)</td>
</tr>
<tr>
<td>NKB-R</td>
<td>243</td>
<td>1,183</td>
<td>181</td>
<td>25</td>
<td>-37</td>
<td>193</td>
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<tr>
<td>NKB-L</td>
<td>459</td>
<td>1,180</td>
<td>477</td>
<td>48</td>
<td>123</td>
<td>66</td>
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<tr>
<td>ABS-L</td>
<td>484</td>
<td>924</td>
<td>230</td>
<td>64</td>
<td>-190</td>
<td>-362</td>
</tr>
<tr>
<td>ABS-R</td>
<td>246</td>
<td>1,088</td>
<td>201</td>
<td>28</td>
<td>-17</td>
<td>-74</td>
</tr>
</tbody>
</table>

For Abshar-Left, this combined groundwater and unofficial water extraction is about 190 mm (table 4.6). The designed command area of Abshar Left Bank is 15,000 ha, while the cropped area, as determined by NOAA, is almost 39,000 ha. It is clear that the additional areas are irrigated by groundwater. Nekouabad Right Bank and Abshar Right Bank show an annual deficit of 178 and 74 mm, respectively. The designed command area for these systems are 13,500 and 15,000 ha, while actual cropped areas are higher (table 4.4). Using the data from the three deficit systems, a simple linear regression was developed (\(r^2 = 0.87\)) to assess the relationship between groundwater extractions, designed and actual cropped area:

\[
\text{Groundwater extraction} = -132 \times \frac{\text{design area}}{\text{cropped area}}
\]

Finally, these results can be used to explore the productivity of the systems. As described before, we used the Productivity of Water, expressed as the biomass production over the amount of water depleted by ET\(_{\text{act}}\). Abshar Left Bank appears to be the least productive of the four systems. Groundwater quality in the Zayandeh Rud is much poorer than surface water, so for Abshar Left Bank, with its high percentage groundwater irrigation, this PW is low. For Nekouabad Left Bank, with limited groundwater irrigation, PW is high. Although groundwater extraction seems high for Abshar Right Bank, PW is not low. Probably, the negative values in the water balance for this system are mainly caused by unaccounted water extraction from the river rather than from groundwater.

Table 4.6. Comparison between the current study (NOAA) and a supply and demand study based on Cropwat and cropping patterns.

<table>
<thead>
<tr>
<th>System</th>
<th>NOAA</th>
<th>Accounting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MCM</td>
<td>mm</td>
</tr>
<tr>
<td>Nekouabad Right Bank</td>
<td>-37</td>
<td>-178</td>
</tr>
<tr>
<td>Nekouabad Left Bank</td>
<td>66</td>
<td>170</td>
</tr>
<tr>
<td>Abshar Left Bank</td>
<td>-190</td>
<td>-362</td>
</tr>
<tr>
<td>Abshar Right Bank</td>
<td>-17</td>
<td>-74</td>
</tr>
</tbody>
</table>

Source: Sally et al. 2001.
4.5. Crop and Land Cover Classification by Landsat 7, and
determination of irrigated areas.
A. Gieske, A. Mamanpoush, M. Akbari, M. Miranzadeh§, M. Torabi
and H. R. Salemi§

Remote sensing provides one way of obtaining more accurate information on total cropped
area and crop types in irrigated areas. The technique is particularly well suited to arid and
semi-arid areas where almost all vegetative growth is associated with irrigation. Using a
LANDSAT 7 image from July 2, 2000, efforts were made to reconcile data obtained from
field surveys and data from both LANDSAT and NOAA images.

4.5.1. Crop and Land Cover Classification

Using a supervised classification system, training areas were selected and initial classifications
were made to determine the validity of the classes. After merging several classes and testing
several new classes, a final classification system was made. All seven Landsat bands were
used in the determination of the feature statistics. The final classification was made with the
minimum distance algorithm.

One problem with this classification has been that the cropping pattern of July shows
a transition from winter to summer crops. Some areas still show winter wheat and barley,
others are fallow between season, while rice is still young and difficult to distinguish from
other grain crops and alfalfa.

Ground data from GPS surveys were used to both georeference the satellite images and
also delimit the boundaries of fields where crop types had been verified. It is recommended
not to take a single point in the middle of the fields, but to try to take coordinates of all
corners. Based on the combination of field data and analysis of the images, a total of 20
land cover classes were determined with each land cover having a specific set of seven vectors,
one for each LANDSAT band.

The classification results with the 20 sample classes are shown in figures 13 to 16 based
on the initial classification method. Some of these classes are very close to each other in terms
of the spectral values and it may be hard to distinguish between them. It depends a lot on the
final purpose of the classification. From an agricultural perspective, we are less interested in
distinguishing non-agricultural land covers such as roads, mountains, and urban areas, and
we do not particularly worry about differences between different types of bare soil. It is therefore
possible to reduce the number of classes if the end use of the classification is known.

Figure 4.13 shows an overview of the Borkhar, Lenjanat, Abshar and Nekouabad Districts.
The green colors show active vegetation, while the light blue color should be interpreted as
irrigated land with vegetation (mainly rice) in the early growing stage. The light blue areas
clearly show that irrigation took place in these areas in the last weeks of June 2000, when
water supplies from the Zayandeh Rud were already getting low. The Borkhar irrigation district
clearly shows much less green vegetation on a background of bare, gypsiferous soils.

§These co-authors are Scientific board members of AERI, Esfahan.
Figure 4.13. Land cover classification with different soil and vegetation types.

Figure 4.14. Land cover and crop types of the Borkhar District.
Figure 4.14 shows a detailed view of a northern Borkhar farm area. Irrigated farmland only is a fraction of the total and is typical of an area irrigated using tubewells. Surface irrigation is normally contiguous while tubewell irrigation tends to be patchy. Water shortage and poor soil conditions are clearly limiting factors in this district.

In Figure 4.15, a detailed view is given of the situation in the Abshar Left and Right irrigation districts. Abshar Right Bank shows freshly irrigated land near the Zayandeh Rud and in the south near the main diversion channel. It is also clear that there are more patches of bare/uncultivated land in Abshar Right Bank than in Abshar Left Bank. It appears that there is not much irrigation for the summer season in Abshar Left at this stage.

Finally, Figure 4.16 shows Nekouabad Right Bank, where normal irrigation was taking place. All the suitable land is utilized and the few brownish areas are rock outcrops and hills. Misclassification occurs on the hill slopes in the northeastern part of the area, where a few blue spots indicate the presence of irrigation. The reason for this is that hill slopes are highly heterogeneous, because of shade. Slopes exposed to the sun become very hot, while those in the shade remain very cool. The properties, cool and dark, are generally those of watered surfaces, because these tend to be cooler than their environment and because they have low reflective characteristics (they absorb the incident light).

Figure 4.15. Detailed view of the Abshar crop classification.
4.5.2. Total Irrigated Area Statistics

Statistics with respect to areas and crop type for the districts were obtained by crossing the raster map with the irrigation district raster map. The results with respect to crop type and total irrigated area per district were compared with those of previous studies, and included both NOAA/AVHRR and conventional agricultural district statistics.

The areas for each class or crop type can be found through some simple GIS crossing operations. Table 4.7 shows the results. The classification based on 13 classes has been taken to subdivide crops and soil types. Classes 12 and 13 are not part of the instantaneous irrigated area (cropped area) as viewed by the satellite, and these were therefore taken out of the sum for the cropped area. This approach has the advantage that comparison can then be made with other satellite methods that also make use of NDVI analyses. It should also be noted that there is a large area classified as sparse green cover. A number of pixels in this category are probably of mixed origin: part vegetation, part bare soil or road. This category therefore introduces another uncertainty in the total irrigated area assessment, probably leading to a slight overestimation of the irrigated area estimates.
Table 4.7. Area per class for the irrigation districts fully covered by the image. Also shown are the total irrigated areas and the gross areas of the districts (July 2000).

<table>
<thead>
<tr>
<th>Area</th>
<th>Lenjanat (ha)</th>
<th>Nejleft (ha)</th>
<th>Nejright (ha)</th>
<th>Borkhar (ha)</th>
<th>Absright (ha)</th>
<th>Abseleft (ha)</th>
<th>Total (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Alfalfa/rice/irrigated</td>
<td>4,741</td>
<td>9,894</td>
<td>6,587</td>
<td>1,600</td>
<td>3,020</td>
<td>4,147</td>
<td>2,9989</td>
</tr>
<tr>
<td>2 Corn</td>
<td>1,054</td>
<td>85</td>
<td>240</td>
<td>2,853</td>
<td>961</td>
<td>2,086</td>
<td>7279</td>
</tr>
<tr>
<td>3 Sunflower</td>
<td>1,362</td>
<td>4,832</td>
<td>1,852</td>
<td>3,501</td>
<td>2,098</td>
<td>4,894</td>
<td>1,8539</td>
</tr>
<tr>
<td>4 Garden</td>
<td>856</td>
<td>6,994</td>
<td>1,612</td>
<td>2,669</td>
<td>2,003</td>
<td>2,923</td>
<td>1,7057</td>
</tr>
<tr>
<td>5 Forest</td>
<td>305</td>
<td>574</td>
<td>278</td>
<td>305</td>
<td>266</td>
<td>279</td>
<td>2207</td>
</tr>
<tr>
<td>6 Sparse green cover</td>
<td>2,290</td>
<td>4,168</td>
<td>1,714</td>
<td>5,547</td>
<td>3,315</td>
<td>6,493</td>
<td>23,527</td>
</tr>
<tr>
<td>7 Water</td>
<td>198</td>
<td>45</td>
<td>16</td>
<td>15</td>
<td>1</td>
<td>3</td>
<td>278</td>
</tr>
</tbody>
</table>

Irrigated area

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Harvested wheat</td>
<td>1,797</td>
<td>951</td>
<td>728</td>
<td>8,533</td>
<td>1,484</td>
<td>4,194</td>
<td>17,687</td>
</tr>
<tr>
<td>9 Harvested barley</td>
<td>68</td>
<td>30</td>
<td>128</td>
<td>992</td>
<td>381</td>
<td>1,242</td>
<td>2,841</td>
</tr>
<tr>
<td>10 Bare soil</td>
<td>9,116</td>
<td>5,520</td>
<td>2,897</td>
<td>40,972</td>
<td>4,753</td>
<td>14,324</td>
<td>77,582</td>
</tr>
<tr>
<td>11 Gypsum oil</td>
<td>14</td>
<td>43</td>
<td>77</td>
<td>8,827</td>
<td>83</td>
<td>1,231</td>
<td>10,275</td>
</tr>
<tr>
<td>12 Saline soil</td>
<td>1</td>
<td>18</td>
<td>20</td>
<td>117</td>
<td>44</td>
<td>11</td>
<td>211</td>
</tr>
<tr>
<td>13 Heterogeneous</td>
<td>5,970</td>
<td>5,725</td>
<td>4,384</td>
<td>7,828</td>
<td>3,582</td>
<td>7,118</td>
<td>34,607</td>
</tr>
</tbody>
</table>

Non irrigated

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>16,966</td>
<td>12,287</td>
<td>8,234</td>
<td>67,269</td>
<td>10,327</td>
<td>28,120</td>
<td>143,203</td>
<td></td>
</tr>
</tbody>
</table>

Total area

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>27,772</td>
<td>38,879</td>
<td>20,533</td>
<td>83,959</td>
<td>21,991</td>
<td>48,945</td>
<td>242,079</td>
<td></td>
</tr>
</tbody>
</table>

Much as we might like to feel that LANDSAT image analysis gives accurate results concerning the irrigated area, it is insufficient to merely make this assumption where other data are available, especially if the analysis is based on a single date image rather than a multi-temporal sequence.

As a result of other project activities, data are available from a variety of other sources that allow us to make a cross-check of the different results. Table 4.8 shows results from nine different efforts to determine total irrigated area, both from remotely sensed data and from secondary sources.

The results show that the variability of methods 1-5 (based on remote sensing) is much less than the range in values of methods 6-8 (secondary statistics and older remote sensing analysis). The explanation for the difference between 6 and 7 lies in the trend observed by Sally et al. (2001). However, not much of a trend is visible in the remote sensing analysis (methods 1-5), based on 1995, 1999 and 2000 figures.

The data from the District Agricultural Statistics sources do not distinguish between winter and summer cropping patterns, and this makes some of the comparison rather difficult, particularly when based on one image in the transition between winter and summer. Some plots are cultivated with two crops a year, others with only one, so no direct comparison is really possible.

It is therefore recommended to continue with the remote sensing method during various parts of the year to check both on winter and summer crop statistics. This will still require
Table 4.8. Comparison of total area calculations with those by NOAA/AVHRR methods and district agricultural statistics.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Lenjanat (ha)</th>
<th>Nekleft (ha)</th>
<th>Nekright (ha)</th>
<th>Borkhar (ha)</th>
<th>Absright (ha)</th>
<th>Absleft (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Landsat 7 2/7/99</td>
<td>10,805</td>
<td>26,593</td>
<td>12,300</td>
<td>16,691</td>
<td>11,663</td>
<td>20,825</td>
</tr>
<tr>
<td>2 Landsat 7 1/8/99</td>
<td>27,912</td>
<td>12,922</td>
<td>15,915</td>
<td>12,382</td>
<td>22,874</td>
<td></td>
</tr>
<tr>
<td>3 Landsat 7 1/8/99</td>
<td>11,673</td>
<td>28,867</td>
<td>13,859</td>
<td>25,920</td>
<td>14,547</td>
<td>27,605</td>
</tr>
<tr>
<td>4 NOAA Jul-Aug, 1999</td>
<td>13,251</td>
<td>25,974</td>
<td>13,608</td>
<td>17,980</td>
<td>12,555</td>
<td>22,948</td>
</tr>
<tr>
<td>5 NOAA Jul-Aug, 1995</td>
<td>11,844</td>
<td>25,015</td>
<td>13,225</td>
<td>15,992</td>
<td>11,701</td>
<td>20,760</td>
</tr>
<tr>
<td>6 NOAA 95 (SEBAL)</td>
<td>40,141</td>
<td>45,203</td>
<td>11,688</td>
<td>27,172</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Agric. statistics  (yr 2001)</td>
<td>48,000</td>
<td>13,500</td>
<td>15,000</td>
<td>15,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Agric. statistics  (1994-1995)</td>
<td>27,268</td>
<td>11,376</td>
<td>9,296</td>
<td>21,612</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Landsat 7 ETM (2 July 2001) study presented in this report.
2. Based on analysis of NDVI values of Landsat 7 image (1 Aug 1999) (Gieske et al. 2002).
4. NOAA/AVHRR upscaled from Landsat (Gieske et al. 2002).
5. NOAA/AVHRR upscaled from Landsat (Gieske et al. 2002).
7. Command areas, District Agricultural Statistics (Sally et al. 2001).

Fieldwork to gather actual crop data for classification purposes and to interview farmers about past cropping practices. Detailed crop comparison is less useful at this stage in view of these large differences in values for total irrigated areas, particularly when making decisions about water allocation between different irrigation systems at different times of the year.

The secondary statistics show higher values of cropping than the remote sensing analysis in 2001 and 2000, especially at Nekouabad Left command area. They give lower estimates of cropped area for 1995. In contrast, the SEBAL estimates considerably exceed 1995 statistics and other values for Nekouabad Left, Nekouabad Right and Abshar Left. It is perhaps not surprising that NOAA and Landsat estimates are consistent, since NOAA is “calibrated” on Landsat. However, single-date analysis does not take into account variations in visible cropping intensity across seasons, during seasonal overlaps and with varying planting dates from year to year. Therefore, a multi-temporal analysis is potentially more useful in defining irrigated area and is investigated in the next section.
4.6. Irrigated area by NOAA-Landsat upscaling techniques
A. Gieske, N. Toomanian and M. Akbari

4.6.1. Upscaling from Landsat to NOAA pixel size

Although LANDSAT images give good accuracy in calculating irrigated areas due to the small pixel size of approximately 30x30 m, the availability of images is less than that of NOAA images. However, while NOAA images are freely available and the satellites pass overhead every day, the pixel size is approximately 1.0 km². By making comparisons of NOAA and LANDSAT images for the same time period, it is possible to obtain comparable information on irrigated and generate time sequence data.

The comparison requires certain calibrations of both images to be made. It is recognized that NDVI values for NOAA images give an unadjusted value for irrigated area that is much lower than LANDSAT because unirrigated areas within irrigation systems will reduce NDVI values for the entire pixel. This is particularly true where irrigation is by groundwater with large unirrigated areas between irrigated fields.

The following assumptions can be made in such comparison:

- All values of NOAA NDVI pixels less than or equal to 0.06 are considered to represent non-irrigated areas. This threshold is quite sensitive and therefore critical to the comparison of NOAA and LANDSAT images.
- For the NOAA NDVI values greater than 0.06, the irrigated area \( I \) is calculated as \( I = A \sum f_i n_i \) where \( A \) is the area of a pixel, while \( f_i \) is taken as \( c \times \text{NDVI} \).
- The proportionality constant \( c \) is then determined by regression against the areas as determined in the Landsat image. This constant should have a value of approximately 3 but must be determined for each calibration because it is sensitive to atmospheric and other transient conditions (see figure 4.18).

A Landsat 7 image of August 1 1999 was used to calculate the irrigated and non-irrigated areas through standard GIS/RS techniques. Five areas were selected: Borkhar, Nekouabad Left and Right Bank, Abshar Left and Right Bank. A set of 5 NOAA images was used (July 7, 8, 25 and August 21 and 29) in the calibration procedure as outlined above. The results of the calculations are summarized in table 4.9. The uncalibrated NDVI values for the main irrigation systems for July 25 1999 are shown in figure 4.17, ranging from 0.0 to 0.38.

Table 4.9 shows that there is a clear increase in area from July 7 to August 29. Comparison with the Landsat values can be made through the averages of the 5 images or through the use of the July 25 NOAA image. Figure 4.18 shows the result of the regression analysis based on average NDVI results of the five NOAA images compared to the LANDSAT image. Theoretical considerations show that the constant should be a number close to 3, and the proportionality constant was determined to be about 2.7 for this time period. The method using the average of 5 images seems to be better than using one single image, and table 4.10 shows the estimated areas using this procedure for 1999 data.
Figure 4.17. NOAA NDVI values in the main irrigation districts on 25-7-1999.

Table 4.9. Comparison of the LANDSAT and five NOAA image results (areas in ha).

<table>
<thead>
<tr>
<th></th>
<th>07-Jul</th>
<th>08-Jul</th>
<th>25-Jul</th>
<th>21-Aug</th>
<th>29-Aug</th>
<th>Average</th>
<th>Std. Dev</th>
<th>Landsat 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borkhar</td>
<td>3,813</td>
<td>7,225</td>
<td>5,462</td>
<td>7,790</td>
<td>8,681</td>
<td>6,594</td>
<td>1,949</td>
<td>15,915</td>
</tr>
<tr>
<td>Nekou-L</td>
<td>6,693</td>
<td>9,590</td>
<td>8,609</td>
<td>11,644</td>
<td>11,094</td>
<td>9,526</td>
<td>1,988</td>
<td>27,912</td>
</tr>
<tr>
<td>Nekou-R</td>
<td>3,415</td>
<td>4,469</td>
<td>5,174</td>
<td>5,985</td>
<td>5,912</td>
<td>4,991</td>
<td>1,075</td>
<td>12,922</td>
</tr>
<tr>
<td>Abshar-R</td>
<td>3,312</td>
<td>4,053</td>
<td>4,142</td>
<td>5,833</td>
<td>5,684</td>
<td>4,605</td>
<td>1,103</td>
<td>12,382</td>
</tr>
<tr>
<td>Abshar-L</td>
<td>6,187</td>
<td>7,836</td>
<td>7,235</td>
<td>10,134</td>
<td>10,689</td>
<td>8,416</td>
<td>1,925</td>
<td>22,874</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>23,420</strong></td>
<td><strong>33,173</strong></td>
<td><strong>30,522</strong></td>
<td><strong>41,386</strong></td>
<td><strong>42,060</strong></td>
<td><strong>34,132</strong></td>
<td><strong>92,005</strong></td>
<td></td>
</tr>
</tbody>
</table>

In general, the errors are larger for Borkhar, Lenjanat and Mahyar where the choice of NOAA NDVI threshold (0.06 in this case) appears to be critical. These districts have less uniform surface water irrigation and large parts of these areas are irrigated with groundwater. The table shows that it is not advisable to make area calculations based on a single NOAA image.
4.6.2. Time series assessment of irrigated areas using NOAA NDVI data.

Based on the approach described above, it is possible to repeat this exercise for a series of NOAA images to understand the annual cropping cycle. Using a total of 26 NOAA images for 1995, roughly one every two weeks depending on cloud and other atmospheric conditions, the changes in irrigated area can be clearly determined.

Figure 4.18. Comparison of NOAA NDVI values and LANDSAT irrigated areas.

Regression relation for the 5 irrigation areas (average NOAA values)

![Regression line graph]

Table 4.10. Irrigated areas from NOAA after calibration for the period July 7 1999 to August 29 1999 (all areas in ha).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Borkhar</td>
<td>0397</td>
<td>19700</td>
<td>14893</td>
<td>21240</td>
<td>23670</td>
<td>17980</td>
<td>15915</td>
</tr>
<tr>
<td>Lenjanat</td>
<td>4204</td>
<td>16537</td>
<td>12172</td>
<td>16602</td>
<td>16741</td>
<td>13251</td>
<td></td>
</tr>
<tr>
<td>Nekou-L</td>
<td>18249</td>
<td>26148</td>
<td>23473</td>
<td>31749</td>
<td>30249</td>
<td>25974</td>
<td>27912</td>
</tr>
<tr>
<td>Nekou-R</td>
<td>9311</td>
<td>12185</td>
<td>14107</td>
<td>16319</td>
<td>16120</td>
<td>13608</td>
<td>12922</td>
</tr>
<tr>
<td>Abshar-R</td>
<td>9030</td>
<td>11051</td>
<td>11294</td>
<td>15904</td>
<td>15498</td>
<td>12555</td>
<td>12382</td>
</tr>
<tr>
<td>Abshar-L</td>
<td>16869</td>
<td>21366</td>
<td>19727</td>
<td>27631</td>
<td>29145</td>
<td>22948</td>
<td>22874</td>
</tr>
<tr>
<td>Rudash-W</td>
<td>4624</td>
<td>6748</td>
<td>4390</td>
<td>5554</td>
<td>6184</td>
<td>5500</td>
<td></td>
</tr>
<tr>
<td>Rudash-E</td>
<td>6718</td>
<td>8681</td>
<td>7490</td>
<td>9011</td>
<td>9450</td>
<td>8270</td>
<td></td>
</tr>
<tr>
<td>Mahyar</td>
<td>1775</td>
<td>5919</td>
<td>4297</td>
<td>7861</td>
<td>8954</td>
<td>5761</td>
<td></td>
</tr>
</tbody>
</table>

The results for the irrigated area patterns of 1995 are shown in figure 4.19. In general, the pattern is clear. The irrigated area increases until May, and then there is a sudden drop associated with the harvesting of winter crops, after which the values rise again in response to the expansion of summer crops. The methodology seems to be able to distinguish different agricultural conditions in different irrigation systems. However, it should be noted that the calibration is really only valid for the summer crop period during the maximum NDVI period.
and it is not correct to assume that the calibration is valid for all times of the year. When the crop is in its initial stage, the relation between NDVI and irrigated area is not straightforward and needs further calibration against Landsat images of different seasons. It is probably best to interpret irrigated areas using the maxima in the graphs of figure 4.19 as the actual irrigated areas, and place less emphasis on the areas estimated before and after these maxima.

The pattern is uniform in Nekouabad for both the Right and Left bank systems. There is a steep rise in NDVI values and a sudden drop towards the end of May, indicating simultaneous harvesting of all winter crops (mainly wheat and barley) in the system, combined with flooding of areas in preparation for rice planting. After this, NDVI values rise again in response to the growth of the summer crops (mainly rice, corn, potato and onion). There is always some land in cultivation (orchards and alfalfa) and this is captured in the NOAA data. Harvesting of the summer crops takes place gradually, leading to a steady decline in NDVI values after August.

The Abshar Right Bank system has higher NDVI values than the Left Bank, which has a higher proportion of unirrigated rocky areas. The cropping pattern changes are similar to that of the Nekouabad systems in winter. However, NDVI values build up much more slowly for the summer crops and the maximum summer NDVI values are lower than for winter. This is probably caused by the relatively more diverse cropping patterns (more corn and vegetables) as compared to the Nekouabad system where rice is dominant.

Both Rudasht systems show a much smaller increase in summer crops after the harvesting of winter wheat and barley. This is indicative of tail-end conditions where water supplies are less, and where salinity affects cropping opportunities for farmers.

Lenjanat is a hybrid system, partly irrigated from the Zayandeh Rud, partly from tubewells. The overall pattern of cropped area is similar to Nekouabad, but there is more fluctuation in individual values reflecting the complication of accurately assessing irrigated area when the irrigated patches are fragmented. This is even truer for Borkhar and Mahyar, where the data appear to have a lot of variability. It seems that cropping intensity in Mahyar is quite low. Nevertheless, the dual seasonality is still captured, which reflects the actual irrigation practices.

4.6.3. Long-Term Changes in Irrigated Area

Comparison between different years becomes possible using NOAA data. As an example, a comparison is made between the actual irrigated areas of July-August 1995 (average of 7 images) and the areas of the corresponding time period in 1999 (average of 5 images), which was also used in the calibration process. The results are summarized in table 4.11 and figure 4.20. The greatest increases in irrigated area have occurred in Mahyar and Borkhar, where new canals have been built to supplement existing groundwater development. Abshar has experienced significant increases in groundwater development, greater in the Left Bank than the Right Bank. Nekouabad has seen little increase in irrigated area, a reflection of the intensive irrigation in that area that had developed before 1995. Rudasht systems have seen little or no growth, presumably because surface water availability is less and groundwater is too saline for widespread exploitation and, for Rudasht East, there appears to have been a decrease in the irrigated area.
Figure 4.19. Seasonal variations in irrigated area estimated from NOAA NDVI data.

Nekouabad (1995)

Abshar (1995)

Rudasht (1995)

(1995)
Table 4.11. Comparison of the irrigated areas for the periods July-August 1995 (7 images) and the calibration period July-August 1999 (5 images).

<table>
<thead>
<tr>
<th></th>
<th>1995</th>
<th>1999</th>
<th>Increase</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lenjanat</td>
<td>11,844</td>
<td>13,251</td>
<td>1,407</td>
<td>11.9</td>
</tr>
<tr>
<td>Mahyar</td>
<td>4,233</td>
<td>5,761</td>
<td>1,528</td>
<td>36.1</td>
</tr>
<tr>
<td>Nekouabad Left</td>
<td>25,015</td>
<td>25,974</td>
<td>959</td>
<td>3.8</td>
</tr>
<tr>
<td>Nekouabad Right</td>
<td>13,225</td>
<td>13,608</td>
<td>383</td>
<td>2.9</td>
</tr>
<tr>
<td>Borkhar</td>
<td>15,992</td>
<td>17,980</td>
<td>1,988</td>
<td>12.4</td>
</tr>
<tr>
<td>Absah Left</td>
<td>20,760</td>
<td>22,948</td>
<td>2,188</td>
<td>10.5</td>
</tr>
<tr>
<td>Absah Right</td>
<td>11,701</td>
<td>12,555</td>
<td>854</td>
<td>7.3</td>
</tr>
<tr>
<td>Rudasht West</td>
<td>5,340</td>
<td>5,500</td>
<td>160</td>
<td>3.0</td>
</tr>
<tr>
<td>Rudasht East</td>
<td>8,801</td>
<td>8,270</td>
<td>-531</td>
<td>-6.0</td>
</tr>
<tr>
<td>Total</td>
<td>116,911</td>
<td>125,847</td>
<td>8,936</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Figure 4.20. Comparison of the actual irrigated areas for the periods July-August 1995 and 1999.

Figure 4.20 shows that the actual irrigated area was 7 percent higher in 1999 than in 1995, amounting to a total increase of 9000 ha. The quality of the regression line of figure 4.2 is very good, which underlines the consistency of the methodology outlined in this paper.

Using NOAA NDVI to estimate total cropped area, delimitation of different irrigation seasons within a year, and comparison of cropped areas from one year to another makes it a very powerful tool for assessing irrigation conditions at basin and system levels. NOAA images are readily available and the processing is quite straightforward. This means that it is a technique that can be used easily over wide areas.
4.7. Basin level water resources development, 1945-2010
H. Murray-Rust, H. R. Salemi and P. Droogers

4.7.1. History of Water Resources Development, 1945-2010

Over the past 50 years, the Zayandeh Rud basin has experienced a series of water resource development projects aimed at overcoming water scarcity in a naturally water short basin. Five phases of development can be identified:

Phase I: Before 1953, water resources development consisted of simple community built diversion structures for irrigation along the plain of the Zayandeh Rud, with little overall control over discharges in the river or into systems. Average annual flows are estimated to have been 900 MCM during this period.

Phase II: In 1953, the first transbasin diversion was completed from the Kuhrang River to the Zayandeh Rud, providing an additional 338 MCM per year. Most of this flow was available only during the spring snow-melt period when the Zayandeh Rud was also at maximum levels.

Phase III: In 1972, the Chadegan Dam was completed, providing storage of some 1,500 MCM, slightly more than the annual flow of the Zayandeh Rud and Kuhrang tunnel No. 1. This allows a small increase in total water supply for the basin but more importantly allows some winter floods to be stored for release during the summer growing season. At the same time, community diversion structures were replaced with modern cross-regulators and traditional irrigation systems in the valley were incorporated into large modern irrigation systems.

Phase IV: In 1986, the second Kuhrang tunnel with an annual capacity of 250 MCM was opened. This is the current level of development in the basin.

Phase V: Planned for completion by 2010 is the development of a third tunnel at Kuhrang with a capacity of 280 MCM per year, and development of local springs and other water sources totaling 150 MCM. Once this is developed, the total planned basin supply will be 1,917 MCM. It is not expected that any other significant water resources will be available once this phase of development is completed.

The progress of water resources development from 1953 to 2020 is shown diagrammatically in figure 4.21. Discharges at the head and tail of the basin and water utilization patterns over the same period are shown in figure 4.22. This figure shows several important aspects of the balance between water supplies and demand in the basin.

Firstly, water supplies vary considerably from year to year. The flow of both the Zayandeh Rud and the Kuhrang rivers are dependent on the winter precipitation in the Zagros Mountains. When precipitation is below normal, discharges in the Zayandeh Rud and the transbasin diversion tunnels are also below normal. In this regard, the tunnels do not provide any significant insurance against a drier than normal winter, and neither does the Chadegan Reservoir, because its capacity is only equal to the annual average flow of the Zayandeh Rud.
Figure 4.21. Development of water resources in the Zayandeh Rud basin, 1945-2020.

Figure 4.22. Flows and water utilization in the Zayandeh Rud, 1945-2000.
There is a clear sequence of wet years, particularly after 1967, but these are offset by
drier periods. Using average data under such circumstances underestimates the impact of
dry periods. Secondly, it is clear that the potential demand for water increases almost
immediately after a new water resource has been developed. This effect was less marked in
Phase II because water supply conditions were poor for much of this phase, but in Phase III
and Phase IV, extractive potential quickly reached the planned supply. This means that each
new development had no influence on the overall vulnerability of the basin to drought because
all new water resources were allocated immediately.

Thirdly, it is clear that water users take as much as they can up to the planned limit.
If supplies are less than the plan, then the impact is clearly seen by looking at flows at
Varzaneh, the gauging station immediately upstream of Gavkhouni swamp. When actual
supplies at Pol-e-Kalleh fall below the planned level, then all water is used up between Pol-
e-Kalleh and Varzaneh, and little or no water reaches the swamp.

Available data indicate the basin closed in 1960 (closed in this context meaning no
flow below Varzaneh because geologically this is an inland basin), and has only had four
periods, totalling 15 years, with the last event occurring in 1993.

4.7.2. Analysis of basin vulnerability to drought

The Zayandeh Rud remains vulnerable to drought despite the series of water resources
development over the past 50 years (Yekom Consulting 1998). This is because the extractive
capacity of all users is at or even above average. If the flows at Pol-e-Kalleh are plotted in
terms of their recurrence interval for each of Phases II, III and IV then, it is clear that the
basin remains vulnerable (figure 4.23).

In phase II, the planned flow at Pol-e-Kalleh was met only half of the time, and was
less than 90 percent of plan one year in three. In phase III, following the construction of the
reservoir, the gauging supply again exceeded half the time and was less than 90 percent of
plan one year in seven. During this phase, the vulnerability against drought appears to have
diminished and overall water conditions appear to have been quite favorable.

In the current phase, however, things have deteriorated again. Even before the
catastrophic drought of 1999-2001, which could not have been mitigated under any level of
water resources development, planned flows were exceeded in only 5 of 11 years, and were
less than 90 percent once every 3 years.

The cause of this continued vulnerability is the result of two interlinked factors. Firstly,
planners apppeare to have used average conditions for planning purposes, meaning that there
will be a shortfall once every 2 years (on average, and with a high probability of 2 or more
consecutive years below average), and the fact that both the natural flows in the basin and
the transbasin flows into the basin are highly correlated to winter precipitation. The steeper
slope of the graph for 1984 onwards suggests more vulnerability to water scarcity than in
earlier years, with little or no margin for coping with water shortages. The construction of
new water resource developments that include the third tunnel at Kuhrang and various local
springs and water resources, will not overcome this overall vulnerability to drought under
current management practices.
Experience to date indicates that in a water-short basin, all available water is used up as soon as it is made available (Molden 2001). This means that the basin has maintained the same relative level of water scarcity throughout each phase of development. It is almost inevitable this will again occur once the final phase of water resources development is complete. The construction of new irrigation infrastructure at Rudasht, in the tail-end of the basin, increases extractive capacity (assuming water reaches there in sufficient quantity). Much more worrying, however, is that irrigation has been extended to Borkhar and Mahyar—areas traditionally relying only on groundwater for irrigation. The logic appears to be that the surface systems can supplement groundwater in periods of water-stress. However, supplying surface water to these areas will likely encourage farmers to increase their irrigated area and in water-short periods when surface water supplies are in deficit, they will merely increase groundwater pumping. Borkhar has already experienced a 15-meter drop in groundwater levels in the past 10 years, and with low rainfall and deficit surface supplies, groundwater levels are unlikely to stabilize in the future.

Groundwater development has always been important, initially as “kariz” or “kanat” systems. Nowadays these traditional systems have been made obsolete by the sinking of large numbers of deep boreholes. Dropping groundwater levels throughout the basin may alleviate short-term water scarcity, but the ratio of extractive potential to actual flows means that there is little prospect of recharge to earlier levels.
4.7.3. Changes in water use for agriculture and other sectors

Figure 4.24 shows that each of the four major developments (Kuhrang Tunnels 1, 2 and 3) and the Chadegan Reservoir (A) have all led to increased shares of water for agriculture. While Chadegan did not increase total basin yield, it allowed more flood water to be stored and released for irrigation later in the year. From 1945 to 2000, the share of water for agriculture remained between 80-90 percent of all water in the basin, but is projected to drop to 60 percent over the next 40 years as demands for other sectors and other basins increase (B is diversion to Yazd). This requires rethinking current management practices, an issue discussed in chapter 6.

Figure 4.24. Changing water allocations to agriculture.
4.8. Hydrologic assessment of the Zayandeh Rud

H. Murray-Rust, H. Sally, H.R. Salemi and A. Mamanpoush

Understanding the hydrology of the Zayandeh Rud is essential to any development of scenarios of future opportunities. Planners and water managers must have a clear idea both of total water availability and its likely variation. The nature of the Zayandeh Rud makes this process comparatively simple, because the Chadegan Reservoir lies at the point below which there is no significant natural flow in the critical summer months when water is at its scarcest. The lower flows in winter months generated below Chadegan are sufficient to meet current needs between January and March but cannot be stored unless there is a program of aquifer augmentation (Zahabsanei 2000).

4.8.1. Inflow Assessment

Flows into the Chadegan Reservoir have been determined using a simple water balance that excludes transbasin diversions. The inflows during the period 1989-1998 are stable, with little year-to-year variation, and we can treat these conditions as being typical for a baseline scenario (figure 4.25). Total annual inflows ranged from just under 1,200 MCM to a maximum of 2,500 MCM during this baseline period.

Figure 4.25. Monthly inflows into the Chadegan Reservoir, 1989-1998.
The inflow pattern is quite different to the precipitation pattern for either Esfahan or Kuhrang (figure 4.26), because most inflow is derived from snow-melt during the spring and early summer. The peak inflows of April and May do not match crop water demand in the later part of the summer.

In addition to natural inflow into the reservoir, two tunnels have been constructed through the Zagros Mountains from the Kuhrang River with a total annual capacity of 540 MCM, and a third tunnel under construction will be able to convey a further 250 MCM yr\(^{-1}\). These tunnels cannot flow full throughout the year, and it is estimated that the total contribution from these tunnels will not exceed more than 50 percent of natural flows in a typical year.

*Figure 4.26. Precipitation at Kuhrang (mm), Inflows and Releases (m\(^3\) x 10\(^6\)/month) at the Chadegan Reservoir, average for 1989-1998.*

**4.8.2. Releases from the Chadegan Reservoir**

Apart from flood releases in early spring, releases from the Chadegan Reservoir are closely matched to downstream demands, and the entire river is regulated from the reservoir downwards. The release pattern is also quite simple.

An important aspect of the capacity of the Chadegan Reservoir is that it has little or no capacity to store water from one year to the next—virtually all inflow is released for irrigation and other uses during the summer, and the system is therefore highly vulnerable to low winter snowfall that means the reservoir fails to fill up completely before April.
Releases, other than those needed to route floods through the reservoir, are kept at a minimum until late March and then are increased to enable the irrigation season to commence on 1 April. By May, releases have reached their peak and are kept more or less within the range of 200-250 MCM month\(^1\) until September. After October 1, releases are cut substantially and gradually decline to their minimum in February. As a result of these operations, the hydrology of the remainder of the Zayandeh Rud is sufficiently simple to allow it to be modeled using a simple spreadsheet accounting approach rather than having to have a more detailed hydrologic model.

**4.8.3. Flows in the Zayandeh Rud downstream of the Chadegan Reservoir**

There are several gauging stations along the Zayandeh Rud that provide enough information to estimate flows along the river under different discharge conditions.

The flow pattern outside the low-flow months of January and February is practically identical at all the observation points (figure 4.27). There are only limited extractions between the Chadegan Reservoir and the Regulating Dam just downstream, and the Regulating Dam and the Zamankhan measuring point. Downstream of Pol-e-Kalleh, however, water extraction begins in earnest. The extractions along the reach from Pol-e-Kalleh to the Nekouabad regulator, plus the extractions for irrigation at Nekouabad itself, account for almost half of the flow released from Chadegan. The same pattern is repeated between Nekouabad and Chom, when more than half the remaining flow is extracted from the river, either for urban and industrial use in Esfahan or for irrigation in the Abshar irrigation systems.

**Figure 4.27.** Average flows (MCM month\(^1\)) along the Zayandeh Rud, 1989-1998.
Irrigation extractions dominate water use in the Zayandeh Rud basin and they have a disproportionate impact in the summer when irrigation demand is low. Although releases decline from May to September, the amount extracted upstream of Nekoubad remains almost constant, and actually increases upstream of Chom. As a result, the percentage of total releases reaching Varzaneh decreases dramatically from April to August and only recovers again once irrigation demand slackens and less water is extracted above the Nekouabad and Chom regulators.

Further extractions for irrigation below Chom for the Rudasht irrigation systems reduce flows at Varzaneh to almost nothing, apart from floodwater or drainage releases that may reach this point. In fact, average monthly measured discharges at Varzaneh have fallen below 1 m³/sec on numerous occasions. Worse, the quality of water reaching Varzaneh is extremely poor with high salt content and many non-agricultural pollutants. Below Varzaneh, there is some return flow of drainage water from the Rudasht irrigation systems, but this effluent is also of very poor quality. As a result, water entering the Gavkhouni salt flats often consists of salinity as high as sea-water.

4.8.4. The importance of return flows in the Zayandeh Rud

The consistency of flows means that it is possible to make reasonably accurate estimates of return flows along each portion of the river. To do this, we need some estimates of total water extractions from the river.

Irrigation deliveries to each of the main irrigation systems are known, based on information collected by the Ministry of Energy at each of the main diversion points. These are the same data as those described earlier in section 4.3. Non-agricultural extractions are harder to quantify. For Esfahan, an average monthly extraction of 4.5 m³ sec⁻¹ is assumed, given a population of 2 million and a daily per capita consumption of 200 l day⁻¹, and an additional 1.9 m³ sec⁻¹ estimated for other urban and industrial uses.

The discharge records and estimates of water use were then entered into a simple spreadsheet-based water accounting model, together with monthly precipitation data adjusted to effective rainfall in areas contributing directly to river discharge. The details of this model and its assumptions concerning all aspects of water extraction are described in Droogers et al. 2000 a.

The results indicate that the gross extractions along the river exceed the net extractions calculated from the discharge data. Net extractions are determined by summing the difference in discharge between one gauging station and the next gauging station upstream. Gross extractions are based on the actual extractions plus assumptions about water use in the urban and industrial sectors. Because the difference is substantial, the only way to account for the gap is to assume there are return flows in each section related to the ratio of net to gross extractions. If there were no return flows, gross extractions would exceed net extractions—an impossible situation.

Using this approach, we determine that average annual return flows are in the order of 30 percent, as illustrated in figure 4.28 for each of the 10 years considered. The annual extractions, both net and gross, show little or no year-to-year variation (coefficient of variation = 0.09), suggesting that there is indeed a consistent set of processes that are operating in the baseline condition.
The significance of high values for return flows is that apparent inefficiencies in one part of the basin, assumed to be losses when considering the water balance of an irrigation system in isolation, are resulting in increased water for downstream users. This underlines the need to look not only at field and irrigation system levels but also the basin-level water balance in order to understand the interrelationships of water management.

The hydrology of the basin is simple but the demands are complex and growing. As a consequence, it is difficult to see how unchecked urban and industrial growth can continue in the basin despite the transbasin diversion systems currently under development.
4.9. Variations in groundwater chemistry to identify source of groundwater
A. Gieske, M. Miranzadeh and A. Mamanpoush

Groundwater plays an important role as an additional source of water when surface water supplies become stressed, and the Zayandeh Rud is no exception. The domestic and industrial water supply for Esfahan is augmented with groundwater in summer. In the irrigation command areas, many farmers operate wells close to the irrigation channels, and during the 2000-2001 drought, groundwater was the only significant source of irrigation water. Further away from the irrigated areas, groundwater plays a dominant role in providing drinking water to small villages and small-scale irrigation schemes. Traditionally, the groundwater was tapped by kanats and hand-dug wells. However, in recent years, many deep tube wells have been drilled that have lowered water tables substantially in both irrigated and non-irrigated areas. In recognizing both the potential of groundwater and the possibility of it being over-exploited, the Ministry of Energy has monitored water levels and quality in the entire Esfahan Province since the early 1980s (Racisi 1995). The total number of wells monitored exceeds 700, scattered throughout the province.

In view of the large amount of hydrochemical data available, it was decided to make an exploratory study of the Lenjanat sub-catchment along the Zayandeh Rud to see if it was possible to identify the extent to which groundwater is largely recharged from the Zayandeh Rud or if it was derived from other sources (figure 4.29.). The Lenjanat sub-catchment was selected because it is upstream of the major irrigation systems and thus represents a situation reflecting the overall hydrogeology of the basin.

Figure 4.29. Location of ground and surface-water sampling points in Lenjanat sub-catchment.
4.9.1. Surface water composition

Average EC values for three stations along the Zayandeh Rud at Pol-e-Zamankhan, Pol-e-Chom and Varzaneh show significant differences—from the first station (close to the Chadegan Dam) to the second (downstream of Esfahan) there is an increase in EC from 0.33 to 0.76 dS m⁻¹, while from the second to the third station (close to Gavkhouni Swamp) the EC increases to 1.7 dS m⁻¹. Therefore the largest increase in EC occurs well beyond Esfahan. While flowing through the Lenjanat District the electrical conductivity of the Zayandeh River water increases only from 0.3 to about 0.6 dS m⁻¹.

The changing ionic composition of the Zayandeh water is shown in a Piper diagram and in three Stiff diagrams (figure 4.30). The Piper diagram clearly shows that the initial composition plots as Ca²⁺-HCO₃⁻ type water, as is expected in a limestone/dolomite environment with relatively high recharge. The Stiff diagram for Pol-e-Zamankhan shows the typical diamond shape of this type of water (Journel 1989). Further downstream, past Esfahan at Pol-e-Chom, the ionic concentrations of sodium, chloride, magnesium and sulphate have increased relative to those of calcium and bicarbonate, and water quality declines sharply. This leads to a more rectangular shape of the Stiff diagram. The Piper diagram shows that the further the sampling points are downstream of Chadegan Dam, the further they plot to the right, following the direction of the three arrows towards the right-hand corners of the rhombus and the two triangles. Finally, in Varzaneh, the ionic composition of the water is dominated by Na⁺, K⁺, Cl⁻ and SO₄²⁻ and the points are plotted in the far-right corners of the triangles and rhombus. The Stiff diagram for Varzaneh attains the typical hourglass shape, characterizing this highly saline brine. The convex shape of the arrows in the Piper diagram suggests that cation exchange processes are involved. Hence, interaction between surface water and groundwater needs to be examined.

Figure 4.30. Piper and Stiff diagrams showing water composition along the Zayandeh Rud.
4.9.2. Groundwater composition

The ionic content and associated hydrochemical changes of the groundwater in the Lenjanat District are less easily understood, as is illustrated by figure 4.31. The points are scattered over the diagram, while the Stiff diagrams show the presence of different types of water. The program WATEVAL (Hounslow 1995) was used to calculate the Langelier saturation index for calcite and several other indices such as Na⁺/(Na⁺+Cl⁻), Ca²⁺/(Ca²⁺+SO₄²⁻), Mg²⁺/(Ca²⁺+Mg²⁺), (Ca²⁺+Mg²⁺)/SO₄²⁻ and HCO₃⁻/(sum anions).

Figure 4.31. Piper and Stiff diagrams showing water composition of groundwater in the Lenjanat sub-catchment.

The hydrochemistry of the Lenjanat District points clearly at groundwater recharge in carbonate rocks of the southern mountain range. On its way northward towards the Zayandeh Rud, the groundwater may come in contact with gypsum deposits. If it does, gypsum is dissolved and water quality deteriorates. The Piper diagram reveals this pattern. Fresh Ca²⁺-HCO₃⁻ water from the southern mountain range is plotted in the left corner of the rhombus. As the groundwater flows northward, it comes into contact with gypsum deposits. The Ca²⁺ and SO₄²⁻ contents then increase and the composition plots more to the right in the Piper diagram.

The scattered distribution in the anion triangle may be explained by the fact that gypsum deposits are not equally distributed over the area. If large quantities of gypsum are dissolved, the evolution will be towards the top of the anion triangle, whereas if the presence of gypsum is less strong, the groundwater evolution will be more towards the right-hand apex of the anion triangle with a relatively higher Cl⁻ content. The variety in Stiff diagrams may be explained similarly.

4.9.3. Analysis of EC values of groundwater

The spatial distribution of the EC values in the Lenjanat District was determined by means of Kriging, using the ILWIS GIS package. A clear picture emerges where groundwater
recharge predominantly takes place in the southern mountain range, and where the groundwater becomes more mineralized as it flows northward (figure 4.32). The high EC values around wells 11, 6 and 18 may have three additional causes:

- The presence of point pollution sources, for example, industry
- The extensive use of groundwater for irrigation in the area around the wells
- The possibility that the deep wells are drilled in a deeper, more saline aquifer

Figure 4.32. EC of groundwater in the Lenjanat sub-catchment estimated through kriging of water quality sample data.

4.9.4. Using chemical analyses to estimate surface and groundwater recharge

Because it seems likely that both groundwater and irrigation return flow reach the Zayandeh Rud and then mix with the fresh river water, it is instructive to make a simple conceptual model of the situation. We consider the stretch of river between Pol-e-Kaleh and Lenj (Nekouabad) as a single cell, as was discussed in Droogers et al. (2000). Five components can be distinguished (as illustrated in figure 4.33.), and their indicative values for flow rates and concentrations are summarized in table 4.12

- River inflow I with concentration $c_i$
- River outflow O at Lenj with concentration $c_o$ (combining the flow through the river with the irrigation offtake at the diversion weir)
- Groundwater seepage $S$ with concentration $c_s$
- Irrigation and urban abstraction $G$ with concentration $c_g$ (according to Droogers et al. 2000, this is about $9.5 \text{ m}^3/\text{s}$ on average)
- Return flow $R$ with concentration $c_r$ (10 percent salt sequestration is assumed)

Figure 4.33. Components of Surface and Groundwater Interactions.

Table 4.12. Concentrations and flow rates of the five component conceptual model.

<table>
<thead>
<tr>
<th>Flow component</th>
<th>Q (m$^3$/s)</th>
<th>EC (mS/cm)</th>
<th>TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pol-e-Kaleh inflow</td>
<td>54.0</td>
<td>366</td>
<td>256</td>
</tr>
<tr>
<td>Nekouabad outflow</td>
<td>50.0</td>
<td>575</td>
<td>403</td>
</tr>
<tr>
<td>Groundwater seepage</td>
<td>?</td>
<td>3,000</td>
<td>2,100</td>
</tr>
<tr>
<td>Irrigation/urban</td>
<td>9.5</td>
<td>471</td>
<td>330</td>
</tr>
<tr>
<td>Return flow</td>
<td>?</td>
<td>2,120</td>
<td>1,484</td>
</tr>
</tbody>
</table>

There are two balance equations for the 5 components, resulting from water and solute mass balance conservation. They may be written as:

$$I + S + R = G + O$$
$$C_I + c_s S + c_r R = c_g G + c_o O$$

Solution yields the following values for return flow $R$ and groundwater seepage $S$: $R = 3.4 \text{ m}^3/\text{s}$ and $S = 2.1 \text{ m}^3/\text{s}$. Thus, the irrigation return flow percentage becomes: $100 \times (R/G) = 36\%$, fully consistent with the results of Droogers et al. (2000a).
4.10. Spatial and temporal analysis of groundwater
P. Droogers and M. Miranzadeh

Using the data provided from the Ministry of Energy on monthly observations from 717 wells over a 10-year period, it is possible to make a number of observations on spatial and temporal changes in groundwater from 1990 up to 2000. The distribution of these observation wells and their relationship to the irrigation systems is shown in figure 4.34.

Figure 4.34. Location of groundwater observation wells and major irrigation systems, Zayandeh Rud Basin.

In water-short basins, groundwater becomes an important additional source of water to supplement surface water supplies, but it is also a vulnerable source because it is easy to deplete aquifers. Aquifer recharge may be through the natural processes of rainfall and snowmelt or through the artificial recharge from irrigation systems where water application is greater than evapotranspirative demand. These two sources of water represent the sustainable maximum yield of an aquifer, and withdrawals in excess of this total will result in declining water tables and may eventually result in long-term damage or destruction of the groundwater resource.

It is clear that in the Zayandeh Rud basin there is not only substantial groundwater exploitation but also a real risk that groundwater resources are under severe stress. Average data for all wells, irrespective of location in the basin, indicate a sustained decline in the
order of 0.75 m yr⁻¹ (figure 4.35.), even excluding data for 1987 where there are relatively few observation points. To determine whether this risk is genuine or not, the data-set as it applies to the irrigation systems was analyzed in two main ways: analysis of longer term trends in water tables over the whole 10-year period, and an analysis of within-year changes in water-table depth.

4.10.1. Analysis of long-term changes in irrigated areas of Zayandeh Rud

To assess the extent to which there are long-term trends in water-table decline within the irrigated areas of the Zayandeh Rud basin, the data were processed to obtain the maximum water-table depth for each observation well within each hydrologic year (i.e., from October 1 to September 30). The maximum level recorded gives an indication of the extent to which the groundwater is under stress. To obtain average values, all data were kriged within ILWIS and a surface obtained for groundwater levels within the irrigation systems. The final step in the analysis was to estimate the total area within each system underlain by a particular water table depth. The results are presented in figure 4.36.

The overall trend can be observed by comparing the lowest water table depths in 1991 with 2000 and determining the difference in lowest water table over the 10-year period (figure 4.37.). It is obvious that some areas are under considerable stress while others are relatively unaffected.
Figure 4.36. Average depth to lowest water table each year in each irrigation system.

Figure 4.37. Change in depth to water table, 1991-2000 in meters.

The recharge of groundwater, either from the Zayandeh Rud or from irrigation systems, is quite apparent. Only a few areas close to the river show water table declines of more than 10m over the 10-year period, but areas away from the river show substantial decline, notably in Mahyar, Nekouabad Left and Right Banks, and in Borkhar. In Abshar and Rudasht, however, overall declines are much less due to the naturally high water table in the flatter part of the basin before the river reaches Gavkhouni swamp. A change of over 1m per year implies that at least 100mm of water has been extracted each year in excess of natural recharge.
Figure 4.38. Groundwater trends for the main irrigation systems obtained from gridded data.

Note: Nekouabad graphs have a range of 16m on the y-axis, all others are 8m.
The actual trends for eight different irrigated areas in the basin can be seen in figure 4.38. Borkhar shows a steep and steady decline through the past 10 years of up to 1.0 meter per year, no doubt due to high rates of pumping for irrigation, while the two Rudasht systems show a slower decline because pumping is reduced due to groundwater salinity. The two Nekouabad systems and Abshar Left Bank show a rise during the first part of the 1990s followed by a decline, which is particularly marked from 1997 onwards as the effects of the drought begin to be felt. Lenjanat and Abshar Right Bank show a somewhat anomalous trend in that there is a substantial rise in the water table during the 1990s and little overall decline during the drought period.

This trend in Lenjanat is analyzed separately in section 4.11 but appears related to recharge from the Zayandeh Rud itself. In other locations, the flow in the river is so low for much of the year that groundwater recharge is negligible.

4.10.2. Analysis of within-year changes in water table levels in irrigated areas

The annual variation in water table from high to low conditions during the year also gives an indication of the stress under which the groundwater resource is being placed. For the year 2000, a severe drought year, the difference between January and June is quite dramatic. The average depth to the water table over the whole of the Nekouabad Left Bank system is illustrated in figure 4.39.

Figure 4.39. Average water table depth, Nekouabad Left Bank, Jan-June 2000.
Figure 4.40. Change in depth to water table (m) in irrigated areas of Zayandeh Rud, January and June 2000.

Figure 4.40 shows the difference in depth to water tables in January and June 2000. The depletion of the water table in western Nekouabad Left Bank is obvious, with a combination of declines of up to 10 meters in only 6 months. This rate of abstraction, presumably for agriculture, drinking water and industrial uses, is far in excess of the annual recharge. Given that the water table in part of this area is more than 50m deep, we can be very sure that groundwater is being mined and will be difficult to recharge.
4.11. Groundwater resources modeling of the Lenjanat aquifer system
A. Gieske and M. Miranzadeh

The Esfahan hydrological province in central Iran is essentially a closed catchment with one perennial river, the Zayandeh Rud. The region has traditionally been supported by irrigated agriculture, predominantly with river water, but also with groundwater tapped by kanats and hand-dug wells. More recently, population growth and industrial development have increased the demand for water, and at present, both the quantity and quality of fresh-water resources are under threat. Groundwater plays an important role as an additional source of water in three different ways: domestic supply to Esfahan, for conjunctive use in major irrigation systems, and in providing drinking water to small villages and small-scale irrigation schemes in more remote areas. The groundwater has been monitored with respect to water level and quality in the Esfahan Province since the early 1980s.

There is a highly complementary relationship between the use of surface water and groundwater. In times of drought, surface water is less easily available and as a result the abstraction of groundwater is intensified leading to decline in groundwater levels (Droogers and Miranzadeh 2001) and loss of groundwater quality. When the Chadegan Dam fills up after good rains or snowfall, surface water is used predominantly again and groundwater levels may slowly recover as a result of natural recharge by precipitation—by infiltration from the Zayandeh Rud or by excess irrigation water leaching to the groundwater table. This study looks at groundwater flow patterns and trends in Lenjanat District, which lies upstream of the major irrigation districts. This area has been a major source of groundwater recharge to the Zayandeh Rud in the past but it is not so clear what the situation is at present.

4.11.1. Sources of information

The modeling of groundwater resources and trends in the area has been made possible by using several different sources of data. The groundwater level database, kindly made available by Mr. A.A. Saberi (Ministry of Energy, Esfahan Office), consists of more than 60,000 well-level observations for over 700 observation wells in the entire Zayandeh Rud Basin, covering the period from 1987 to 2000. A distinction is made between shallow and deep wells. The groundwater levels of 1997 (1,376) were used for the steady state modeling.

Abstraction data were also provided for wells, kanats and springs. Many springs lie on the boundary between mountains and plains but some lie close to the Zayandeh Rud indicating that groundwater does flow towards the river, or has flowed towards the river in the recent past. The kanats are more evenly distributed over plains and mountains. Most of the inflow from the mountainous area into the plains occurs through subsurface flow. Total abstraction information is summarized in table 4.13 and based on this information, the steady state model uses 200 MCM yr⁻¹ of abstractions as an initial value.
Table 4.13. Estimated water abstractions from the Lenjanat aquifer.

<table>
<thead>
<tr>
<th></th>
<th>Ministry of Energy</th>
<th>Lenjanat District</th>
<th>Lenjanat Plains Aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wells (deep &amp; shallow)</td>
<td>150</td>
<td>187</td>
<td>158</td>
</tr>
<tr>
<td>Kanats</td>
<td>156</td>
<td>135</td>
<td>75</td>
</tr>
<tr>
<td>Springs</td>
<td>41</td>
<td>32</td>
<td>7</td>
</tr>
</tbody>
</table>

With annual precipitation only 200 mm yr⁻¹, the direct recharge from rainfall is probably less than 6 mm yr⁻¹ and can be ignored. Aquifer transmissivity and storativity values were derived from pumping tests from three representative wells, and the data was analyzed with the AQUITEST software package. Large variations in storage coefficients point to varying confined-unconfined conditions, such as is frequently the case when an alternating and laterally heterogeneous sequence of fine and coarse deposits is found.

Figure 4.41. Composite of two ASTER images of Lenjanat aquifer.

Composite of two ASTER for 2001 in false colour. The aquifer boundary is depicted by the thick red line, irrigated areas by red patches. The black area in the centre is the Mobarake Steel Mill. Alluvial fans cross the area, running north-north-easterly towards the Zayandeh Rud River, which forms the northern boundary of the aquifer.
Cross-sections (figure 4.42) indicate that the groundwater levels generally follow the topography, and near the river they reach the Zayandeh Rud’s water level. When abstractions are not too high, groundwater will seep into the river.

The thickness of the saturated zone and the depth to the aquifer's bottom is difficult to ascertain. The aquifer’s thickness is probably highly variable in view of the small rocky hills that are visible on the surface. One should visualize the aquifer as a weathered sedimentary rock of low permeability with an irregular surface, overlain by successions of coarse erosional deposits and fine sand-clay layers.

**4.11.2. Model results**

The outcome of the modeling process is a steady state volumetric budget, which is given below as table 4.14. The total seepage into the river is 76 MCM yr$^{-1}$, the total abstraction from the wells, kanats and springs amounts to 192 MCM yr$^{-1}$, while the total recharge is about 267 MCM yr$^{-1}$. The model shows that under these conditions the groundwater flow components are in balance. If the total outflow is larger than 267 MCM yr$^{-1}$ then groundwater levels will drop.

The groundwater will flow perpendicular to the contour lines shown in figure 4.43, mostly in a northeasterly direction. The flow from the bottom-right corner of the figure is expected to flow straight north. However, the exception to this is the outflow from the large alluvial fan (see figure 4.41). The flow here appears to the east, which probably may be explained by a zone of low transmissivity on the north side of the fan.
Table 4.14. Volumetric budget for the steady state model.

<table>
<thead>
<tr>
<th></th>
<th>m$^3$ d$^{-1}$</th>
<th>MCM yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seepage into the river</td>
<td>207,003</td>
<td>76</td>
</tr>
<tr>
<td>Wells, kanats, springs</td>
<td>524,754</td>
<td>192</td>
</tr>
<tr>
<td>TOTAL</td>
<td>731,757</td>
<td>267</td>
</tr>
</tbody>
</table>

Figure 4.43. Groundwater level contour map from the PMWIN and MODFLOW modeling.

4.11.3. Temporal aspects

Two ways of the estimation of trends in groundwater conditions over time are looking at discharges of un-pumped water sources (kanats and springs), and the measurement of water levels of wells.

Records of representative kanat and spring discharges are available from 1,367-1,379 (1988-2000). On average, the discharge from kanats and springs is reduced by about 2 percent annually over the period 1988-2000, although there are a few locations where discharges have actually increased during the same time period. The importance of long-term data sets is clear, because there is high year-to-year variability due to aquifer recharge and irrigation return flows.
Figure 4.44. Estimated annual decline in meters of water levels in representative wells.
Well-water level fluctuations show a similar pattern, with most areas showing a substantial decline over the 12 years. As a first approximation of changes in water levels, linear regression coefficients were determined for each of the representative wells or a period of 6-10 years of records. These regression coefficients are used as an estimation of annual water level declines, and the results are shown in figure 4.44.

There is a substantial drawdown of groundwater in the northwest portion of the aquifer, towards the Zayandeh Rud River, and in the southeast corner. Both of these areas appear to be using a lot of groundwater for irrigation, as indicated by the density of irrigated areas shown on the ASTER images. The central portion shows modest increases in groundwater levels, indicating sub-surface recharge is sufficient to meet demand in that area. However, the overall trend for the basin is negative with average water levels dropping by some 0.2 m yr⁻¹.

4.11.4. Conclusions and discussion

A steady-state model was developed using PMWIN as pre- and postprocessor for MODFLOW. The 1-layer model used 500x500m cell size, with 4,996 active cells with a total area of 1,249 km². The steady state water budget shows that with a total recharge of 267 MCM yr⁻¹, a total abstraction (wells, kanats, springs) of 192 MCM yr⁻¹ and seepage into the Zayandeh Rud of 76 MCM yr⁻¹ overall, these components are in equilibrium. However, much depends on the aquifer’s hydraulic transmissivity and conductivity values. If these decrease, then so does the total recharge and with that, all components are changed.

If abstraction increases beyond 192 MCM yr⁻¹ then, according to the model, a new steady-state will be reached with lower ground-water levels. This in turn increases the hydraulic gradients. If there are increasing abstractions, ground-water levels near the Zayandeh Rud will be drawn lower than the river level, leading to losses from the river to the aquifer. This will likely have a considerable impact on the hydrology of the river itself, reducing flows to downstream areas.

The aquifer is not in a steady state at present, which is shown by the decreasing groundwater levels and the diminishing discharge from the kanats and springs. Therefore, over-abstraction is clearly taking place. The northwest and northeast corners of the aquifer are clearly areas in need of detailed attention, because well levels here are going down at a rate of 0.5 m yr⁻¹, whereas the yield of springs and kanats is only 50 percent of what they were 10 years ago.

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

At basin level, the traditional concepts of irrigation system efficiency are not necessarily valid, largely because of opportunities to reuse water further downstream—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 suffer from salinity or salinity related problems, which is 50 percent 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. If groundwater is highly saline and not used, then any accessions to groundwater are in fact losses, and the conventional concept of efficiency is useful.

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 is 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, and in their physical soundness. For the Zayandeh Rud basin in Iran, a simplified approach has been 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.

4.12.1. 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 an oriented style to support this transparency and flexibility.
Figure 4.45. Schematic stream flow network of the Zayandeh Rud.

Chadegan Reservoir

Reg. Dam

P. Zamankhan

Pol-e-Kalleh

Nekouabad

Musiyan

Pol-e-Chom

Varzaneh

Gavkhouni Swamp

Note: Dom = domestic; Prec = precipitation; SSI = small-scale irrigation
WSBM assumes that the river is divided into reaches defined between two successive nodes. Nodes are located at typical points in the river where 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 set up 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.

**Input data**

A schematic representation of the stream network can be seen in figure 4.45. The Borkhar and Mahyar irrigation schemes started to function in 1997 and 1998, respectively. Table 4.15 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). Because variation in deliveries to the different irrigation schemes considered is low, monthly averages from the other years were used to fill in the missing data. Model performance was checked at seven sites along the river where monthly gauge data are available.

For all the irrigation systems, some return flow is assumed. As a best estimate return flows were set at 20 percent of total delivery (table 4.15). This relatively low value was assumed to be realistic as this is the overall irrigation scheme return flow because internal return flows within a scheme are not considered. Moreover, almost all water-scarce systems 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 fixed amount of salt accumulation was assumed, which can be flowed to the deep groundwater, some uptake by the crop, and storage in the soil profile. This accumulation was assumed to be 10 percent of the total salt inflow, resulting in a salt return flow of 90 percent. This salt return flow of 90 percent combined with the water return flow of 20 percent is the primary cause of increasing salinity levels downstream along the river.

For each reach, a fixed amount of 1.9 m³ s⁻¹ for urban and industrial use was assumed. Return flows of these extractions are normally high and were set at 50 percent, 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 as representing 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 sufficiently accurate.
Table 4.15. Nodes defined in the simulation model and observed annual average extractions at reaches.

<table>
<thead>
<tr>
<th>Node</th>
<th>Extraction</th>
<th>Avg. flow m³/s</th>
<th>Return flows %</th>
<th>Salt accumulation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chadegan Reservoir</td>
<td>Domestic</td>
<td>1.9</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Precipitation</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Regulating dam</td>
<td>Domestic</td>
<td>1.9</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Precipitation</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pol-e-Zamankhan</td>
<td>Small-scale irrigation</td>
<td>1.9</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Domestic</td>
<td>1.9</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Precipitation</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pol-e-Kal-e</td>
<td>Mahyar</td>
<td>1.7</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Nekouabad LB</td>
<td>16.4</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Nekouabad RB</td>
<td>6.9</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Small-scale irrigation</td>
<td>4.7</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Domestic/industrial</td>
<td>1.9</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Precipitation</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nekouabad</td>
<td>Small-scale irrigation</td>
<td>4.7</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Domestic/industrial</td>
<td>1.9</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Precipitation</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Musiyan</td>
<td>Borkhar</td>
<td>1.1</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Esfahan</td>
<td>4.6</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Small-scale irrigation</td>
<td>4.7</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Domestic/industrial</td>
<td>1.9</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Precipitation</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pol-e-Cham</td>
<td>Abshar LB</td>
<td>7.2</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Abshar RB</td>
<td>7.0</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Rudasht</td>
<td>0.4</td>
<td>20</td>
<td>10</td>
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<td></td>
<td>Small-scale irrigation</td>
<td>4.7</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Domestic/industrial</td>
<td>1.9</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Drain inflow</td>
<td>9.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Precipitation</td>
<td>1.2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Note: Return flows and salt accumulation are estimated values.*
The model was set up for an 11-year 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 in chapter 5.

4.12.2. 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 than measured. Increasing the small-scale irrigation extractions resulted in negative values during some months and still high values during 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 m³ s⁻¹) was assumed.

Including this adaptation in the model, recorded and simulated streamflows were compared for the seven locations along the river. Table 4.16 shows this comparison and some statistics. Observed and simulated values for the Regulating Dam were similar to the Pol-e-Zamankhan ones. Calculated values were close to observed ones, especially for the more upstream nodes.

<table>
<thead>
<tr>
<th>Node</th>
<th>RMSE m³ s⁻¹</th>
<th>r²</th>
<th>Absolute Difference m³ s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulating Dam</td>
<td>3.87</td>
<td>0.99</td>
<td>0.67</td>
</tr>
<tr>
<td>Zamankhan</td>
<td>5.09</td>
<td>0.98</td>
<td>1.63</td>
</tr>
<tr>
<td>Pol-e-Kaleh</td>
<td>5.63</td>
<td>0.98</td>
<td>3.17</td>
</tr>
<tr>
<td>Nekouabad*</td>
<td>13.43</td>
<td>0.69</td>
<td>5.63</td>
</tr>
<tr>
<td>Musiyar</td>
<td>7.48</td>
<td>0.71</td>
<td>2.85</td>
</tr>
<tr>
<td>Pol-e-Chom</td>
<td>10.65</td>
<td>0.81</td>
<td>5.78</td>
</tr>
<tr>
<td>Varzaneh</td>
<td>15.48</td>
<td>0.67</td>
<td>10.18</td>
</tr>
</tbody>
</table>

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

The excellent performance of the model for the Regulating Dam, Pol-e-Zamankhan and Pol-e-Kaleh nodes is related to the fact that almost no extractions take place in the upstream part. Between Pol-e-Kaleh and Nekouabad, a substantial amount of water was extracted (about 20 m³ 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 Pol-e-Chom and Varzaneh. In general, calculated flows were somewhat higher than observed ones and model performance was better for the upstream nodes than for the downstream nodes.

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\(^{-1}\). Huge 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 Pol-e-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 Pol-e-Chom and Varzaneh respectively.

4.12.3. Conclusions

For the Zayande Rud, a simple spreadsheet-based water and salt balance model has been developed that 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.

Some general conclusions can be drawn from this study. The flow to the Gavkhouni 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. Improved field-scale management, more productive crops, minimizing accessions to saline groundwater and decreased non-beneficial evaporation are ways to achieve this higher agricultural productivity.

The Water Salt Balance Model is an important element of the scenario analyses made in chapter 5, because it enables us to examine not just production impacts of alternative water management options but also some of the environmental ones as well, which are discussed later in the text.
4.13. Options for charging for irrigation water in Iran

C. Perry

In many countries where water is scarce, agriculture still consumes more than 80 percent of all water. Many people believe that if there were some form of water pricing that discouraged excessive use by farmers, more water would be made available for others, or there would be significantly higher productivity in water utilization due to responsiveness to the cost of water. Water pricing also brings with it the prospect of financing irrigation on a sustainable basis through a program of cost recovery.

4.13.1. Water pricing for financing irrigation through cost recovery

Cost recovery requires several mechanisms to be in place to be effective. Firstly, the true value of recurrent costs for O&M needs to be quantified. This is not as simple as it seems because some costs are periodic and will result in peaks of expenditure every few years. Secondly, a decision is required on how much of the capital cost, and capital replacement cost, should be borne by water users, how much by other beneficiaries, and how much by government in the form of a subsidy. In reality, it proves difficult to determine an accurate figure, although data from Egypt and Haryana, India indicate that O&M costs are in the range of US$0.002-0.003 m⁻³ delivered.

At this level, it is unlikely that there will be a large incentive for water users to consume less. Values of water invariably exceed US$0.02, and typically average US$0.02 m⁻³, US$0.10-0.20 m⁻³ and may be many times higher, so that the cost of water is a small fraction of the benefits accrued. Further, O&M recoveries are often made on the basis of an areal charge rather than a volumetric one, so there is no real incentive to reduce volume consumed.

4.13.2. Water charges to encourage efficient use

Charging water at a rate that discourages waste is essentially a form of taxation. It also requires a capacity to accurately measure water so as to establish an effective volumetric price that can be charged to the consumer.

Regulatory measures are essential to impose high levels of water charges. The regulation has to cover both the supplier of water, to ensure that agreed delivery schedules and promised volumes are maintained, and on water users to prevent unauthorized tampering with physical structures or coercion of operational staff of the irrigation agency.

Operational requirements are also very high. There has to be a verifiable system of water measurement so that both supplier and consumer can agree on the discharge or volume delivered. This is hard where holdings are small or fragmented, and wholesaling to groups of water users raises a whole set of additional institutional questions about the sharing of water and of payments. This type of arrangement favors “free-riders”, who can be wasteful at the expense of other members of the water user organization. There is also pressure on the supplier to develop a quick billing system so that defaulters can have action taken against them as quickly as possible, which will deter future missed payments.
Economic requirements aim either at discouraging waste by billing for all water consumption and hoping the consumer will respond through application of thrift, or by fixing a marginal price that will optimize water delivery and use. We have already seen that the cost of delivering water is many times less than the potential benefit, and prices would have to be set so high as to have a major impact on farm incomes.

Water savings anticipated from trying to get consumers to be more efficient may, in many cases, be illusory. If there is a high degree of recycling within a basin so that water not used in one part can be captured and reused by other people, then reducing farm-level consumption may have no overall effect at basin level. The “saved” water still reaches the downstream user directly, whereas the “wasted” water merely gets there by a more circuitous manner (but may be of lower quality).

4.13.3. The Zayandeh Rud case study

Given the acute scarcity of water in the Zayandeh Rud, and the common perception that irrigation, and particularly rice irrigation, is inefficient, there would appear to be plenty of opportunities for water saving. However, given the high level of reuse, both through surface drains that discharge back to the Zayandeh Rud, or through rapidly increasing exploitation of groundwater, these savings may in large measure be illusory except in the tail-most areas where groundwater and drainage water are both highly saline.

If farmers invest in high technology to try to effect some water savings, then there is an element of investment that must be discounted against current costs of water. Table 4.17 shows that investment of US$1000 ha⁻¹ will result in savings between US$0.11 and US$0.14 m⁻³. Allowing for some degree of sensitivity of the cost of water, we can assume that cost to the farmer will be in the range of US$0.08-0.21 m⁻³. This compares very unfavorably with the current cost of water, approximately US$0.004 m⁻³. It would require a 20-fold increase in the cost of water to cover the capital expenditure of the farmer, and would make lower value crops such as wheat unattractive, if not totally uneconomic.

<table>
<thead>
<tr>
<th></th>
<th>Water demand (m²/year)</th>
<th>Cost ($/m²)</th>
<th>Delivery reduction (m²)</th>
<th>Annual capital cost ($/year)</th>
<th>Annual operational cost ($)</th>
<th>Total annual cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-season use</td>
<td>10,000</td>
<td>0.14</td>
<td>3,175</td>
<td>148</td>
<td>200</td>
<td>348</td>
</tr>
<tr>
<td>Single-season use</td>
<td>5,000</td>
<td>0.11</td>
<td>1,587</td>
<td>120</td>
<td>100</td>
<td>220</td>
</tr>
</tbody>
</table>

Note: Assumes on-farm losses reduced from 30 percent to 10 percent, discount rate of 10 percent p.a., life length of 10 years for two-season use and 15 years for single-season use

Looking more closely at the marginal value of water, we find that it changes significantly throughout a single season, and thus it becomes very difficult to set a single figure. It is more practical to use the average value, but even that has difficulties due to uncertainties over crop valuation, cash inputs, non-cash inputs, and whether we look at consumed water or delivered water.
Table 4.18. Average gross and net costs and values for various grain crops.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Production costs ($/t)</th>
<th>Yields (t/ha)</th>
<th>Price ($/t)</th>
<th>Gross value of production($/ha)</th>
<th>Net value of production($/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>420</td>
<td>6.0</td>
<td>120</td>
<td>720</td>
<td>300</td>
</tr>
<tr>
<td>Barley</td>
<td>420</td>
<td>6.0</td>
<td>100</td>
<td>600</td>
<td>180</td>
</tr>
<tr>
<td>Maize</td>
<td>420</td>
<td>7.0</td>
<td>100</td>
<td>700</td>
<td>280</td>
</tr>
<tr>
<td>Rice</td>
<td>1,000</td>
<td>7.0</td>
<td>4,500</td>
<td>3,150</td>
<td>2,150</td>
</tr>
</tbody>
</table>

Given that water still costs roughly US$0.004 per m3 and will amount to some $30 ha⁻¹ for most grains, and US$100 for rice, the costs are only about 10 percent of the net value of most grains and only about 4 percent for rice (table 4.18). This makes it virtually impossible to consider volumetric pricing as a mechanism for controlling water use unless the water price is raised many times. Given the price bias towards rice, this is unlikely because the price will still be low in relation to the value of the crop.

Salt balance also plays a role in considering how to price water. Saline water is inherently less productive that fresh water, and so there should be some mechanism for compensating farmers who have access only to saline water. But this adds yet another complicating mechanism into the process which will bring additional institutional stresses.

4.13.4. Pricing vs. allocation

The Zayandeheh Rud study illustrates that even if prices and production costs were uniform for different crops, it is difficult to imagine that the price can be set high enough to bring about optimal use of water within irrigation systems. The gross returns per cubic meter are presently many times higher than the cost of water so that there would be severe political and social difficulties in raising water prices to a level that affects water consumption.

The logical alternative is to explore some form of allocation of water. Water rationing between different users is relatively common when water is scarce. Competition, not only between different agricultural users, but also with other sectors means that allocation becomes a critical component of water management at basin, system and field level.

In Zayandeheh Rud this is undertaken, albeit inefficiently, by the design capacity of irrigation canals at each regulator. Current management practices run canals at or close to full supply level during seasons of peak demand, and upper-end systems are somewhat constrained in meeting crop requirements under these conditions.

However, there is no clear system of water rights that translates into a transparent water-allocation system, and it appears that this will be increasingly needed in the future. As the share of water for agriculture drops due to the growth of demand in other sectors, the shortfall in different irrigation systems will increase. Tail-end systems will experience greater shortfalls than head-end ones whenever water supply is below normal because head-end systems can take up to the canal design capacity.

Under these systems, we require a two-fold approach: charges for water that cover recurrent O&M costs, and a system of water rights or shares that reflect not only "normal" conditions but also conditions of water scarcity when there is increased need to consider equity and livelihoods as well as production.

H.R. Salemi and H. Murray-Rust

In any river basin, and particularly one which is perennially water-short, it is important to have reliable estimates of both likely water supply and demand by different sectors. With this information, it is possible both to contemplate new water-resources development and to adjust allocations between sectors as demand patterns change.

The Zayandeh Rud basin has been water short for many years, and this has resulted in a program of water resources development from 1952 onwards (Montazpur 1995). By 2010, almost all potential water resources will have been developed, including three trans-basin diversion tunnels, the Chadegan Reservoir and several smaller springs and other local water sources. Once that stage of development is complete, the focus in the basin will be primarily one of allocation between different sectors so as to continue to match supply and demand into the future.

In this section, we examine demands for water at three separate times: 2000, representing present supply and demand, and 2010 and 2020 as future projections.

4.14.1. Water supply

Planned water supplies for 2000 totaled 1,487 MCM, consisting of 900 MCM of natural inflow and 587 MCM from two diversion tunnels from the Kuhrang River (table 4.19).

Projected water resource developments comprise an additional tunnel from Kuhrang providing another 280 MCM, and local springs and other sources totaling 150 MCM. This means that before 2010 the total water planned for the basin will be 1,917 MCM. This figure appears to represent the maximum available water for the basin for the foreseeable future (figure 4.46).

Figure 4.46. Planned water supplies for Zayandeh Rud, 2000-2020.

<table>
<thead>
<tr>
<th>Water Balance for Zayandeh Rud, Esfahan - Year 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Estimates</td>
</tr>
<tr>
<td>Natural Flow of Zayandeh Rud at Chadegan</td>
</tr>
<tr>
<td>Kurang Tunnel 1</td>
</tr>
<tr>
<td>Kurang Tunnel 2</td>
</tr>
<tr>
<td>Kurang Tunnel 3</td>
</tr>
<tr>
<td>Langan and Khadangestan Springs</td>
</tr>
<tr>
<td>Total Supply</td>
</tr>
</tbody>
</table>

Demand Estimations

Urban Areas

<table>
<thead>
<tr>
<th>Greater Esfahan</th>
<th>210</th>
<th>275 l/day/person for 2,100,000 people</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply for Other cities near river</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total Urban Supply</td>
<td>210</td>
<td>14</td>
</tr>
<tr>
<td>Return flows from urban areas</td>
<td>-105</td>
<td>-7</td>
</tr>
<tr>
<td>Industry</td>
<td>100</td>
<td>7</td>
</tr>
<tr>
<td>Agriculture</td>
<td>1500</td>
<td>101</td>
</tr>
</tbody>
</table>

Return flows from agriculture                         | -300| -20                                   |
| Environmental Demand                                  | 0   | 0                                   |
| Transbasin Deversion                                  | 34  | 2                                   |
| Evaporation                                           | 74  | 5                                   |
| Total Demand                                          | 1513|                                     |

Deficit                                                | -26 | -2                                  |


Table 4.20 also summarizes the main demands for water in 2000. These cover normal demands for urban, industrial and agricultural use, including an allowance for return flows from urban areas (50 percent) and agriculture (20 percent). Substantial volumes of wastewater are used to irrigate forests around cities and industrial plants so that return flows are lower than is normal for urban and industrial areas.

In addition, there is a trans-basin diversion out of the basin to Yazd, currently at 34 MCM but planned to rise to 80 MCM, and to Kashan which is under development and will take 45 MCM. Environmental requirements for the Gavkhouni Swamp have been set at 70 MCM per year, but in 2000 this was not included in the water budget. These allocations are fixed and will not change in the future. Evaporation losses from the reservoir and other places within the basin are estimated at 5 percent of total supply.

It can be seen that even in 2000, water demand exceeds supply by some 26 MCM, although this is probably within the error of estimation of both supply and demand.
4.13.3. Projection of future demands for water

There are many different possibilities for projection of demand for water between different sectors in the basin. To do this, we have adopted a set of increasingly complex scenarios and examined the implications for growth in the basin. The scenarios are as follows:

Scenario 1: All sectors grow by 2 percent a year
Scenario 2: All sectors grow by 1 percent a year
Scenario 3: Urban demand increases by 2.5 percent a year, other sectors by 1 percent a year
Scenario 4: Urban demand grows by 2.5 percent, industry by 1 percent, and agriculture is adjusted to balance total supply and demand in the basin

These scenarios all assume that water supply is at a planned level. Two additional variations on scenario 4 were therefore developed:

Scenario 4a: Scenario 4 with a 10 percent shortfall in water supply
Scenario 4b: Scenario 4 with a 20 percent shortfall in water supply

The results of the first three scenarios are summarized in table 4.20.

Table 4.20. Water supply and demand projections with growth for all sectors.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2000</th>
<th>2010</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supply</td>
<td>Demand</td>
<td>Surplus/Deficit</td>
</tr>
<tr>
<td>1</td>
<td>1,487</td>
<td>1,513</td>
<td>-26</td>
</tr>
<tr>
<td>2</td>
<td>1,487</td>
<td>1,513</td>
<td>-26</td>
</tr>
<tr>
<td>3</td>
<td>1,487</td>
<td>1,513</td>
<td>-26</td>
</tr>
</tbody>
</table>

These three scenarios all anticipate growth in all sectors, although Scenario 3 assumes a higher growth rate for urban areas than for other sectors. While Scenarios 2 and 3 show a modest surplus in 2010 when all water resources are developed, all three Scenarios are in deficit by 2020 and continue to get worse into the future.

To try to balance out supply and demand, agriculture was selected as the sector, which has to give up water, partly because it is the largest user of water in the basin, and because other sectors have higher priorities for human health and welfare.

Scenario 4 balances out supply and demand by treating agriculture as a residual. Table 4.21 examines the impact on agriculture of these changes.

Table 4.21 shows that with an increase in basin supplies of 430 MCM per year, agriculture will gain an additional 172 MCM in 2010, but this will shrink to 118 MCM over current levels by 2020.

However, in the event that water supplies drop to less than 90 percent of the planned supply—an event expected at least once every 3 years—then agriculture will never receive current levels of water allocation despite the increased supply at basin level. When water
Table 4.21. Impact of changed water allocations on agricultural water availability.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2000</th>
<th>2010</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basin supply</td>
<td>Change from</td>
<td>Basin supply</td>
</tr>
<tr>
<td></td>
<td>to agriculture</td>
<td>2000</td>
<td>to agriculture</td>
</tr>
<tr>
<td>4</td>
<td>1,487</td>
<td>1,200</td>
<td>0</td>
</tr>
<tr>
<td>4a</td>
<td>1,338</td>
<td>1,032</td>
<td>-168</td>
</tr>
<tr>
<td>4b</td>
<td>1,190</td>
<td>891</td>
<td>-309</td>
</tr>
</tbody>
</table>

Supplies fall to less than 80 percent of that planned, then the share to agriculture is much less than at current levels.

It is unclear to what extent there are effective mechanisms to apportion shortfalls in water at basin level, either between sectors or within the agricultural sector. Experience at present is that all sectors take as much water as they can up to the extractive limit. The result is that the environment is the main sufferer, as is shown by very low flows, or even dry conditions, at Varzaneh whenever supplies fall below the planned level.

These projections overall do not allow for large growth in the Zayandeh Rud basin. Scenario 4, considered the most realistic from a hydrologic and social point of view, allows for a population growth rate of only 20 percent per decade, industrial demand of less than 1 percent a year, and fixed allocations for environment and trans-basin diversions. There is really only a very limited opportunity for increasing supplies to agriculture, and only if supplies are at or above planned levels. Whenever these conditions are not met, then agriculture is the main loser in the struggle to obtain sufficient water in the Zayandeh Rud.

It is in this context of shrinking water supplies predicted for agriculture in the Zayandeh Rud basin that we can move on to the assessment of different scenarios for the future, and the water availability projects they entail.
Chapter 5

Water management options for the future in the Zayandeh Rud Basin

5.1. Introduction

The previous chapter showed the utility of models in understanding current processes and relationships across a wide variety of different aspects of water management. While this is of considerable utility, it is not the only benefit of using models.

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.

It is this ability to link across scales that makes the integrated approach to modeling so valuable. Without this benefit, modeling at a single scale in isolation may lead us to improper policies—the benefits that accrue at that scale alone cannot be assessed in terms of the relative cost or benefit at another level. This is particularly true in water-short basins where all water is already used productively. Any increase in one sector will inevitably means less water for other sectors, and the cost of such water reductions needs to be looked at in a holistic, basin-wide manner.

5.2. Scenarios, projections and water management options

Three clear steps should be distinguished in the process of defining future water management: scenario, projection, and water management options. Scenarios define what is likely to happen in the future. They can include exogenous as well as indigenous factors. Projections are the consequences of these scenarios and describe what the impact of a certain scenario is. An example of this link between scenario and projection in climate change studies is: CO2 levels rise by 2 percent a year (= scenario) which will lead to a rise in sea level of 20-40 cm (= projection). Another example is that as a scenario we expect that the number of inhabitants in the Zayandeh Rud basin will rise from 2.2 million to 3.5 million (= scenario), resulting in an increase in urban water requirements of 30-60 MCM (= projection). It is clear that a scenario is a fixed and well-defined expected change, while a projection describes the consequence and is therefore not exactly known.

The water management options, also called adaptation strategies, describe how we can cope with a given scenario and projection. It might be clear that there are innumerable water management options and that the best should be selected to adapt to the expected situation as
defined by the projection. In order to select the best water management option, we should evaluate each option by a set of so-called performance indicators. The best water-management options depend to a great extent on the policy in place, as often choices have to be made whether emphasis should be on agriculture, industry, environment, equity, total productivity etc. However, the set of performance indicators associated to each water-management option helps to make a sound decision about which option is best in the context of the policy in place.

To assist us in identifying realistic scenarios for which water management options should be tested using a range of integrated models as developed during the project, it is useful to recognize that there are four distinct groups of factors that represent the scale at which changes in present practices or conditions can occur. These four factors are all related to the scenario-projection-water management option relationship and are shown in figure 5.1, together with an indication of the most likely types of linkages between each level.

Figure 5.1. Pathways for assessment of scenarios.

Exogenous factors
response to climatic change and droughts

Basin
policy changes on allocation to different sections

Irrigation system
changed allocations between systems, revised scheduling

Irrigated agriculture
new crops, new crop calendars, new technologies

Red lines (on left) represent responses to exogenous changes, solid lines being direct responses and dashed lines representing indirect responses. Green arrows (solid centre and right) are direct linkages between different scales. Blue arrows (dotted, right) represent indirect consequences of direct linkages. The implication is that change at any one level must be assessed by impact on basin, irrigation system and farm level.
5.2.1. Exogenous factors

Exogenous factors are ones over which we have no control. They are at a level greater than that of an individual basin, and represent conditions to which we have to respond through effective planning but which we cannot control directly. These may be related to climatic change which may directly affect total precipitation or indirectly lead to changes in land cover, or they may be the direct impact of human disturbance of natural systems through land use changes, industrial development and food self-sufficiency policies that affect basin hydrology.

The effect of all of these changes is to change the overall water availability at basin level from normal conditions to ones that require commensurate changes in management within the basin. It is assumed that direct impacts of climatic change or drought may elicit response at basin or farm level, while irrigation system management will likely respond indirectly because of changes in policy or farm level demand.

5.2.1. Basin level factors

At basin level, most of the factors leading to different scenarios relate to allocation decisions related to some form of policy change. They generally reflect the changing balance in supply and demand at basin level; they invariably affect the allocation of water resources between sectors, and may also impact directly on the allocation of resources within a particular sector by favoring or discouraging a particular type of water use.

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 will be allocated for agriculture, and when it will be made available.

5.2.3. Irrigation system level factors

The third level of factors comes at irrigation system level, and reflects management decisions made concerning the share of water allocated to the agricultural sector. Initially, the allocation and distribution decisions have to be made at those locations where water can be diverted into irrigation systems, deciding on what share each irrigation system receives. At a lower level, decisions are required concerning allocation and distribution practices within irrigation systems. Both sets of decisions will likely reflect conditions when water was more abundant at basin level, or when water for the irrigated agriculture sector was more assured. Changes can occur both by modifying current delivery patterns and schedules while still using the same overall volume of water, or operating the system when less water is available. At this level, managers are not concerned directly with water use, but with water allocation and distribution to secondary and tertiary portions of the system.
5.2.4. Field-level factors

The final level is that of farm-level irrigated agriculture. Farmers may choose to modify their agricultural practices in a variety of ways: for example, through adoption of new technologies, changing cropping patterns, or changing the ratio of surface water to groundwater in conjunctive use systems. Direct changes on irrigation systems may be caused by changing demand patterns, while impacts at basin level will normally be indirect.

Some field level factors represent direct farmer response to water conditions, while others may reflect response to policy or regulations that attempt to influence the way individual farmers respond. This highlights the multi-level interactions we have to examine when doing scenario assessments because there can be direct links between different levels at the same time.

5.3. Scenarios for Zayandeh Rud Basin

In section 4.14 some scenarios for the Zayandeh Rud Basin have been presented, including an increase in basin-water availability as a result of the completion of an additional inter-basin transfer from Kurang of 280 MCM in 2010 and development of local springs and other water sources totaling 150 MCM. At the same time, an increase in water demand by different sectors is expected as well as some inter-basin transfer outside the Zayandeh Rud. Four scenarios were presented for this increase in water demand, and it was concluded that scenario 4, where urban demand grows by 2.5 percent, industry by 1 percent, and agriculture is adjusted to balance total supply and demand in the basin, is the most realistic.

We take the year 2020 as a reference point to develop our projections and water management options focusing on agriculture. This can be accomplished by using the total volume of water available to the agriculture sector as our starting point for undertaking water management options assessment. From the perspective of farmers, it does not make much difference whether there is a reduced water allocation due to drought or due to allocation to another sector—the result is simply less water available for agriculture. We therefore make our assessments based on the result of upstream actions or processes.

In summary, this means that the scenario analyzed here is that water availability will increase from 1,487 MCM average to 1,917 MCM and that annual demand by the urban sector will rise from 210 to 345 MCM and by industry from 200 to 244 MCM.

5.4. Projections for Zayandeh Rud Basin

As mentioned above, one scenario can lead to more than one projection, as uncertainties should be accounted for. In section 4.14 we found that overall water availability for agriculture in the basin can range from a high of 1,715 MCM to a low of 1,100 MCM under balanced budget scenarios. The high figure represents water available to the agricultural sector in 2010 with all water resources developed and normal water conditions, and meeting all non-agricultural demands. The low figure represents water available in 2000 at 80 percent of normal supply, which still meets all non-agricultural demands. However, projections should normally look at extreme conditions as well as normal ones. The drought of 1999-2000 in
the basin saw water availability far below 500 MCM, way out of the range of scenarios examined in section 4.14 of chapter 4.

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 therefore, we can use six projection values for impact assessments that allow us to examine the whole range of conditions from severe drought to abundant water conditions. These values are shown in table 5.1.

<table>
<thead>
<tr>
<th>Projection</th>
<th>Water availability (MCM/year)</th>
<th>Index value for impact assessment (MCM/year)</th>
<th>Water availability classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt;625</td>
<td>500</td>
<td>Severe Drought</td>
</tr>
<tr>
<td>2</td>
<td>625-875</td>
<td>750</td>
<td>Drought</td>
</tr>
<tr>
<td>3</td>
<td>875-1,125</td>
<td>1,000</td>
<td>Below Average</td>
</tr>
<tr>
<td>4</td>
<td>1,125-1,375</td>
<td>1,250</td>
<td>Average</td>
</tr>
<tr>
<td>5</td>
<td>1,375-1,625</td>
<td>1,500</td>
<td>Above Average</td>
</tr>
<tr>
<td>6</td>
<td>&gt;1625</td>
<td>1,750</td>
<td>Abundant Water</td>
</tr>
</tbody>
</table>

5.5. Water Management Options

The main interest of water managers and water policy makers is how to respond best to the six projections as presented in table 5.1. It is important to realize that these responses take place at different levels and each level has its own set of options.

At basin scale, options are limited and are already decided at a higher hierarchical level in terms of inter-basin transfer and a further increase in urban and industrial water supply. In fact, this water management option decided at a higher scale is the base for the scenario and projections we are focusing on.

5.5.1. Irrigation system level water management options

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, which is a kind of mixture between preference to upstream irrigation systems and equal allocation. The Nekouabad systems are allowed to use a substantial amount of water and have the option to grow rice, while downstream users have second priority and suffer most during droughts. However, some mechanisms are built in to ensure at least during one season that some water is allocated to downstream users.
The second option is equal allocation between irrigation systems based on the designed command area. All available water is divided up proportionately between the systems irrespective of total water availability, unto the limit of the designed capacity of the main canal—all water shortages are shared equally between all systems, while surpluses will flow to Gavkhouni swamp.

The third option is the “first-come, first-serve” allocation, which progressively satisfies the demand of the headmost systems, and allocates the 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 is an infinite number of intermediate conditions between these three options, and analysis of these three alone will provide the extreme conditions in terms of impact assessment.

Table 5.2. Water management options for system managers in the Zayandeh Rud basin.

<table>
<thead>
<tr>
<th>Option</th>
<th>Management characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>Current situation</td>
</tr>
<tr>
<td>S1</td>
<td>Equal allocation among systems</td>
</tr>
<tr>
<td>S2</td>
<td>Unequal allocation among systems</td>
</tr>
</tbody>
</table>

5.5.2. Field-level water management options

Field level water management options reflect the actions of individual water users either collectively or working in isolation. For assessing impacts of different options, however, we generally assume some form of collective action from water users so as to obtain the maximum impact of those actions. In terms of options available in Zayandeh Rud, we look at a few that might be expected to have major impacts. Small changes in cropping patterns that do not significantly change ET are not assessed because the results will more or less approximate current conditions.

The options we have selected for analysis reflect a combination of changes we think are likely to occur in given current trends, and those that are being advocated by different groups (table 5.3). While this is not a selective list, we feel it provides a sufficient range of options for policy makers and farmers to consider.

Table 5.3. Field-level management options in the Zayandeh Rud.

<table>
<thead>
<tr>
<th>Option</th>
<th>Management characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>Current cropping patterns</td>
</tr>
<tr>
<td>F1</td>
<td>Farmers stop growing rice</td>
</tr>
<tr>
<td>F2</td>
<td>Farmers adopt improved farm level water management techniques</td>
</tr>
<tr>
<td>F3</td>
<td>Deficit irrigation</td>
</tr>
</tbody>
</table>
These four farm level options, combined with three system level options, give 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.

5.6. Assessing water management options

To assist in the process of evaluating the different water management options, it is important to have a set of performance indicators that can be compared across all options. Without such a set of common indicators, comparison remains subjective and open to misunderstanding.

At each level, therefore, a set of performance indicators has been identified that will help to determine what the impact is of a change at one level on the performance at other levels. A list of common indicators is presented in table 5.4. It must be clearly understood that this is not an exhaustive list of indicators, merely a subset of all possible indicators. Having too many indicators does not help in determining the relative suitability of a particular option.

It is also clear that, for a number of water management options, the outcomes at a different level may be identical. Changes in the total water availability at farm level may result from several different causes, e.g., reduced water allocation by sector, drought, changed irrigation system scheduling, or restrictions on use of groundwater, which makes the evaluation procedure more streamlined.

<table>
<thead>
<tr>
<th>Table 5.4. Performance indicators for assessing different scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level</strong></td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>Basin Level</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Irrigation System</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Farm Level</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

123
Once the values of these parameters have been determined for each management option, it becomes possible to see which options are better and which are worse. As mentioned earlier, this depends on political decisions on where to put emphasis. There is no simple way to optimize the management options. Instead, we have first to try to eliminate those that result in acceptable values for one or more performance indicators, and then come to consensus among all involved parties (policy makers, managers and water users) as to which management option appears to be most suited to a particular level of water availability.

5.7. Modeling approaches

5.7.1. Basin and irrigation system scale

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 (Droogers et al. 2000c). The model has been generalized and was setup for only 1 year, using average conditions as occurred from 1989 to 1999. This 11-year period included a wet year (1993) and the first dry year (1999) of the drought that occurred from 1999 to 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 (table 5.5). This data is used for the S0 option, where water is allocated according to the current situation.

<table>
<thead>
<tr>
<th>System</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mahyar</td>
<td>3</td>
</tr>
<tr>
<td>Nekouabad LB</td>
<td>27</td>
</tr>
<tr>
<td>Nekouaamad RB</td>
<td>12</td>
</tr>
<tr>
<td>Borkhar</td>
<td>2</td>
</tr>
<tr>
<td>Abshar LB</td>
<td>14</td>
</tr>
<tr>
<td>Abshar RB</td>
<td>12</td>
</tr>
<tr>
<td>Radaah</td>
<td>10</td>
</tr>
<tr>
<td>Small-scale Systems</td>
<td>20</td>
</tr>
</tbody>
</table>

Note: Data originates from average water allocation over the period 1989-1999.

With regard to 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 Gieske et al. (2002) to assess the water allocation rules according for option S1 (table 5.6).
Table 5.6. Water allocation rules equal distribution according to area.

<table>
<thead>
<tr>
<th>System</th>
<th>Area (ha)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mahyar</td>
<td>24,000</td>
<td>12</td>
</tr>
<tr>
<td>Nekouabad LB</td>
<td>26,872</td>
<td>13</td>
</tr>
<tr>
<td>Nekouanad RB</td>
<td>13,183</td>
<td>6</td>
</tr>
<tr>
<td>Borkhar</td>
<td>18,500</td>
<td>9</td>
</tr>
<tr>
<td>Abshar LB</td>
<td>23,002</td>
<td>11</td>
</tr>
<tr>
<td>Abshar RB</td>
<td>12,570</td>
<td>6</td>
</tr>
<tr>
<td>Rudasht</td>
<td>47,000</td>
<td>23</td>
</tr>
<tr>
<td>Small-scale Systems</td>
<td>40,000</td>
<td>20</td>
</tr>
</tbody>
</table>

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. This means that first all water will be used by the Mahyar and the Nekouabad systems, then by Borkhar, followed by the Abshar system and finally by Rudasht. The implications of these water management options are displayed in table 5.7, where for each system the total amount of water allocated is presented, calculated based on average irrigation depths.

Table 5.7. Water distribution according to water management option S2: unequal, with upstream users given highest priority.

<table>
<thead>
<tr>
<th></th>
<th>Mahyar</th>
<th>NKL</th>
<th>NKR</th>
<th>Borkhar</th>
<th>ABL</th>
<th>ABR</th>
<th>Rudasht</th>
<th>SSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total supply (MCM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1 = 500</td>
<td>143</td>
<td>160</td>
<td>78</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P2 = 750</td>
<td>214</td>
<td>240</td>
<td>118</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P3 = 1,000</td>
<td>286</td>
<td>320</td>
<td>157</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P4 = 1,250</td>
<td>288</td>
<td>322</td>
<td>158</td>
<td>116</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P5 = 1,500</td>
<td>288</td>
<td>322</td>
<td>158</td>
<td>222</td>
<td>8</td>
<td>4</td>
<td>17</td>
<td>43</td>
</tr>
<tr>
<td>P6 = 1,750</td>
<td>288</td>
<td>322</td>
<td>158</td>
<td>222</td>
<td>78</td>
<td>43</td>
<td>159</td>
<td>480</td>
</tr>
<tr>
<td>Relative water supply</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1 = 500</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>P2 = 750</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>P3 = 1,000</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>P4 = 1,250</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.52</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>P5 = 1,500</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>P6 = 1,750</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Percentage of total available</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1 = 500</td>
<td>0.29</td>
<td>0.32</td>
<td>0.16</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>P2 = 750</td>
<td>0.29</td>
<td>0.32</td>
<td>0.16</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>P3 = 1,000</td>
<td>0.29</td>
<td>0.32</td>
<td>0.16</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>P4 = 1,250</td>
<td>0.23</td>
<td>0.26</td>
<td>0.13</td>
<td>0.09</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>P5 = 1,500</td>
<td>0.19</td>
<td>0.21</td>
<td>0.11</td>
<td>0.15</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>P6 = 1,750</td>
<td>0.16</td>
<td>0.18</td>
<td>0.09</td>
<td>0.13</td>
<td>0.04</td>
<td>0.02</td>
<td>0.09</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Note: SSI = small scale irrigation.
These three water management options were analyzed using the previously developed and validated Water and Salinity Basin Model (WSBM) as described earlier (Droogers et al. 2001).

5.7.2. Field scale

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 earlier (Van Dam et al. 1997). The model was tested and applied for one crop in Rudabasht (Droogers et al. 2001b) and an extended study included the major crops and soil types in Zayandeh Rud Basin. The latter study will be used here to assess the different water management options at field scale.

Some simplifications and assumptions were necessary to assess all the water management options of which the most important one is that all soils are clay. This assumption is justified as most of the irrigated areas are indeed on clay soils.

Instead of running the SWAP model over and over, we have used the results from the SWAP runs to fit yield functions for each crop. The number of crops has been limited to the main crops and other crops were grouped together, for example, wheat and barley were considered similar. Table 5.8 shows the crops considered, their yield functions and some other characteristics. The yield function applied here is:

\[ Y = a + b \cdot EC + c \cdot Irr + d \cdot EC^2 + e \cdot Irr^2 + f \cdot EC \cdot Irr \]

Where: \( Y \) is yield (ton ha\(^{-1}\)), \( EC \) is salinity level or irrigation water (dS m\(^{-1}\)), \( Irr \) is total irrigation application (mm) and \( a, b, c, d, e, \) and \( f \) are constants.

**Table 5.8. Crops included in the water management options.**

<table>
<thead>
<tr>
<th></th>
<th>Rice</th>
<th>Alfalfa</th>
<th>Sugarbeet</th>
<th>Wheat</th>
<th>Vegetables</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>7.47E-01</td>
<td>8.50E-01</td>
<td>1.16E+00</td>
<td>8.50E-01</td>
<td>1.47E-01</td>
</tr>
<tr>
<td>b</td>
<td>-2.31E-01</td>
<td>-1.78E-01</td>
<td>5.98E-01</td>
<td>-1.79E-01</td>
<td>-7.54E-02</td>
</tr>
<tr>
<td>c</td>
<td>-8.43E-04</td>
<td>1.05E-02</td>
<td>5.13E-02</td>
<td>6.51E-03</td>
<td>5.60E-03</td>
</tr>
<tr>
<td>d</td>
<td>4.67E-02</td>
<td>2.41E-02</td>
<td>-8.08E-02</td>
<td>1.30E-02</td>
<td>2.79E-02</td>
</tr>
<tr>
<td>e</td>
<td>3.13E-06</td>
<td>-1.48E-06</td>
<td>-1.51E-05</td>
<td>-1.32E-06</td>
<td>5.89E-07</td>
</tr>
<tr>
<td>f</td>
<td>-6.68E-04</td>
<td>-5.61E-04</td>
<td>-7.45E-04</td>
<td>-2.69E-04</td>
<td>-6.54E-04</td>
</tr>
<tr>
<td>Optimal irrigation (mm)</td>
<td>1,800</td>
<td>1,800</td>
<td>1,200</td>
<td>1,000</td>
<td>1,800</td>
</tr>
</tbody>
</table>

| Return (US$/kg) | 0.43 | 0.11 | 0.03 | 0.04 | 0.25 |

Parameters \( a \) to \( f \) refer to the crop yield function and the irrigation depth can be considered as the amount of water where production in terms of kg ha\(^{-1}\) and $ m\(^{-1}\) are optimal.

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 (table 5.9).

An explorative study on the impact of converting the irrigation systems to pressurized system for the basin has been described before (Droogers et al. 2001b). 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 substantial, 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.

Table 5.9. Original and water management option F1 (no-rice) cropping patterns for each irrigation system.

<table>
<thead>
<tr>
<th></th>
<th>Mahyar</th>
<th>NKL</th>
<th>NKR</th>
<th>Borkhar</th>
<th>ABL</th>
<th>ABR</th>
<th>Rudasht</th>
<th>Small-scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>0.13</td>
<td>0.13</td>
<td>0.23</td>
<td>0.23</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.10</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0.08</td>
<td>0.08</td>
<td>0.06</td>
<td>0.06</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.12</td>
</tr>
<tr>
<td>Sugarbeet</td>
<td>0.10</td>
<td>0.10</td>
<td>0.11</td>
<td>0.11</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.31</td>
<td>0.31</td>
<td>0.33</td>
<td>0.33</td>
<td>0.53</td>
<td>0.53</td>
<td>0.53</td>
<td>0.41</td>
</tr>
<tr>
<td>Vegetables</td>
<td>0.38</td>
<td>0.38</td>
<td>0.27</td>
<td>0.27</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
<td>0.28</td>
</tr>
<tr>
<td>Scenario F1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0.09</td>
<td>0.09</td>
<td>0.08</td>
<td>0.08</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.13</td>
</tr>
<tr>
<td>Sugarbeet</td>
<td>0.11</td>
<td>0.11</td>
<td>0.15</td>
<td>0.15</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.10</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.36</td>
<td>0.36</td>
<td>0.42</td>
<td>0.42</td>
<td>0.54</td>
<td>0.54</td>
<td>0.54</td>
<td>0.46</td>
</tr>
<tr>
<td>Vegetables</td>
<td>0.44</td>
<td>0.44</td>
<td>0.35</td>
<td>0.35</td>
<td>0.19</td>
<td>0.19</td>
<td>0.19</td>
<td>0.31</td>
</tr>
</tbody>
</table>

This F2 water management option has been implemented in the modeling environment by assuming that the irrigation system return flows would be reduced from the original of 20 percent to 10 percent. Although these return flows seems quite low, we look at the overall irrigation system return flows understanding 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 percent of the original optimal irrigation depth. Table 5.10 shows the original as well as adjusted irrigation depths for the crops considered.

The reduced irrigation applications for option F2 would result in reduced crop yield according to the crop yield functions derived, as these were derived for applied rather than consumed water (Eq. 1). This is obviously wrong as deficit irrigation reduces water supply when there is no impact on crop production and therefore the c, e and f parameters in this equation have been adjusted to compensate for this. At the same time, it is well known that changing to drip irrigation is not a feasible option for all crops considered (e.g., rice and other staple crops). This option should therefore be understood to include all other improved field water management practices.
Table 5.10. Water requirements for irrigation (extractions, not depleted) for actual field practice (F0), as well as water management option F2: drip and improved field irrigation practices, and F3: deficit irrigation. All values in mm.

<table>
<thead>
<tr>
<th></th>
<th>F0</th>
<th>F2</th>
<th>F3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>1,800</td>
<td>1,440</td>
<td>1,260</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>1,800</td>
<td>1,440</td>
<td>1,260</td>
</tr>
<tr>
<td>Sugarbeet</td>
<td>1,200</td>
<td>960</td>
<td>840</td>
</tr>
<tr>
<td>Wheat</td>
<td>1,000</td>
<td>800</td>
<td>700</td>
</tr>
<tr>
<td>Vegetables</td>
<td>1,800</td>
<td>1,440</td>
<td>1,260</td>
</tr>
</tbody>
</table>

The last water management option, F3, looks at the opportunity to practice deficit irrigation to cope with water shortage. Deficit irrigation already takes 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 getting 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.

The option F3 is implemented in the modeling approach by assuming that water deliveries for irrigation are reduced to 70 percent of the original ones, as shown in table 5.10. At the same time, return flows from systems will, similar as to option F2, also reduce to 10 percent.

5.8. Results

The combination of the water management options at system and field scale, the six projections on water availability and the performance indicators resulted in a huge amount of output. We have divided the results into two groups: single-factor performance indicators, and trade-off analyses between indicators.

5.8.1. Single factor performance indicators

Basin-scale allocation

As a starting point, we look at allocations between different sectors at 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 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.

As presented in chapter 4, 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. Figure 5.2 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, ..., 1750 MCM).

Flow requirements to the downstream located wetland Gavkhouni were 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, 1,750 MCM to agriculture, the full demand by agriculture is still not satisfied by canal irrigation due to design limitations of the main canal system.

Figure 5.2. Basin supply and associated water allocation to agriculture for the six projections defined (500, 750, ..., 1750 MCM for agriculture).

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 percent and is already reached at average water availabilities (P4, 1,250 MCM), while the percentage extracted increases even at the highest projection rate.

Irrigated areas

Another important basin-scale aspect is the impact of different water management options on the total cropped area (figure 5.3). Obviously, the main trend shows that the more water available for agriculture, the larger the irrigated area. A somewhat S-shaped curve relationship can be observed from Figure 5.3 caused by the fact that farmers will adopt deficit irrigation under water-scarce conditions and will be less concerned about productive use of water under...
abundant conditions. In reality one would expect that this adaptation will be stronger. However, the water management options studied included deficit irrigation under all projections from water scarce to water abundant. Similarly, improved water management options were also included when water was not scarce at all. It is clear that in reality if water is abundant, deficit irrigation will never be practiced, and if water is scarce, deficit irrigation will be normal practice. For completeness we have included all those options for all water availability projections.

The different field water management options F0 to F4, presented in different colors in figure 5.3, indicate, not surprisingly, that under deficit irrigation the area cropped is maximal. Also, a change to more advanced field-water management practices (F2) will save some water that can be used to crop a larger area. Surprisingly, stopping rice cultivation (F1) does not influence substantially the total cropped area in comparison to the current situation (F0). The reason is that we assumed that as farmers will stop growing rice they will grow another crop, and although rice requires a substantial amount of irrigation to be extracted, in terms of consumption the difference between rice and other crops is in the order of 20 percent. Since almost all return flows in the basin are reused, the difference between water extracted and consumed for rice is reused anyhow. Moreover, the area under rice is only 10 percent of the total area.

In terms of water management options at system level, the equal allocation practice (S1) guarantees that the area that can be cropped is maximal. The allocation of 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 5.3. Impact of available water for agriculture and water management options on basin-scale cropped areas.

( lines represent the 4 field and 3 system water management options.)
Gross return

One of the main performance indicators that gives an overall picture of the performance of the basin—including water availability, cropping patterns, and water management options at system and field level—is the gross return. Gross return, expressed as the total value produced by all crops in the basin, for the combination of the three system level and four field level water management options, is shown in figure 5.4. The first salient result is that field water management options are more important than the system water management ones. The F1 option, stop growing rice, is by far the worst one in terms of basin scale gross return, and a reduction of about 20 percent can be expected.

This rice cultivation appears to be a dominant factor in defining options for improved and sustainable water management and that mainly the high price of rice is contributing to this. A further analysis of the impact of rice will be discussed later.

Figure 5.4 indicates also that the two alternative field level water management options, improved field practices (F2) and deficit irrigation (F3), will provide a higher gross return than the current practice. Although the F2 option appears to be the best, we should remember that this option includes a range of measures, such as drip irrigation, land leveling, improved fertilizer and pesticide application systems, and improved tillage, for which substantial investments are required. If we assume here that, on average, these investments are annually about US$100 ha⁻¹, and we take the average water availability projection, where the cropped area is about 150,000 ha, total costs will be about US$15 million a year. This is in the same

Figure 5.4. Gross return, expressed as the value of all the crops produced in the basin in million dollars, versus the amount of water available for agriculture for the 4-field and 3-system management options.
order as the difference between option F0 and F2. However, if we consider that option F2 includes also a change to drip irrigation, which will cost about $300 ha⁻¹ y⁻¹, the net return of this investment is negligible.

It appears that the water allocation options S0-S3, have only a limited scope to change the basin level gross productivity. A somewhat closer look shows that depending on the amount of water available, a different system water management option is preferable. If water availability is average or lower than average (P1-P4), a system where water allocation is unequal, so as to serve first upstream systems (S2), is the best one. However, if more water is available, the current water allocation is almost as good as the unequal allocation.

Water productivity

As land is not the main constraint in the Zayandeh Rud Basin but water, it is important to maximize the return per cubic meter of water. The concept of Water Productivity has become increasingly important and a measure of the effectiveness of water use in contrast to land productivity. From figure 5.5 it is clear that deficit irrigation and the improved field-water management option result in the highest water productivity figures. Stopping rice cultivation will reduce water productivity substantially, since rice commands a very high price and yields are high too.

In terms of system water management options, the current situation (S0) gives the lowest productivity. Allocating water equally between systems (S1), or serving upstream farmers first (S2), appear to be better ways to improve water productivity. The preferred choice depends also on the farm water management option adopted.

Figure 5.5. Average water productivity for the entire basin for Projection 4, average water availability.

![Water Productivity Chart](image-url)
Figure 5.5 reflects the water values based on projection P4: average water availability. Estimates for other water availability projections (P1-P3 and P5-P6) show the same trend. This is somewhat unexpected 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. 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}$.

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 percent. This projection is for the next 20 years, during which rural population will grow significantly, with the result that per capita food production will be little different from the current situation.

**Equity among systems**

Water allocation to the seven major systems considered and the five small-scale irrigation systems is influenced by the three defined water allocation options (S0-S2), as well as by the total amount of water available. At the same time, field-scale water management options will influence this allocation as water requirements might be lower (F3, deficit irrigation) and return flows can vary. Variation in water allocation to the systems has been expressed as Coefficient of Variation in allocation (in %) and is presented in figure 5.6.

*Figure 5.6. Variation in water allocation to the different irrigation systems.*
Overall, more water results in a more equal allocation, and at lower water availability the water allocation scenarios (S0-S2) dominate this. In absolute terms, however, the coefficient of variation is still quite high (>40 percent) for most scenarios. Obviously, the equal allocation option (S1) provides the highest amount of equity. At higher water availability, the field water management options influence also the variation in water allocation as return flows and water requirement are different.

A striking example of this is the S2F3 option: upstream system priority and deficit irrigation. At low water availability, this option leads to a high inequity, but with increasing water availability, equity increases drastically. It is clear that practicing deficit irrigation requires less water to be allocated to upstream farmers and already with average water availability (P4, 1,250 MCM), more water can be allocated to downstream systems.

Figure 5.7 shows nicely how water will be distributed if upstream systems will be served first. At the average water projection (P4, 1,250 MCM), full supply is realized to the Nekoubad systems and to Mahyar and the other systems are not provided with any water, with the exception of Borghar 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 percent 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.

The option to adopt deficit irrigation (P3) might be one solution to this basin water deficit. Figure 5.8 shows what the impact will be in terms of system water allocation. So figure 5.8 represents the same situation as figure 5.7 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, upper systems are fully supplied, but the most downstream ones are still only at a level of 65 percent relative water supply.

One of the assumptions made is that, in the year 2020, Mahyar and Borghar will rely completely on surface water. Although these systems were constructed to rely to a great extent on groundwater, current groundwater levels are dropping at an alarming rate, as presented earlier, so it is unlikely to remain the main source of water for these systems.
Figure 5.7. Water allocation between systems according to system water management option S2, serving upstream farmers first with current field water management practice (FO).
Figure 5.8. Water allocation between systems according to system water management option S2, serving upstream farmers first with deficit irrigation (F3).
5.8.2. Trade-offs between indicators

Gross return versus water productivity

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 tradeoff between gross production and water productivity is plotted in figure 5.9 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.

Figure 5.9. Water productivity versus gross return for each of the 6 water availability projections and the 12 combinations of system and field water management options.

In this example of gross return versus water productivity, the tradeoff between these two is straightforward. 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.

Farm income

One of the most relevant factors for farmers is, beside whether they get water or not, what their expected income might be. For the two major systems, Nekouabad and Abshar, the
average income of farmers receiving water is plotted (figure 5.11). Note that this is somewhat different from what we used in figure 5.10, where income was averaged over all farmers whether receiving water or not. 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 of stopping rice cultivation (F1) or practicing deficit irrigation (F3) reduce incomes in especially Nekouabad. Somewhat surprisingly it 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.

Figure 5.10. Relationship between income variation and gross return for the 72 combinations of water management options and projections.

Gross return versus income variation

The coefficient of variation in farmers' income has been represented in variation in gross return per hectare. In terms of equity, it is desirable to have the lowest variation in income and most water managers and policy makers will aim for this. The question is whether the highest equity is also the best option in overall production of the basin.

Figure 5.10 presents for the 72 combinations of water availability and management options the relationship between variation in farm income and the total gross production of the basin. The overall trend is clear that income variation is lower and gross production higher with increasing water availability.
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 in the previous chapter, there is no best management practice that satisfies both 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 was calculated for all farms, so it includes farms not receiving any water and thus having a zero income.

These charts clearly explain the prevailing incentives for farmers, in that more water use results in more income.

**Environment vs. agriculture**

In the initial calculation of how much water would be available to agriculture, it was assumed that the full value of 70 MCM would be maintained in the river at Gavkhouni. Figure 5.2 shows that it is only when basin level water availability is above about 1,100 MCM that flows to Gavkhouni increase above the 70 MCM actually allocated. For the three lower-basin water-availability levels, it requires specific management action to occur for the 70 MCM to be maintained, particularly at the main cross-regulators serving irrigation systems.
Let us speculate on what the benefits are to agriculture if these minimum allocations for Gavkhouni are not maintained, so that at each of the three lower water availability levels the 70 MCM can be used by agriculture. We can best express these in percentage terms, as indicated in Table 5.11. For condition S0, F0 at the lowest water availability (P1) there is a 14 percent increase in water for agriculture if environmental demands of 70 MCM are not met, decreasing to 7 percent for level P3. Assuming that these same percentages are translated into increases in gross production at basin level, then the increase for each case will be approximately US$9 million per year.

The lowest gross production (S1, F1) at basin level is US$51 m yr⁻¹, the highest (S2, F2) is US$81 m/year. From a strictly agricultural perspective, therefore, the cost in terms of production foregone in order to maintain 70 MCM of flow per year to the Gavkhouni Swamp is somewhere between US$7 and US$11 × 10⁶ yr⁻¹ for water levels P1, P2, and P3.

The benefits will be disproportionate between irrigation systems, however, because there will be sufficient capacity in the upper irrigation systems to use the full 70 MCM. In both the S0 and S2 scenarios, all benefits will go to Nekouabad, Mahyar and Borkhar. Only if scenario S1 is operating will the benefits be spread more equitably.

### Table 5.11. Potential trade-offs between agriculture and the environment, with and without environmental water allocations, present conditions (S0, F0).

<table>
<thead>
<tr>
<th>Water availability for agriculture (MCM)</th>
<th>% Change</th>
<th>Gross income at basin level (m$)</th>
<th>Added benefit (m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>With</td>
<td>Without</td>
<td>With</td>
<td>Without</td>
</tr>
<tr>
<td>P1</td>
<td>500</td>
<td>570</td>
<td>14.0</td>
</tr>
<tr>
<td>P2</td>
<td>750</td>
<td>820</td>
<td>9.3</td>
</tr>
<tr>
<td>P3</td>
<td>1,000</td>
<td>1,070</td>
<td>7.0</td>
</tr>
</tbody>
</table>

With 70 MCM/year maintained at Gavkhouni with environmental controls
Without: No water allocated to Gavkhouni
Chapter 6

Conclusions and Recommendations

Our research indicates that all water in the Zayandeh Rud is used. Indeed, we find that basin level water resources are declining due to the overpumping of groundwater for both urban and agricultural use, and that there is effectively no flow to the Gavkhouni Swamp during the summer months when demand for water is at its highest. The flows that reach the swamp are invariably of very poor quality.

Because there is no flow to the swamp and because groundwater levels are dropping, we see very few opportunities for saving water at the basin level. Only where there is deep percolation to saline groundwater, mostly in the lower portions of Abshar and in Rudasht, is there any possibility of saving water, and this is a small percentage of the overall volume of water used by agriculture.

It is true that at field level, application efficiencies are sometimes low. However, increasing these efficiencies does not save water at basin level because the water lost from one field flows to other fields or to shallow groundwater or returns to Zayandeh Rud and is used economically and productively by other farmers through re-use.

The adoption of precision irrigation technology, such as micro-irrigation, does not save water overall. It does allow the individual user to obtain greater benefit from the water available at farm level, and therefore makes that water more productive. Indeed, what appear to be water savings at field level really only end up as the redistribution of the same overall volume of water.

Our results in the Zayandeh Rud Basin confirm the findings from other locations that in water-short basins there is little or no prospect to save water because it is already all used up, but there is great opportunity to make use of that water more productively. In a closed basin, water use in one sector has to be seen as part of the wider use of basin level resources and therefore has to compete on more equal terms. This can only be achieved if the value of water for agriculture is significantly higher than it is at present.

Water in the Zayandeh Rud is valuable because it is scarce, and yet we find that much of the water allocated to agriculture continues to be used for relatively low-value crops. Under these conditions, agriculture water will be valued at a low level, making agriculture a weak competitor against other water uses.

We therefore feel strongly that for agriculture to remain an important part of the regional economy, there must be an accelerated shift from low value crops to high value ones: fruit and vegetables should take priority, particularly those that can have added value through processing for export. This improvement in productivity of water will have a far greater impact than efforts to improve water use efficiency at farm level.

This does not mean we do not promote more up-to-date water management techniques at farm level. These are important because improvements in productivity will benefit farmers economically, and will help to reduce some of the threats to the sustainability of agriculture.

Threats to sustainability of agriculture include salinization and sodicity, lowering of groundwater levels, reduced water quality, reduced water availability and persistently low
incomes that make farming unattractive in worst affected areas. Groundwater mining has mitigated the worst effects of the recent drought but it is unlikely that groundwater levels will return to pre-drought levels, and we cannot rely on groundwater to solve current water scarcity.

The reality is that in the future there will be fewer people involved in agriculture, so that the farmers who will prosper are the ones who can capture more fresh water and grow the highest value crops. Continuing to grow low-value crops is unlikely to bring prosperity to average farmers, and eventually they will leave agriculture.

In a complex and wide-ranging project of this nature, our conclusions and recommendations are also wide-ranging, and address a number of different types of issues. We have therefore divided the package into three parts. The categories of conclusions and recommendations are presented in table 6.1 for easy reference.

The main technical conclusions for a range of different issues are presented, followed immediately by recommendations that identify specific management actions, which may be at different levels: farm, system, or basin. Policy issues are those which require discussion among two or more Departments or Ministries because they propose financial, regulatory or institutional changes. Research issues are those that we feel are important for the future but where at present we do not have sufficient information to make a definitive set of recommendations.

Table 6.1. Categories of conclusions and recommendations.

<table>
<thead>
<tr>
<th>Technical issues at field level, system level, and basin level</th>
<th>Policy issues that relate to various aspects of water management</th>
<th>Research issues that require further study and investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Field Level</strong></td>
<td>Drought insurance scheme</td>
<td>Water pricing</td>
</tr>
<tr>
<td>Promoting more productive</td>
<td>Water allocation between sectors</td>
<td>Crop pricing</td>
</tr>
<tr>
<td>farm level water management practices</td>
<td>Establishment of a strong Basin Water Management Authority</td>
<td>Water rights</td>
</tr>
<tr>
<td>Micro irrigation</td>
<td>Effective regulation</td>
<td>Water trading</td>
</tr>
<tr>
<td>Deficit irrigation</td>
<td>Training</td>
<td>Additional out-of-basin transfers</td>
</tr>
<tr>
<td><strong>System Level</strong></td>
<td></td>
<td>Moving towards agro-industry</td>
</tr>
<tr>
<td>Measurement of actually irrigated areas</td>
<td></td>
<td>Trading in virtual water</td>
</tr>
<tr>
<td>Irrigation performance assessment</td>
<td></td>
<td></td>
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<tr>
<td>Allocation of water between networks</td>
<td></td>
<td></td>
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<tr>
<td>Water allocation within irrigation systems</td>
<td></td>
<td></td>
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<tr>
<td>Conjunctive use of canal and groundwater</td>
<td></td>
<td></td>
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<tr>
<td>Special attention for new irrigation networks</td>
<td></td>
<td></td>
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<tr>
<td><strong>Basin Level</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water resources development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater monitoring and regulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil salinity monitoring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitoring and development of a coordinated central database</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
For the sake of simplicity, recommendations are given following each set of conclusions. But although they are listed separately, the recommendations are intended to be considered as a package. If selected recommendations are adopted and others ignored, the overall impact will be significantly lower than if there is a concerted effort to try to work together for the mutual benefit of all concerned. We believe that there is no "magic bullet", no single or simple intervention that will solve all of the problems of the basin. Water belongs to everyone, and needs to be managed by everyone.

6.1. Technical conclusions and recommendations

6.1.1. Field level

Promoting more productive farm level water management practices

The results from the scenario analysis indicate that there are major gains to be had in terms of water utilization and farmer income if there is the adoption of a package of farm level water management practices. These practices include:

- Matching irrigation application to crop, water quality, soil type and soil salinity
- Precision land leveling
- Correct furrow shaping
- Mulching
- Use of low cost polythene piping for water conveyance
- Micro irrigation (this is discussed separately below)

Not all farmers can adopt all aspects of this package. Many field crops are unsuited to micro irrigation, and it would be inappropriate to recommend these techniques to farmers who grow these crops. In general, farmers will only adopt such techniques which cost money and often require more labor, if they grow higher value crops, particularly fruit and vegetables.

The technologies are aimed at promoting the more productive use of water. In many cases, they will not actually save water because individual farmers will have an opportunity to increase the area they irrigate with limited water supplies. If an individual cannot use all of the water because of the adoption of more precision irrigation, other farmers will happily use the additional water. Again, this does not save water but increases its productivity.

The main reason why higher value horticultural crops are best suited to adoption of these techniques is that the capital and labor costs are significant, and that the higher value of horticultural products makes such investments economic. For field crops such as wheat, water productivity values are so low that the increased farm-level investment costs may not be covered by the potential increase in farm-level production.

We recognize that a lot of research has been carried out through AREO and other organizations, and we strongly feel this approach should continue to receive considerable attention. But we are concerned that there is too much hope placed on the philosophy that if
a large proportion of farmers adopt these techniques, a great deal of water will be saved and there will be a reduction in the water-scarcity problem.

Instead, the focus should be less on water-use efficiency and more on improving the productivity of the water used by farmers—when water is scarce, it is everyone's responsibility to utilize that water to the best advantage. High water application efficiency on a low-value crop will result in far less benefit to both the farmer and society in general than the same effort applied to a high-value crop.

**Recommendations**

*There should be continued active research by the AREO organisation on the suitability of different on-farm water application techniques that lead to increases in water productivity. Analysis of the results of experiments must focus on water productivity both in terms of yield/cubic meter applied and income/cubic meter applied. The results have to have a strong economic focus to build into the assessment the true cost (capital and labor) to farmers in adoption of more productive farm-level technologies.*

*In addition to experiment station research on technologies, there needs to be a detailed socio-economic survey of current adoption practices of these technologies. We need to understand what motivates farmers to either adopt or not to adopt new technologies so that the extension services can provide more relevant information and support to farmers. Of particular importance is to determine those technologies that farmers will be willing to adopt under different soil, crop, water availability and water quality conditions. This should be carried out through AREO.*

**Matching crops to soil and water conditions**

Our research indicates that there are very significant differences in yields and water productivity values for different combinations of soil, crop, water quantity and water quality. There are two related aspects to this problem:

1. Farmers have insufficient knowledge on these complex relationships, and need more focused advice on what to do.

2. Access to water, particularly good quality water, is highly variable throughout the basin and within irrigation systems. Many farmers simply do not have much choice in varying water applications to their crops because they do not get sufficient water, and frequently the quality is inferior when water is scarce.

Our research has demonstrated that it is possible to cut short some of the arduous and time-consuming field experimentation processes by using crop response models that simulate the outcomes of using different water applications and water qualities for different crops on different soils. The outputs from the SWAP model provide a comprehensive picture of relationships, particularly in the less favored areas of Abshar and Rudasht.
The output indicators of the SWAP model are not restricted to traditional measures such as yield per hectare. They include productivity of water at farm level and, if data are available on market prices and costs of production, it can also determine productivity in terms of income per hectare and value of water. The SWAP model is able to determine long-term soil moisture and soil salinity balances if a multi-year set of data is used.

This means that without having to undertake extensive field measurements and trials on experiment stations, it is possible to obtain a reasonable indication of agronomic performance of different crops on each of the soil types in the basin. Because SWAP is tested already under many different soil, crop and climate conditions, the methodology used in this project can easily be transferred to other parts of Iran with confidence.

Most farmers do not get sufficient water to irrigate their entire holding at optimal levels of water application. They therefore can choose between deficit irrigation, reducing the area they irrigate, or switching to less water consuming crops. However, farmers have little or no access to scientific knowledge that allows them to consider the implications of different strategies to cope with reduced water supplies. As a result, they may end up with sub-optimal use of land and water resources.

The long-term value of the SWAP model outputs is that extension advice can be tailor-made to the specific requirements of each section of an irrigation system rather than being more general recommendations. If there is information on soils, water availability and water quality for a particular location, then the best crops and water application practices to meet production, productivity or income objectives can be selected from the SWAP nomographs. We say long-term here because there is in the short-run insufficient information on farm level water availability, water quality and soil health. Without more detailed farm-level surveys, recommendations will remain general and have limited impact. Extension agents can easily be trained on how to interpret the outputs and use them during field visits.

**Recommendations**

*The SWAP model should be widely disseminated to other soil and water research institutes, and appropriate training arranged, so that a similar comprehensive assessment of performance of different crops on different soils with varying water application depths of varying salinity can be undertaken. This will provide an excellent baseline for assessing potential productivity in all parts of the country for all major crops. This should be coordinated through AREO to support this initiative in all of its major research stations.*

*A set of specific guidelines should be drawn up based both on SWAP model results and farm surveys that give farmers information on the best ways to manage crops, land and water under varying conditions of water availability and water quality. This is particularly important where farmers may have access to groundwater of poor quality and may be either reducing their yields or increasing soil salinity. This program would be the responsibility of the Agricultural Research Service in conjunction with the Extension Services, and would take the form of a handbook that includes the results of the SWAP model and provides simple guidelines to farmers.*
Micro irrigation

The cost of high technology (US$1000-1300/ha), such as drip or sprinkler irrigation, means that farmers are unlikely to recoup their investment costs unless they move towards high value horticultural and orchard crops. We recognize that there is a program of subsidized loans to encourage farmers to invest in these technologies which may help to partially offset the capital investment costs, but there are also recurrent operational and labor costs that may discourage some potential users. Drip and other forms of micro irrigation are greatly preferred to sprinkler irrigation as a significant amount of water will be lost in arid and semi-arid conditions through evaporation in the air and from leaves when using sprinklers. In the Esfahan region, we do not recommend sprinkler irrigation as an effective way of increasing application efficiency.

As a general rule, we conclude that micro-irrigation does not really save water. Water savings at system and basin levels that result from using drip irrigation are largely restricted to the reduction of soil surface evaporation. For crops that have high leaf area indexes for much of the growing season, this means that the savings will only occur early in the season, and typically drip irrigation saves only 20 percent of all water applied. Reductions in percolation will, for the large part, merely reduce the amount of reuse elsewhere because there will be reduced surface run-off and reduced recharge of groundwater.

We strongly encourage continued research into improvements in micro-irrigation technology, and we advocate wider adoption of such technologies. However, we feel that the benefits will not be in water saving as much as in improved water productivity for farmers who adopt the technology, and probably increased incomes due to higher quality horticultural products. Water must be of reasonable quality if the build-up of salts on emitters is to be avoided.

In the Zayandeh Rud basin, micro-irrigation is being adopted by many farmers, almost exclusively by those growing horticultural products. Field surveys to understand why they adopted these technologies are required, as well as survey of farmers who have not adopted the technology.

Research is also required on use of saline and sodic water for micro irrigation, particular with regard to emitter clogging problems, because it is in areas of low water quality that water can actually be saved through adoption of micro irrigation. This is particularly important for Rudasht, Mahyar and Abshar.

Recommendations

The adoption of drip irrigation should only be promoted in conjunction with the adoption of high-value crops and where water quality is good to enable recovery of investment costs. Vegetables are particularly suitable for drip irrigation because they will be of higher quality and get a higher price, while orchards can be established more quickly and will yield 1-3 years earlier if established with drip irrigation. Extension services should focus on using precision irrigation for specific crops, not as a general recommendation for all farmers.
For most other crops, drip irrigation is still too expensive and saves much less water than commonly believed. It is not recommended as a mechanism to save large volumes of water.

Deficit irrigation

Deficit irrigation—deliberately underirrigating a crop so that less water is used but yield reduction is minimized—is a strategy adopted by farmers when the water available does not meet total crop requirements. It is a strategy of last resort because input costs are more or less the same, so overall profitability is reduced. Farmers are unlikely to adopt such techniques if they can access groundwater, or obtain additional surface water.

Yet we find substantial areas where farmers already practice deficit irrigation, notably in the tail ends of Abshar and throughout Rudasht. They do this because water is inadequate, and they have sufficient land to spread the available water a bit more thinly. This increases water productivity to some extent, but of course reduces per hectare yields. We can conclude that deficit irrigation is a practice forced on farmers through inadequate water supply rather than a widespread practice.

It is difficult to promote deficit irrigation as a basin-wide strategy that all farmers can follow. Head-end farmers are unlikely or unwilling to use less water on their farm and give up potential income just so that other downstream farmers can obtain a crop.

It is also necessary to consider carefully whether a farmer should be advised to irrigate part of the farm with their full water allowance, leaving the rest fallow, or to practice deficit irrigation over the entire farm. This appears to vary according to crop and soil type, as well as water salinity, and on the price of the crops he is cultivating. As farmers gain farm planning skills, they can work out the optimum combination each year for themselves, depending on likely water availability.

In very dry years, however, deficit irrigation can be one of the strategies promoted for dealing with a short-term water crisis. It may be adopted not as a voluntary technique by head-end farmers, but as a response to severely curtailed water deliveries at the head of irrigation systems. Indeed, this was observed on a wide scale during the 1999-2001 drought.

Deficit irrigation is not recommended as a routine practice. Deficit irrigation carries with it the risk of increased soil salinization due to lack of leaching. For one or possibly two seasons this is acceptable if there is then sufficient water provided for leaching, but the apparent benefits of irrigating a wider area are offset by lower productivity and risk to soil health if adopted as a permanent measure.

Recommendation

In dry years when water is known to be scarce, deficit irrigation may be promoted as a short-term measure to overcome the effect of drought in combination with a reduction in water availability at the head of irrigation systems. But we do not recommend it as a long-term strategy to be adopted by farmers due to the risks of soil salinization.
6.1.2. Irrigation System Level

Measurement of actual irrigated areas

A major constraint encountered during this project is that the area actually irrigated in each season is largely unknown. Data from Agriculture Department sources is based on administrative units (village surveys and sample fields aggregated to district level), but these units do not match irrigation system boundaries. The project has been successful in using remotely sensed data to estimate cropped areas, and moderately successful in delimiting different crops. It has been only partially successful in using GIS to try to cross-match data based on district data, with data based on irrigation systems.

The remote sensing techniques used in our research appear to be successful in determining annual and within-season changes in cropped areas, making it possible to use this as a management tool given the access to cheap, timely images. At basin level, the resolution of NOAA or MODIS images is of sufficient accuracy, while at system level we recommend a combination of NOAA and LANDSAT images.

Without accurate data on irrigated area in each system and its variation during a season it is difficult to accurately manage canal discharges, or to measure various performance indicators. Remotely sensed data for irrigation performance includes estimation of yields, water productivity, soil moisture, biomass growth and actual evaporation.

Measurement of actual transpiration is really the key parameter in a water-short basin because it tells us exactly how much water has actually been used. This is much more useful than classical approaches based on CROPWAT or equivalent models which rely largely on potential evapotranspiration and tells nothing about actual evapotranspiration.

Recommendations

Reporting of irrigated areas and cropping patterns must be based on canal boundaries at both main canal level and, where feasible, at secondary canal level. In this way, information on planned and actual discharges can be directly linked to cropping pattern and cropping intensity data, a critical first step in assessing irrigation system performance. Ministry of Agriculture reporting procedures should therefore be changed to reflect this new direction and combined with data available from the Ministry of Energy.

Remote sensing should be a major tool in this program because it is increasingly becoming cheap and reliable. The upscaling of freely available NOAA images appears to have an important role in assessing area irrigated in major irrigation systems, and images from newer satellites with higher resolution offer simultaneous opportunities. At system level, it is better to combine data from NOAA or MODIS with LANDSAT in order to track within-season changes in irrigated area and actual crop water demand. Multi-temporal image analysis is clearly superior to single date estimates, but this implies higher costs. The remote sensing capacity of both the Ministry of Energy and the Ministry of Agriculture should be upgraded to make maximum use of these technologies, a specific cadre trained, and ready access to.
both high and low resolution images established. This access can be independent or through the Iranian Remote Sensing Agency, although the last named organization must change its de facto policies concerning access to images.

Irrigation system performance assessment

The project found little accurate or comprehensive information on irrigation system performance despite the fact that water is the most critical resource in the Zayandeh Rud basin. Data on discharges were aggregated to monthly and annual level, and no systematic results are evident to calculate a set of standard performance parameters. There are no data available on water productivity despite the fact that water is a scarce resource and improvements in water productivity are the best way to increase farmer incomes when water is scarce. Of particular concern is the lack of readily available data at secondary level that examines the extent of equity of water distribution between different parts of irrigation systems. The primary role of the system manager is to ensure that water deliveries are timely and equitable, in accordance with the rights of water users.

In on-demand downstream control canals, it is much more difficult to monitor actual water deliveries unless there is instrumentation in place at the turnout level. For this reason, the analysis of water distribution on the basis of actual Et, and corrected for salinity effects, has good potential in indicated overall equity and sufficiency of supply.

Recommendations

Irrigation systems in the Zayandeh Rud basin should be included in the IPTRID/IWMI Benchmarking program which allows system managers to assess their performance in terms of a limited set of key performance parameters. They can compare their performance with similar systems in Iran and elsewhere, and measure changes in performance in an individual system over time.

Individual systems should follow a similar program for the larger secondary canals. If these are managed effectively, system level performance as a whole will also improve.

The use of GIS-based databases for each irrigation network will be invaluable for system managers to track performance over successive years. Databases of this kind allow a comprehensive inventory of discharges, per hectare water deliveries, cropping patterns, yields and a whole range of performance parameters to be determined. The GIS version of the NAGA program under development by IWMI would be very suitable for this purpose, and produces seasonal and monthly reports of performance for all important parameters.

Remote sensing for system level performance monitoring should be adopted as a regular part of irrigation management. Using MODIS data, it is possible to determine not merely irrigated area but also actual evapotranspiration, soil moisture conditions, biomass production, and estimated yields of major crops. MODIS has better spectral and pixel resolution than AVHRR and is freely available on a near real time basis from USGS/NASA data gateway in the US.
Allocation of water between irrigation networks

Current water allocation to each network is based on a trade-off between crop water demand and canal capacity. From April to August, canals are run at or close to maximum capacity, while from September to December canal discharges are reduced more or less in proportion to potential evapotranspiration. When water is in short supply from the reservoir, then there is a tendency for head-end systems to continue to get maximum discharges while tail-end systems get a reduction. This results in high levels of inter-system inequity in dry years.

We also find that potential demand for water is based on largely agronomic criteria: crop type and potential evapotranspiration. Yet in dry climates with a risk of salinization and other impacts of irrigation, it may be necessary to include non-agronomic factors into the water allocation process in order to maintain adequate soil health.

Our results indicate that there are more beneficial ways of allocating irrigation water than are presently undertaken. In wet years, there needs to be greater equity between networks so that tail-end areas obtain a fair share. At present, in a normal year, Rudasht gets only half of the water it would be entitled to if there were an equal distribution between systems based on command area, while many systems get their full entitlement. This additional water would be invaluable for leaching and alleviation of salt problems.

We therefore conclude that there should be different allocation rules according to the water available in the reservoir and to provide specific water allocations to deal with environmental issues, rather than just basing allocations on estimated evapotranspiration.

Recommendations

The allocation of water between different irrigation networks should be related to the overall water supply estimated at the time canals are scheduled to be opened in April each year. If water supplies are average or above, current water allocations appear satisfactory and should be maintained, but in dry years a more rigid reduction in discharges to all irrigation networks should be considered. This is a trade-off between productivity, where head-end networks always perform best, and equity where tail-end interests must be safeguarded. The Ministry of Energy needs to make a thorough study of the possibilities for such allocation.

The present system of water allowances needs to be reviewed to ensure that issues of sustainability of irrigation networks are included in calculating water allowances and discharges. It is probably not sufficient to use evapotranspiration as the only criterion when there are also water demands for leaching and other aspects of soil management. The Ministry of Energy, in collaboration with the Ministry of Agriculture, needs to assess the costs and benefits of allocating more water to tail-end systems in wetter years.

Water Allocation within irrigation systems

Water requirements are generally based solely on knowledge of probable cropping patterns and estimation of evapotranspiration. This is normally sufficient if water and soils are of
good quality, but when soils and water quality are problematic other factors need to be taken into account when determining water allocations. If water is of low quality or soils suffer from salinity, then they may merit a larger water application so that farmers can obtain the same levels of income as those who have access to the best resources.

**Recommendation**

The allocation of water to each irrigation system should be reviewed to include not just evapotranspiration demand but also allocations to cope with salinity, decreased water quality and other adverse conditions that may threaten the physical and economic stability of parts of irrigation systems. The Ministry of Energy, in collaboration with the Ministry of Agriculture, needs to look at the costs and benefits of providing more water for leaching in salt-affected areas when water supplies at the head of a system are at design level.

**Conjunctive use of canal and groundwater**

The rapid expansion of the pump sector in the Zayandeh Rud reflects both the increased demand for water from all users and the dropping prices as technology improves. Conjunctive use of canal water and groundwater is a very rational way to overcome uncertainties in canal water supplies, make up for deficits in meeting crop water requirements, and fine tuning irrigation applications. It is a worldwide phenomenon, one that has greatly increased productivity of irrigation systems. But it is not risk-free.

Our results show that in the majority of the irrigated area in the Zayandeh Rud, and particularly in the last few years, pumping rates exceed recharge rates, and groundwater levels are dropping in almost all parts of the basin. We find that in some areas, notably Borkhar, Mahyar and around Najafabad, this has become groundwater mining and that groundwater levels may never recover. Indeed, in Najafabad, large areas of productive orchards have been abandoned due to the drop in groundwater levels caused by pumping for urban, industrial and agricultural purposes.

Our conclusion is that current levels of agriculture are unsustainable because groundwater resources are fragile, particularly where distant from the Zayandeh Rud, and that alternative management of surface and groundwater resources needs to be implemented.

There is little evidence of the effective integration of surface and groundwater resources for agriculture at system or basin level. Virtually all groundwater exploitation is in the hands of individual water users. They can construct wells and boreholes on their own initiative and at their own expense, although they may have to follow a nominal licensing procedure. As a result, there is absolutely no information available on how many wells there really are, how much water they consume and what quality of water they are pumping. The last comprehensive assessment or census of groundwater use appears to have been in 1988, although it has been partially updated about 3 years ago. This is not sufficient information to meet the current challenges of water management.

Without knowledge of groundwater level changes, and of the interaction of surface and groundwater exploitation, it is impossible to develop a rational water resources management plan for the Zayandeh Rud basin and we see this as a very high priority area for further action.
Recommendations

A comprehensive census is required that inventories the total number of wells, depth to groundwater, water quality, date of installation, etc. and documents actual usage patterns of farmers: what crops do they irrigate, how do they combine groundwater with surface water, and so forth. This has to be a joint effort of the Ministry of Energy and the Ministry of Agriculture, and is of very high priority.

The results of this survey should be utilized in two ways: a set of guidelines for farmers on optimal conjunctive use of surface and groundwater of different qualities, and an analysis of likely trends in continued groundwater exploitation for agriculture. The first should be a task of the Ministry of Agriculture, the second of the Ministry of Energy.

Where necessary, steps may be required that severely restrict or even close wells that are pumping very saline water. The entire licensing system has to be re-examined to ensure that current permits are not abused, and that pumping limits are not exceeded. This is the task of the Ministry of Energy.

Continued efforts must be made to model carefully the groundwater levels and groundwater quality as agricultural and other water extractions continue to grow. MODFLOW provides one mechanism for doing this, and the use of this model or similar ones, should be investigated by the Groundwater Division of the Ministry of Energy.

Special attention for new irrigation networks

Our studies indicate that Rudasht, Borkhar and Mahyar require special attention. Both systems have new irrigation networks that bring surface water into areas that have been irrigated only by deep boreholes. The arrival of good quality canal water, particularly in Mahyar where groundwater is quite saline, may be seen as a blessing by farmers, but it also poses high risks for sustainable agriculture. At present, groundwater levels in both locations are dropping, and have done for some years. At the same time, many crops grown are fairly low in value, and cropping intensities have been constrained by the lack of water. More water means farmers can expand irrigation, and they are likely to do this rather than substitute groundwater with surface water. In years when surface water supplies are below normal, they may pump more groundwater, thereby increasing the risk of salinization. In order to maintain sustainable agriculture in these basins, special attention will be required.

Recommendation

In the Borkhar and Mahyar systems, there should be a special monitoring program established that looks at total water use—both surface and groundwater—agricultural practices and soil salinity. This program needs to be established very quickly because if water is not properly managed at both system and farm level, there is a real risk of salinization that will put land out of production and threaten the livelihoods of farmers.
6.1.3. Basin Level

Water resources development

The past 50 years have seen major investments in water resources development including transbasin diversions and reservoir construction. We believe that if it is economic then such initiatives should continue, but with the warning that the development of additional water resources is not seen as a simple solution to the water problems of the Zayandeh Rud. History tells us that as soon as new water is made available, it is fully allocated. This leaves the basin vulnerable to drought and does not alleviate problems of salinity or water shortages in the tail-end.

Climatic change predictions are that there is likely to be an increase in extreme conditions—more floods and more droughts. The Zayandeh Rud basin is vulnerable to both—floodwaters cannot be stored due to the limited capacity of the Chadegan Reservoir, and droughts will affect natural and transbasin discharges.

The development of water resources over the past 55 years has been highly beneficial to the economy of the basin, and yet there is no capacity in reserve to deal either with extremes or increased demand from all sectors.

Recommendations

*Investigations must continue into the technical and economic viability of additional transbasin diversions into the Zayandeh Rud. However, the plans must be accompanied by a clear plan of action for utilizing the additional water in a way that leaves the basin less vulnerable to drought and more likely to be sustainable into the future. Concerned consulting companies have to take care in assessing absolute minimum levels of water availability in the case of a recurrence of a 2- to 3-year drop in precipitation in the upper watersheds of the Kurang and Zayandeh Rud Rivers.*

*Investigations by consulting companies and the Ministry of Energy should continue into the feasibility of creating more storage within the basin, either at Chadegan or elsewhere, particularly where it provides the opportunity for some storage between years. However, the feasibility study must also be accompanied by a clear plan of action for utilizing the additional water in a way that leaves the basin less vulnerable to drought and more likely to be sustainable into the future. But it should be noted that additional storage does not create additional water for the Zayandeh Rud—it merely redistributes it in time.*

Groundwater monitoring and regulation

Groundwater use and protection is pivotal to the sustainability not just of agriculture but a whole range of water uses. At present, it is being exploited too fast and this will have adverse consequences for water availability, soil and water quality, and indeed the livelihoods of future generations.
Our results indicate that while surface water rights are fairly well understood, there is very little understanding of groundwater rights, issues of common access to a shared resource, and management strategies for the sustainable use of groundwater.

In a dry environment like the Zayandeh Rud basin, widespread recharge is not realistic because effectively all surface water resources are consumed. We find that the short-term management is leading to permanent damage to water table levels, and would prefer to see groundwater used more as a supplement in dry years only, allowed to recover during more water plentiful years.

This tendency to over-exploit groundwater, not only in drought years but as a matter of routine, is the single largest threat to the sustainability not only of agriculture but many aspects of economic activity in the basin.

**Recommendations**

Current programs of groundwater monitoring require strengthening so that a comprehensive picture of groundwater consumption and groundwater quality can be built up. A strengthening of basin-wide modeling of groundwater conditions, and its interaction with surface water is required, that uses models such as MODFLOW or its equivalent. A review of existing regulations for the installation and operation of new wells needs to be made, and plans drawn up for temporary or permanent well closures in response to groundwater levels.

Opportunities for the artificial recharge of groundwater during snowmelt season in aquifer recharge areas near the mountains should be pursued so that a minimum level of water is lost to evaporation on the surface of alluvial fans. All of these tasks remain within the responsibility of the Ministry of Energy.

Plans for the management of groundwater based on the rate of change of groundwater levels needs to be drawn up by the Ministry of Energy, which involve not merely the Ministry of Energy but all concerned water users within specified groundwater districts.

We recommend specific groundwater management plans for each hydrogeological sub-unit of the basin, which includes inputs from all sectors using groundwater, to establish sustainable levels of extraction and monitoring plans to assess stability of groundwater levels.

**Soil salinity monitoring**

Soil salinity in irrigation systems is not static but dynamic, and must be treated as a variable to be monitored on a routine basis. The development of salinity over time needs to be understood, especially in light of the implementation of strategies to mitigate it. It is essential to have a long-term, forward-looking strategy for salinity management, and understand the impacts of decisions taken now on the situation in 30, 50 and 100 years time. It is also highly advisable to develop a vision for the management of salinity with associated targets.
Salinity monitoring is essential in an environment where there is little rainfall and where many farmers are intensively using groundwater through individually owned pumps. As vertical recycling of groundwater increases, there is an increased risk of soil salinization, and this will be more marked in areas where good quality water supplies are limited. There seems to be insufficient reliable information both on the scale of soil salinity in the basin, and the extent to which it is increasing in more vulnerable areas.

Our results appear to indicate that parts of Abshar and most of Rudasht are susceptible to secondary salinity development, and both Borkhar and Mahyar may be even more susceptible depending on how the irrigation systems in those areas actually function. SWAP modeling indicates that with proper management of water application it is possible to stabilize salinity levels even in the worst affected area. However, overall productivity will be lower in these areas due to the effect of salt on plant physiology, and these areas will require more water and good drainage if they are to obtain satisfactory incomes for farmers.

**Recommendation**

There is a need for periodic surveys that focus on salinity development at different depths in the soil profile throughout the irrigated areas of the system, and particularly where there is extensive groundwater pumping. While some of this may be possible through remote sensing, a field-based program is a much better strategy at this stage. This needs to be taken up by the Soil and Water Research Institutes of AREO as a major exercise to be repeated every few years to track changes in salinity conditions.

SWAP modeling will identify water requirements for salinized areas that can be used to determine alternative water allocations to different parts of the basin, and help predict likely levels at which salinity will stabilize. However, the lack of precise field information on salinity in different soil horizons in irrigated systems requires that the field surveys be undertaken first.

We recommend an investigation into the feasibility of using airborne electromagnetic sensing systems for soil salinity mapping. This provides an early warning of salinity build-up that satellite imagery cannot match. While initial capital costs are expensive, the airborne systems provide cheap assessment over a wide area. Although operation and analysis of the data is technically complex, it would be a long-term investment that would be highly beneficial, particularly if the airborne platform were fitted with other useful sensors.

**Monitoring and the development of a central coordinated database**

This project has found that there is no coordinated information base that can be used for the integrated management of the Zayandeh Rud water resources. This is not to say data do not exist; indeed, in some cases, there are remarkably good databases. But they suffer from the lack of coordination and cohesion because they are maintained by a diverse set of organizations that each have specific objectives for their databases.
For example, different agencies use different boundaries for delimiting their data: administrative boundaries, hydraulic boundaries, hydrologic boundaries, and geologic boundaries. This makes it difficult to integrate data from different sources. Coordinate systems vary between different data sets so it is difficult to piece together data from different sources. The frequency of data collection also varies—what is useful for one agency may be quite useless for somebody else.

Our research finds that water is shared by many different users and that change by one water user affects all other water users. Fragmented databases are insufficient to deal with the coordinated management of water resources at basin level and, in some cases, may actually be a direct hindrance to basin-level objectives.

Who owns and operates this central database is a complex and difficult issue for many agencies to face—nobody wants to give up the power associated with the ownership of knowledge and information. Nevertheless, we conclude this is precisely what has to happen if we are to move to an era of comprehensive basin-level water management.

**Recommendations**

A systematic database must be established that forms a neutral body of information available to all concerned members. In line with current technology, it should be a GIS-based database that facilitates interconnectivity between different data sets, and allows different users to query the database to obtain specific information for their needs. Several examples of this type of integrated water management database can be found in Europe and other regions and are well within the current technical capacity of Iran to establish.

The home of this database should probably be the Master Planning Organization but specific protocols would need to be established to protect the interests of other agencies.

The use of remote sensing should be greatly encouraged as part of the monitoring process. Recent advances and newer satellites make it possible to use remotely-sensed data for a wide range of monitoring activities, and the scale and climatic conditions of the Zayandeh Rud make the technology highly appropriate.

6.1. Policy conclusions and recommendations

**Drought insurance scheme**

In the event of more droughts in the future, some form of extended drought insurance or assistance may help farmers recover at least their investment costs in crop production. If such assurance is forthcoming, then there is likelihood that farmers will use recommended levels of inputs with confidence, so if a drought occurs they will not be completely out-of-pocket. If this is correct, the benefits may be felt even in non-drought years because overall input use will be higher.
Our conclusions are that current drought insurance is patchy, few farmers adopt it, and it does not provide effective regular relief. In emergencies, other forms of compensation may be available anyway, thereby diluting the impact of drought insurance.

**Recommendation**

The viability of a more comprehensive drought insurance scheme that protects farmers from loss of input costs should be investigated, and if found feasible, should be implemented on a trial basis to determine if farmers take proper advantage of the scheme. This should be undertaken by AREO in conjunction with the Drought Insurance Scheme of the Agricultural Bank.

**Water allocation between sectors**

As long as water is sufficient to meet all needs, there is little need for a coordinated allocation process that sets limits to the total amount of water each sector can expect to receive. In water-scarce basins, however, allocation between sectors becomes absolutely critical.

In the Zayandeh Rud basin, agriculture has always been by far the largest user of water, but slowly and steadily, requirements for other sectors have increased. These sectors offer the prospect of generating more income per unit of water than agriculture, and this leads to potential conflict among sectors. The situation is made more complex when demands come along that are not based directly on economics but on value to society: water for environment, for recreation and for maintaining a particular type of landscape.

Our studies indicate that the Zayandeh Rud basin has been water short for many decades but a succession of water resource developments bought a bit more time before allocation between sectors became critical. The recent drought brought the water allocation issue to a head, forcing hard and unpopular reductions in supply to be made.

The current pattern of priorities (domestic first, industrial second, and then agriculture, environment and other uses last) has evolved over time. What is needed now is a systematic process that can determine the allocation of water to each sector under varying levels of water deficit.

We find that routine water allocations are made by the Water Resources Allocation Council within the Water Authority of the Ministry of Energy. Many sectors are not directly represented in this procedure (e.g., municipalities, industry, environment) although they can make representations to the Council to increase their share.

We also find that on an emergency basis, as was the case in 2001, the Provincial Governor can call together a council that represents all concerned parties to make special decisions. In 2002, for example, the amount of water for agriculture was drastically cut to less than 100 MCM so as to meet urban and industrial demands.

Our conclusion is that neither approach really meets the long-term steady needs of the basin. The hydrology of the Zayandeh Rud is not complex and our results indicate that, given reasonable projections of urban and industrial demand, it is possible to come up with multi-year priorities that are based on actual water conditions at the Chadegan Reservoir in March or April each year.
We also recognize that the political aspects of the water allocation process are very complex. We believe that water allocation needs to be a joint action among all water users, above the level of an individual Ministry or Department—an issue addressed in the following section.

**Recommendations**

The allocations to each sector are based on agreed priorities, which are translated into specific water allocations for that year. Some sectors will be non-negotiable (e.g., domestic water supply) and will not be affected by year-to-year water availability conditions. Others will be subject to annual change (e.g., agriculture and environment). These priorities must be determined by consensus among all water user interest groups.

Water availability for each year should be classified into a set of levels of scarcity that are fully agreed on: (e.g., above average, average, below average, scarce, extremely scarce) and the volumetric allocation by sector in each category agreed in advance. Water allocations within each sector should then be determined, again on an annual basis, in line with the total amount allocated to that sector by the appropriate basin-level water authority. This will be the responsibility of the constituent agencies involved, and they should prepare an operational plan that is agreed by consensus among all water user interest groups.

**Establishment of a strong basin water management authority**

Water resources in the Zayandeh Rud have to be managed in a coordinated manner that crosses departmental and other administrative boundaries. Water in the basin is a single resource and it is physically integrated: groundwater and surface water are interconnected and the actions of any one water user impact on all others. Historically, when water was not scarce, different agencies and user interests were able to operate more or less independently, each looking at a particular part of the management of the whole water resource, but now that there is insufficient water for all users in Zayandeh Rud, integration is essential.

Experience from several countries that have had to cope with the management of water-short basins shows that some form of coordinating agency is essential if there is to be integrated management of water. The exact nature of this organization varies considerably from one country to another, but all have in common three basic roles: monitoring, allocation, and regulation. Each of these issues is discussed below.

Many existing agencies see a basin level authority as a threat to their own power. To some extent this is true, but it is important to recognize that the nature of water management changes as the balance between supply and demand at basin level changes over time and this impacts directly on the role of different agencies. Three significant changes have occurred in Zayandeh Rud over the past decades, a pattern repeated in almost all water-scarce basins.

Firstly, the phase of water resources development is almost over. All available water resources have been captured, either through reservoir construction, transbasin diversion and tapping local sources. To be sure, there may be some limited opportunities for exploitation of additional sources but they are unlikely to repeat the doubling of water availability that
has occurred in the past 50 years. Water managers now have to face issues of allocation rather than development and management of water resources.

Secondly, agricultural dynamics have changed. When water was not particularly scarce, the focus was almost exclusively on improving yields, in other words, improving the productivity of land. Now it also has to be concerned with improving the productivity of water, so that each drop of water produces more output. This output is not just restricted to yield—increasingly there is enormous pressure to increase incomes to help raise rural standards of living. Agricultural research, and particularly agronomic research, will not by itself accomplish these targets, and it requires more integration with managers of water and other resources.

Thirdly, environmental concerns suddenly become important when some level of threshold of water scarcity is reached. Water needs for ecosystems were originally met from natural flows, or more recently from return flows. As pressure on water increases, then specific water allocations for environmental needs must be added to the equation.

IWMF's experience in many countries is that there needs to be a realignment of institutional arrangements when water becomes scarce. Part of the rationale stems from the genuine conflict of interest an agency may face when it has to deal both with operational implementation of plans and regulation that enforces implementation of that plan. When housed in a single agency, operational actions normally override regulatory concerns.

Further, no single agency has the capacity to deal with this full range of issues and concerns. This is particularly true when environmental and social issues are added to more traditional technical aspects of water resources development, irrigation management and matching crop water demands and water deliveries. Agencies have to become partners in a process that looks at integrated basin management, fulfilling the three main roles of monitoring, allocation and regulation.

For these reasons, we feel that the processes of allocation, monitoring and regulation need to be coordinated at a level higher than individual line agencies responsible for implementation tasks. It has to be at Provincial level, or at basin level if it crosses more than one province. For the Zayandeh Rud, basin level coordination is required. Issues related to water extractions from the Kuhrang River and the rapid growth of pump-based irrigation between Chadegan and Lenjanat are inter-Provincial issues that cannot be handled by Esfahan Province alone.

Our experience is that, in water-short basins, a basin level agency has to have strong regulatory authority to safeguard water allocations and water quality.

If allocation and regulatory standards are only taken as far as the planning and decree stage, then there is no effective sanction against those who do not follow the regulations or decrees. Part of the difficulty we find in the Zayandeh Rud at present is that in many cases the same organization is responsible for implementation and regulation. This is an inherent conflict of interest. Regulation needs to be undertaken by an independent or neutral body that can then interact with implementing bodies.

We also find that while there are many regulations regarding water use and pollution, they are largely ignored and rarely enforced. The regulatory arrangements in terms of allocation need to apply both to the allocations between sectors to ensure that annual plans are followed, and to allocations within sectors, particularly agriculture, so that different
irrigation networks receive their fair share. The allocation for the environment is particularly
difficult to implement and requires special attention.

Regulation also applies to water quality standards, and any water management authority
needs to rely on an accurate and impartial monitoring of conditions.

We recognize that this is a far-reaching and probably highly politically sensitive
recommendation. But we feel that in the long run it is absolutely essential to the well-being
of the Zayandeh Rud basin.

Recommendations

To this end we feel that there is a need to establish a specific basin level water
management agency that has the triple responsibility of monitoring, allocation and
regulation for the Zayandeh Rud basin. This would be directly under the control of
the relevant Governors, and would have representation from all concerned
government agencies (e.g., Planning, Energy, Agriculture, Environment, Meteorology,
Industry, etc.), and representatives of different water user interests (farmers,
municipalities, industry, environmental groups, etc).

The basin level water management agency should not be a line agency but one
responsible for helping to set policy and direction for the constituent members.

We also recommend that this agency be given very strong powers to enforce the
allocation and regulatory aspects of water management.

Whatever its actual form, the basin level water management authority has to be given
full powers to regulate proper implementation of water management plans and
monitor water use and water quality standards. It has to be able to sanction those
who break the regulations. The authority should not have to take responsibility for
the implementation of operational plans. A review needs to be undertaken at the
Provincial level to determine the feasibility of current and future regulatory
requirements, and establish this as soon as possible.

Training

Many of the technical recommendations require the upgrading of skills of various cadres in
different organizations. Most relevant are those that focus on using modern technologies and
techniques to address water management issues.

Our experience from this project is that by using a combination of remote sensing,
geographic information systems, selected models and a coordinated database, it is possible
to greatly improve the understanding of existing processes and make reliable estimations of
future trends and conditions.

However, we also find that many of the line agencies and other departments that are
required to have an effective and integrated water management program lack the trained
manpower to replicate the results obtained in this pilot study.
We find that there is no shortage of well-trained manpower in both the public and private sectors which can be trained in these techniques, and believe that they can be trained easily. The necessary technology, computers and software are all sufficient and readily available.

However, we also find that there is not yet sufficient commitment to such training programs that provide the opportunity to integrate modern techniques into the day-to-day operation and management of water in a water-short basin and fear that many of the potential benefits that this project has demonstrated may be lost if such a commitment is not forthcoming.

**Recommendations**

*Appropriate departments in the ministries of Energy, Agriculture, Planning and Environment should be included in a significant training program within Iran to enable the adoption of techniques developed and used in this project. This involves such topics as remote sensing, GIS, computer modeling, database creation and management, and the use of these technologies to provide decision-support for managers and policy makers.*

*The experiences of the Iran-IWM Collaborative Research program should be used as the basis for such training, building upon the knowledge and experience already gained. However, these experiences should be transferred to other basins within Iran rather than focus exclusively on the Zayandeh Rud.*

**6.3. Research and requirements for further studies**

This section aims at the identification of a number of issues where additional research and investigation is required before we can make specific recommendations. Who undertakes such studies is somewhat outside the scope of this report, and requires additional discussion among the concerned parties. But we see roles for the research institutes of the Ministry of Agriculture and the Ministry of Energy, the Master Planning Organization, Universities and international research organizations in all of the topics discussed below.

**Water pricing**

We do not find that changes in current approaches to water pricing will lead to any significant differences in behavior or irrigating farmers. There are several reasons for this.

Water prices are low and are more geared to the repayment of operational costs of line agencies than as a mechanism to control demand. They would have to be raised to very high levels to act as a financial mechanism, perhaps to as much as US$0.10-15 per cubic meter, and at these levels it would discourage farmers from growing many of the less profitable crops.

If surface water prices get too high, farmers will increasingly move towards groundwater irrigation, even in irrigation networks, and this will have further detrimental effects on groundwater resources.

Volumetric measurement of water is problematic both conceptually and practically. While newer networks have modules that provide a reasonably accurate discharge, they only
extend to the level of the tertiary network. Below that, there is no capacity to measure water. Charging groups of farmers a common water fee raises significant institutional issues, does not prevent free riders from getting more than their fair share, and is only directly linked to individual water consumption. The costs of implementing a proper program of volumetric pricing would be extremely high.

We feel that while irrigators should indeed pay for a water delivery service, this should be restricted largely to the level of repayment of operation and maintenance costs. Additional research on water pricing issues is clearly required, but we feel more attention should be paid to water rights (see below) than to water pricing.

**Crop pricing**

Our results show that the effect of market prices of crops has a dramatic effect on the likelihood of adoption/disadoption of various crops. Farmers already respond positively to higher crop prices by trying to maximize the area under high-value crops. In the case of Zayandeh Rud, the high price for rice makes it unlikely that many farmers will give up growing rice. If they stop growing rice, they will likely go for vegetables that also require significant volumes of water.

The reality in Zayandeh Rud is that it is only about 10 percent of the total irrigated area grows rice, which consumes somewhere in the order of 15 percent of total water used for irrigation and contributes at least 30 percent of the total basin level gross value of agricultural production. We also find that most rice is grown on clay soils that may not be well suited for other crops. Taking this land out of rice and growing other crops only marginally increases the area irrigated in the basin, but dramatically reduces total agricultural value at basin, system and farm level. Only horticultural products and some fruits may compete with rice in terms of profitability, both per hectare and per cubic meter of water, and some of these crops also consume above-average levels of water.

While we do not recommend policies that try to dissuade farmers from growing rice, we feel that crop pricing needs to be considered carefully as a mechanism for encouraging or discouraging particular cropping patterns, and suggest this is taken up as an issue for future investigation.

**Water rights**

We believe that having clear and transparent water rights for both surface and groundwater is absolutely essential for the effective management of water resources within the Zayandeh Rud. Without effective water rights, there is little or no prospect of improved equity, transparent water allocation at basin, system or local level, and there will be continued mining of surface and groundwater resources.

Water rights are a statement of entitlements of water users, whether they are irrigators or water users in other sectors. They have three primary advantages: they define the amount of water a user can anticipate (either fixed or variable depending on water conditions), they facilitate water trading and they are a basis for establishing a system of more reliable water deliveries.

The exact water rights of irrigators are complicated. At network level, they are effectively seasonal rights given to them by the Ministry of Energy in line with water
availability. Thus in 2000 and 2001 many irrigators had no right to water and could not grow crops without access to groundwater.

At village level, a different set of rights exist, some of which go back many generations, and which are largely outside the control of government.

Our findings indicate that in the middle- and tail-end portions of systems, farmers feel frustrated because they have little assurance of water either between years or between irrigation turns during a season. Again, access to groundwater can help mitigate this uncertainty, but that is not a full solution to overcoming conditions of uncertain or unreliable water supplies.

We find that there is little evidence of a clear and transparent set of agreements between those who deliver water and those who receive it. This is true within the main and secondary canal system, as well as between secondary canals and the tertiary system. We believe this leads to less efficient use of water because when water supplies are uncertain there is a tendency for farmers to apply more as a form of insurance against future deficits.

We strongly advocate the implementation of a cross-sector policy review of water rights in the Zayandeh Rud, preferably commissioned at Provincial level that will result in a stronger regulatory framework that benefits all water users in the basin.

Water trading

We do not find any significant incentive for farmers to use less water when they have undefined water rights. However, if water users, either individually or as a group, have well-defined water rights, then they can quickly establish the right to sell water they do not use. This approach builds in an immediate incentive to use water more efficiently and effectively, maximizing both the benefit of the total water used and the water not used. If an individual or a group uses less than its allocated share, it can sell the unused portion to other users. Given the fact that none of the irrigation networks in the Zayandeh Rud basin receive sufficient water, trading can be done within the context of a single network rather than trying to address the much more complicated process of trading between networks.

However, we recognize that some tail-end networks might find selling their water right to middle or upstream networks a practical solution to their water and income problems.

We find that some farmers who own boreholes sometimes sell water to others, but we feel that as part of the study proposed on water rights the issue of whether bulk water trading between villages or canals could be an effective mechanism to encourage saving of water.

Guaranteeing water rights

A second immediate benefit of established water rights is that they can be translated into operational rules that help provide more reliable and predictable water supplies. The total annual or seasonal right can be disaggregated into timings and discharges throughout the irrigation season, particularly when there is no rainfall to disrupt routine irrigation schedules.

We do not find that most irrigators really know how much water they will receive, although in head-end systems there is much less uncertainty than in middle and tail systems. We find some evidence that this leads to two undesirable conditions: farmers take more water than they really need as insurance against possible shortfalls in their next turn, and that conflicts arise between water users because of uncertainty and its associated frustration.
We believe research is required to see how clear “level of service” agreements can be developed between managers of systems along the river, between secondary canals within a network, and between system managers and water users. These “level of service” agreements specify an acceptable range of discharge and timing of deliveries, and provide other relevant information to water users. They are being developed in other countries, and this may provide a model for adoption in Iran.

Additional out-of-basin transfers

The Zayandeh Rud is chronically water scarce and can use all of the water it receives and more. The current level of water availability makes additional out-of-basin transfers generally inappropriate. Out-of-basin transfers appear to have high priority, certainly higher than agriculture, and that means in drought years the agricultural sector is even more exposed to the effects of drought that they would otherwise be.

We recommend a careful review of the possibilities for additional out-of-basin transfer insofar as they may affect the volume of water available for agriculture, and also increase the vulnerability of the basin to droughts.

Move to agro-industry

Our assessment of the future of the basin from the agricultural perspective is not particularly favorable given current farming conditions. Too much valuable water is used to irrigate relatively low-value crops such as wheat and barley, and this makes agriculture a weak negotiator in the process of allocation of water between sectors. Further, we do not expect farmers who cultivate grain crops to become substantially more prosperous.

Instead, we conclude that the agricultural sector needs to be completely revitalized through the establishment of a viable agro-industrial sector. Such an approach requires the identification of crops suitable for value-added processing close to the point of production. This has many advantages: it means farmers can grow under contract to processors (in some countries they themselves have a direct share in the processing of their own produce through cooperatives or their equivalent), the produce is fresh and thus of higher quality, and the rural community has the opportunity to obtain steady employment in the processing of crops.

The crops identified need to be high value so that there can be adoption of more efficient and effective farm level water management techniques such as drip, plastic greenhouses, and plastic water conveyance systems. They will mostly be fruits and vegetables, which can command good prices either fresh or processed.

This type of transformation requires significant investment, both in the processing facilities and in upgrading farm level infrastructure. This means it requires a combination of public and private sector capital, and sufficient commitment during the years of establishment to allow for initial periods of loss or low profitability.

The development of intensive horticulture in Mediterranean countries is the model we see for the Zayandeh Rud, focusing precious water into profitable agro-industry, and moving away from extensive irrigation of low-value grain crops.

We recommend a multi-sector review of the possibilities for the establishment of a viable agro-industrial sector in the Zayandeh Rud basin, focusing on areas that have better soils and water conditions to maximize the productivity of the enterprises.
Trading in virtual water (imports of staple grains)

The Zayandeh Rud is poorly suited to be a major grain producing area in the future. Water is too scarce and too valuable to be used to grow low-value crops that can be imported into the basin. Water use therefore has to be viewed in a wider national perspective.

The rain-fed grain growing areas of western Iran are able to produce more than their own local requirements, using rainfall that is essentially free. Doubling the water productivity of these rain-fed areas is feasible and would be more than sufficient to meet the grain requirements of other basins. In return, the Zayandeh Rud should, through the process of agro-industrialization, be exporting higher value fruit and vegetable products to grain-growing areas. This represents a trade in virtual water—for every ton of grain imported into the basin is in effect 500 to 1,000 cubic meters of water saved at current levels of wheat and barley water productivity. This water, if used to grow high-value crops, can be exported at far higher value than that of the water used to grow grain imported from other parts of the country.

This concept of virtual water is basic for a water-short basin that has the potential to grow high value crops, and forms much of the justification for long-term investment in agro-industrial complexes.

We believe there will be great benefit from a policy review that looks for a long-term vision for the establishment of an agro-industrial sector and that the concept of virtual water trading at national level be incorporated into the justification. We do not feel that water in Zayandeh should be used to meet regional food security goals, when it can be made more profitable as part of the national efforts towards food self-security and a viable agro-industrial economy.
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