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# *Modeling the water economy of the Jordan River Basin*


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Economic Research Forum
For the Arab Countries, Iran and Turkey

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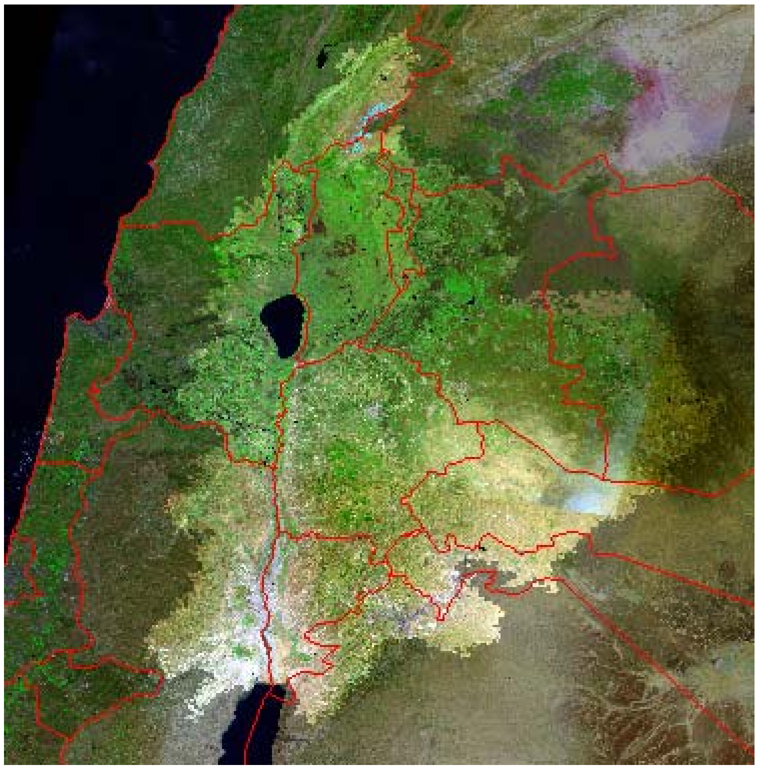
# Modeling the water economy of the Jordan River Basin



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**Final report for the project: Regional Integration and Resource Use in the Middle East: Oil, Water and the Need for Peace**

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## Summary

Water scarcity is most binding to the economic development of the Middle East. The situation is likely to worsen in the coming years due to overexploitation of aquifers beyond their regenerative capacities and to the persistent political tensions, which at least in part result from a quest for the control of water resources.

The present study develops a model of the water economy of the Jordan River basin and this report describes the status of the project by December 2004, the end of the funding period from the FEMISE-grant that has sponsored the research so far, jointly with the Netherlands Ministry of Foreign Affairs (Development Co-operation).

The findings thus far indicate that interbasin transfers from Syria and Lebanon could offer a promising and sustainable alleviation of the prevailing scarcity. Yet, implementation of infrastructure require a peaceful situation, especially because the region is characterized by peak discharges from snowmelt in a period of the year when agriculture has little use of the water, and in case of Syria, transfers over long distances. Moreover, these transfers cannot be expected to occur without due payment.

Against this background, the aim of the project is to provide decision makers and negotiators with a support tool that may assist them in quantifying in physical as well as economic terms the implications of different options for water management in the basin, building as much as possible on consensus about scientific relationships and empirical facts. Hence a careful description of the interaction between water flows and land use management is needed.

A first step was, therefore, the precise demarcation of the Jordan River Basin and construction of a spatially linked database that covers the geographical diversity and describes the monthly hydrological conditions and economic activities at the level of 25,301 distinct sites, over an area of about 18 thousand km$^2$.

Next, a theoretical model was formulated that considers each site as an economic agent and can handle non-convexities of hydrology. This spatially explicit model accommodates the water and salt flows and relates these to location-specific production functions accounting for both agricultural production and other uses of water, mainly by households. The specification allows for scenario simulations under various modes of co-operation among stakeholders, nationally with adequate payments for water deliveries and salt discharges by the economic agents concerned.

The sheer size of the model, with all its interdependent cells to be solved for at least the 12 month of one annual cycle, for water and salt, and for at least two layers, surface and groundwater, with monthly constraints on economic activity, and under different modes of co-operation, clearly generates a problem with hundred thousands of simultaneous endogenous variables. To solve this model and to calibrate it accurately to the available data several dedicated algorithms had to be developed.

At present, work is still in progress on improving the database so as to enhance the model’s reliability. In the follow up phase, for which funding has been secured, the implications for the use of the model as a decision support tool in future negotiations and river basin management operations will be looked into, in close cooperation with the JRB-stakeholders.

# Section 1

# Introduction

***Genesis 26, verse 17,19-22***

*"So Isaac left that place and encamped in the valley of Gerar, and stayed there. Then Isaac's slaves dug in the valley and found a spring of running water, but the shepherds of Gerar quarreled with Isaac's shepherds, claiming the water as theirs. He called the well Esek, because they made difficulties for him. His men then dug another well, but the others quarreled with him over that also, so he called it Sitnah. He moved on from there and dug another well, but there was no quarrel over that one, so he called it Rehoboth, saying, 'Now the Lord has given us plenty of room and we shall be fruitful in the land'".*

## 1.1 Background of the project

The Water and Agriculture project (FEM21-02) to model the water economy of the Jordan River Basin is being conducted at the Centre for World Food Studies of the *Vrije* Universiteit, The Netherlands (Dutch acronym SOW-VU), with grants from FEMISE and the Netherlands Ministry of Foreign Affairs (Division for Development Co-operation).

Several organizations in- and outside the region were contacted and have contributed information and insight to the project, notably the Bureaus of Statistics from Israel, Jordan and the Palestinian Authority. Furthermore, various institutes and working groups active in the region have been consulted (Austria Research Center at Seibersdorf and the EXACT-team of the Institute for Climate Impact Research at the University of Potsdam). The project also benefited from SOW-VU's previous involvement in IFAD-projects in Lebanon and Syria (Keyzer et al., 2001; Syrmap, 2004).

The present report describes the status of the project in December 2004, the end of the funding period from the FEMISE-grant. The grant specifies the following deliverables:

*"The output consists of a report describing the model structure, the database and the outcomes of the scenario analysis. These outcomes will be presented both as quantitative accounts at country and watershed level. Maps with a fine grid resolution will show the spatial distribution of water use, discharges of pollutants, economic activity and water charges. Attempts will be made to gain the interest of research groups in the relevant countries in pursuing this research, and to restitute the software developed in this project to these groups."*

Most of these aims were achieved, but not all. Broadly, the methodological and data work has been completed, but the model so far has not yet reached a stage where it would be appropriate to contact policy makers in the region for discussions on policy scenarios. Clearly, in view of the undeniable sensitivity of the issues at stake, premature discussions on policies may only add confusion to the debate. Fortunately, follow-up funding could be secured to finalize the activity in 2005, including the organization, preferably in co-operation with local institutes, of a workshop in the region and of some training of interested counterparts in the use of the tools developed under the FEMISE-grant. Based on the response of counterparts proposals will be developed for further work.

### 1.2 Project team

The SOW-VU project team consists of:

(1) Michiel A. Keyzer, economist: project leader, model specification and algorithms
(2) Ben G.J.S. Sonneveld, agronomist: communication with counterparts, mapping of hhydrological and economic data from various sources, hydrological data and coefficients, and GIS-work, including satellite interpretation.
(3) Bart J. M. van den Boom, economist: compilation of economic data at the district level, and software development for data file creation.
(4) Harold Houba, economist: data compilation, literature review on economy and game theory perspective, external relations.

### 1.3 Overview of the paper

This research report is organized as follows. First, the general problematique of the water economy is introduced in Section 2, starting from a regional perspective before focusing in on the Jordan River Basin.

Section 3 describes the decision support tool. After a brief literature review on the modeling of the water economy, it elaborates on the specificity of water from the perspective of economic analysis. This yields the requirements for specification of our decision support tool. The section provides the model specification, and briefly sketches the algorithms designed to compute the allocation for a range of solution concepts. The first is the efficient allocation that maximizes social welfare, in which every user pays for the water received from upstream and is compensated for discharges of salt. At the other end comes the allocation in which no one pays for the water received or for the salt discharged. In between, we consider an allocation in which full payments are only made to sites in the own country. Furthermore, we indicate how a unique steady state can be computed in which initial stock on 1$^{st}$ January is at all sites equal to the end stock on 31$^{st}$ December of one year.

Next, in Section 4 we turn to the empirical elaboration needed to feed the model with initial values for variables and parameters. An important first task involved demarcating the Jordan River Basin from available altitude maps and, hence, to provide both an operational definition of the basin and a definition of the spatial linkages of hydrological flows. Such a step is necessary, because all available altitude maps inevitably contain small measurement errors leading to small inconsistencies in river and surface flows such as rivers flowing over small bumps in the landscape or surface flows in the basin that are unable to feed into observed streams and rivers. Dedicated algorithms were developed for this purpose. Since the valuation of water calls for a spatially-explicit description of the economic outputs from water using processes, in agriculture, households, and in industry, where the order reflects the importance in the Jordan River Basin. Satellite images are particularly useful for this, since they provide up-to-date information on land use patterns. We describe the approach to process these data into a format (a land use classification) needed by the model, and to integrate them with both ground statistics and crop-specific information on the yield response of various crops to water. We also indicate how salinity reduces this response.

Section 5 summarizes the results obtained so far, which as mentioned already, are largely of a methodological nature but comprise some empirical findings as well. The section also discusses the scheduled consultations with stakeholders as well as possible extensions of the tool to allow for uncertainty of climatic and political nature.

# Section 2

# Problematique

## 2.1 The water shortage in the region and scope for its alleviation

Before focusing on the Jordan River Basin (JRB) proper, we briefly review the water situation in the five countries that share this basin. Israel, Jordan, Lebanon, Syria and the Palestinian Authority lie in an area with generally low levels of precipitation and significant differences across countries, as illustrated in Table 2.1.

**Table 2.1 Annual precipitation (average 1961-90), water availability and use (2001) by JRB country**

| | Precipitation | | Water availability | Irrigation | Domestic use | Industrial use |
|---|---|---|---|---|---|---|
| | mm | MCM* | MCM | in per cent | in per cent | in per cent |
| Israel | 435 | 9,160 | 2,040 | 63 | 31 | 7 |
| Jordan | 111 | 9,930 | 1,020 | 75 | 21 | 4 |
| Palestinian Authority | 542 | 3,263 | 244 | 59 | 41 | 0 |
| Syria | 318 | 58,890 | 19,950 | 95 | 3 | 2 |
| Lebanon | 661 | 6,870 | 1,370 | 67 | 33 | 1 |

*MCM= million cubic metres.

Source: Aquastat (2004)

Average precipitation is lowest in the deserts of Jordan and Syria and highest in the coastal mountain regions of Israel, Lebanon and the West Bank. Only a small fraction of the water in the basin is exploitable for pumping of groundwater or diverting flows from rivers and lakes. For decades, water delivery from natural sources on Israeli, Jordanian and Palestinian territory reached its maximum capacity. Total deliveries comprise steadily rising amounts of reclaimed water for secondary and tertiary use, and in the near future, with the opening of the Ashkelon plant, desalinated water as well. With shares in the range of 60 to 75 per cent, agricultural water use is by far the largest use category, followed by domestic water use. Syria is an exception with agricultural water use of 95 per cent. Since ancient times, water scarcity has led to low prevalence of often water intensive manufacturing activities and electricity plants. On the Palestinian Authority, the political situation and constraints in water availability have dwarfed most industrial activity and reduced the water use in agriculture. Consequently, it has the region’s largest share of water use for domestic purposes.

Confronting agricultural and domestic water use with data on population and irrigated area reveals enormous differences across countries, as Table 2.2 demonstrates. At an estimated 145 m3 per capita per year, domestic water use is highest in Lebanon, followed by 101 m3 in Israel, a level that is typical for high-income countries in arid areas. Conversely, at around 40 m3 per capita per year, domestic water use is low in Jordan and Syria while the average of less than 30 m3 reflects a particular severe rationing in the area under the Palestinian Authority.

Irrigation per hectare of a specified crop is a rough indicator of irrigation efficiency. While Israel's technological advantage in irrigation technology has resulted in a high efficiency (low water application per hectare), its specialization on vegetables and tropical crops, which are water intensive, imposes higher water requirements than other irrigated crops. By contrast, Lebanon has a more traditional cropping pattern that requires less irrigation per hectare and more temperate climatological conditions. Jordanian farmers apply water about twice as much per hectare as the Israeli farmers and Syrian farmers even two and a half times. The water-constrained Palestinian farmers apply much less water per hectare under irrigation and also have much less irrigated land: 51 per cent for Israel against only 10 per cent in the Palestinian Authority.

**Table 2.2 Population and water use intensity (2001), by JRB country**

| | Population Million | Irrigated area km2 | Domestic water use $m^3$ pc / year | Irrigation mm per ha |
|---|---|---|---|---|
| Israel | 6.300 | 1,630 | 101 | 788 |
| Jordan | 5.401 | 500 | 40 | 1,530 |
| Palestinian Authority | 3.464 | 160 | 29 | 900 |
| Syria | 16.320 | 9,490 | 37 | 1,987 |
| Lebanon | 3.111 | 1,170 | 145 | 785 |

Source: ICBS (2003), PCBS (2004), Aquastat (2004) and Table 2.1.

Water leaves the JRB at several locations until it reaches its natural outlet in the Dead Sea. The most important withdrawal comes from Israel's National Water Carrier (NWC) that diverts the water from Lake Tiberias to the coastal areas in Israel. Estimates of the NWC's extraction from the lake range from 60 per cent (UNEP, 2004) to 100 per cent (Libewski, 1995) of annual inflow from the Upper Jordan River, which varies according to seasonal rainfall from 250-450 MCM/Yr. Average extraction is around 380 MCM/Yr and constitutes 18.6 per cent of Israel's annual water use (ICBS, 2002). Other points of withdrawal are located at the Upper Yarmuk river, where water is pumped to irrigated areas of the Dimashq Province (Syria), and groundwater withdrawals in the upper Amman-Zarqa Region (Jordan) and the Eastern Mountain Aquifer (Palestinian Authority) for irrigated areas in the, respectively, Karak province and agricultural sites on the West Bank.

Next, Table 2.3 gives estimates of the transnational water flows and shows a clear-cut picture: Israel and Jordan are recipients and Syria, Lebanon and the West Bank are contributors. Syria and Lebanon provide the headwaters and groundwater flows of the Jordan, whereas the West Bank mainly delivers underground flows. For Israel these transnational flows constitute a major share of total water availability, whereas for Jordan these shares are less. According to Beaumont (2000) the contribution of the West Bank to Israel is even of the magnitude of 450 MCM/Yr. Given the limited water resources for the West Bank, this is a significant drain.

Clearly, these water transfers have an economic value, albeit it is not fully clear to whom this value would have to accrue if it was monetized, because the ownership issues are at the heart of the political conflict. Without a transnational water market, a market price reflecting the economic value of water is difficult to assess. Fishelson (1994) estimates the value at 20 USD cents in Israel, which would imply that the value associated with transnational water flows would be in the order of 219 million USD.

**Table 2.3 Transnational flows among JRB countries (MCM).**

| Recipient | Contributor | | | Percentage of recipient's water production |
|---|---|---|---|---|
| | West Bank | Syria | Lebanon | |
| Israel | 275 | 460 | 160 | 44 |
| Jordan | - | 200 | - | 20 |

Sources: FAO Aquastat (2004) and Table 2.1.

*Water scarcity*

Water scarcity is a dominant constraint for the economies of Israel, Jordan, the Southern Lebanon, Southwest Syria and the Palestinian Authority. The World Bank classifies the three downstream countries as water stress zones. Freshwater is drawn from limited and shared sources, namely the Jordan, Litani, Zarqa and Yarmuk Rivers and shared aquifers on the West Bank, the Golan and Jordan's upland. The region is known for its unsustainable overdraft of existing water sources, but given the pressure from high rates of population growth in the region the current practice is not likely to change in the near future. Indeed, the Jordan River is deprived of almost all of its natural flow when it reaches the Dead Sea and, with no changes in policies, it is estimated that this 'sea' will have evaporated almost totally by the year 2025 (MFA, 2002). Furthermore, in each of the countries government subsidizes agricultural water users, leading to inefficient use. Furthermore, poor water quality, salinity in particular, is a complicating factor because it comes up with groundwater extraction that cannot be dispensed of, and also because some of the natural springs are saline. Unwanted brackish water and untreated wastewater are often diverted to downstream users across the national border without any consideration of harmful effects. All this demonstrates the urgency of regional agreements on managing available water resources.

Clearly, the Arab-Israeli conflict has for many years created significant instability in the region. Some even claim that water plays a central role in this conflict. The earlier quote from Genesis illustrates that rivalry over water sources is an imminent problem for the region that has persisted through the ages and was often settled through force rather than peaceful co-operation. Since the early 1950s, all parties in the conflict quarrel about the waters of the Jordan River, with the unratified Johnston Plan of 1955 as one of the early attempts to settle the water dispute. The completion of Israel's National Water Carrier in the early 1960s created significant unrest and eventually was a major cause of the Six Day War in June 1967. The current status quo, with Israel occupying Palestinian territory and the Golan is a direct consequence of this war. Hence, water security must be an integral part of any peace process, witness several paragraphs in both the Oslo Accords of 1993 and the Israel-Jordan Peace Treaty of 1994 (Amery and Wolf, 2000). From a water management perspective, a peaceful settlement should contain an interregional agreement on managing supply and demand for available water resources.

*Increasing supply, and improved demand management*

Since almost all of the natural water sources in the Jordan Valley are currently already exploited beyond sustainable levels, there is not much to gain from supply management to increase available water from those sources. This leaves only two options for supply management: desalination of brackish sources and seawater, or imports of freshwater from relatively water rich countries areas outside the valley, such as Lebanon, Turkey and Egypt. Both are frequently proposed as providing the ultimate solution to this water stressed region.

However, Israel already in 1978 abandoned its earlier plans for conventional and nuclear desalination as technologically premature and economically unfeasible, (e.g. Wolf, 1998), and despite major technological innovations since that time desalination remains capital and energy intensive. Jordan on its part did not engage in desalination of seawater at the Gulf of Aqaba because this is costly, requires transport of freshwater over long distances and would increase this country's dependence upon oil imports (Abu Qdais and Batayneh, 2002). The current cost of desalination is about 35 USD cents per cubic meter for brackish water (Afonso et al., 2004) and 78 cents for seawater (own calculations). Though still falling, these cost prices are too high to be profitable and sensitive to energy prices (Afonso et al., 2004; Bick and Oron, 2000; Gruen, 2000; Kronenberg, 2002, 2004; Liu, 2000; Murakami, 1995, 1998; Shuval, 2000; and Wolf, 1998). Nonetheless, to reduce dependency on natural fresh-water sources a desalination plant for the annual production of 100 MCM of desalinated water is scheduled to start operating by the end of 2004 near Ashkelon in Israel (Einav and Lokiec, 2003). Furthermore, large-scale desalination is envisioned in a plan for restoring the Dead Sea (MFA, 2002) that received a grant of 10 million USD from the World Bank for a feasibility study in 2004 (Fitleberg, 2004). Some preliminary cost price calculations performed during this study show, however, that these cost prices for water are still high. Water imports from nearby water-abundant countries would be a more cost effective way to increase the water supply. as implied by the cost price estimates of around 16 USD cents per cubic meter from Egypt and 40 cents from Syria/Turkey (Gruen, 2000; Kohn, 2003; and Shuval, 2000).

*Lebanon and Syria as potential water suppliers*

Lebanon and Syria are relatively well endowed with water resources and could, potentially, become future suppliers to the JRB-region. Lebanon, has high natural rainfall and significant snow melt; Syria receives much water through its river network that originates in the Turkish Taurus Mountains as well as the Iranian Highlands. However, there is an important difference compared with countries that are situated at the foot of mountains in more temperate regions. In Western Europe, for example, snowmelt in spring provides ample water for freshly sown field crops such as wheat, barley and potatoes that are harvested in the course of summer. In the JRB-region the harvesting of field crops ends by mid-April, and the sowing is in the fall. While this fits the predominant rainfall pattern with a dry season from May to September, it also means that discharges from major rivers, whose peaks coincide with snowmelt in spring,

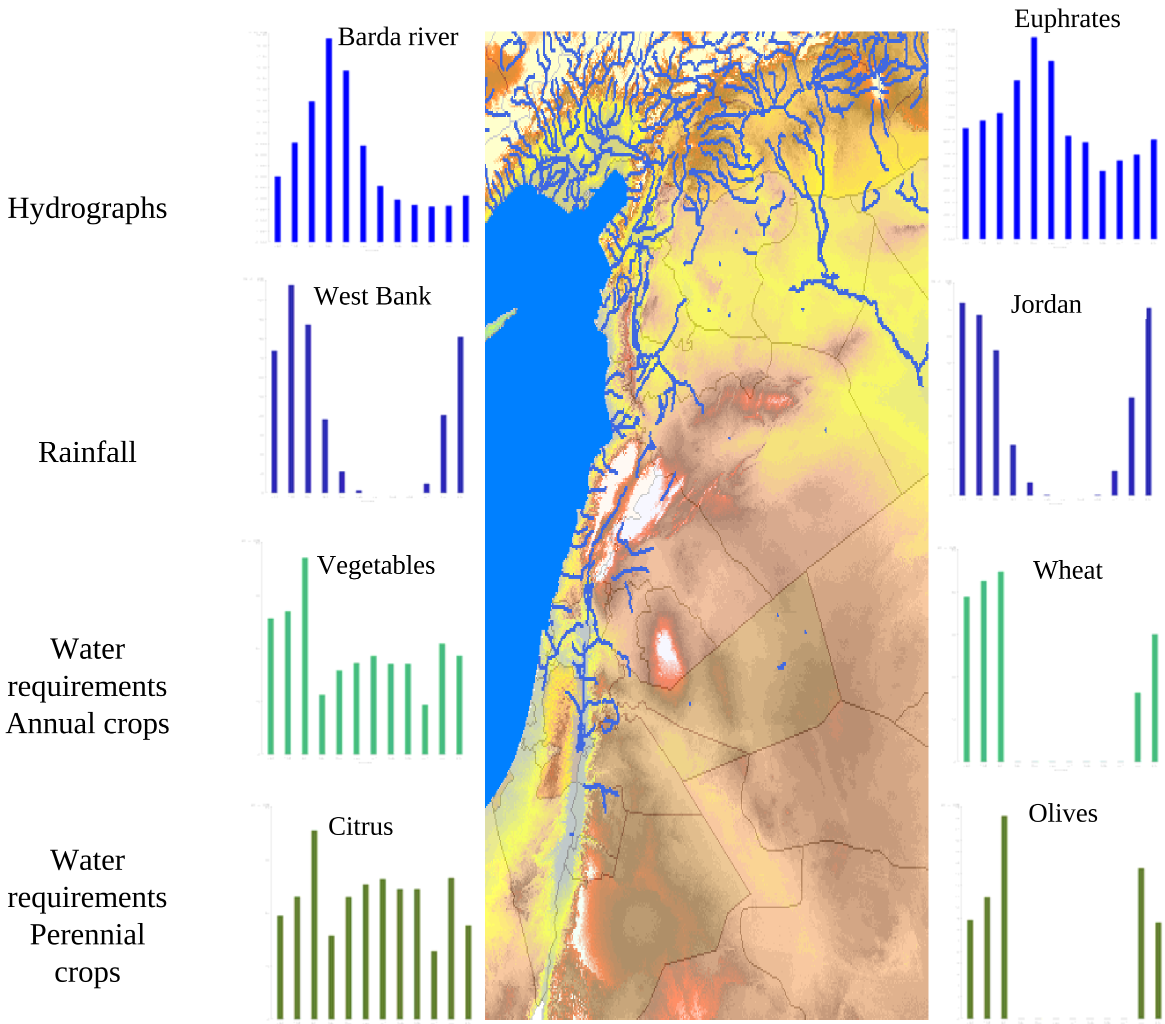


**Figure 2.1 Monthly water sources and requirements**

can, in the absence of water reservoirs, not be used for irrigating the major field crops, hence, the importance of dams on these rivers. In the absence of dams, the water supply from rivers is in crop agriculture mainly useful for cultivation of irrigated crops that are cultivated in all seasons like vegetables or perennial cash crops that need a regulated water supply, for reducing the salinity of soils, and possibly for replenishment of groundwater reserves. In addition, it obviously is of vital importance for people and livestock.

Figure 2.1 gives a schematic overview of the discussion above. It shows how water demands for rainfed crops (wheat and olives) follow the prevailing precipitation patterns, while major peak discharges of Syrian and Lebanese rivers occur after the harvesting period of field crops. Yet, and without flow regulation, these discharges could be useful contributions to the water demand of irrigated crops (vegetables and citrus) which remains unrelentingly high during the dry spell.

Lebanon could deliver considerable discharges to the JRB if it conserved part of the approximately 2,300 MCM/Yr fresh water that drain into the Mediterranean Sea, while Syria and Jordan could save much of their water resources by improving irrigation efficiency. If, for example, the current irrigation practices could be upgraded to a modest irrigation efficiency of 12,000 cubic meter water per hectare in Syria and Jordan, the nationwide savings would be 7,565 MCM/Yr in Syria and 165 MCM/Yr in Jordan, which is 16 per cent of Jordan's annual use. Especially, the al Khabour river that takes Iranian water to the Euphrates could be used for water transfers since its water is of a good quality, annual discharges are stable at approximately 1,200 MCM/Yr (Bazza and Najib, 2003), the major orientation of its headwaters is directed to the JRB, and the highest flows are reached in spring when snow melts in the Iranian Mountains, essentially around harvest time in the region Northeast of the Euphrates. Lebanon, however, is the most likely candidate water supplier in the near future, basically because the proximity of major water flows (Litani and Awali rivers) to the JRB facilitates water transfers through a relatively simple construction of a 10 km long canal at a cost price of 4 USD cents per cubic meter (Kohn, 2003).

**Table 2.4 Water flows in Lebanon (in MCM)**

| Utilization/Destination | Surface water | Ground water | Total | Percentage of total |
|---|---|---|---|---|
| Agriculture | 499 | 377 | 876 | 18.3 |
| Domestic | 184 | 184 | 368 | 7.7 |
| Industry | 50 | - | 50 | 1.0 |
| Israel | 160 | 180 | 340 | 7.1 |
| Syria | 510 | 130 | 640 | 13.3 |
| Mediterranean Sea | 2367 | 159 | 2526 | 52.6 |
| Total | 3770 | 1030 | 4800 | 100.0 |

Source: FAO (1997).

***Israel's water security***

In 1999, Syria and Israel started bilateral peace talks concerning peace and water security in return for Israel's retreat from the Golan Heights. In the same year, these talks ended without agreement and have not been resumed since. Prior to these talks, it seemed that the cease-fire lines established in the Armistice Agreement of 1949 would be agreed upon as the official border, but it appeared the countries failed to agree on their mutual boundaries. The Armistice Agreement assigned to Israel the entire 10-meter strip along the Eastern fringe of Lake Kinneret as delineated by the 1923 International Border between Mandatory Palestine and Syria, as well as the Hamat Gader (El Hama) springs area contiguous to the Yarmuk River. The boundary is important because had both countries accepted the 1929 border, international water conventions would deny Syria any title to waters of Lake Tiberias.

Within Israel there is strong opposition to withdrawal from the Golan Heights as part of a peace settlement with Syria. Although the underlying motivations and ideologies vary, military and water security of the Jordan River Basin is a dominant argument. Israel is concerned that Syria and Lebanon might renew its 1965-attempts at diverting the sources of the Jordan River to prevent Israeli use of the Jordan Water.

Shuval (2000) proposes two possible alternative borders with Syria and associated arrangements that provide Israel a water security of on average 330 MCM/Yr. One would be the drawing up of water security borders with Syria based upon the water divides on the Golan Heights. This would leave a significant part of the Golan under Israeli control, and, therefore, be unacceptable to Syria. The more feasible alternative would be along the 1923 International Border with a special status water security zone under joint and/or international management, inspection and control. This zone would include a strip of 1-3 kilometres width along the entire Eastern side of the border within Syria that could include all the main water sources and no direct Syrian access to the springs, river and lake. The water from these critical sources could then continue to flow freely into the Jordan River for Israeli use, except for the amount of water that would be allocated under a peace agreement to Syria. Such a treaty with special arrangements could be made to comply with international law, that allows for special arrangements and assurances in water issues in case one of the partners has committed a serious violation in the past. With respect to this distribution, implementation of the 1955 Johnston Plan would allocate about 80 MCM/Yr to Lebanon and Syria, which is regarded as a pragmatic compromise in Shuval (2000). The consequence for Israel would be a drop of 5 per cent in its renewable water resources and a 10 per cent drop in its agricultural water use, which would have a limited effect on Israel's food self-sufficiency in percentage terms, because the country already imports 85-90 per cent of its staple foods, while its agricultural sector has specialized in exports of exotic high quality flowers, vegetables and fruits in a successful attempt to optimize profits from growing crops with the highest economic return. Though significant, the share of irrigation costs in total production and marketing costs of these products is not excessive (8 per cent for Israeli farmers under current subsidized water use), and overall water security would not be threatened.

Be this as it may, allowing downstream countries to keep control of springs upstream to safeguard water security remains an exception in international law rather than a rule. Accepting the rule that control over natural resource supplies extends outside the national territory when this is vital to the national economy goes against basic principles of national sovereignty. Similarly, The Netherlands could hardly justify taking over parts of Germany, France and Switzerland to secure its provision of water from the Rhine. Yet, there is recognition that water is different from say, petroleum, precisely because of the mutual dependence. The Netherlands need the water but Germany would be flooded if the Netherlands built a dam on the Rhine to keep the river out. Hence, the long tradition all over the world at setting up and managing multinational watersheds through dedicated supranational institutions (e.g. the Rhine and Danube in Europe, the Incomati in Africa, and the many water treaties between Pakistan, India and Bangladesh). Nonetheless, the scope of these treaties may have to be broadened. Wolf (1998) reports on an investigation of a database containing 145 of the approximately 300 of such treaties signed since 1814. It appears that almost all these treaties dealt with the allocation of surface flows in river systems and only few address water quality and land use issues.

*Water allocation to the West Bank*

Currently, the water allocation among the countries in the JRB rests both on the appropriation of upstream deliveries through armed force and the rationing of water supplies to downstream users, in particular the Palestinian settlements of the West Bank, where permits for drilling new wells are in short supply and the prices charged by Mekorot, Israel's main water supplier, are relatively high. As water supply from existing wells is under Israeli control, Palestinian farmers often resort to drought resistant crops. By contrast, the Israeli settlements on the West Bank receive subsidized water from Mekorot and have easier access to permits for groundwater (Berck and Lipow, 1994). Furthermore, Israel's National Water carrier extracts large amounts from Lake Tiberias and deprives the Lower Jordan River of most of its natural inflow before it reaches the West Bank. Moreover, brackish spring water from wells surrounding Lake Tiberias is diverted to the Lower Jordan. Not surprisingly, salinity and drought are persistent problems in this area, dwarfing the development opportunities at the West Bank in the Lower Jordan Valley.

Nonetheless, the conflict of interests between Israel and the Palestinian Authority is not the only issue at stake. Syria deprives the Jordan River Basin from inflows through a dam on the Yarmuk River, and pumping stations that return Yarmuk water to Syria, and through the King Abdullah Canal, to Jordan's capital Amman, and fields on the east bank of the Lower Jordan River. In addition, the Johnston Plan of 1955, that still enjoys strong international support, assigns 480 MCM/Yr to Jordan (inclusive of the West Bank at the time), with the understanding that some 150-200 MCM/Yr of this allotment would be transferred to the West Bank through a siphon under the river to the proposed West Ghor Canal, which could then be used for the resettlement of Palestinian refugees in agricultural communities. These old commitments might provide some basis for distribution of property rights over water to the Palestinian Authority, in this respect with obligations for present-day Jordan.

## 2.2 Geography of the Jordan River Basin

*Climate, rivers and altitudes*

The Jordan River Basin (JRB) is not an entity for which statistical data are readily available and an elementary but necessary first step in the compilation of a database for this basin has been to demarcate it. This was done by identifying all locations from which water can in principle flow freely to the observed drainage network of streams, rivers and canals. In this manner, an area of 18,056 square kilometres has been isolated, whose major water flows are shown in Figure 2.2. A dedicated procedure to perform this task has been developed and implemented, as is explained in Section 4.1.

A large part of the JRB has a Mediterranean climate with hot, dry summers and cool winters. Short transitional seasons predominate in the northern, central, and western parts of the basin, while the eastern and southern parts experience a semi-arid to arid climate. Winter begins around mid-November and summer starts at the end of May. Rainfall exhibits large seasonal variations and occurs mainly during the winter months, decreasing from west to east and from north to south, ranging from 1,200 millimetres (mm) at the northern tip to less than 50 mm in the desert areas. Temperatures in the basin follow the north-south latitudes and altitudes. Average daily mean temperatures in the Jordan Rift Valley area range from 15 °C in the winter to about 31 °C in the summer.

The JRB is often subdivided into four physiographic areas (EXACT, 2004). Relatively high and secure rainfall regimes prevail with snowfall in winter in the main catchment area in the north-east that is formed by the *slopes of Mt. Hermon and the Golan Heights*, which are bounded by the Upper Jordan River, Lake Kinneret, the Yarmuk River. The Upper and Lower Jordan River flow through the narrow *Jordan Valley*, which is a large rift extending further into Lebanon to the North and for many thousands of kilometers into the African Rift Valley to the South. This part contains the Hula Valley, one of Israel's major irrigation areas, and the well-known Lake Tiberias and the Dead Sea, which is the lowest point on the earth's surface of about 400 m below sea level. The valley has long been used for agriculture relying on water from the Jordan River and numerous wells and springs along the flanks of the

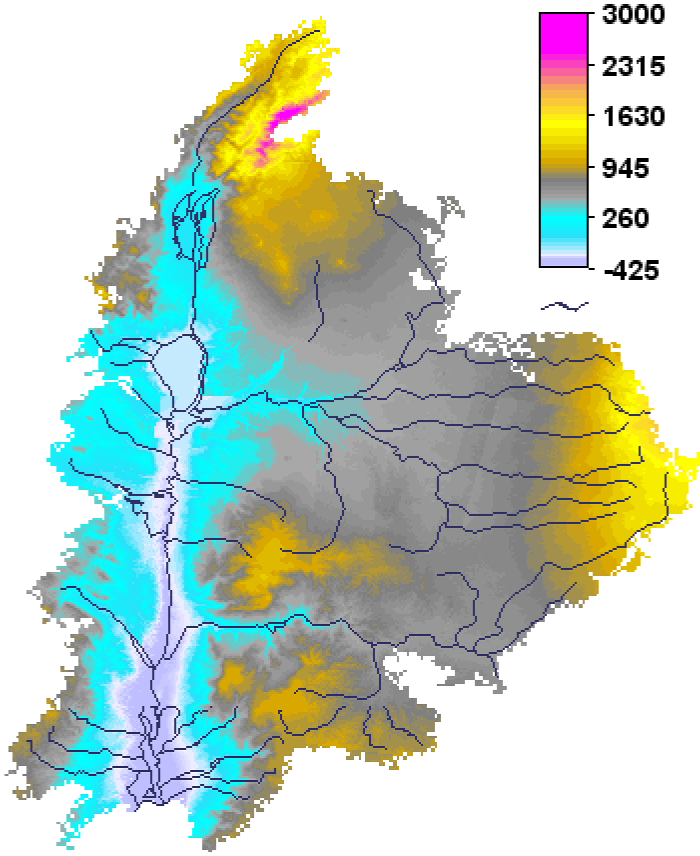


**Figure 2.2 Altitude map and rivers in the Jordan River Basin**

valley. The lower parts of the Jordan Valley are bordered by the *Western and Eastern Escarpments*, with its abrupt valley walls and deeply incised wadis across the escarpments that cut through the underlying rocks. East of the valley and its escarpments we find the *Jordan Highland*, which also consists mainly of deeply incised rocks with altitudes of as much as 1,200 m above sea level.

Groundwater is contained in aquifers that are composed of highly permeable and karstic carbonate rocks with a high capacity to transmit water, but also to move water to discharge zones, usually karstic springs. The water from many of the springs below sea level are saline, in particular those around Lake Tiberias and further south in the Jordan Valley. The saline springs that discharge to Lake Tiberias are diverted from the lake through the Chlorine Water Carrier into the Lower Jordan River, worsening the salinity of this stretch.

The main rivers and lakes that dominate the surface water flows in the JRB are already mentioned. The Upper Jordan River consists of the Dan and Banias Rivers and delivers a median 490 MCM/Yr into Lake Tiberias. Water leaves Lake Tiberias primarily through Israel's National Water Carrier intakes and surface evaporation. From the outlet of Lake Tiberias, the Lower Jordan River flows south to the Dead Sea, but at present the Lower Jordan River is mainly fed by the Chloride Water Carrier. It is joined by the Yarmuk River just south of Lake Tiberias. The Yarmuk River receives its 210 MCM/Yr of water from the

Golan Heights, Mt. Hermon and the Jordan Highland. In general, the water quality of this river is good with very low salinity. The northern end of the King Abdullah Canal feeds on this water through a diversion via a 900-meter long tunnel. Almost the entire water flow is extracted depriving the Lower Jordan of inflow. Further south, the Zarqa River drains to the Lower Jordan but its flow of 63.3 MCM/Yr is largely controlled by the King Talal Dam and extracted for use in the most densely populated and industrialized area on the east side of the Jordan River. The dam is connected to the King Abdullah Canal and also serves as a reservoir for water from the Yarmuk. The water is also used for irrigation on the east bank in the Jordan Valley. The water of many smaller tributaries that cross the eastern and western escarpments are stored and do not reach the Lower Jordan River. Since only a small percentage of the inflow to Lake Tiberias is released to the Lower Jordan River and much of the discharge from the Yarmuk and the Zarqa Rivers and other tributaries is also diverted for water supply before its confluent with the Jordan River, water availability in the lower Jordan is far below its natural level, and consequently, suffers from high salinity, because of the diversion from Lake Tiberias mentioned earlier as well as saline springs along the lower Jordan River and return flows from irrigation. The Dead Sea where the Jordan River ends has the highest salinity of any water body in the world, and because of the limited inflow has a gradually falling water level.

Given the economic and political constraints to raising water supplies, policy makers for the time being have to resort to demand management. Since water demand at one site significantly impacts on availability at downstream locations, efficient demand management calls for basin wide co-ordination, requiring either some handing over of national autonomy in water management to a supra-national river management board, or at least a pricing of water, with associated cross-border payments by users, that signals the scarcity in downstream use as well as the present value of future cost associated with the overexploitation of groundwater resources. Hence, both the spatial and the intertemporal effects are to be accounted for, and in fact have much in common analytically. While the upstream user of water denies downstream inhabitants (part of) a scarce good, the extraction of groundwater withdraws water from future use. Consequently, both aspects must be considered jointly.

*People and water in the JRB*

Comparison of the population data in Table 2.2 and 2.5 shows that almost all Jordanians live in the basin, followed by one quarter of the Palestinians, 15 per cent of the Israelis, 10 per cent of the Syrians, and less than 5 per cent of the Lebanese people. Clearly, in terms of population and area, the Jordanians are the main stakeholder, comprising almost 40 per cent of its population and 60 per cent in terms of area. Of the total irrigation in the JRB of around 100,000 hectares, more than 40 per cent is done in the Israeli part (including the Golan), a quarter in the Jordan part, a quarter in the Syrian part, and less than 4 per cent on the West Bank. As regards to precipitation, the relative contribution to the basin’s total precipitation is about 2 per cent for every per cent point of area for the net contributors Lebanon and Golan, slightly above 1 per cent for Israel, about 0.9 per cent for Syria and the West Bank and below 0.8 per cent for Jordan. Syria is a net contributor to the basin with relatively high precipitation around the slopes of Mount Hermon. Although the relative contribution is lowest for Jordan it still covers the largest area in the basin and receives 30 per cent of total precipitation. However, much of this precipitation cannot be transformed into surface or groundwater and simply evaporates.

**Table 2.5 Precipitation, population, area, and irrigation in the Jordan River Basin.**

| | Precipitation | | Population | Area | Irrigated area |
|---|---|---|---|---|---|
| | (mm) | (MCM) | (1000) | (km$^2$) | (km$^2$) |
| **Entire basin** | 374 | 6743 | 8,920 | 18,056 | 1015 |
| Israel | 451 | 927 | 886 | 2061 | 326 |
| Jordan | 298 | 1995 | 5,420 | 6680 | 258 |
| Palestinian Authority | 328 | 617 | 797 | 1901 | 38 |
| Syria | 346 | 1875 | 1,620 | 5403 | 257 |
| Lebanon | 773 | 592 | 120 | 762 | 30 |
| Golan Heights | 591 | 737 | 75 | 1247 | 106 |

Source: this study.

## 2.3 The water shortage as an agricultural policy issue

Agriculture, by far the largest user in the Jordan River Basin, often produces too little value to pay for pumping water over large distances and purification cost of the water used, let alone for the full cost, or for compensations to upstream suppliers of water. Berck and Lipow (1994) argue that the water shortage of Israel and the Palestinian Authority is really an agricultural policy issue. Similar observations can be made for the other countries in the Jordan River Basin. Then, reducing agricultural water use would seem to be called for. The authors review various political reasons for the Israeli government to subsidize agriculture; comprising food security for a besieged nation – an unreasonable argument in our view since Israel is currently importing virtually all of its staples –, and control of remote areas by agricultural settlements, a standard colonization argument beyond economics. Similarly, on the Palestinian side a certain degree of food self-sufficiency is deemed necessary to avoid potential starvation through Israeli blockades, while the political instability hampers industrial development, making agriculture one of the few sectors in which Palestinians can exercise economic control and act as entrepreneurs. Hence, in the absence of peace, neither Palestinians nor Israelis have any political motivation to reform the current allocation of water. Nonetheless, Berck and Lipow (1994) envision transferable, divisible and prioritized water rights that include the marginal transport costs in order to arrive at an efficient allocation and to resolve the agricultural crisis.

Another indication that the water shortage is due to agriculture is reported in Fishelson (1994), where Israel's aggregate supply and demand curves for water are derived from empirical data. The demand curve consists of three parts: at low prices demand comes from domestic, industrial and agriculture water users, whereas at high prices only domestic users remain and in the intermediate range agriculture water users are the first to drop out. An aggregate supply curve is constructed in a similar way. Supply intersects demand in the low-price range where agriculture constitutes the largest demand. In the early 1990s, the marginal product of Israeli agriculture with respect to water is estimated at somewhat less than 20 USD cents and this is far below the average supply cost of on average 45 USD cents, when capital costs are included. The author finds that land use by the agricultural sector would dramatically change if it were charged the true cost price of supplying water and 'half the land would turn from green to yellow-brown in the summer'.

At the same time, in Israel the scope for further technological improvements in irrigation is rather limited, as is shown by a large survey on the adoption of water saving technologies in Israel and the West Bank reported in Yaron (1994). For Israel there still is a non-negligible potential for water saving, but it has to be realized by improving the management and efficiency of modern equipment installed and by better scheduling, better timing and more accurate quantities of water applications (precision agriculture). By contrast, Fishelson (1994) advocates increasing the national water supply. Since fresh water supply is at its maximum capacity, it can only increase through desalination, which raises the cost price to 80 USD cents (including capital costs), or cheaper imports of Nile water. In order to free sufficient amounts of Nile water it would be necessary that Israel sells water-saving irrigation hardware, training and maintenance to Egypt in exchange for part of the water that is saved, see e.g., Kally (1989). As calculated in Ben-Shahar et al. (1989), the cost price of water associated with such a deal are estimated at 40 USD cents for the Gaza Strip and the Negev Desert, which would be just below the current cost price of conveying water from Lake Tiberias over long distances to these areas through the National Water Carrier.

As reported in Shuval (2000), the Harvard Middle East Water Project has modeled water markets for Israel, Jordan and the Palestinian Authority and computed that demand and supply would equate at a water price or marginal value of only 20 USD cents for agricultural water use, more or less the marginal benefit reported in Fishelson (1994) for Israeli agriculture. As a consequence, the monetized sum of the water disputed between the three downstream countries was found to be small. Projecting the results from this study, to the 80 MCM/Yr of the Jordan River's headwaters under a compromise on the Johnston Plan would require a mere payment of 16 million USD/Yr to the two upstream countries, which is about 0.014 per cent of Israel's GDP. In case Syria and Lebanon decided to divert the 80 MCM/Yr after an agreement, then replacing this amount by desalination of seawater would be an economic alternative to supplying the municipal and industrial water demand at projected marginal costs of 70 USD cents, or 56 million USD/Yr. Substitution by desalination would in addition produce an additional 50 MCM/Yr of treated wastewater available for agricultural use. Shuval (2000) concludes that in rational social and economic terms the water dispute is 'over a small amount of money that is hardly enough to justify an ending to peace negotiations or starting a water war'. The Israeli cost of compensating settlers, resettling military camps and special security and warning systems runs in the billions of dollars. We conclude that water cannot be the cause of prolonged conflict. On the contrary, providing additional water to improve the livelihood of the Palestinian population would most likely be conducive to peace.

## 2.4 The need for integrated management of the Jordan River Basin

Feitelson (2000) argues that existing international water treaties are unlikely to address future water issues effectively given the deterioration of water resources worldwide, and in the Jordan River Basin in particular, mainly because these treaties focus on river flows and for instance neglect aspects of land management that affect water runoff and infiltration onto aquifers. The author mentions several potentially effective modes of international management for the Jordan River Basin and the aquifers underneath the West Bank. He sees as the main challenge for policy makers to establish management structures that are able to cope with the more complex issues of governing the transboundary effects of the entire hydraulic cycle rather than the current 'simple' allocation of water, noting that the Israeli-Arab conflict so far stood in the way of any win-win solution.

Laster (2000) also points out that within Israel the physical area of jurisdiction of water or drainage boards was never organized according to hydrological boundaries and, in later years, vested (agricultural) interests and a lack of political will and foresight led to a dismantled management system. He indicates that Israel is not alone in a single catchment basin. The country straddles the Jordan River Basin, the Yarmuk and the Litani, all flowing on or outside the borders of Israel. In his view, Israel cannot negotiate its national river use without an overall catchment basin approach that takes into account other countries' needs.

The political will to participate in joint river basin management in the Jordan River might be enhanced by making the idea of sustainable use and benefit sharing of international rivers operational through facts and figures. This could focus the policy debate on the opportunities of sustainable win-win situations that include compensations for stakeholders that are adversely affected and rewards for those enhancing the recharge of aquifers and taking initiatives to reduce salinity. Especially for the JRB, the consequences of land and water use on downstream users are momentous, while current water allocations are neither efficient nor equitable. This calls for an analysis of options at the level of the entire river basin, taking account of both specificities of the hydrology, of the water-related economic activities, and of the prevailing geopolitical distortions. The present project seeks to address this river basin management problem for the Jordan River by developing and applying an interdisciplinary framework that can eventually be applied to compute the gains from co-operation under different settings.

We may note that the strong international research tradition within Israel and the absence of such a tradition in the neighbouring countries, have naturally resulted in an over-representation of Israeli research in the literature on river basin management for the Jordan River as compared to research from Lebanon and Syria. Not surprisingly then this literature has almost exclusively focused on Israel, Jordan and the Palestinian Authority taking the current water supplies from Lebanon and Syria to the Jordan and Yarmuk basins "for granted" as it were. To our knowledge the present study is the first to take in an integrated river basin management viewpoint that includes all five countries.

# Section 3

# Modeling the water economy

## 3.1 Economic valuation of water: a brief review of modeling approaches

Various hydrological studies have developed and implemented dedicated decision tools to support river basin management. Over time the focus of these studies been shifting from quantity control of stocks and flows to the economic valuation of the scarcity of water resources (Barbier et al, 1997; Creemers and Van den Bergh, 1998; Colavito, 2002), with due recognition of the importance of seasonality and spatial aspects of water allocations (Bockstael, 1996; Van den Bergh et al., 2004). We briefly review major contributions in this field.

Economic studies for the region include the Harvard Middle-East Water project conducted during the mid 1990s. The agricultural sub-model of this project is described in Amir and Fisher (1999), specifically tailored to the case of Israel at district level. The model is a linear program maximizing agricultural income under land and water constraints and allowing for several water sources of different quality and crop selection in different seasons. The authors consider their spatial resolution at the district level as too crude, in particular because the average transport cost of water cannot reflect that water intensive crops such as bananas would become unprofitable whereas in reality such crops are located close to water sources and have a lower than average transport cost. Water prices above 35 USD cents per cubic meter would half the irrigated land and induce migration from agricultural areas in the Jordan River Basin to the coastal areas. The Middle-East Water project therefore concludes, like Fishelson (1994), that only geopolitical reasons would warrant water subsidies in these regions.

In another study, Amir and Fisher (2000) argue that the combination of price policies and quantity restrictions imposed by the Israel Water Commissioner on agriculture involves two policy instruments to reach a single goal, meaning one instrument must be redundant. In their study for the Yzre'el Valley increasing water prices did hardly affect crop choices, because at the prevailing water quota, water prices were below the marginal product. The two studies abstract from inter-seasonal allocation of available water through storage, though, this issue is crucial for the Jordan Valley. The linear programming model in Salman et al. (2001) tries to address the issue by allowing for inter-seasonable water allocation and applies the model to three areas of the East Bank of the Lower Jordan River.

*Representation as a cooperative game*

The conflict, the negotiations and the benefit sharing between the countries would seem to offer a perfect setting for application of game theory. Indeed, Yaron (1994) sketches how cooperative game theory could apply to investigate the conflict over joint sharing of the Mountain aquifer by Israel and the Palestinian Authority. However, he also points at a major limitation of the cooperative game approach: it presupposes a well-recognized initial division of property rights. Moore (1994) tries to establish a calculation procedure for defining such rights over the West Bank aquifers between Israel and the Palestinian Authority in an equitable manner. The proposed solution consists of defining several one-dimensional equity standards per country that are expressed as volumes, such as recharge of aquifers (also in area), national needs and existing use, before choosing the division in volumes for use that is minimal in distance to all the equity standards. The proposed equitable division then coincides with the average over all these simple equity standards. This solution has as serious drawback that it is defined independently of any economic use or welfare criterion and that it is vulnerable to data manipulation by both parties. Moreover, the approach fails to make a connection to the literature on arbitrage and bargaining.

In Dinar and Wolf (1994) a standard cooperative approach is extended to allow for political aspects of the regional conflict. The extended analysis takes into account the political pressure by Sudan and Ethiopia on Egypt in case Nile water would end up in Israel. This reduces the probability of coalitions emerging that would include Israel. Arab countries such as Egypt would then have to receive stronger enticement for entering such a coalition. Under these conditions, the lion share of the gains from cooperation would accrue to Egypt. Surprisingly, the West Bank benefits more than the Gaza Strip, because it can get hold of a share of Israel's electricity savings via reduced conveyance from Northern Israel to the Negev. The analysis in this study though disregards the role played by the upstream countries with relatively rich water resources.

Dinar et al. (1992) discuss two small-scale case studies in which cooperative game theory is applied to determine income transfers associated with providing low-quality water from treated wastewater (or other sources) to agriculture. The authors question the use of cooperative game theory because it failed to provide indisputable solutions, even to several relatively 'simple' cases, proved to be computationally difficult for small problems (but computational tools have significantly improved since 1992) and, most importantly, produced income transfers that are in no way related to the notion of a price per cubic metre.

*Representation as a node-link network*

At the methodological level, and not necessarily related to the Middle East, Rosegrant et al. (2000), in the spirit of the Indus Basin model (Duloy and O' Mara, 1984; Ahmad and Kutcher, 1992; Ullah et al., 2001), are among the most prominent among the studies that represent water flows in spatially explicit models jointly with economic decisions. The authors use a node-link network to represent spatial differentiation within the Maipo River basin in Chile and to model the river flows. Each node represents a location where water is diverted to different locations and each link represents the connection between locations through the water flow. The efficient allocation of water follows from a partial equilibrium (i.e. surplus maximizing) welfare program with net benefit functions per node that distinguish the demand for domestic, industrial and agricultural use. Water quality is incorporated through relationships for salinization. The model specifies water and salt balances per node, as has also been done in the Jordan River basin. However, the solution method for this model is unsatisfactory because the model's production functions relating water use to monetary net benefits feature setup costs that are non-convex, and so is the relationship representing the negative impact of salinity on crop yield through the Chistiensen Uniformity Coefficient. Nonconvexities imply that the program cannot be solved by standard (convex) optimization routines used by the authors. Consequently, the solution presented might be a stationary point far from the welfare optimum the authors claim to describe (see e.g. Ginsburgh and Keyzer, 2002, ch. 10).

Zeitouni et al. (1994) present a model for the Israeli water markets that can also be interpreted as a node-link model. In this model, auctions for percentage shares versus prioritized claims are analyzed as two second-best implementations of a welfare optimum under climatic risk. The voluntary participation in an auction guarantees that each of the four regions gains from participation (individual rationality), whereas this is not a priori guaranteed under a stochastic welfare optimum, since it maximizes overall expected benefits without reference to the benefits of the initial situation. The authors report on a highly stylized empirical model of the water economies of Israel and the Palestinian Authority that distinguishes four geographical areas: the Gaza Strip, the Negev Desert, remaining Israel, and the West Bank. Each area represents a node and the nodes are linked. Six scenarios runs are performed: the welfare optimum, the two auction forms, and whether or not the selling of Nile water is considered. It appears that the percentage shares auction is relatively more (welfare) efficient than the prioritized claims, albeit that the prioritized claims are likely to be preferred by the geographical units with a surplus of water. Furthermore, all entities (including Egypt) would gain about 12 per cent in overall welfare from augmenting Nile water to the regional water sources.

### 3.2 The specifity of water from an economic perspective

It appears, as was also discussed in Albersen et al. (2003), that the available water valuation methodologies fall in two groups. One “hydrologist”-group respects the structure of hydrological models but gives up the possibility to derive efficient water allocations from these models. The other, “economist”-group views water as a regular scarce economic good but by this loses the possibility of accounting for the specifity of water. A main challenge within the present project has been to seek an intermediate position. Therefore, we elaborate in this section on both viewpoints but we proceed in a somewhat counter-intuitive order.

In line with common intuition, hydrologists find it natural to look at water flows in a particular region as a physical process driven by the laws of gravity that feeds on rainfall as well as the influx of water in rivers. Hence, intuition might suggest to start from the hydrology angle and append an economy of water users to this system, as is indeed the practice in many multidisciplinary water projects. However, though widespread, such a modular approach compromises the interfacing with mainstream economic theory. In particular, the logic of efficient allocation and pricing of scarce resources suggests a micro-economic viewpoint based on first principles. For this, it is necessary to find out how water flows differ from regular scarce goods. We discuss the features that water has in common with regular economic goods before turning to its specifity.

*Water as a regular economic good*

While at the global level the economic scarcity of freshwater has only recently gained recognition worldwide beyond academic circles, this scarcity is deeply enshrined in Middle Eastern civilizations, witness the quote from Genesis on the front page of this report. Quite naturally, the early sites of human settlements along the Mediterranean coincide with the estuaries of rivers, where ships could replenish their stocks of freshwater. In this part of the world it has always been clear that uses of water are often competing, water allocated to one group goes at the detriment to the others, and that exercise of control over wells, catchment areas and rivers is a central element of political economy. Yet, relatively rare are the situations where water has been marketed and priced as a regular economic good, like say, chocolate that will serve as our standard economic good in this report. The sparkling water sold in bottles presumably is the best example.[1] There is no problem with its pricing and the functioning of its market. A factory exploits a natural spring (or digs a deep well) and distributes the water in quantities that maximize its profits. Government usually does not provide any subsidies, and rarely taxes the water other than through the auctioning of a concession. Consumers buy the water like any other good, and indeed purchase it in the supermarket, jointly with chocolate.

*The specificity of water as an economic good*

Clearly, we cannot expect farmers in the Jordan Basin or anywhere else for that matter to rely on markets for their water needs. For them, water like sunshine belongs to the fruits of nature to which they feel entitled. Often there will be a historically established right to pump up or channel in an agreed quantity of water in every month of the year, for irrigation, household use, and also for disposal of salty sediments. As long as the population pressure, and more generally, the demand by various agents, remains fixed, the system can operate in this way, that is, by quantity rationing without need for prices or markets. Customary law can then, with due enforcement by some authority, deal with water allocations. To deal with the vagaries of climate, this law will have to be flexible and to specify rules more sophisticated than the mere assignment of fixed quantities.

Nonetheless, rationing imposes severe demands on co-ordination. Problems arise when the authority that controls the basin becomes split, and, clearly, worsen when the parties engage in conflict. However, reflecting on the reasons for water supply not being organized like that of chocolate bars, and to rely on this type of rationing in so many cases, we may note the following difference.

First, unlike chocolate, water does not disappear fully in use. Only a fraction evaporates or transpires during the use, and the rest is returned to the land for subsequent economic activities, downstream and in the future. While it is not so difficult to envisage water users paying for the quantity tapped like for any economic good, proper water management also requires accounting for the value of the water returned. In some sense the user only rents water but the complexity as compared to regular lease is that only a part of the good is returned, that the quality of the good is affected negatively by use, and that only part of the water is returned through water ways and pipes where measuring devices can be placed. Agriculture in particular returns the water to the soil in quantities that are not easily measured. Hence, land utilization by agriculture is an essential element of the water economy.

[1] Such sales often are a puzzle to economists, as the quality of this water is often inferior to that of the much cheaper tap water.

Second, partly because of these complexities, the property rights over water are not well established. Whereas the marginal value of water for its users could in principle be derived through dedicated auctioning schemes, the issue to whom the payment should accrue is highly controversial. In principle, the downstream users should pay to the upstream suppliers and be compensated for the pollution emitted upstream that they have to accommodate but this is only a first round of payment. However, the proceeds should eventually accrue to the rightful owners of the water and it is far from established that, say, up-North in the Jordan basin, Lebanon should be considered as the owner of the water it discharges to the river. Israel claims a natural title to these discharges. Until the initial distribution of property rights over a resource has been established and respected by all who can affect it, no market can function for this resource. Unfortunately, military force is an essential element in this process.

Nonetheless, economists would tend to argue that a consensus will have to be reached on this issue and that, eventually, an international water market in which users pay to the owners is called for to decentralize water use decisions effectively to individual agents. Since water is so scarce, a payment by downstream users to upstream suppliers seems inescapable, even if eventually part of the proceeds are to be redistributed, through taxation, to others than those who happen to live upstream. Such pricing is necessary to create incentives for upstream inhabitants to limit their withdrawals. By the same token, the price paid for upstream water will make downstream users aware of the value of water. Thereby they will put extra effort in increasing the efficiency of water use, and change water-related activities in favor of activities that use the scarce water most efficient. As is well-known, the leading economic principle would be that water is used where it contributes most to welfare, either upstream or downstream, and taking into account evaporation losses and transportation cost related to the construction of waterways.

It may be noted at this stage that the relation between up- and downstream neighbours is not as top-down hierarchical as might seem at first, with the upper level supplying a good to the lower level. The lower level could decide to construct a dam on its own territory that would stop all water. Now suppose, that unlike in the Jordan River Basin, water was plenty. Under such conditions the capacity of the channels along which the water can flow is often more scarce and hence economically important than the water volume itself. The dam would cause the upper level to be plagued by floods, and encounter problems with its navigation and possibly its hydropower generation. Under the semi-arid conditions of the Jordan basin, when freshwater itself is scarce, stopping the water also halts salt disposal.

Hence, we may conclude that in all cases there is scope for negotiations between the various levels. Yet, since the number of levels involved is so large, co-ordination remains an issue. Furthermore, since for various reasons the mentioned externalities are important, market failure is likely to be present unless water allocations are sufficiently guided and supervised by a watershed authority.

*Modeling the specifics*

Rather than concluding from the specifics mentioned that the water economy needs a modeling approach that is completely different from the model of, say, the chocolate market, we propose to view the economy as a transport system in a multi-commodity setting, where chocolate could be produced, shipped and consumed in parallel with water. Water, though, is subject to a specific production and transport technology. First, while chocolate can be transported by truck in all directions as long as the road network permits, the natural flow of water is constrained by gravity. Consequently, from any cell on a map a flow cannot move upwards to sites with higher altitude. Second, whereas the chocolate factory will stop shipping to a neighbouring destination once the price of chocolate is lower there than at the factory, the water factory cannot be stopped as long as rainfall persists. We refer to the first point as "restricted routing" and to the second as "no possibility of inaction". The latter creates many difficulties for economic modeling because it implies indivisibility of the hydrological process, and may cause non-convexity of the model. We formulate a piecewise linear specification that can avoid this. Given such a specification, we are able to obtain a well-behaved (convex) welfare program that optimally sets the water use intensity at every site, so as to maximize the revenue of that site, given a valuation of end-of-year stocks and a payment for outflows of water and salt, and given the inflow into the site as set by upstream neighbours.

An efficient allocation of water in the entire Jordan River Basin can then be obtained by solving a (convex) welfare program, whose shadow prices (Lagrange multipliers) are the prices that individual sites would have to face to choose the same level of water use as the one given by the welfare optimum. Then, the remaining difficulties are essentially to calibrate this very large model so as to replicate a validated set of data, and to run it by means of a dedicated set of algorithms under various policy options. With respect to pricing, these options distinguish situations with and without water payments between sites (with penalties for discharges of salt), some of which only allow for payments to sites within the same country. Nonetheless, computing water prices in this manner does not mean that their use as signals to individual agents is actually envisaged. As is well known, every allocation supported by prices can also be implemented by quotas (rations). Especially when property rights are not well established, and when externalities prevail, flexibly supervised rationing may be inescapable. Hence the need for a well established, empirically solid decision support tool, albeit that under all circumstances in the end the international policy process will have to decide about the financial payments between countries.

Finally, we observe that such a tool may be useful not only to establish an allocation scheme among users and to manage demand but also to choose about the various options to expand supply through desalination of river and seawater, or through diversion of riverwater from other watersheds, in Lebanon and Syria.

### 3.3 Proposed approach

As mentioned in section 3.1, available studies on the Jordan River Basin have significant limitations, some of which we seek to overcome in this study. First, there are no studies for the entire basin, while the studies that cover part of the basin have little or no spatial resolution. Second, the game-theoretic representations have been disappointing due to computational difficulties even at a small scale, and, more importantly, because the computed transfers could not be related to water prices. Third, while the node-link network approach provides a framework that can address water pricing in a spatial context, it still suffers from computational problems and seems to exhibit high sensitivity to small changes in policy instruments. We conclude that existing approaches need adaptation and extension. This need motivates the present project's focus on the design of methodologies that can combine hydrology and economics and can provide stable algorithms to compute the gains from various modes of co-operation within the context of the geopolitical complexities in the Jordan River Basin.

The welfare model we have adapted and implemented for this purpose is a spatially explicit one that represents the various users, in fact also as suppliers to downstream users reflecting in full the geographical diversity of the Jordan Valley, particularly its potentials for irrigation and agricultural production. This implies that the welfare model should among its constraints include at every site the processes of evapotranspiration by crops, of infiltration of water into lower layers and capillary rises from lower level, of the leaching of salt at varying levels of irrigation intensity, and for different land use patterns. Next, the salt and water outflow from each site will flow along the prevailing relief to neighbouring downstream sites, and so on, until the water has (i) evaporated, (ii) been stored in the ground, in Lake Tiberias, or in the Dead Sea, (iii) left the watershed via a pumping station.

This welfare program offers what may be viewed as an adaptation and generalization of the stylized node-link network approach in Rosegrant et al. (2000). The adaptation is that the non-convexities of this model are avoided by appropriate (essentially linear) functional specifications. As was mentioned the physical relationships of hydrological models usually have an indivisibility property because the flows cannot be stopped. A welfare approach though has to impose the restrictions of production theory so as to maintain convexity. This is less limiting than might seem at first, because water flows, once subject to human intervention, may be seen as inputs and outputs of production processes that generally possess the property of divisibility in the sense that multiple processes can be run at every location, say, cultivating different crops on a given parcel of land. Divisibility implies convexity after aggregation over a continuum (see e.g. Arnott et al., 1991, Keyzer et al. 2001).

The generalization attempted here is to accommodate a much finer spatial resolution than the Rosegrant or other economic studies of even small parts of a river basin (e.g. Goldson, 1994; Iftikhar, 2002). Our model distinguishes a $30 arcsec \times 30 arcsec$ grid as its node-link network, or about .73 square kilometer per grid cell (site). Every site in the interior of the basin's territory can communicate with each of its 8 neighbours, while water can flow to downstream neighbours only. In all, we consider 25,301 sites that sum to a watershed size of 18,055 square kilometers. The formulation of an economic model on this scale and that can handle non-convexities of hydrology was a first milestone. Clearly, it would be wrong to impose the divisibility property on major infrastructural water works but within a welfare framework, these can be analyzed by treating technological options as different scenarios.

Hence, a related challenge was to do justice as much as possible to the geographical diversity of the basin. In this respect, satellite images provide the most reliable component among the data available on the basin even though ready-made approaches to interpret these data and to transform them into a land use map that is linked to economic activities are not available. Disclosing satellite imagery for economic modeling was a second milestone of the project. In fact, the data for this grid are obtained from aggregation of satellite images and basic altitude data from $1 arcsec$ to $30 arcsec$. Also, though for the Lower Jordan Valley a harmonized water database exist (Orthofer et al., 2001), while farming systems in the Lower Jordan part of the basin have been described in some detail (Venot, 2003; Hijawi, 2003), an integrated database of the hydrology of the entire basin was unavailable, let alone its integration with economic statistics. The compilation of a more or less coherent database that fits the scope and the scale of the project was a painstaking task.

Finally, the size of the model with all its interdependent cells to be solved for at least the 12 month of one annual cycle, for water and salt, and for at least two layers, surface and groundwater, and with monthly constraints on economic activity, clearly generates a problem with hundred thousands of simultaneous endogenous variables. This calls for a dedicated set of algorithms on the one hand to calibrate the model to its data and on the other hand to solve it effectively. The project was successful in this respect, which is a third milestone. Since existing computational approaches cannot handle such a large number of cells, it was necessary to develop a dedicated algorithm for this purpose (Keyzer, 2002, 2004).

Nonetheless, the work is far from complete. While the calibration procedure is technically operational, it has revealed implausibilities in the database that still have to be corrected for, and hamper a discussion of realistic scenarios. As mentioned in the introduction, in view of the sensitivity of the political sensitivity of the issues, we refrain from presenting current findings in any detail, not only because of their tentative nature but also because we feel that the scenarios should be developed in close consultation with stakeholders, who will expectedly be involved in the follow up project.

*The model in a nutshell*

The spatially explicit welfare model maximizes the annual economic surplus of the site, subject to technological restrictions, at fixed market prices of economic outputs and inputs, and for given external deliveries to the region, and under assumed conduct with respect to payment for water and salt. The technological restrictions describe to what economic uses the water can be put in every month of the year, how this water infiltrates into the soil layers and how it flows to downstream sites and varying levels of water use intensity.

Water use intensity relates to all uses of water, including household use. For firms the surplus maximization is a profit maximization, for households we maximize the consumer surplus from water use. Hence, every site has a classic partial equilibrium welfare program that maximizes the sum of consumer and producer surplus from water use.

The model is solved under three modes: no payments, full payments, and partial payments. If no payments are made, every site simply receives the water and salt, uses as much as it finds appropriate for its surplus maximization over the annual cycle, accumulates into the soil in accordance with physical relationships and discharges to downstream neighbours. In this case every site is a firm with non-internalized external effects on downstream neighbours. At the other extreme, if all sites pay a competitive market price for their water and salt, they still act as individual firms but the overall model becomes a surplus maximization as well. Intermediate cases deal with partial payments.

## 3.4 A spatially-explicit welfare representation of water allocations

We start by modeling economic decisions at a given site, subdividing the annual cycle into twelve months, and the soil into a surface, a sub-surface and a groundwater layer, distinguishing flows and stocks of salt and water. With respect to water use, we introduce special restrictions ensuring that at given selling prices, each site can solve its model in closed form. Next, we proceed to the linkage of the water allocation at the various sites and present a spatially-explicit welfare model of the 25,301 sites that form the Jordan River Basin.

*Monthly production function*

Production is treated as a land use process whose intensity depends on the water stock that is available in every month, as well as on direct precipitation *b*, and inflows from other sites *q*. Water can be used in production of, say, a crop, or passed on to the downstream sites or cells via a stream and surface runoff *y*. Use in production implies in part evaporation and in part accumulation of stock of soil moisture, and groundwater. Salt is diluted in water, and, obviously, does not evaporate.

A water input pattern $c_\tau$ in months $\tau = 1,...,T$, for $T = 12$, with $\tau = 1$ referring to October, leads to an annual production in money metric that is equal to $min_\tau\, g_\tau(c_\tau)$. This production structure possesses the following properties.

**Assumption P (production):** (a) The production function has an output expressed in monetary units discounted to the beginning of the year and obeys $min_\tau\, g_\tau(c_\tau)$, where $c_\tau$ is the water input in month $\tau$; (b) the monthly production functions satisfy $g_\tau(c_\tau) = f(\frac{c_\tau + \eta_\tau}{\kappa_\tau})$, where $\kappa_\tau$ is positive and $\eta_\tau$ unconstrained in sign, and $f$ is homogeneous, strictly concave increasing and has a Lipschitz continuous derivative, and is also well defined for negative *c*; (c) for given positive constants $f_0$ and $f_0^{'}$, both $f(c) = f_0$ and $\frac{\partial f(c)}{\partial c} = f_0^{'}$ possess a solution in analytical form whenever a solution exists.

We note that months with zero marginal demand for water $\kappa_\tau = 0$, say, during the post-harvest period, can be dealt with separately, but for convenience we take this coefficient to be strictly positive in every month.

*Water balance*

We distinguish between surface water including subsurface water reaching until the root zone of crops, and two groundwater layers. For this, we introduce the index *i*, $i = 1,2,3$, respectively.[2] Hence, for surface water, precipitation $b_{1\tau}$, jointly with the lateral inflow $q_{1\tau}$ adds to the end-stock $k_{1,\tau-1}$ of the previous month plus fractions of capillary rise from other layers minus the seepage to lower levels. This lateral inflow only partly contributes to water availability at the site, since a fraction $(1-\theta)$ directly transits through it, say, along a river. Hence, water availability becomes:

[2] We denote the layers by numbers because this eases the subsequent matrix-representation used in deriving the closed-form solution.

$$a_{1\tau} = b_{1\tau} + \theta q_{1\tau} + k_{1,\tau-1}$$
$$+ \delta_\tau(\upsilon_{2\tau}k_{2,\tau-1} - \sigma_{1\tau}(b_{1\tau} + \theta q_{1\tau} + k_{1,\tau-1}))$$
$$+(1-\delta_\tau)(k_{2,\tau-1} + \upsilon_{3\tau}k_{3,\tau-1} - \sigma_{2\tau}k_{2,\tau-1} - \bar{k}_{2\tau}) \quad (3.1)$$

where $\sigma_{i\tau}$ and $\upsilon_{1\tau}$ are seepage and capillarity (upward rise) coefficients, respectively. The coefficient $\delta_\tau$ is zero or one, and represents a linearization of the upward bound $\bar{k}_{2\tau}$ on $k_{2\tau}$. The bound is taken to be active in given months, determined on the basis of previous hydrological simulation. If the bound is active, $\delta_\tau$ is zero and water does not infiltrate but remains on the surface. The reason to keep these functions linear is that this maintains convexity of the constraint set: the functions appear in the equation for sub-surface stock and the equation for groundwater stock with an opposite sign.

Of the available water $c_{1\tau}$ has economic use, in agriculture or elsewhere, and $n_{1\tau}$ is not used, and has outflow and infiltration coefficients of its own:

$$c_{1\tau} + n_{1\tau} = a_{1\tau}. \quad (3.2a)$$

A fraction of this water leaves the system through evapotranspiration by crops and evaporation by ground and water surfaces. Another fraction is absorbed by the root zone and adds to the initial stock in the next month, and a part flows to downstream sites contributing to the inflow of neighbouring sites. Accordingly, the destination of net available water (3.2a) is also written as

$$e_{1\tau} + k_{1\tau} + y_{1\tau} = a_{1\tau}. \quad (3.2b)$$

We suppose that lateral flows of groundwater are zero. Hence, stock and outflow Including transit flow $(1-\theta)q_{1\tau}$ follow as:

$$k_{1\tau} = k^c_{1\tau}(c_{1\tau}) + k^n_{1\tau}(n_{1\tau})$$
$$y_{1\tau} = y^c_{1\tau}(c_{1\tau}) + y^n_{1\tau}(n_{1\tau}) + (1-\theta)q_{1\tau}$$

$$k_{2\tau} = \delta_\tau[\sigma_{1\tau}(b_{1\tau} + \theta q_{1\tau} + k_{1,\tau-1}) - \sigma_{2\tau}k_{2,\tau-1}$$
$$+ \upsilon_{3\tau}k_{3,\tau-1} - \upsilon_{2\tau}k_{2,\tau-1} + k_{2,\tau-1}] + (1-\delta_\tau)\bar{k}_{2\tau} \quad (3.3)$$
$$k_{3\tau} = \sigma_{2\tau}k_{2,\tau-1} - \upsilon_{3\tau}k_{3,\tau-1} + k_{3,\tau-1}.$$

*Site-specific welfare program*

The site-specific welfare program treats the value $\psi_{iT}$ of the end stock $k_{iT}$ as given as well as the (selling) price $\pi_{i\tau}$ of the water and salt outflow. Every site maximizes its revenue and the site-specific model reads:

$$
\begin{aligned}
V = \max_{a_{1\tau}, c_{1\tau}, k_{i\tau}, n_{1\tau}, y_{1\tau} \geq 0, c} \; & f(c) + \sum_i \psi_i k_{iT} + \sum_i \sum_\tau \pi_{i\tau} y_{i\tau} \\
& \textit{subject to} \\
& c_{1\tau} \geq \eta_\tau^c c - \eta_\tau^o \\
& k_{1\tau} = k_{1\tau}^c(c_{1\tau}) + k_{1\tau}^n(n_{1\tau}) \\
& y_{1\tau} = y_{1\tau}^c(c_{1\tau}) + y_{1\tau}^n(n_{1\tau}) + (1-\theta)q_{1\tau} \\
& c_{1\tau} + n_{1\tau} = a_{1\tau} \\
& a_{1\tau} = b_{1\tau} + \theta q_{1\tau} + k_{1,\tau-1} \\
& + \delta_\tau(\upsilon_{2\tau}(k_{2,\tau-1}) - \sigma_{1\tau}(b_{1\tau} + \theta q_{1\tau} + k_{1,\tau-1})) \\
& + (1-\delta_\tau)(k_{2,\tau-1} + \upsilon_{3\tau}(k_{3,\tau-1}) - \sigma_{2\tau}(k_{2,\tau-1}) - \bar{k}_{2\tau}) \\
& k_{2\tau} = \delta_\tau[\sigma_{1\tau}(b_{1\tau} + \theta q_{1\tau} + k_{1,\tau-1}) - \sigma_{2\tau}(k_{2,\tau-1}) \\
& \quad + \upsilon_{3\tau}(k_{3,\tau-1}) - \upsilon_{2\tau}(k_{2,\tau-1}) + k_{2,\tau-1}] + (1-\delta_\tau)\bar{k}_{2\tau} \\
& k_{3\tau} = \sigma_{2\tau}(k_{2,\tau-1}) - \upsilon_{3\tau}(k_{3,\tau-1}) + k_{3,\tau-1}\,.
\end{aligned}
\tag{3.4}
$$

given $k_{i0}$, while $\tau = 1,...,T$ and $T = 12$.

We observe that, through the inequality constraint, and the fact that the scalar $c$ is unconstrained in sign while inflows are non-negative, we can always achieve a feasible allocation, with $c_{1\tau} = 0$. This allocation may, however, yield negative income.

*Representing salinity; piecewise linearization*

Next, salt is accounted for in each of these zones. We model salinization because in the Jordan basin this is the most direct threat to crop production. Salt is disposed of with the harvesting of crops that absorb it, and, more importantly, with runoff to downstream sites. In high densities salt kills all life and the Dead Sea where the Jordan River ends, owes its name and reputation to its high degree of salinity.

To represent this, we maintain a record of salt accumulation in each layer. Thus, we modify the model presented so far. We distinguish commodities indexed $i = 1,2,...,m$, $m = 6$. We also distinguish between commodities that contribute to production ("goods" or water: $I^+ = \{1,2,3\}$, for surface, sub-surface and groundwater), and pollutants ("bads" or salt $I^- = \{4,5,6\}$ for surface, sub-surface and groundwater) that frustrate production.

The distinctive properties to be accounted for are that (a) salt does not evaporate; (b) it has a negative impact on crop production; and (c) it only leaves the site with the water flows and is distributed in the same shares as water to the downstream sites. Property (a) means that for salt the commodity balances hold with strict equality, without any loss. To incorporate property (b), we include an additional step in the mapping between $c$ and $c_{1\tau}$:

$$r_{1\tau} = \eta_{\ell\tau}^c c + \eta_{\ell\tau}^o \tag{3.5a}$$

$$c_{1\tau} = r_{1\tau} + \eta_\tau^s a_{4\tau}\,. \tag{3.5b}$$

**Assumption WR (water requirement functions):** the water requirement functions $r_{1,\tau}(c)$ are convex increasing, homogeneous and piecewise linear: $c_{1,\tau} = \eta^c_{\ell\tau} c + \eta^o_{\ell\tau} + \eta^s_{\ell\tau} a_{4\tau}$; the function has fixed threshold points $\hat{c}_\ell$, $\ell = 1,...,L$ on the line segment $\hat{c}_{\ell-1} \leq c \leq \hat{c}_\ell$; $\eta^c_{\ell-1,\tau}\hat{c}_\ell + \eta^o_{\ell-1,\tau} = \eta^c_{\ell\tau}\hat{c}_\ell + \eta^o_{\ell\tau}, \hat{c}_0 << 0;\ \eta^o_{0\tau} = 0;\ 0 \leq \eta^c_{\ell-1,\tau} \leq \eta^c_{\ell\tau};\ \eta^o_{\ell-1,\tau} \leq \eta^o_{\ell\tau}$. ◊

The total water requirement $c_{1,\tau}$ of the crop is used for three purposes: evaporation, flushing and storage in the sub-surface. A higher yield requires more flushing, among others to dispose of the salt. We return to this aspect below. Hence, associated to the monthly water requirements are the flushing and the storage functions. In the sequel we denote all piecewise linear function in the same way as the water requirement, with a regime dependent slope and intercept.

**Assumption WOS (water outflow and storage):** The (non-transit) water outflow and the storage functions $y^c_{1\tau}(c_{1\tau})$, $k^c_{1\tau}(c_{1\tau})$, $y^n_{1\tau}(n_{1\tau})$ and $k^n_{1\tau}(n_{1\tau})$ are (i) piecewise linear, homogeneous, convex, with fixed switch points $c_{1\tau}(\hat{c}_\ell)$; (ii) $y^c_{1\tau}(c_{1\tau}) \leq y^n_{1\tau}(c_{1\tau})$ and $k^c_{1\tau}(c_{1\tau}) \leq k^n_{1\tau}(c_{1\tau})$ (iii) they satisfy $y^c_{1\tau}(c_{1\tau}) + k^c_{1\tau}(c_{1\tau}) \leq c_{1\tau}$, and $y^n_{1\tau}(n_{1\tau}) + k^n_{1\tau}(n_{1\tau}) \leq n_{1\tau}$, for all $c_{1\tau}$ and $n_{1\tau} \in [0,\bar{a}]$. ◊

We use the symbols $\kappa$ and $\zeta$ for the coefficients of these $k$- and $y$-functions, respectively. To incorporate property (c), we formulate outflow functions:

**Assumption SO (salt outflow):** The salt outflow functions $y^c_{4,\tau}(c_{1,\tau})$ and $y^n_{4,\tau}(c_{1,\tau})$, are piecewise linear, homogeneous and convex in $c_{1,\tau}$, with fixed switch points $c_{1,\tau}(\hat{c}_\ell)$. ◊

We use the symbol $\mu$ for the coefficients of these $y$-functions. Finally, we postulate the simplest possible specification for the downward and upward streams between layers.

**Assumption WSC (water and salt: seepage and capillary flows):** The seepage and capillary flow functions $\sigma$ and $\upsilon$, are fixed, regime independent, but site and month-specific fractions.

**Assumption SD (salt damage):** In the salt damage function $\eta^s_\tau$ is a fixed, nonnegative coefficient.

Now substituting the piecewise linear relationships, the site-specific program becomes:

$$V = max_{a_{1,\tau}, c_{1\tau}, k_{i\tau}, n_{1\tau}, y_{1\tau}, y_{4\tau} \geq 0, c} \; f(c) + \sum_i \psi_i k_{iT} + \sum_i \sum_\tau \pi_{i\tau} y_{i\tau}$$

*subject to*

*water constraints:*

$$\begin{aligned}
a_{1,\tau} &= b_{1,\tau} + \theta q_{1,\tau} + k_{1,\tau-1} \\
&\quad + \delta_\tau(\upsilon_{2\tau}k_{2,\tau-1} - \sigma_{1\tau}(b_{1\tau} + \theta q_{1\tau} + k_{1,\tau-1})) \\
&\quad + (1-\delta_\tau)(k_{2,\tau-1} + \upsilon_{3\tau}k_{3,\tau-1} - \sigma_{2\tau}k_{2,\tau-1} - \bar{k}_{2\tau}) \\
c_{1\tau} &= \eta^c_{\ell\tau}c + \eta^o_{\ell\tau} + \eta^s_\tau a_{4\tau} \\
c_{1\tau} + n_{1\tau} &= a_{1\tau} \\
k_{1\tau} &= \kappa^c_{\ell\tau}c_{1\tau} + \kappa^n_{\ell\tau}n_{1\tau} + \kappa^o_{\ell\tau} \\
k_{2,\tau} &= \delta_\tau[\sigma_{1,\tau}(b_{1,\tau} + \theta q_{1,\tau} + k_{1,\tau-1}) - \sigma_{2,\tau}k_{2,\tau-1} \\
&\quad + \upsilon_{3,\tau}k_{3,\tau-1} - \upsilon_{2,\tau}k_{2,\tau-1} + k_{2,\tau-1}] + (1-\delta_\tau)\bar{k}_{2,\tau} \\
k_{3,\tau} &= \sigma_{2,\tau}k_{2,\tau-1} + (1-\upsilon_{3,\tau})k_{3,\tau-1} \\
y_{1\tau} &= \zeta^c_{\ell\tau}c_{1\tau} + \zeta^n_{\ell\tau}n_{1\tau} + \zeta^o_{\ell\tau} + (1-\theta)q_{1,\tau},
\end{aligned} \tag{3.6}$$

*salt constraints:*

$$\begin{aligned}
a_{4,\tau} &= b_{4,\tau} + \theta q_{4,\tau} + (1-\sigma_{4,\tau})k_{4,\tau-1} + \upsilon_{5,\tau}k_{5,\tau-1} \\
k_{4,\tau} &= a_{4,\tau} - y_{4,\tau} + (1-\theta)q_{4,\tau} \\
k_{5,\tau} &= k_{5,\tau-1} + \upsilon_{6,\tau}k_{6,\tau-1} - \sigma_{5,\tau}k_{5,\tau-1} - \upsilon_{5,\tau}k_{5,\tau-1} + \sigma_{4,\tau}k_{4,\tau-1} \\
k_{6,\tau} &= k_{6,\tau-1} - \upsilon_{6,\tau}k_{6,\tau-1} + \sigma_{5,\tau}k_{5,\tau-1} \\
y_{4,\tau} &= \mu^c_{\ell\tau}c_{1,\tau} + \mu^n_{\ell\tau}n_{1,\tau} + (1-\theta)q_{4,\tau}
\end{aligned}$$

Here we combine the constants of the outflow functions into a single coefficient, with superscript *o*. These salt constraints satisfy the commodity balance and can for given $c_{1,\tau}$ and $n_{1,\tau}$ be solved moving from the bottom-layer constraint upwards.

Next, we write program (3.6) in a more compact form, to facilitate the notation for the model of the basin. We note that in this program the water intensity scalar $c$ is driving all processes. When it becomes too large, the availability $a_{i\tau}$ may hit a non-negativity bound in some month. This is the non-linearity to be addressed. We assert without proof that an upper bound is necessary for fixed initial stocks $k_{i0}$ to derive a closed form upper bound $\tilde{c}_\ell$, as a function of deliveries $d = (\theta q + b, (1-\theta)q)$ to the site, we can now write the program in the simple form

$$V(\pi, d) = max_{0 \leq c \leq \tilde{c}(d)} \; f(c) + \sum_i(\sum_\tau \pi_{i\tau}\tilde{y}_{i\tau}(c,d) + \psi_{iT}k_{iT}(c,d)), \tag{3.7a}$$

where we drop the subscripts for regime and land use type in the understanding that the calculation is only for the line-segments $\ell$ that are optimal on a given site, for given prices.

Furthermore, since the number of sites is very large, each iteration of the algorithm involves solving the local model $S = 25{,}301$ times, which puts a burden on the computational speed of finding the optimal water allocation. Also solving the local model by applying a numerical software package means that each call of a solution routine creates a numerical imprecision. Then, given the large number of sites and downward and upward shifts, the accumulation process over time can generate error accumulation with numerical instability as a possible result. Therefore, we insist on parametrizing (3.7) in such a way that it can be solved in closed form. One element is that thanks to the closed form of $\tilde{c}$, the problem has a single decision variable constraint only consists of a scalar with simple bounds as sole constraint. Moreover, due to the linearity, the second term in (3.7) has a fixed derivative w.r.t. *c*. Hence, a closed form solution can be obtained provided the first order solution $f'(c) = \xi$ has an analytical solution. This will be the case for the form:

$$f(c) = g_0 + g_1(max(c,0) + g_2)^{g_3} + g_1 g_3 (g_2)^{g_3 - 1} \; min(c,0) - \kappa \,(min(c,0))^2 , \quad (3.7b)$$

for positive $g_0, g_1$ and $g_2$ and $g_3 \in (0,1)$. Finally, the water selling prices $\pi_{i\tau}$ of every site should in the welfare optimum agree with the derivative of *V* with respect to inflows $q_{i\tau}$, in the sense that the selling prices are the weighted sum of the marginal contributions to the various client cells. Hence, we also seek an analytical solution for the derivative. The same applies to the derivative with respect to the inflow of salt.

*Welfare program of the basin*

The site-specific models (3.6) are solved for every site in decreasing order of altitude. Given the outflows of water and salt of site *r*, and outflow shares $\alpha_{rs}$ that respect this order, we can compute the inflows as:

$$q_{is\tau} = \sum_r \alpha_{rs} y_{ir\tau} , \qquad i = 1,4 , \qquad (3.8)$$

enabling us to solve the successor programs.

We are now ready to formulate a welfare program that has as its objective the sum of the objective of all local users and that obeys local hydrological conditions. The market clearing conditions are given by

**Assumption A (adjacency and gravity):** For given site of origin *r*, the fraction $\alpha_{rs}$ accruing to destination *s* will be zero whenever the destination is non-adjacent to *r*, and also if it has a higher elevation.

It is important to note that these fractions are the same for all commodities *i*, reflecting that salt and other commodities that flow with the water are diluted in it. Other commodities do not flow out of the site. If prices $\pi$ of the site-specific program (3.7) are such that markets for water are competitive (all take prices as given) and these markets clear, then in the absence of further externalities, these prices can be obtained from the welfare program:

$$\begin{aligned}
&W^* = \max_{c_s, d_{i\tau s}, q_{i\tau s}, y_{i\tau s} \geq 0} \textstyle\sum_s \left( f_s(c_s) + \sum_i \psi_{is} k_{iTs}(c_s, d_s) \right) \\
&\textit{subject to} \\
&\quad c_s \leq \tilde{c}_s(d_s) \\
&\quad y_{i\tau s} = \tilde{y}_{i\tau s}(c_s, d_s) \\
&\quad d_{i\tau s} = q_{i\tau s} \qquad\qquad (p_{i\tau s}) \\
&\quad q_{i\tau s} = \textstyle\sum_r \alpha_{rs} y_{i\tau r},
\end{aligned} \tag{3.9}$$

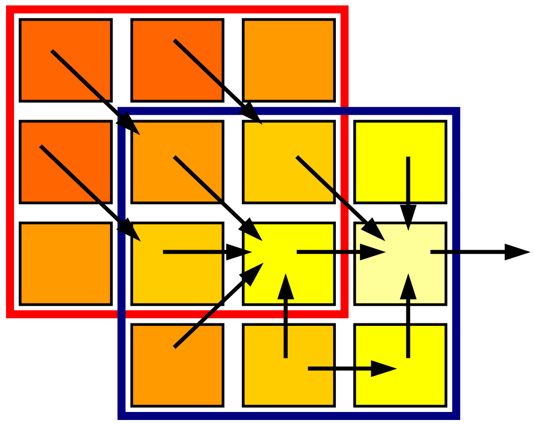

**Figure 3.1 Gravity imposing an order of calculation from high to low altitudes**

Within the function $\tilde{y}$, the available inflow $d$ is partly routed directly (transit) and partly used within the cell, according to fractions $\theta_s$. This is a convex program, whose Lagrange multipliers can be obtained via the marginal valuation as derivatives of the value functions in (3.7), which, as we recall, may exhibit discontinuous switches when bounds become active and regime changes take place, and reflect the price that the local user would be willing to pay for additional inflow from upstream neighbours. To decentralize the program, we compute the price that the local user would charge if he could supply extra water to his downstream neighbours as:

$$\pi_{is} = \textstyle\sum_{r \in N_s^-} \alpha_{sr} p_{ir}, \tag{3.10}$$

where $N_s^-$ is the set of upper neighbours. Thus, selling prices conform to downstream delivery prices for received inflow in fixed proportion to outflow leaving to downstream. Note that this price determination is bottom-up, contrary to the physical flow direction. It can be shown that water allocations described in (3.9) coincide with decentralized allocations described in (3.6), provided that decisions are coordinated by properly connected price signals as in (3.10), and flows (3.8).

### 3.5 Computation of efficient allocations

Because of its large size, welfare program (3.9) cannot be solved by standard optimization software, hence the need for a dedicated algorithm. As mentioned earlier, the idea underlying this algorithm to solve welfare program (3.9) is to exploit the gravity principle of the water flows (Figure 3.2). In a single iteration, given a price vector of selling prices from the last iteration, all sites are visited once from high to low altitude in order to update local water use given updated selling prices from the last iteration by (3.10) and to update inflow satisfying (3.8).

The key step is to prove that if we adjust the prices in a sufficiently smooth way from one round of iteration to the next, these prices will converge to an equilibrium that solves the welfare program. Specifically, we specify the price adjustment algorithm for $\tilde{p}^t$ according to the simple averaging process:

$$\tilde{p}^{t+1} = (1-\sigma)\,\tilde{p}^t + \sigma\,\hat{p}^t, \qquad t = 0,1,... \tag{3.11}$$

for a positive stepsize constant $\sigma$ (not to be confused with the seepage function of assumption WSC above). We observe that this process can be interpreted as a discretization of the differential equations $\frac{d\tilde{p}}{dt} = \hat{p}(\tilde{p}) - \tilde{p}$, where $\hat{p}(\tilde{p})$ is the vector of Lagrange multipliers of (3.9). Given these prices, we adapt the selling prices according to:

$$\pi_{is}^t = \sum_{r\in N_s^-} \alpha_{sr}\,\tilde{p}_{ir}^t. \tag{3.12}$$

The convergence argument considers the wedge $(\tilde{p} - \hat{p})$, interpreting it as a wedge between the selling and delivery prices, i.e. as an indirect tax. The basic principle of the algorithm is to reduce these taxes proportionately for all sites. As shown in Ginsburgh and Keyzer (2002) such a reduction raises welfare. The difference with the standard distorted welfare approach is that here the selling prices rather than the wedges adapt and that these prices are endogenous. Yet, we can prove convergence of the proportionate tax-reduction procedure by showing that, locally, the proportionate reduction in price wedges is implementable in the sense that it maintains feasibility of the prevailing solution, reduces actual taxes and eventually leads to a zero-tax situation.

### 3.6 Other solution concepts

Clearly, the current situation in the JRB is not one of efficient water allocation. Yet, the proposed algorithm provides the basis for the solution procedure of alternative solution concepts, which we now discuss briefly. Under each of these concepts the solution will be unique.

One, which best describes present conditions, supposes that sites do not pay to one another, i.e. that the objective of the program has an additional term $-\sum_i \sum_\tau \zeta_{i\tau} y_{i\tau}$, where $\zeta_{i\tau} = \pi_{i\tau}$, which taxes away all proceeds from sales to downward locations. The solution is now computed in a single round, since the after tax selling prices are zero and hence directly find their "optimal" value.

A second approach is to assume that taxation only takes place at national borders. However, in this case, the convergence proof requires us to set the tax at a fixed level rather adjusting it to exactly tax away all revenue. Such a fixed tax easily fits within the framework of the efficient algorithm, since it amounts to a straightforward extension of the objective in (3.9) by a linear term.

A third approach is applicable when the territories that do not pay to one another are ranked by altitude. Then, the models can be solved in top-down sequence. However, for the JRB this condition does not hold at all. Nonetheless, it would seem that convergence will persist when the tax exactly eliminates all payments, since it maintains the principle that the price at such a border site is given, and that all neighbouring upstream sites have prices that follow from it. Yet, uniqueness is not ensured in this case.

### 3.7 Intertemporally efficient path and steady state

The procedure for a single year of simulation is in principle easily run for several years in sequence, as the future can be considered to lie downstream of the present and the bottom-to-top price calculations to evaluate the selling prices can therefore also be conducted from the last period backward. Hence, the computational procedures sketched so far apply for any simulation over a finite horizon, and the co-operative solution will yield an intertemporally efficient accumulation path.

The steady state can be looked at as an infinite sequence of such calculations, whereby the initial stock coincides with the end stock, and consequently, the initial marginal value of stocks agrees with the end-value. As it clearly is not possible to run infinite sequences, we must compute a steady state in a different way, and since all simulation years are identical, it is natural to address a single-year problem, where we seek to adjust the end prices $\psi_{iTs}$, at the end of month 12 of the current year, as well as the initial stocks $k_{i0s}$, the end-stocks of month 12 of the previous year, until in a fixed point is reached at which:

$$k_{i0s} = k_{iTs}, \text{ and } \psi_{i0s} = \mu\psi_{iTs}, \text{ in}$$

$$W^*(\psi_T, k_0) = max_{c_s, d_{i\tau s}, g_{i\tau s}, q_{i\tau s}, y_{i\tau s} \geq 0} \sum_s ( f_s(c_s) + \mu \sum_i \psi_{iTs} k_{iTs}(c_s, d_s, k_0)), \quad (3.13)$$

where $\mu$ is a given discount factor over 12 months, $\psi_{i0s}$ is the current stock price at the beginning of the year, $\psi_{iTs}$ is the current stock price at the beginning of next year, $k_{i0s}$ the stock level at the moment, and $k_{iTs}$ the stock level at the beginning of the next year, i.e. $T$ months later, and we recall from Assumption P that $f_s$ was already discounted to the beginning of the period. Formally, the steady state poses a saddlepoint problem, which can be obtained from the welfare program (3.9) by treating the end-price $\psi_T$ and the beginning stock $k_0$ explicitly as variables:

$$W^*(\psi_T, k_0) = max_{c_s, d_{i\tau s}, g_{i\tau s}, q_{i\tau s}, y_{i\tau s} \geq 0} \sum_s ( f_s(c_s) + \mu \sum_i \psi_{iTs} k_{iTs}(c_s, d_s, k_0))$$

*subject to*

$$c_s \leq \tilde{c}_s(d_s) \tag{3.14}$$
$$y_{i\tau s} = \tilde{y}_{i\tau s}(c_s, d_s, k_0)$$
$$d_{i\tau s} = q_{i\tau s} \qquad\qquad (p_{i\tau s})$$
$$q_{i\tau s} = \sum_r \frac{1}{(1+\rho_{i\tau r})} y_{i\tau r}\alpha_{rs} \, ,$$

where *W** will now be convex in $\psi_T$ and concave in $k_0$, and the steady state solves:

$$\overline{W} = min_{\psi_0 \in \Psi} \; max_{k_0 \geq 0} \{ W^*(\psi_0, k_0) - \psi_0{}' k_0 \} . \tag{3.15}$$

with $\psi_0{}'$ denoting the vector-transpose, for given price bounds $\Psi = [\underline{\psi}, \overline{\psi}]$, where water has a zero lower bound, and a positive (arbitrarily large) upper bound, and salt a large negative lower bound and a zero upper bound. The accepted way to solve such problems is to apply the saddlepoint (gradient-) algorithm that adjusts prices and stocks in parallel introduced by Arrow and Hurwicz (1958):

$$\psi_0^{t+1} = min(max(\psi_0^t - \overline{\sigma}(k_T^t - k_0^t), \underline{\psi}), \overline{\psi}) \tag{3.16}$$
$$k_0^{t+1} = max(k_0^t + \overline{\sigma}(\psi_T^t - \psi_0^t), 0), \; t = 0,1,...,$$

For positive stepsize $\overline{\sigma}$ chosen small enough , this iteration converges globally to a stationary point. The Envelope Theorem implies that $\dfrac{\partial W^*(\psi_T, k_0)}{\partial \psi_T} = k_T$ and $\dfrac{\partial W^*(\psi_T, k_0)}{\partial k_0} = \psi_0$ and hence that the stationary point is a steady state. For positive stepsize $\overline{\sigma}$ chosen sufficiently small, this iteration converges globally. Indeed, with a stepsize sufficiently below the reduction factor $\sigma$ of (3.11), the adjustment can be conducted in parallel with the solution of the welfare program.

*Markov chain*

Finally, we remark that the fixed shares $\alpha_{rs}$ could be interpreted as the probability of transition of a drop of water from state *r* to state *s* along a Markov chain with an annual cycle. Hence, even the deterministic welfare program has a stochastic interpretation. Naturally, further stochastic elements can be incorporated by allowing for a branching of future periods into mutually exclusive classes of states, i.e. for a stationary process by allowing for a third, non-spatial subscript *n* that defines shares $\alpha_{rsn}$ .

Under this interpretation the tax on outflows of Proposition 4 operates as a site-specific (infinitely large) rate of discount, similar to a physical loss that, however, only influences valuation. Consequently, the equilibrium with missing markets can be interpreted as a social plan with a specifically strong discounting profile, and the resulting plan is, because of the convexity of the program, unique and efficient for this given discounting profile.

*Limitations of the model*

The model by design focuses on the water economy, which obviously limits its scope. It takes all the commodity prices as given and by concentrating on the water use intensity in every month, it a neglects many of the substitution possibilities at site-level. This not for theoretical or computational reasons but because the aim of our study is to find out what the JRB could do with additional water and how reforms in payment procedures and increase in water supplies to the JRB would affect financial flows. We feel that the detail is sufficient for this purpose, and that the restrictions facilitate its already very difficult empirical elaboration, to which now turn.

# Section 4

# Empirical Elaboration

## 4.1 Altitude map and spatial hydrology linkages

So far, we have taken the set of sites *S* that constitute the Jordan Basin as given. This section describes the algorithm used: (i) to construct this set (see also Vincent and Soille, 1991; Cederstrand and Rea, 1996, for similar algorithms); (ii) to modify the elevation map so as to ensure proper draining from all sites and proper routing to known major streams; and (iii) to compute the outflow shares $\alpha_{rs}$ that respect the gravity order for the modified elevation map.

The central issue to be tackled is that the grid-based elevation map is inaccurate in the sense that water (rainfall) poured over it in a laboratory model would remain stuck in an unrealistically large number of lakes without outlets (sinks), and existing rivers (drainage network) would not receive the appropriate inflow. The causes of these deficiencies are essentially twofold. First, even the most detailed elevation map available (of $30 \times 30$m grid) is subject to errors in positional (horizontal) and attribute (vertical) accuracy (Ehlschlaeger and Shortridge, 1996) that prevent realistic drainage. Second, the projection of the rivers to the target geo-reference results in small horizontal deviations from the drainage network of the DEM (Digital Elevation Model, in fact the altitude database), which might lead to unnatural drainage patterns.

To perform the correction, application of available GIS-procedures was not possible, because the particularly accidented landscape of the JRB requires a subtle treatment that avoids any brute force technique. Hence, a new algorithm for altitude correction was designed that proceeds in three (non-iterative) steps.

*(a) Enforcing downward flow through prespecified river segments*

River maps are available that describe existing rivers in terms of $R$ segments of a (directed) graph, each line segment of which represents a part of the river. All these segments are projected on the grid-based elevation map. For a typical river segment, the grid-based cells $r_\ell, \ell = 1,2,...,L$, cover the entire segment with $\ell = 1$ the highest upstream point on the segment and $\ell = L$ the lowest. Since $r_1$ is supposed to represent the highest altitude, the procedure starts at $\ell = 1$ and follows the segment. In case the altitude rises with respect to the level of the previous upstream grid point, it is lowered to this level minus epsilon, and so on until the end of the segment at $r_L$. The adjusted altitude $a_{r\ell+1}$ is calculated as

$$a_{r_{\ell+1}} = min( a_{r_\ell} - \varepsilon, \hat{a}_{r_{\ell+1}} ), \qquad \ell = 1,2,...,L, \tag{4.1}$$

given initial altitudes $\hat{a}_r$.

*(b) Demarcating the watershed*

A watershed is defined as the set of sites that could, if available, deliver water through gravity driven flows, to a given set of client cells or destinations $\Omega$, such as the point where the Lower Jordan enters the Dead Sea or at the confluence of the Jordan and Yarmuk rivers. The watershed is the catchment area of the client set. Indeed, it is not possible to define a watershed on the basis of an elevation map alone and also requires a given set of destinations, sinks or outlets, that in fact constitutes the origin of the set demarcating the watershed. Here we assume that $R \in \Omega$, and we start from the adjusted altitudes of step *(a)*.

From this origin $\Omega$ it is possible to identify uniquely all the points that could deliver to it. Specifically, suppose we set the outflow shares $\bar{\alpha}_{rs}$ of grid cells in the elevation map to either 1 or 0, where 1 represents that *r* is upstream of destination *s*, then these cells satisfy:

$$\bar{\alpha}_{rs} = 1 \text{ if } a_r \geq (a_s + \varepsilon) \text{ and } s \in N_r^- \text{ and } 0 \text{ otherwise,} \tag{4.2}$$

where as before $a_s$ is the adjusted altitude, $N_r^-$ is the set of downstream neighbours and $\varepsilon > 0$ the minimal altitude difference needed to maintain the flow. We can in a single round of visits of sites determine the watershed set by the bottom-up procedure:

(1) Assign unit label to the client set: $m_r = 1 \text{ for all } r \in \Omega$;
(2) Loop over sites $\ell = 1,...,S$, ranked by increasing altitude ($a_{r_\ell} \leq a_{r_{\ell+1}}$), recurrently assign unit label to attainable points:

$$m_{r_\ell} = 1 \text{ if for any } s \in N_{r_\ell}^-, \ \bar{\alpha}_{r_\ell s} > 0 \text{ and } m_s = 1, \tag{4.3}$$

until the top point has been reached. The watershed is now defined by the set of points with unit labels:

$$M(\Omega, a, N) = \{ r \in S \mid m_r(\Omega, a, N) = 1 \}. \tag{4.4}$$

Clearly, it is invariant under extension of the client set to members of the watershed, i.e. the set is idempotent:

$$M(\Omega, a, N) = M(M(\Omega, a, N), a, N), \tag{4.5}$$

and inclusive:

$$\Omega' \subseteq \Omega \text{ implies } M(\Omega', a, N) \subseteq M(\Omega, a, N). \tag{4.6}$$

Furthermore, watersheds defined on the basis of different client sets will in general overlap. Consequently, since the possible number of client sets is virtually infinite, watersheds do not subdivide the surface into non-overlapping zones.

In practical terms, the more accurate the altitude map, the smaller the client set can be kept. When the altitude map is relatively coarse, say, because the grid cells are large, it is advisable to treat all known river flows as elements of the client set. Then, wherever possible, the procedure will direct the (virtual) flows to these rivers and assure connectedness of the watershed.

*(c) "Busting"*

If the altitude map had sufficient resolution and no errors of measurement, it would surely generate a consistent matrix of flows and hence of flow shares that obey:

$$\alpha_{rs} = 0 \text{ for } s \in N_r^+, \tag{4.7}$$

and aggregation to a gridcell of larger size would still reproduce observed aggregate flows for that size, by computing aggregate flow shares $\alpha_{rs}$. However, this would generate a share matrix that cannot be reduced to triangular form, and hence to a system that, to meet the physical balances at every point, cannot be solved recursively from top to bottom but requires iteration instead. Such a setup seems less appropriate for the large scale application under consideration. Therefore, we choose to preserve recursivity and since it is not possible to deal with every gridcell separately, we proceed according to generic rules.

Here we specify a procedure that maintains proper drainage by requiring that, for flows obeying steepest descent, a descent direction should exist at every point with a potential discharge above a given minimal level. Thus, we remain within the framework of (4.2)-(4.3) used to determine the watershed.

As an introduction to the procedure, let us briefly list the factors that may hamper drainage within a watershed demarcated in accordance with step (b). We remark that problems can only arise at the boundary (i.e. within the client set and at the fringes) because every cell in the interior has by definition an outlet and hence a steepest descent.

Regarding the client set, we note that it may not exhibit proper drainage. Only the segments treated under step (a) are known to flow downward. The procedure may have to act on this so as to ensure that the junctures between downward sloping riverbeds are downward flowing as well, and in the appropriate direction.

With respect to the fringes, under the second model, part of the flows originating from within the watershed may lead out of it and face jams at an (internal or external) boundary. If these arise in the steepest descent direction, we also apply a correction that amounts to forcing a steepest descent flow to take place inside the watershed. Hence, it remains possible for water to leave the watershed points outside the client set but in this particular application, we avoid local sinks as outletless lakes of any size are very few in this region.

Finally, proper drainage we require a higher altitude difference than the constant $\varepsilon$ in (4.2). The procedure (4.8) that performs these tasks (see also Figure 4.1 for an illustration) is as follows.

1. Rank sites by decreasing altitude: $r_\ell$, $\ell = 1,...,S$ such that $a^t_{r_\ell} \geq a^t_{r_{\ell+1}}$, where $a^t_r$ denotes the given altitude at site $r$ at the beginning of iteration $t = 1$ of the procedure.

2. Run over sites in order $r_\ell$, $\ell = 1,...,S$ :

2.1 Evaluate the water flows:

$$y_r^t = (1-\sigma_r)(q_r^t + b_r) \text{ where } q_r^t = \sum_s y_s^t \alpha_{sr}(a^t),$$

and $\sigma_r$ denotes the retention factor, $q_r^t$ the inflow and $y_r^t$ the outflow.

2.2 Get steepest descent outflow direction, $\underline{s}$ from:

$$V_r(a^t) = min_{\hat{\alpha}_{rs} \in \{0,1\}, s \in N_r} \{ \sum_s (a_s^t - a_r^t) \hat{\alpha}_{rs} \mid \sum_s \hat{\alpha}_{rs} = 1 \}.$$

2.3 Busting: for flows above the threshold $\underline{q}$ : $q_{\underline{s}}^t > \underline{q}$

*if* $V_r(a^t) > \varepsilon_2$, *then* $a_s = a_r - \varepsilon_2$ *for nearest higher neighbour and its nearest higher neighbour*

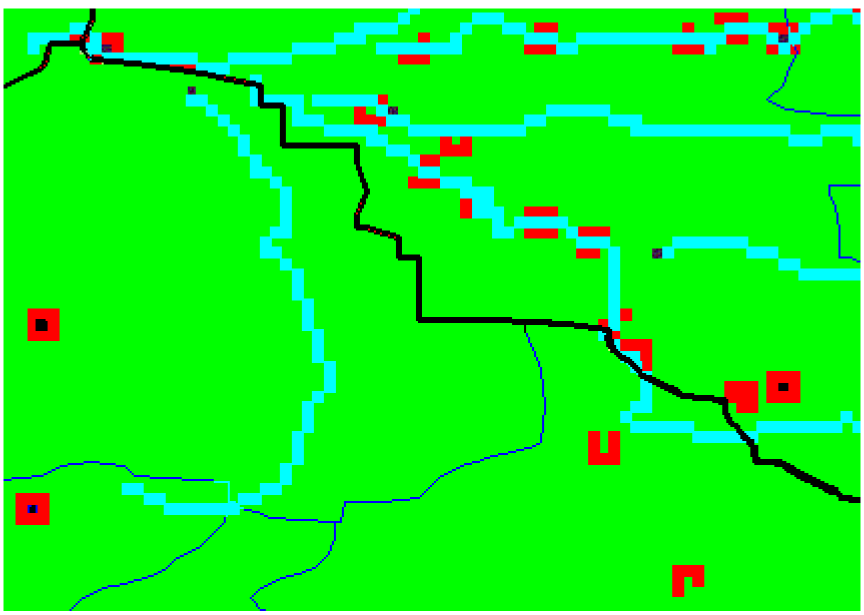

**Figure 4.1 'Busting' (red spots) in Yarmuk River Basin**

We call this step (2.3) "busting" because at sites where flows along the steepest descent are stuck, this step essentially blows away the rocks of the lowest neighbouring site and, if necessary, its lowest neighbour until their altitude becomes lower, so as to "free" the water. Since these neighbouring sites were visited already (they had higher altitude), this cannot incapacitate (lock) outflows from any upstream site, and the procedure ends after a single round, when only the client set of the Basin can have flows above (the possibly site-specific) level $\underline{q}$ ,without a further destination. Busting will ease the flows between segments of the client set but proper flowing along the client set requires extending these segments in step (a) *(d) Final adjustment, and calculation of outflow shares*

As the busting may create ditches that cross a river, it is necessary to repeat step *(a)* after the busting. This yields the final altitude map, and hence the order of visits of sites in the model.

Now based on a priori outflow shares $\hat{\alpha}_{rs}$ obtained from aggregation over outflow directions in the $1 \times 1$ arcsec map, and the transit shares $(1-\theta_r)$ measuring the fraction of flows that immediately cross the site without use, in case the site has a river ($\delta_r = 1$), we compute, the outflow shares of the model as

$$\alpha_{rs} = \frac{(1-\sigma_r)\hat{\alpha}_{rs} + (1-\theta_r)\delta_r}{(1-\sigma_r)\sum_{s'|a_{s'}<a_r}\hat{\alpha}_{rs} + (1-\theta_r)\delta_r}, \qquad (4.9)$$

for all sites with outflow (i.e. all sites except the final sinks), and hence with a positive denominator. Sinks have $\sum_s \alpha_{rs} = 0$ (See Figure 4.2). Recall that we allow flows leaving the watershed.

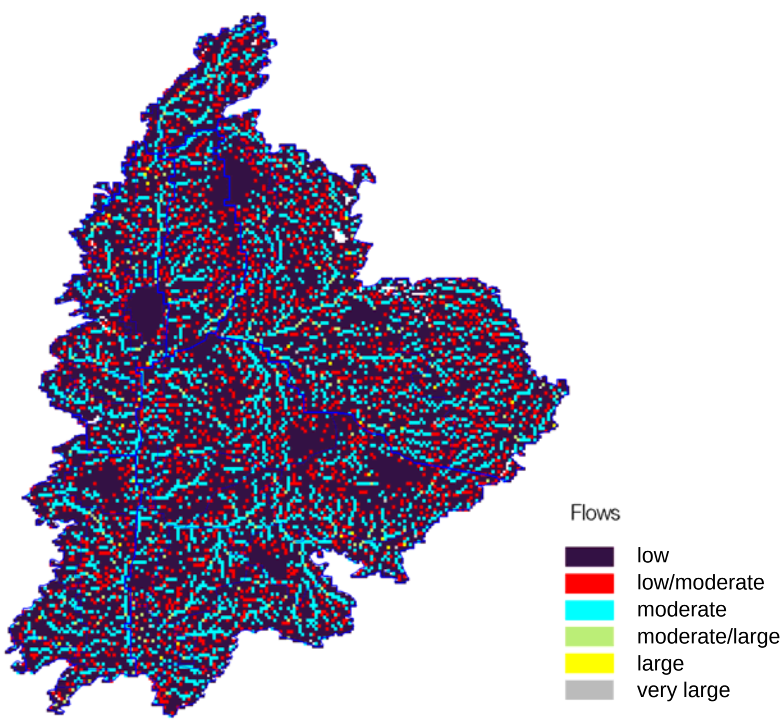


**Figure 4.2 Drainage network and flow volumes**

We conclude that step (a) of ensuring proper drainage of the client set seems to be the critical element in our application, where the flooding of depressions is not an issue. The procedure is actually semi-automatic, as the blockades remaining after busting in step (c) provide an indication of the river segments that need to be supplied additionally.

*Subwatersheds.* We mentioned earlier that the demarcation of watersheds will exclude depressions, i.e. territories surrounded by the watershed. The boundaries of such areas lie below the watershed, and are excluded because they do not contain any client point, nor are they surrounded by it. In fact, these are mini-watersheds that can be represented within the main one, by defining additional client points. Similarly, once the watershed has been defined, it is possible to specify new client cells for subsets of the current watershed in order to study the flows in a subregion, e.g. a region delivering to a pre-specified hydrograph (point on a river where flows are being measured).

*Canal irrigation.* Canal irrigation is represented through a separate map of downward flows that drain into the land, starting from the tapping point on the river. With a slight modification the leveling procedure can be used to ensure that all irrigated land can be reached, including the return flows to the river. The difference is that in step (c), leveling is not activated for sites at the fringes of the irrigated zone.

*Lake Tiberias and Transnational Carrier.* As the aim of the modeling exercise is not to study the aquatic resources and flows in the lake, we represent it by a hollow land surface with a single outlet point. At this point the whole water volume of the lake is stored, a fraction of which is extracted for the Transnational Carrier to the West, thereby leaving the watershed.

*Extraction from the Yarmuk river by Jordan and Syria.* The Yarmuk separates Jordan and Syria in the Western part of its bedding. At the Adashiya Dam, water enters into the King Abdullah Canal, that runs through Jordan and is the source of water for the (pump-based) conveyor to Amman, where it is discharged on the Zarqa River within the Jordan basin. In addition, a Northern Conveyer has been planned that pumps from the Yarmuk at an upstream location, and also eventually discharges in the basin. Similar conveyors are already operational in Syria. For our modeling, the difficulty is that the pumped water moves against the gravity order while the non-evaporated fraction remains within the watershed. Our approach can only represent the gravity driven flows in a spatially explicit manner, since upstream flows go against the order of calculation, essentially causing simultaneity in the flow structure. While it is possible to allow for this between annual cycles, and through the introduction of an additional level of iteration, it would be impossible to obtain convergence of the simultaneous system as well (because the share matrix is non-expansive), we choose to avoid this because model calibration becomes significantly more difficult. Hence, the net disappearance of water in the conveyors is treated as a tapping that leaves the watershed and, to deal with the return flows, we draw virtual underground canalization that resurfaces at points below the source of the conveyor, where the water re-enters the basin.

## 4.2 Basic data sources and processing

A spatially explicit analysis to determine the efficient allocation of water is especially demanding in its need for data spatial-temporal distribution of discharge patterns and water use efficiencies. Hence, a large number of sources had to be consulted. These sources vary significantly in their geographical detail, ranging from national statistics to point data from satellite images. Spatial data also exist in various formats, polygons versus grids and different geographical projections. The data coverage on, say, rainfall data gathered by meteorological stations is very different across the countries. Consequently, extensive data harmonization was needed until a unified spatial-temporal database could be obtained. We briefly report on the processing of data sources that vary both in their spatial resolution and in their spatial coverage.

The spatial information sources that were compiled for the JRB consist of polygons, segments, grid cells and point information. These data were imported in Geographical Information Systems (ArcView; ILWIS) and projected in a fixed georeference of grid cells with LatLonWGS84 geographic coordinates in degrees. To maintain a balance between model size and spatial-temporal detail, the analysis operates with grids of 30 arcsec mesh and on a monthly basis. The grid cell size is the same as in other regional hydrological studies (e.g. Guo et al., 2002; Ochi and Shibasaki, 1998).

**Table 4.1 Overview of data used, formats, processing methods and sources**

| Data | Format | Processing | Source |
|---|---|---|---|
| Precipitation | Point data | anisotropic kriging | FAO (2002a) |
| Evapotranspiration | Grid 30 arc seconds | bicubic resampling | FAO (2000) |
| Soil units | Polygons | nearest neighbour | FAO/UNESCO (2003) |
| Water holding capacity | Grid 5 arc minutes | Nearest neighbour | FAO (2002a) |
| Soil suitability | Grid 5 arc minutes | Nearest neighbour | FAO/IIASA (2000) |
| Topography | Grid 1 arc second[3] | Aggregation | USGS/NASA (2004) |
| Population | Grid 30 arc seconds | Bicubic resampling | Deichmann (1995) |
| Water network | Vector | nearest neighbour | Orthofer et al. (2002), |
| Global river discharge data | Grid 5 minutes | bicubic resampling | Vörösmarty et al. (1998) |
| Administrative Units | Polygons | Nearest neighbour | Orthofer et al. (2002), ICBS (2003), Deichmann (1995) |
| Land use | Grid 1 arc second | Aggregation | NASA (2004) |
| Cattle density | Grid 5 arc minutes | Nearest neighbour | FAO (2002b) |
| Socio-economic data sets | Polygons | Nearest neighbour | ICBS (2003), PCBS (2004), JDS (2002) |

[3] A grid cell of 1 arc second corresponds to 812.25 $m^2$.

Data sources with polygon and segment formats or grid sizes larger than the target georeference were resampled using the nearest neighbour method for discrete classes (e.g. soil units) and bicubic resampling for continuous data (e.g. population). The interpolation methods used for meteorological stations are explained in some detail below. Satellite images and the Digital Elevation Model were processed at the 1 arcsec level, and subsequently aggregated to the 30 arcsec level. Table 4.1 shows the data format, the methodology applied to obtain a common georeference and the sources of the information.

*Administrative units*

Three spatial data sources (Deichmann, 1996; Orthofer et al., 2002; ICBS, 2002) were merged to define the boundaries of the national, provincial, and district level. These administrative areas were used to relate economic data at the national and sub-national level to the spatial data base. Table 4.2 lists the names, areas and area shares of the districts in the watershed. Figure 4.3A shows the two levels of administrative subdivision of the JRB. The finest resolution is the district level, the black delineated areas refer to the country areas with the Golan Heights as a special (grey) map unit.

*Population*

The population distribution in the JRB was based on the global database in Tobler et al. (1995). The basic assumption for the construction of the global population distribution is that densities are strongly correlated with accessibility, which was made operational by distributing the share of the total population at district level according to the relative density of the transportation network linked to urban centers, consisting of roads, railroads and navigable rivers. The population density for the JRB was updated to the year 2002 and is illustrated in Figure 4.3B.

*Digital Elevation Model*

For the assessment of the altitude in the JRB we used data from the Aster Digital Elevation Model (DEM), which generates altitude levels with an output image resolution of 1 arc second. The data are only available in several overlapping layers leaving part of the North-Eastern watershed uncovered. For this area we resampled the GTOPO30 (USGS, 1997), a global DEM that gives elevations regularly spaced at 30-arc seconds, using the bicubic resampling method to obtain an assessment for the 1 arc second grid. Figure 4.3C illustrates the DEM. The DEM was used to identify for each pixel of 1 arc second, the altitude, slope, and routing shares for water flow following the deepest descend to one of the adjacent neighbours. The distribution of this topographic information was mapped to the corresponding 30 arc second grid cell, and adjusted in the way described in procedure (4.8) above.

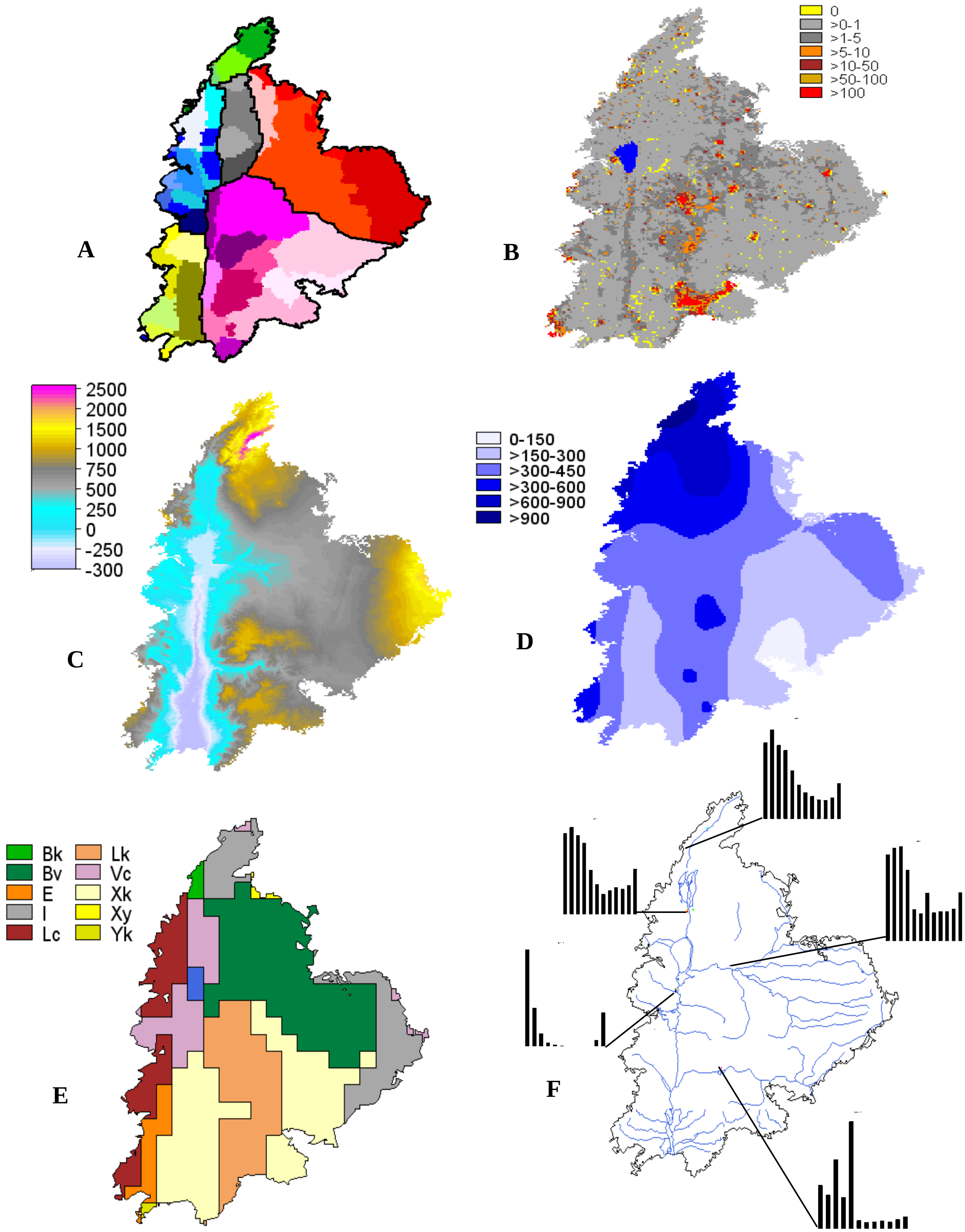


**Figure 4.3 (A) Administrative subdivision; (B) Population density (pers/km$^2$); (C) Altitude (m); (D) Annual precipitation (mm); (E) Dominant soils; (F) Hydrographs.** (Source: see Table 4.1)

**Table 4.2 Administrative areas in the Jordan River Basin**

| Country | Region | total area (km2) | area share watershed (km2) | area share in watershed (%) |
|---|---|---|---|---|
| Israel | Lake of Tiberias | 16.30 | 16.30 | 100.00 |
| | Judean Mountains | 22.81 | 0.66 | 2.88 |
| | Hula Basin | 26.61 | 26.46 | 99.45 |
| | Eastern Upper Galilee | 40.94 | 36.92 | 90.18 |
| | Hazor Region | 9.72 | 9.72 | 100.00 |
| | Kinnerot | 17.11 | 17.11 | 100.00 |
| | Eastern Lower Galilee | 35.09 | 33.04 | 94.17 |
| | Bet She'an Basin | 22.22 | 21.35 | 96.05 |
| | Harod Valley | 9.94 | 8.63 | 86.76 |
| | Kokhav Plateau | 15.50 | 15.50 | 100.00 |
| | Yzre'el Basin | 29.83 | 7.02 | 23.53 |
| | Nazareth-Tir'an Mts. | 28.95 | 7.31 | 25.25 |
| | Shefar'am Region | 25.15 | 1.83 | 7.27 |
| | Karmi'el Region | 10.53 | 0.59 | 5.56 |
| | Yehi'am Region | 24.27 | 1.54 | 6.32 |
| | Elon Region | 14.33 | 0.07 | 0.51 |
| Golan Heights | Hermon Region | 10.82 | 10.82 | 100.00 |
| | Northern Golan | 52.56 | 52.56 | 100.00 |
| | Middle Golan | 30.41 | 30.41 | 100.00 |
| | Southern Golan | 29.90 | 29.90 | 100.00 |
| Jordan | Aghwar Shamaliyah | 23.54 | 23.54 | 100.00 |
| | Dayr Alla | 23.91 | 23.91 | 100.00 |
| | Shoonah Janoobiyah | 25.44 | 24.42 | 95.97 |
| | Amman | 667.13 | 83.92 | 12.58 |
| | Balqa | 63.89 | 63.60 | 99.54 |
| | Zarqa | 302.21 | 56.00 | 18.53 |
| | Madaba | 72.66 | 16.89 | 23.24 |
| | Irbid | 155.86 | 155.86 | 100.00 |
| | Mafraq | 323.77 | 147.96 | 45.70 |
| | Jarash | 35.53 | 35.53 | 100.00 |
| | Ajloun | 41.08 | 41.08 | 100.00 |
| Palestinian Authority | Jenin | 57.02 | 8.41 | 14.74 |
| | Tubas | 36.04 | 36.04 | 100.00 |
| | Nablus | 61.11 | 24.05 | 39.35 |
| | Ramallah& Al Bireh | 79.54 | 28.95 | 36.40 |
| | Jericho | 73.18 | 72.37 | 98.90 |
| | Jerusalem | 32.46 | 14.84 | 45.72 |
| | Bethlehem | 61.70 | 3.14 | 5.09 |
| Syria | Damascus Rural | 217.41 | 24.05 | 11.06 |
| | Dara'a | 389.86 | 294.31 | 75.49 |
| | Quneitra | 46.71 | 46.71 | 100.00 |
| | Swida | 542.35 | 177.35 | 32.70 |

**Table 4. 2 (contd.) Administrative areas in the Jordan River Basin**

| | | | | |
|---|---|---|---|---|
| | Rachaya | 43.28 | 34.58 | 79.90 |
| | Bekaa Gharbi | 49.05 | 3.22 | 6.56 |
| | Marjaayoun | 24.86 | 6.14 | 24.71 |
| Lebanon | Bent Jbayl | 23.10 | 1.90 | 8.23 |
| | Hasbaya | 30.78 | 28.73 | 93.35 |
| | Jezzine | 24.86 | 0.29 | 1.17 |

*Monthly precipitation*

Spatial climatic assessments were made for monthly precipitation and monthly evaporation. Full spatial coverage of monthly precipitation necessarily relies on interpolation of point data from meteorological stations. From a literature survey (Genton and Furrer, 1998; Naoum and Tsanis, 2004a, 2004b; Velasco et al. 2004; Demyano et al., 1998) and consultations with meteorological experts in the region (e.g. Furshpan, 2004) it appeared difficult to find a single preferred method for interpolation of precipitation data in the JRB. Therefore, we decided to test the reliability of three interpolation methods against the observations of 188

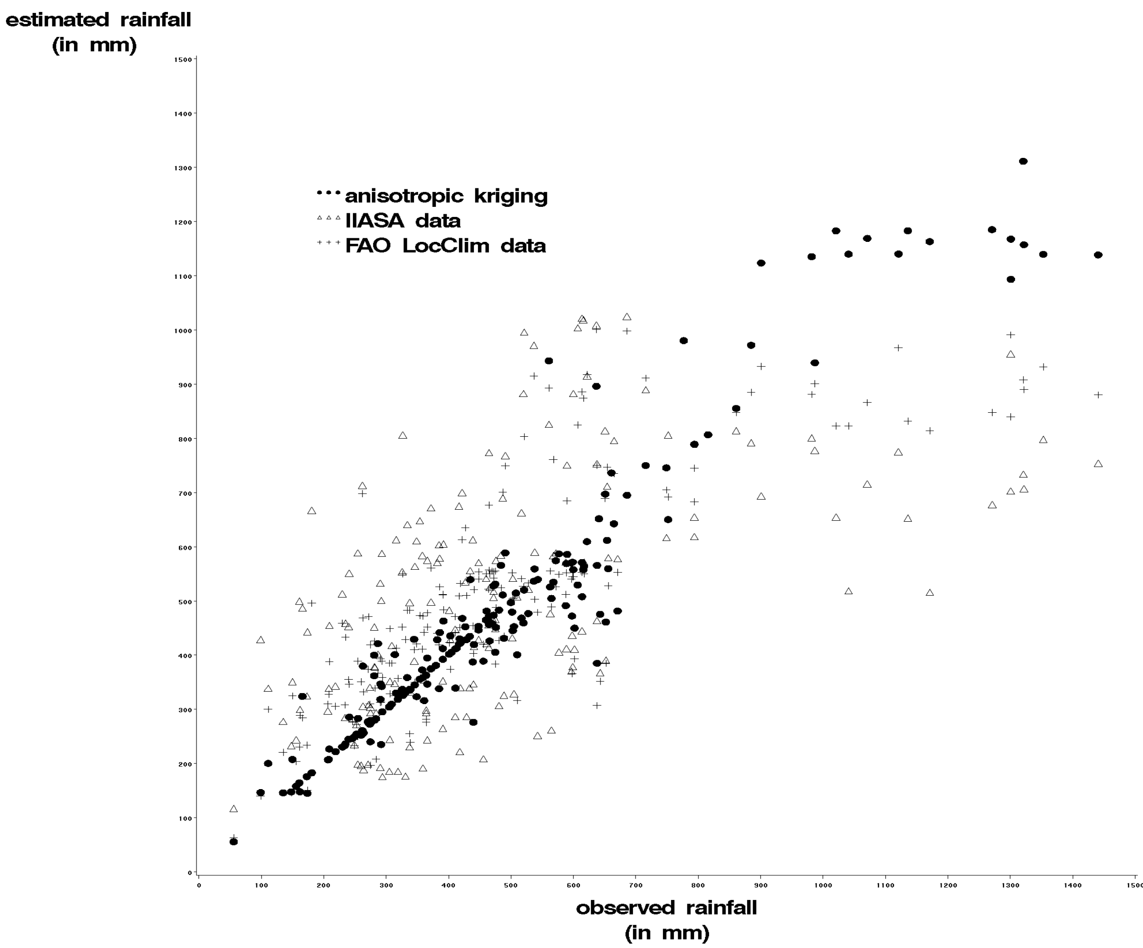


**Figure 4.4 Scatter plot of interpolated and observed annual rainfall data**

meteorological stations in and around the JRB: a triangulation interpolation method used for the global IIASA precipitation data base; the Inverse Distance Weighted Average interpolation used by the Meteorological Department of the FAO (FAO, 2002d) and a kriging procedure, commonly applied in geostatistical exercises. It appears that precipitation had an anisotropic pattern (relatively constant along a southwest-northeast axis) and low correlation with altitude. Hence, instead of standard kriging we opted for anisotropic kriging (Goovaerts, 1999) without any covariate for altitude.

Figure 4.4 presents a scatter plot of the three interpolated data sets for annual rainfall data against observed values of the meteorological stations. The results give the visual impression that the anisotropic kriging procedure gave the best results and this is confirmed by the Nash-Sutcliff coefficients in Table 4.3.

**Table 4.3 Nash-Sutcliff coefficients for comparing observed data and model results**

| Data set/Interpolation | Nash-Sutcliff coefficient |
|---|---|
| IIASA data | 0.26144 |
| FAO LocClim | 0.64685 |
| Anisotropic | 0.91347 |

The poor performance of the IIASA and FAO data might be partly due to the different time periods that were used for the interpolation exercise. However, the differences are considerable and we conclude that the anisotropic kriging method is the most suitable interpolation method to assess the monthly rainfall values in the Jordan Watershed. Figure 4.3D shows the annual precipitation pattern in the Watershed as a result of the anisotropic kriging method.

Figure 4.5 presents the results of the estimated monthly rainfall as a scatter plots against observed rainfall values. Most months show a good correlation between estimated and observed values, and this is also confirmed by the results of the Nash-Sutcliff coefficient for the different months (Table 4.4). The months April to September give somewhat lower values but precipitation in these month is close to zero.

**Table 4.4 Nash-Sutcliff coefficients for interpolated monthly rainfall data**

| Month | Nash-Sutcliff coefficient |
|---|---|
| January | 0.87 |
| February | 0.88 |
| March | 0.87 |
| April | 0.75 |
| May | 0.81 |
| June | 0.84 |
| July | 0.76 |
| August | 0.73 |
| September | 0.81 |
| October | 0.91 |
| November | 0.84 |
| December | 0.82 |

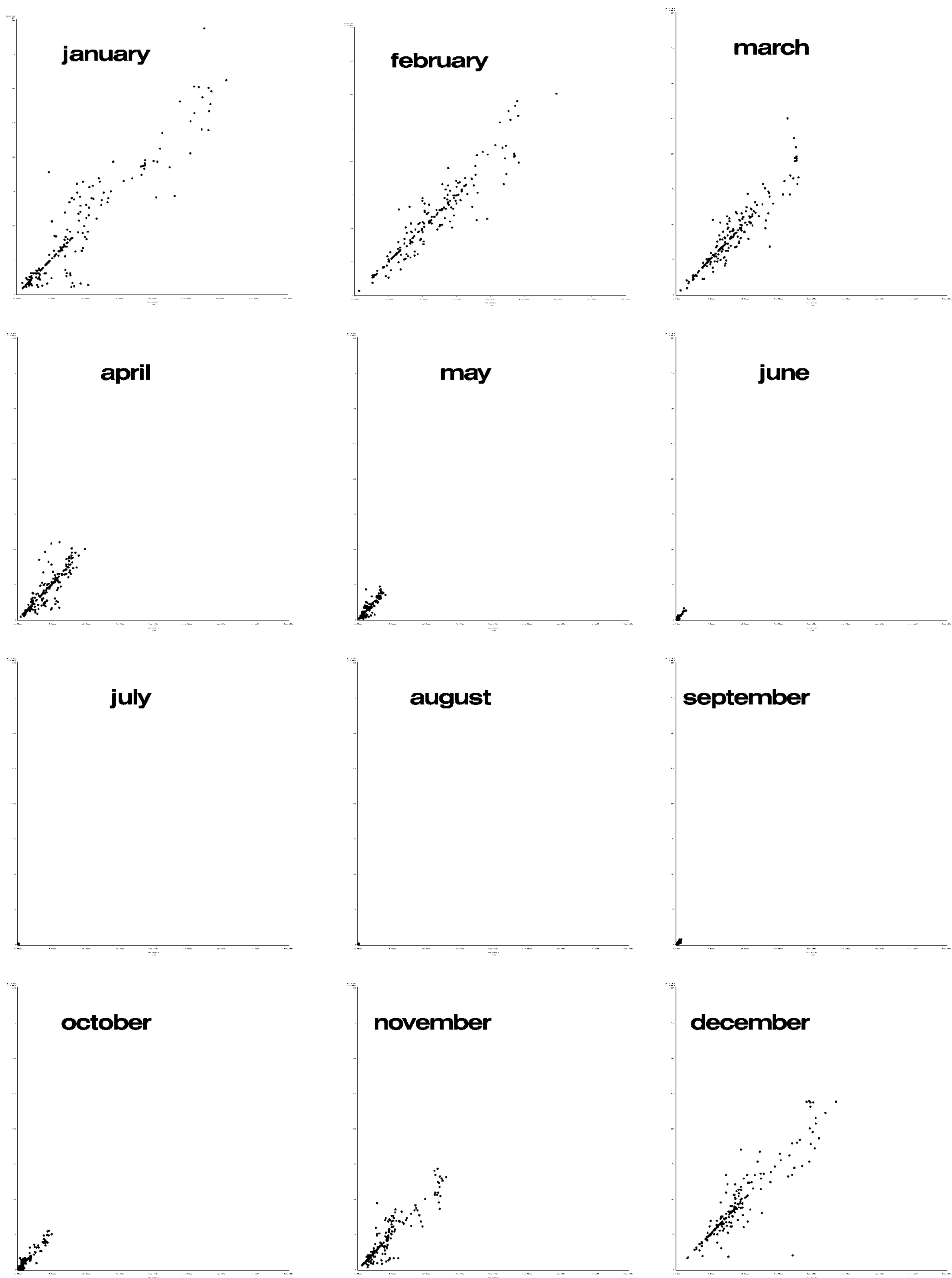


**Figure 4.5 Estimated (x-axis) against observed (y-axis) monthly rainfall values**

*Monthly evapotranspiration*

For the monthly evapotranspiration, we used the global database with a spatial resolution of 30 arc minutes developed at IIASA (2004). This database is constructed to facilitate the calculation of GIS-based water balance models for regional studies with an area surface that is comparable to the JRB. The dataset contains mean monthly values for the period 1961-1990 and has been prepared according to the Penman-Monteith method (FAO, 1998). Input data were derived from the Climate Research Unit of the University of East Anglia, UK. As we did not have at our disposition any large independent data set to test the reliability of the evaporation rates, the testing consisted of comparing evaporation data with figures from the literature (Doorenbos and Kassam, 1977) and maps that show the spatial distribution. The IIASA data seemed reasonable for the JRB and followed the prevailing spatial patterns of other sources.

*Soils*

Data on soil characteristics were derived by combination of the Digital Soil Map of the World (FAO/UNESCO, 2003), the Global Agro-Ecological Zones inventory (FAO/IIASA, 2000) and digitally available spatial data sources derived from the FAO GeoPortal[4].

**Table 4.5 Area share of soil groups and soil units in the Jordan River Basin**

| Soil Groups | area share (%) | Soil Units (code) | area share (%) |
|---|---|---|---|
| Cambisols | 15.5 | Eutric cambisols (Be) | 0.7 |
| | | Calcic cambisols (Bk) | 0.5 |
| | | Vertic cambisols (Bv) | 14.4 |
| Rendzinas | 7.7 | Rendzinas (E) | 7.7 |
| Gleysols | 0.8 | Gleysols (G) | 0.8 |
| Lithosols | 17.8 | Lithosols (I) | 17.8 |
| Fluvisols | 0.0 | Calcaric fluvisols (Jc) | 0.0 |
| Luvisols | 20.9 | Chromic luvisols (Lc) | 11.2 |
| | | Calcic luvisols (Lk) | 4.4 |
| | | Orthic luvisols (Lo) | 4.9 |
| | | Vertic luvisols (Lv) | 0.3 |
| Regosols | 5.1 | Regosols (R) | 0.0 |
| | | Calcaric regosols (Rc) | 5.0 |
| Vertisols | 10.3 | Vertisols (V) | 0.3 |
| | | Chromic vertisols (Vc) | 9.9 |
| Xerosols | 14.0 | Calcic xerosols (Xk) | 11.4 |
| | | Luvic xerosols (Xl) | 2.4 |
| | | Gypsic xerosols (Xy) | 0.2 |
| Yermosols | 4.0 | Calcic yermosols (Yk) | 3.9 |
| | | Gypsic yermosols (Yy) | 0.0 |
| Solonchaks | 4.1 | Solonchaks (Z) | 4.1 |

Source: FAO/UNESCO, 2003

[4] www.fao.org/geonetwork/

The Digital Soil Map of the World presents map units that consist of soil units or associations of soil units. When a map unit is not homogeneous, it is composed of a dominant soil (Figure 4.3E) and component soils. The latter are: associated soils covering at least 20 percent of the area; and inclusions of important soils covering less than 20 percent of the area. The attribute tables of the soil map contains information on soil units and their area share, see Table 4.5, phases and soil texture. The characteristics of the soil units are related to crop specific land suitability classifications. Phases such as indurated layers and hard rock occurring at shallow depth were used to adopt the water holding capacity of the soil. Five textural classes, reflecting the relative proportions of clay, silt and sand in the soil, were distinguished and related to hydrological characteristics: drainage class, capillary rise, percolation rate and water holding capacity (ILRI, 1974; Euroconsult, 1981).

**Table 4.6 Hydrological parameters for different texture classes**

| Texture class | Percolation in mm/day | Capillary rise in mm/day | Drainage class | Water holding capacity in mm/m |
|---|---|---|---|---|
| Sand | 1.00 | 0.25 | very good | 4 |
| Sandy loam | 0.20 | 0.35 | good | 6 |
| Loam | 0.33 | 0.50 | moderate | 9 |
| Clay loam | 0.07 | 0.75 | bad | 20 |
| Clay | 0.04 | 1.00 | very bad | 29 |

Source: ILRI, 1974; Euroconsult, 1981

Discharge patterns

Monthly river discharges over a period from 3 to 15 years were collected for 10 hydrological stations in the region. The average monthly discharges are used to calibrate the hydrological part of the model. Hydrographs of five selected stations are shown in Figure 4.3F.

### 4.3 Land use: reconciling satellite images with ground statistics

To represent the economic activities and production levels in the JRB, a spatial inventory was prepared by combining satellite imagery with ground statistics. For the imagery, we compiled a mosaic of satellite pictures with a resolution of 1 arc second. Next, production data at the national and district level, were distributed to corresponding grid cells. The mosaic of satellite images was built for the year 1999, from the Landsat 4 NASA satellite that produced an uninterrupted multispectral record of the Earth's land surface. The images were processed in ILWIS/GIS, using a natural color composite that combined three bands 4, 1 and 7 displayed in shades of red, green and blue, respectively. The selection of bands was based on the Optimal Index Factor, that selects by a regression technique, the combination of bands out of all possible 3-band groupings, with the highest amount of 'information', expressed as the highest sum of standard deviations and with the least amount of duplication (lowest correlation among band pairs). Through a supervised classification of 10 land use categories (rainfed annual crops; irrigated annual crops; rainfed perennials, irrigated perennials, grassland, shrubland, forest, urban areas, bare land, water bodies) a training set of pixels that was related to similar spectral values of the images color composites. As a classification

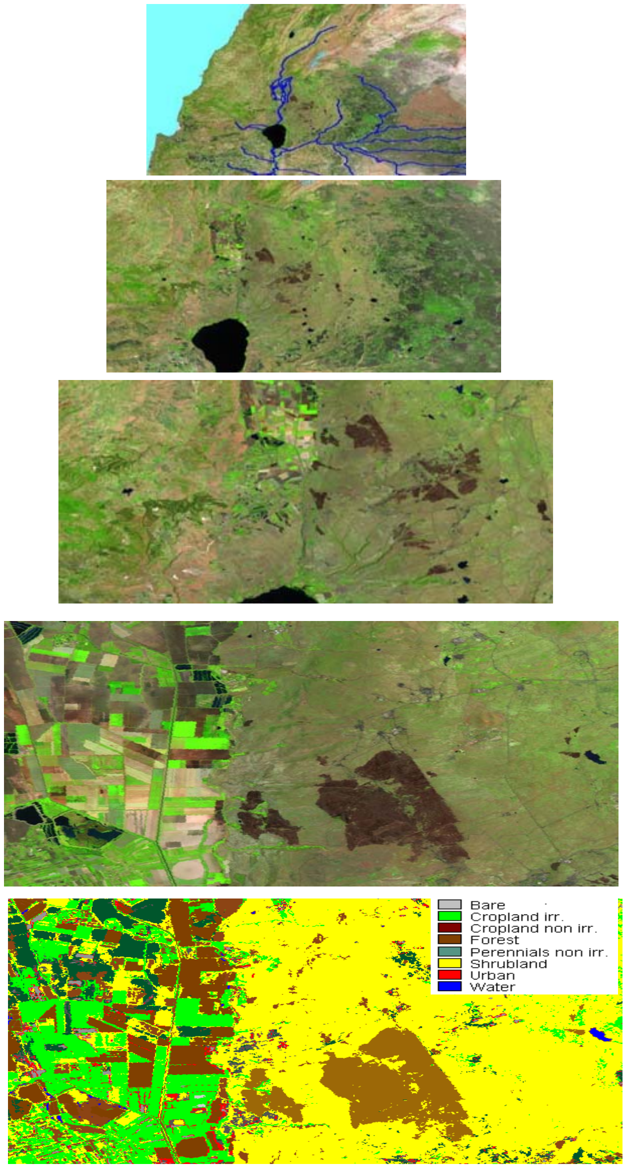


**Figure 4.6 Zooming in and classifying land use**

method we used the minimum distance classifier, based on the Euclidean distances towards class means. This classifier essentially regresses the supervised classification on the spectral values, and given such a regression, the classification at intermediate points is obtained by feeding the spectral values into the regression function.

Figure 4.6 illustrates the process of satellite image interpretation. The upper image shows the Northern part of the Jordan basin, with Lake Tiberias as focal point. With the lower images we zoom in and get a more detailed fragment of the watershed at which land use patterns are recognizable. At some points, more information about the situation on the ground is known than for others, for example that one point corresponds to a village street and another to an irrigated field. Thus, a particular spectrum of radiation can be associated with the radiation at the points of which the land use classes are known. The more such points are identified, the better the correct inference at points where no ground information is available.

*Distributing production data at national and district level*

Production levels were related to land uses (except for non-economic land uses ‘bare land’ and ‘water bodies’) and population by the following procedures. The spatial distribution of non-agricultural production was assessed by relating national GDP’s per caput, for industry and services (CBS, 2002; PCBS, 2004; JDS, 2002; Syrmap, 2004; Keyzer et al., 2001), to the population map.

Agricultural production at the district level has been distributed over the grid cells in three steps. First, we assigned typical cropping and livestock systems to land uses (Table 4.7) and calculated their total production at district level by multiplying average yields with the corresponding area.

**Table 4.7 Classification of agronomic land use and production**

| Land use | Agricultural production | Source |
|---|---|---|
| Cropland irrigated | Tomato | ICBS (2002), PCBS (2004) |
| Cropland | Wheat | ICBS (2002), PCBS (2004) |
| Crop/Grass | Cattle | FAO (2002c) |
| Perennials | Olives | ICBS (2002), PCBS (2004) |
| Perennials irrigated | Citrus | ICBS (2002), PCBS (2004) |
| Forest | Wood/fuel | EarthTrends (2004) |
| Shrubland | Small ruminants | FAO (2002b) |

Second, we used soil and climate inventory to assign site-specific maximum and minimum production levels following the Agro-Ecological-Zones method (FAO/IIASA, 2000). This method combines soil and climate characteristics for a crop specific suitability rating that is associated with maximum production levels. The minimum level for each location was set on 10 per cent of the maximum production. Third, we applied a finite bisection method to desaggregate the agricultural production over the corresponding grid cells. The bisection method allows for a consistent desaggregation that respects a priori on boundaries and, simultaneously, retains equality between the sum of distributed data and production at district level.

A visual comparison between interpreted land use categories and the color composite showed that many bare areas were difficult to distinguish from urban areas. Furthermore, comparing aggregated land use areas at district level with statistical data (provided by Central Bureaus of Statistics and Ministries of Agriculture) shows that crop land areas were largely overestimated. A closer look into the satellite images resulting from interpretation showed that most grassland area was assigned to cropland areas. We corrected for such biases as follows. Urban areas were corrected by combining the categorized land use map with the population density map, assigning all ‘urban areas’ with population densities of less than 2 persons per km2 to ‘bare land’. The overestimated cropland areas were corrected by assigning ‘fallow irrigated cropland’ and ‘fallow rainfed cropland’ to the category grassland.

To verify the final results, we compared the aggregated agricultural areas of the interpreted images for irrigated crop land, rainfed crop land, irrigated perennials and rainfed perennials with the statistical information of the administrative districts in the watershed area (Figure 4.7). In general the correlations between observed and simulated land use are reasonably high and we conclude that we can use the results to simulate land uses in the Jordan Watershed.

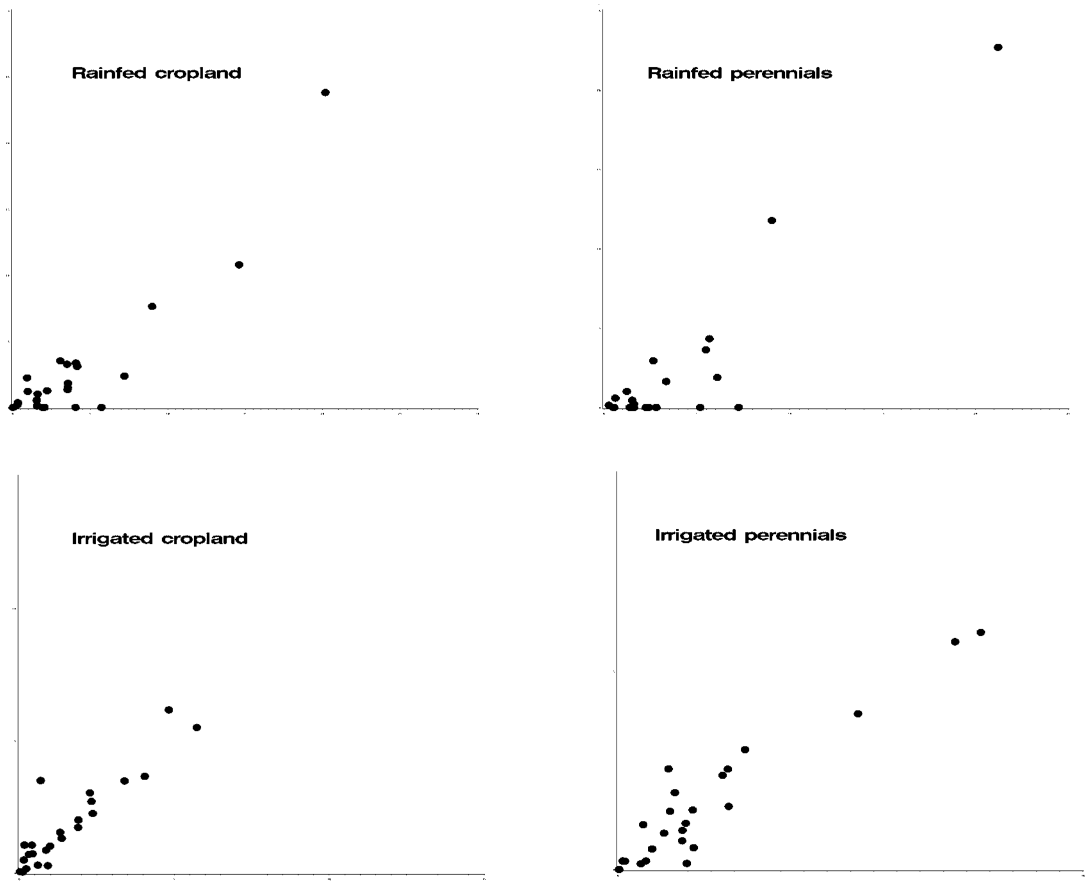


**Figure 4.7 Agricultural areas: assessments from satelite images (y-axis) vs district statistics (x-axis)**

## 4.4 Production and income patterns in the Jordan River Basin

*Land use pattern*

Figure 4.8 shows the landuse classification in the JRB at the level of the 25,301 sites that we distinguish. In Table 4.8 (page59) we have aggregated these spatial landuse data to the different parts of the Jordan River Basin. Of the total area of 18,056 km2 of the watershed, 1% concerns water, 2% is classified as urban and built-up area, and 30% as unused bare land. Another 25% is rangeland, mainly used for cattle livestock production, while shrub land, mainly used to herd goats and sheep, is estimated to account for 16% of the total area. As regards cultivation of the remaining 415,000 hectares (23% of the total area) it appears that

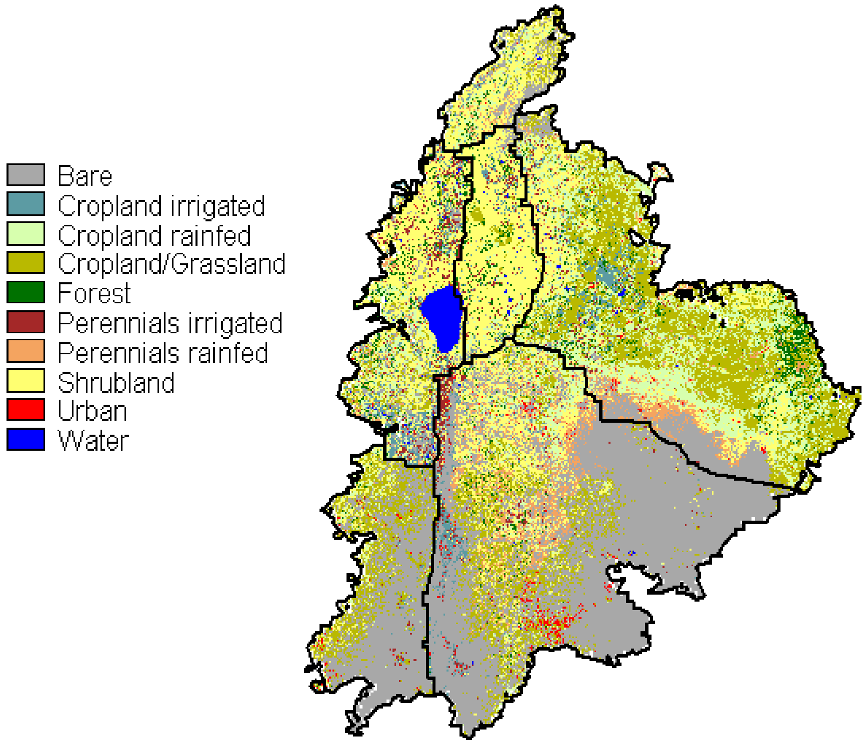


**Figure 4.8 Land use types**

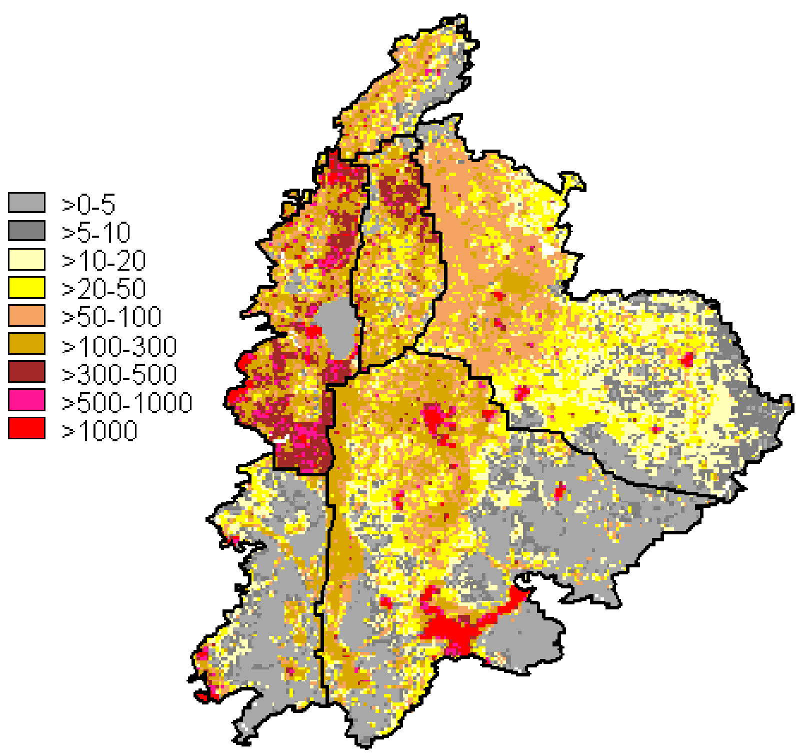


**Figure 4.9 Income patterns in the JRB (1000 USD per km$^2$)**

rainfed annual crops are most prevalent (51%), followed by rainfed tree crops (24%), while irrigated annual and perennial crops also cover about one quarter of the cultivated area of the basin (14 and 10%, respectively).

*Production and income estimates*

Clearly, no statistics are available on production and incomes earned at every site on the JRB-map, let alone on the contribution of water to income formation. Hence, imputations are necessary, the results of which are shown in Figures 4.9, displaying the estimated income in 1000 USD per $km^2$. These are computed as the sum of net revenues from the seven agricultural land uses listed in Table 4.7 incremented with an imputed income in urban area based on per capita GDP figures (World Bank, 2004).

The calculation underlying the farm income estimates is based on location-specific yields and livestock densities (see section 4.3), which provided production estimates, which are summarised in Table 4.9.

**Table 4.9 Agricultural production pattern in the JRB (1000 MT and 1000 heads)**

| | Irrigated annuals | Rainfed annuals | Large ruminants | Rainfed perennials | Irrigated perennials | Small ruminants |
|---|---|---|---|---|---|---|
| Israel | 1415 | 55 | 85 | 18 | 519 | 80 |
| Jordan | 719 | 82 | 39 | 44 | 183 | 513 |
| Palestinian Authority | 165 | 19 | 9 | 36 | 42 | 238 |
| Syria | 529 | 244 | 69 | 26 | 236 | 643 |
| Lebanon | 143 | 23 | 5 | 5 | 9 | 83 |
| Golan heights | 576 | 12 | 15 | 1 | 183 | 14 |
| JRB | 3548 | 434 | 221 | 129 | 1172 | 1571 |

Source: preliminary own calculations.

Gross revenues are then computed using country-specific 2002 prices of the typical produce (CEC, 2004). Next, following the farm system analysis by Orthofer et al. (2002), Venot (2003) and Hijawi (2003), a first basin-wide estimate of current input costs is estimated at 10% of gross revenue for rainfed crops and forest products, 55% for irrigated crops, and 25% for livestock products. This yielded a spatially-explicit estimate of farm income.

In Table 4.10 we have aggregated the spatial farm income data obtained in this manner. The figures are obviously only crude calculations based on limited information from household and farm surveys. Yet, they show how agronomic and economic data can be harmonised consistently in a spatially explicit way. Also the preliminary results are indicative of the spatial income pattern in the JRB.

It appears that income from irrigated agriculture is predominant. Cultivation of irrigated field crops and perennials are estimated to account for 72% and 10% of total agricultural income, while rainfed field and tree crops cover some 3% each. Livestock production is estimated to account for 11% of the agricultural income in the Jordan River Basin. Farm income patterns dominated by irrigation are observed throughout the basin, even though in the Syrian and Jordanian part of the basin rainfed agriculture contributes more to farm income.

**Table 4.8 Land use in the JRB (km2)**

| | Irrigated annuals | Rainfed annuals | Rangeland | Rainfed perennials | Irrigated perennials | Forest | Shrub land | Urban area | Bare land | Water | JRB |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Israel | 178 | 216 | 704 | 56 | 148 | 117 | 264 | 28 | 163 | 186 | 2061 |
| Jordan | 147 | 312 | 799 | 422 | 110 | 70 | 806 | 186 | 3824 | 4 | 6680 |
| Palestinian Authority | 22 | 82 | 495 | 228 | 16 | 8 | 122 | 28 | 899 | 0 | 1901 |
| Syria | 169 | 1413 | 2064 | 268 | 88 | 267 | 622 | 55 | 444 | 13 | 5403 |
| Lebanon | 25 | 78 | 260 | 32 | 4 | 24 | 192 | 4 | 142 | 1 | 762 |
| Golan heights | 58 | 42 | 112 | 1 | 49 | 77 | 862 | 3 | 35 | 9 | 1247 |
| JRB | 600 | 2143 | 4434 | 1006 | 415 | 563 | 2869 | 305 | 5507 | 213 | 18056 |

**Table 4.10 Farm income in the JRB (million USD)**

| | Irrigated annuals | Rainfed annuals | Large ruminants | Rainfed perennials | Irrigated perennials | Small ruminants | JRB |
|---|---|---|---|---|---|---|---|
| Israel | 634 | 10 | 103 | 9 | 96 | 6 | 858 |
| Jordan | 322 | 14 | 22 | 23 | 34 | 10 | 426 |
| Palestinian Authority | 74 | 3 | 5 | 19 | 8 | 5 | 113 |
| Syria | 237 | 43 | 26 | 12 | 44 | 39 | 400 |
| Lebanon | 64 | 4 | 3 | 3 | 2 | 5 | 80 |
| Golan heights | 258 | 2 | 18 | 0 | 34 | 1 | 314 |
| JRB | 1589 | 76 | 178 | 65 | 217 | 66 | 2191 |

# Section 5

# Results

This concluding section discusses the results obtained so far. As mentioned in the introduction, the work will continue, and while this is the final report of the activities undertaken under FEMISE-funding, this definitely does not mark the end of the JRB-research program as such. Nonetheless, as it is important to answer for the research funds provided, we end with a summary of the milestones that were reached.

## 5.1 Methodology: model specification, analysis, calibration and solution

On the methodology front, all the aims that were set were reached. Of the more technical results, we only mention the nature and relevance without giving any details.

*(1) Specification.* A mathematical model was formulated that can incorporate major hydrological and agricultural processes at site-level, and consistently link these spatially as well as in time. The economic choice of producers at every site can be represented as a profit maximizing decision, under different modes of co-operation between districts and countries, including various forms of pricing of water and salt. Furthermore, the model can be used to compute the user value of projects that may increase the supply of water to the basin, from other watersheds (e.g. Lebanon or Syria) and through desalination, locally and of seawater. Most importantly, the model allows to represent the specificities of water as an economic good, in particular the feature that it does not disappear fully in use, that disposing of it is necessary, to avoid flooding and salinization, but not always costless, and that property rights are not well established, while control of the scarce water is weak at best, especially outside river beddings.

*(2) Analysis.* Existence and uniqueness of quantity allocations has been proved. For a model of this size, multiplicity of equilibrium solutions may easily arise. This is undesirable, since the model user needs assurance that the computed outcome from policy intervention is unequivocally the solution that is shown. There should be no other, hidden solution possible. In addition, analytical forms have been obtained for the derivatives of the producer decisions to inflows and to model parameters. This will enable us to characterize in great detail the model responses to shocks, which could be used in subsequent extensions, when climatic and other stochastic fluctuations may be taken into consideration so as to account for risk.

*(3) Estimation and calibration.* Various procedures were implemented, in several instance newly designed, for model estimation and calibration. Specifically, these serve (a) to demarcate the watershed, (b) to estimate landuse on the basis of satellite images trained with ground information, (c) to aggregate the slope and altitude profile from 1 to 30 arcsec gridcells; (d) to correct this altitude profile (busting) so as to avoid water accumulation at unrealistic locations; (e) estimating production and water demand functions. Next, a modular

calibration procedure (see Appendix A) assures that the optimal water allocations in the welfare program exactly replicates the hydrographs with monthly discharge data at selected points. These allocations also replicate the economic accounts at district and basin level that were compiled on the basis of available statistics. We note that a modular decomposition of the calibration process (economics following calibrated hydrology) is essential for future applications of this type of spatially explicit watershed models. It makes it possible to keep database operations separate from model revisions, while improvements in the database are in a transparent way transmitted to model results. Replacements in specific components can be implemented without requiring a new calibration full of surprises of the entire framework. Moreover, initialization at a calibrated base solution provides a large number of checks and clues for detecting programming errors during in the debugging phase of model building and also speeds up computation.

*(4) Solution.* The project developed a new, globally convergent algorithm to solve the spatially explicit welfare model with 25,301 sites that may supply to downward sites in accordance to gravity. The tailormade algorithm solves social welfare over each site, terminates in a finite number of iterations, and has an exact solution. This property of finite and exact termination makes it possible to embed the site-specific water allocation problem within a price-adjustment loop and to prove global convergence of the welfare problem at the level of the watershed as a whole.

### 5.2 Empirical findings

Turning to empirical aspects, it appears that the region has ample scope for alleviating the water scarcity in the basin if Syria and Lebanon agreed to interbasin transfers, obviously with due financial compensation. In theory, both countries have potentially large quantities of surplus water in the period from April to August, when water is most scarce in the JRB. Syria receives much of its water from the Turkish and Iranian mountains, Lebanon is well endowed with natural rainfall and also has snowmelt. Lebanon could conserve part of its, approximately, 50 per cent of renewable water resources that currently end up in the Mediterranean Sea, and could easily transfer water to the Upper Jordan Basin at low cost. Within the JRB these additional inflows could boost high value summer crops such as citrus fruits and vegetables and also improve significantly the water supplies to households and towns. Moreover, the water could be used to fight salinity. Dams would be needed to regulate the peak discharges and provide a steady flow. Clearly, the financing, construction and management of such infrastructural works is only feasible under peaceful conditions.

Against this background, the aim of the project is to provide decision makers and negotiators with a support tool that may assist them in quantifying in physical as well as economic terms the implications of different options for water management in the basin, building as much as possible on consensus about scientific relationships and empirical facts. Hence a careful description of the interaction between water flows and land use management is needed.

A first step was, therefore, the precise demarcation of the Jordan River Basin and construction of a spatially linked database that covers the geographical diversity and describes the monthly hydrological conditions and economic activities. The project started with a precise demarcation of the Jordan River Basin and the construction of a spatially linked database for this basin that describes at each site the prevailing land use and water requirements. To our knowledge, this is the first time that such a comprehensive and operational data base is created for the entire basin.

This database confirms that water becomes more scarce and salinity more severe along the basin from the Lake of Tiberias to the Dead Sea. Jordanians or Palestinians make up some two-thirds of the basin's population, they cultivate less than one third of the total irrigated area of the basin. Israelis on their part cultivate more than one third of this area and comprise some ten per cent of the population. This irrigation pattern is reflected in production and incomes that range from more than 10,000 USD per hectare in the northwestern, Israeli part of the basin to less than 1,000 USD per hectare at farms along the Lower Jordan River.

A most preliminary estimate of the total farm income in the JRB amounted to USD 2.2 billion. Notably, this income is mainly attributable to irrigated cultivation, where it contributes around 82 per cent to the total, much higher than the mere 11 and 7 per cent in animal husbandry and rainfed agriculture, respectively.

## 5.3 Follow up

Significant work still is to be done until the model will be sufficiently reliable to warrant a discussion with JRB-stakeholders about its implications for policy and its use as a decision support tool in future negotiations and river basin management operations. Yet, the plan is to reach that stage in 2005, and to present the results at workshops with adequate stakeholder participation. In parallel, articles will be prepared and submitted to journals.

Next, we intend to address a major limitation of the current study by accounting for climatic and other, say, political uncertainties. Because of its recursive and multistage nature, the algorithmic approach pursued within our project has natural extensions to multiperiod and multistate formulations. Every map presented in this paper can then be interpreted as a realization in a stochastic field. The aim of this research will be to generate distributions of maps, and to identify water management policies, particularly reservoir levels, that can efficiently cope with the prevailing climatic and political uncertainties.

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## Annex. Model calibration

The calibration process is an adjustment of a subset of model parameters to ensure that the optimum of the welfare program will, for levels of exogenous variables that coincide with baseyear values, fully replicate the carefully constructed and internally consistent data set for this base year, also at subwatershed level. The calibration can also be looked at as an inclusion of fixed (site-specific) effects so as to ensure that the first-order conditions of the welfare program are met at (and, since the program is strictly convex, only at) a point that agrees with base year data.

The calibration proceeds in three stages: (i) calibration of water flows between sites on the basis of hydrographs (monthly flows for a typical year usually at a site with a river, but possibly over a larger surface); (ii) calibration of site specific coefficients on water requirements and stock accumulation at given water intensity ($c = 1$ in our case); (iii) calibration of production function $f_s$ of each site to ensure that $c = 1$ is optimal for the site in the scenario without payments across sites.

### *Calibration of water flows on basis of hydrographs*

For given precipitations $b_{1\tau s}, b_{4\tau s}$, initial stocks $k_{i0,s}$, retention factors $\rho_s$, stock infiltration factors $\phi_{1s}$, surface (non-river) flow shares $\theta_s$, outflow shares $\alpha_{rs}$ from both surface and river and seepage coefficient $\sigma_{i\tau s}$, we calculate flows $y_{1\tau s}$ and $y_{4\tau s}$ and $k_{1\tau s}$ and $k_{4\tau s}$ according to:

$$a_{1\tau s} = [(1-\sigma_{1\tau s})(b_{1\tau s} + \theta_s q_{1\tau s} + k_{1,\tau-1,s}) + \upsilon_{2,\tau s} k_{2,\tau-1,s}]$$
$$y_{1\tau s} = (1-\rho_{\tau s})a_{1\tau s} + (1-\theta_s)q_{1\tau s}$$

$$k^*_{2,\tau s} = \sigma_{1,\tau s}(b_{1,\tau s} + \theta_s q_{1,\tau s} + k_{1,\tau-1,s}) - \sigma_{2,\tau s} k_{2,\tau-1,s}$$
$$+ \upsilon_{3,\tau s} k_{3,\tau-1,s} - \upsilon_{2,\tau s} k_{2,\tau-1,s} + k_{2,\tau-1,s}$$
$$k_{2,\tau s} = min(k^*_{2,\tau s}, \bar{k}_{2,\tau s})$$
$$k_{1\tau s} = \phi_{1s}\rho_{\tau s} a_{1\tau s} + k^*_{2,\tau s} - \bar{k}_{2,\tau s}$$
$$k_{3,\tau s} = \sigma_{2,\tau s} k_{2,\tau-1,s} + (1-\upsilon_{3,\tau s})k_{3,\tau-1,s}$$

$$y_{4\tau s} = (1-\rho_{\tau s})s_s a_{1\tau s} + (1-\theta_s)q_{4,\tau s}$$
$$y^d_{4\tau s} = (1-\rho_{\tau s})s_s a_{1\tau s}$$

$$k_{4,\tau s} = b_{4,\tau s} + \theta_s q_{4,\tau s} + (1-\sigma_{4,\tau s})k_{4,\tau-1,s} + \upsilon_{5,\tau s} k_{5,\tau-1,s} - y^d_{4\tau s}$$
$$k_{5,\tau} = k_{5,\tau-1,s} + \upsilon_{6,\tau s} k_{6,\tau-1,s} - \sigma_{5,\tau s} k_{5,\tau-1,s} - \upsilon_{5,\tau s} k_{5,\tau-1,s} + \sigma_{4,\tau s} k_{4,\tau-1,s}$$
$$k_{6,\tau s} = k_{6,\tau-1,s} - \upsilon_{6,\tau s} k_{6,\tau-1,s} + \sigma_{5,\tau s} k_{5,\tau-1,s}$$

$$q_{1\tau s} = \sum_r \alpha_{rs} y_{1\tau r}$$

$$q_{4\tau s} = \sum_r \alpha_{rs} s_r y_{1\tau r}$$

given initial stocks $k_{i0s}$, and

$$\theta_s \in [0,1], \sigma_{1s} \in [0,1], \upsilon_{1s} \in [0,1], \rho_{\tau s} \in (0,1).$$

and hydrograph $\hat{q}_{1\tau m}$ at selected points of measurement $m \in S^m \subset S$.

*Adjusting the retention factors*

Now to ensure satisfaction of the hydrograph, we adjust $(1-\rho_{\tau s})$, by a factor $\lambda_{\tau m}$ in top-down sequence, while keeping all fractions within preset bounds on the unit interval, around their original values. Starting from the point of measurement of highest altitude the adjustment is applied to all sites that lead to it and were not adjusted for an earlier hydrograph.

$$y_{1\tau s} = (1 - max(\underline{\rho}_{\tau s}, min(\rho_{\tau s} + \delta_{h\tau}, \overline{\rho}_{\tau s})))a_{1\tau s} + (1-\theta_s)q_{1\tau s},$$

where $\delta_{h\tau} = 0 \;\; if\, s \notin S_h$ where $S_h$ is the “free” catchment area of the hydrograph, i.e. the catchment area not belonging to any hydrograph of higher elevation. In matrix terms, the flow model can now be written

$$q_h = \sum_{h'} \Delta_h(\delta) F_{hh'} q_{h'} + b_h$$

where $F$ is a lower triangular, nonnegative square matrix with the number of months times the number of hydrographs as row dimension, with subscript $h$; $q_h$ is the inflow into a site in any month, and $\Delta_h(\delta)$ the adjustment on the discharge rate, a continuous non-decreasing function that maps on the interior of the unit interval that depends on $\delta$ a vector with elements $\delta_{g\tau}$, of the hydrograph and month specific-vector adjustment factors ranging between minus and plus one. The adjustment function $\Delta_h(\delta)$ is such that sites depend on one hydrograph alone, i.e. the hydrograph their water is tributary to, and it has value unity whenever it does not contribute to any hydrograph.

Hence, we can write the matrix form as:

$$q = \Delta(\delta)Fq + b$$

where $\Delta$ is a diagonal matrix function. Since $F$ is lower triangular we can solve

$$q = [I - \Delta(\delta)F]^{-1} b$$

where the inverse is an uppertriangular matrix $G$ with positive diagonal elements

$$G_{hh} = \frac{1}{1-\Delta_h}.$$

Hence, we can solve for the adjustment factors in top-down order, and for hydrograph $g$, given the solution $\delta_1^{\circ},...,\delta_{g-1}^{\circ}$ of the adjustment factors for the higher hydrographs, we can define the (12-dimensional) adjustment procedure:

$$\begin{aligned} q_{h_g}^t &= q_{h_g}(\Delta\left(\delta_1^{\circ},...,\delta_{g-1}^{\circ},\delta_g^t\right)+b_{h_g}) \\ \delta_g^{t+1} &= max(-1,min(\delta_g^{t+1}+\bar{\sigma}(q_{h_g}^t-\hat{q}_{h_g}),1)) \end{aligned}$$

that, for stepsize $\bar{\sigma}$ small enough, act as a contraction mapping and hence converge to a unique solution.

***Quantity calibration at the site***

On the basis of the flow calibration, we have available for every site (dropping the site-subscript): $\delta_\tau$, $q_{1\tau}$, $q_{4\tau}$, and $k_{1\tau}$. Hence, we can at every site calculate the water and salt availability

$$\begin{aligned} a_{1,\tau} &= b_{1,\tau}+\theta q_{1,\tau}+k_{1,\tau-1} \\ &\quad +\delta_\tau(\upsilon_{2\tau}k_{2,\tau-1}-\sigma_{1\tau}(b_{1\tau}+\theta q_{1\tau}+k_{1,\tau-1})) \\ &\quad +(1-\delta_\tau)(k_{2,\tau-1}+\upsilon_{3\tau}k_{3,\tau-1}-\sigma_{2\tau}k_{2,\tau-1}-\bar{k}_{2\tau}) \end{aligned}$$

$$a_{4,\tau} = b_{4,\tau}+\theta q_{4,\tau}+(1-\sigma_{4,\tau})k_{4,\tau-1}+\upsilon_{5,\tau}k_{5,\tau-1}$$

and at $c=1$, the switchpoint between regimes 1 and 2, we calibrate on a period by period basis, starting at $\tau=1$. The coefficients available at the site were derived on the basis of landuse data (see section 4). We denote the coefficient values prior to calibration by a tilde.

$$\begin{aligned} \tilde{c}_{1\tau} &= \tilde{\eta}_{\ell\tau}^c+\tilde{\eta}_{\ell\tau}^o+\tilde{s}_{4\tau} \\ \tilde{c}_{1\tau}+\tilde{n}_{1\tau} &= \tilde{a}_{1\tau} \end{aligned}$$

Confrontation with water availability permits to define $\lambda_\tau^a = a_{1\tau}/\tilde{a}_{1\tau}$ and hence to obtain scaled values:

$$\eta_{\ell\tau}^o = \lambda_\tau^a\tilde{\eta}_{\ell\tau}^o,\ \eta_{\ell\tau}^c = \lambda_\tau^c\tilde{\eta}_{\ell\tau}^o,\ \eta_{\ell\tau}^s = \lambda_\tau^a\tilde{s}_{\ell\tau}/a_{4\tau}$$

where the salt coefficient is expressed per unit of salt availability. Next, we scale outflows on the basis of the ratio:

$$\lambda^d_{1\tau} = y^d_{1\tau} / ( \tilde{\zeta}^c_{\ell\tau} c_{1\tau} + \tilde{\zeta}^n_{\ell\tau} n_{1\tau} + \tilde{\zeta}^o_{\ell\tau} ),$$

and water stock accumulation from

$$\lambda^k_{1\tau} = k_{1\tau} / ( \tilde{\kappa}^c_{\ell\tau} c_{1\tau} + \tilde{\kappa}^n_{\ell\tau} n_{1\tau} + \tilde{\kappa}^o_{\ell\tau} )$$

and finally salt from

$$\lambda^y_{4\tau} = y_{4\tau} / ( \tilde{\mu}^c_{\ell\tau} c_{1\tau} + \tilde{\mu}^n_{\ell\tau} n_{1\tau} )$$

Note that this proportionate scaling maintains the convex-continuity of input demand functions.

***Calibration of production functions*** $f_s$

Finally, for given end-stock prices, assuming that agents do not pay to upstream neighbors ($\pi_{i\tau s} = 0$), we adjust coefficients of the production functions $f_s$, to make $c = 1$ optimal, while maintaining their concavity, monotonocity properties. This ensures that the initial solution will be optimal under this non-payment regime, and hence replicate original data.

$$f_s(c) = \tilde{f}^o_s + a_s(max(c,0) + \bar{c})^{b_s} + a_s b_s \bar{c}^{b_s - 1} min(c,0) - \kappa\, (min(c,0))^2 .$$

The derivatives are, $c = 1$:

$$f^{'}_s(1) = a_s b_s (1 + \bar{c})^{b_s - 1} = \chi^o_s ,$$

and, simultaneously

$$\tilde{f}^o_s = f^o_s - a_s(1 + \bar{c})^{b_s} ,$$

while

$$b_s \le \bar{b}_s \ , \ \tilde{f}^o_s \ge 0 \text{ and } (\bar{b}_s - b_s)\tilde{f}^o_s = 0$$

i.e.

$$a_s = \chi^o_s / (b_s(1 + \bar{c})^{b_s}),$$
$$\tilde{f}^o_s = f^o_s - \chi^o_s / (b_s(1 + \bar{c})^{b_s - 1})(1 + \bar{c})^{b_s} ,$$

implying that we can readily obtain

$$f^o_s / (1 + \bar{c}) = \chi^o_s / b_s ,$$

and hence

$$b_s = min(\bar{b}_s , \chi^o_s (1 + \bar{c}) / f^o_s)$$
$$\tilde{f}^o_s = f^o_s - \chi^o_s (1 + \bar{c}) / b_s ,$$
$$a_s = \chi^o_s / (b_s(1 + \bar{c})^{b_s}) .$$