Chapter 2
Water Management in a Complex Hydrological Basin—Application of Water Evaluation and Planning Tool (WEAP) to the Lake Kinneret Watershed, Israel

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Abstract Sustainability of fresh water ecosystems and human activities in Mediterranean watersheds under future climate change can be supported with integrated hydrological modeling. The Lake Kinneret Watershed (LKW), which spans over 2730 km^2, is divided between three Mediterranean countries, Israel, Lebanon, and Syria; and incorporates four different hydrogeological units: Mt. Hermon in the north, the Golan Heights in the east, the eastern Galilee Mountains in the west, and the Hula Valley in the central part of the watershed. In this study, we used several modeling tools together with a detailed observed database to assemble, test, calibrate and predict simultaneously the water availability within the entire LKW. The hydrological tools that we used compounded of two built-in catchment modules in the Water Evaluation and Planning (WEAP) tool, a model of karst hydrology (HYMKE), lake water balance calculations and artificial rain series based on a stochastic rainfall generation tool. With this setup we defined the "coverage" parameter for water availability and identified vulnerable partial areas inside the watershed, which are more sensitive to extreme draught conditions. The heterogeneity of the LKW water system and the tools we operated enabled the

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separation of the watershed into regions affected by "climate change" scenarios (mainly reduced amounts of annual rainfall) compared to regions impacted mainly by operational decisions.

Keywords Lake Kinneret watershed · Mount Hermon · Golan Heights · Water evaluation and planning · Integrated water resources management · Climatic scenarios · Lake water balance

2.1 Introduction

Increasing demand of water for irrigation and domestic usage are threatening rivers in general, and specifically those situated in semi-arid or Mediterranean climates. Future sustainability of such fresh water ecosystems given the human activities that surround them can be supported by improvements of regional water management (Grantham et al. 2012). Logically, such improvements require a better understanding of the hydrological system behavior under current and future climatic scenarios as well as under various human activities. Modeling both the natural processes and human demands of the hydrological system requires the use of an integrated approach in order to understand how climate change may impact the entire water system.

Integrated hydrological models using the Water Evaluation and Planning (WEAP) platform (Yates et al. 2005a, b), have been used by some researchers to assess the potential effects of climate change in basins with significant agricultural activity. A case study for the Sacramento River basin suggested that improvement in irrigation efficiency and change in cropping pattern have the potential to reduce the effect of climate change on water demand in the agricultural sector (Purkey et al. 2008). Similar conclusions were found in a work done on a smaller basin in California (Mehta et al. 2013). Vicuña et al. (2011a) suggested that reservoir and groundwater storage were key factors for water management under future climate change in the semi-arid climate in Chile. Joyce et al. (2011) concluded that the increasing demand for agriculture in California's central valley under future climate change may result in over-exploitation of groundwater. However, they concluded that while changing operation rules could lead to better water allocation, it could not mitigate all the reduction in water availability.

By dividing a basin into smaller sub-basins, an integrated hydrological modeling approach has the ability to identify sub-basins which are more vulnerable to climate change (Joyce et al. 2011; Vicuña et al. 2011a). The concept of vulnerability was defined by Vicuña et al. (2011b) as the ability to sustain a given level of agricultural activities as a consequence of climatic change. In the dry region of the Middle-East, with limited amount of water, this is an important characteristic of the watershed.

The northern part of Israel, like other Middle East semi-arid regions, is susceptible to climate change due to generally dry conditions and limited water

availability. The IPCC global circulation models (IPCC 2007) as well as runs of four different global climate models (20 km mesh) agree on a drying scenario in the Middle East before the end of the 21st century (IPCC 2007; Krichak et al. 2011). Models also predict higher incidence of extremely wet and extremely dry events (Krichak et al. 2007; Samuels et al. 2009). A former work on water availability in the region predicted a 15 % decrease in water availability, together with increasing of 6 % in water demand for agriculture in Lebanon (Bou-Zeid and El-Fadel 2002). The potential decrease in water sources and steadily growing freshwater demands already impose great amounts of pressure on all available water resources in the region in general, and in Israel in particular.

Located in the northern part of the Jordan Valley (Northern Israel), the Lake Kinneret watershed (LKW), including the northern part of the Jordan River (JR), is the most important surface water source in Israel. Despite the large variety of hydrological studies of LKW (*see review in* Rimmer and Givati 2014), modeling of water resources and consumption in the entire LKW and along the course of the JR for managing purposes has never been done. This task, however, is not trivial because of the following reasons:

a. The LKW includes four different hydrological units with large differences in their precipitation to stream flow and groundwater recharge relations, as well as in the quantity of local water consumption (Fig. 2.1): (1) The Jurassic mountainous karst of Mt. Hermon; (2) The basalt plateau of the Golan Heights; (3) The Cenomanian-Turonian carbonaceous karst of the Eastern Galilee Mountains; and (4) The flat alluvial Hula Valley (for details see Sect. 2.2).
b. Simultaneous prediction of precipitation-stream flow relations for the three main tributaries of the JR (Dan, Snir and Hermon) is feasible only by using a hydrological modeling approach, suitable for karstic regions (Rimmer and Salingar 2006).
c. The continuously changing water consumption and groundwater extraction at the Hula Valley, the Eastern Galilee, and the Golan Heights, complicates significantly the calculations of water balances along the JR.
d. The annual precipitation in the entire LKW ranges from >1300 mm annually at the top of the Hermon Mountain to ∼400 mm (∼ is used instead of "about") annually at the Lake Kinneret, only 50 km south of the Hermon.

The complexity and unknowns of the hydrological and water supply systems increased the need of a basin scale water balance and modeling tool. Such a model can integrate between various data bases, four sub-basins and lake water balance in order to help decision makers in managing the water system in the region. In this case study, we simulate the complex hydrological system of LKW, focusing on two main objectives: (1) Incorporating the main hydrological components of the LKW into an integrated water resources management (IWRM) tool for a large heterogeneous watershed, and (2) Identifying vulnerable areas inside LKW which are more sensitive to climate change. The complexity of LKW required the integration of several modeling tools, constructed on the basis of one central platform (WEAP).
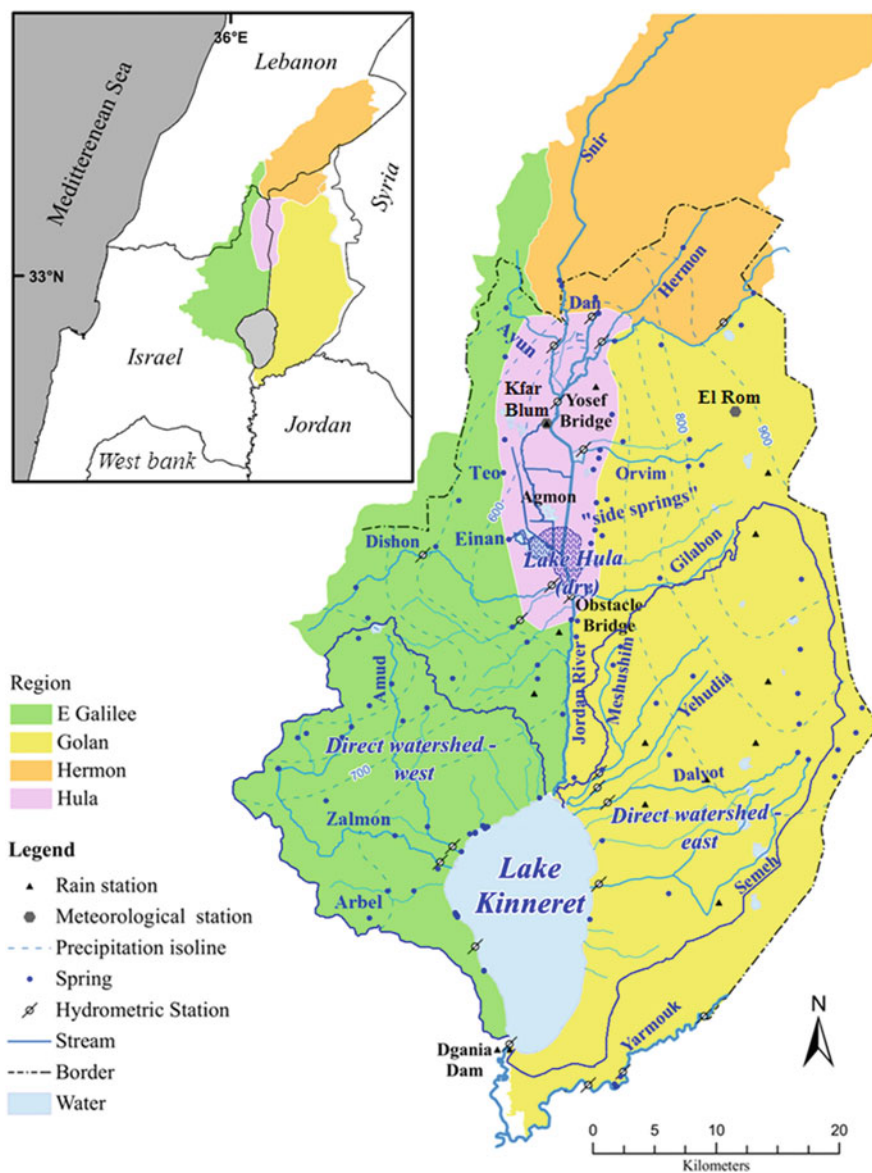
Fig. 2.1 General map of Lake Kinneret Watershed

2.2 Study Site—The Lake Kinneret Watershed

Approximately 35 % of Israel's natural fresh water resources originate from the watershed of Lake Kinneret (Sea of Galilee). The area of the LKW is $\sim 2{,}730$ km^2, of which ~ 780 km^2 are in Syria and Lebanon. This area holds some of Israel's most important fresh water ecosystems. Agricultural use of $\sim 150 \times 10^6$ m^3 annually for irrigation is the main water consumer in the entire LKW. Water supply comes from various sources: The Jordan River, groundwater and effluent. The expected future reduction of available water in the watershed due to climate change will create great challenges for the water management in this region. Future climate is predicted to cause reduction of groundwater recharge, which in turn may reduce the inflows into Lake Kinneret by an average rate of $\sim 3 \times 10^6$ m^3 year^{-1}. An increase of $\sim 0.4 \times 10^6$ m^3 year^{-1} in evaporation from the lake is also expected (Rimmer et al. 2011).

2.2.1 The Hermon Mountain

The Hermon Mountain range (Fig. 2.1) is an elongated anticline of mostly karstic limestone of Jurassic age with thickness greater than 2000 m. The Hermon high regions (above 1000 m a.s.l.) receive precipitation above 1300 mm/a, restricted to the wet season from October to April. The Hermon basin recharges the main tributaries of the JR: Dan, Snir (Hatzbani), and Hermon (Banias).

The karstic nature of the Hermon basins is evident when the annual flow of each stream is introduced compared to its attributed surface area. The Dan stream that emerges from a small topographic catchment of only 24 km^2 is the largest spring in the region (255×10^6 m^3 annually). The annual flow of the Snir stream, which exhibits the largest topographic drainage area (612 km^2) is 118×10^6 m^3, originated mainly by the Wazani and Hazbaya springs located near the Israel-Lebanon border. The Hermon stream (annual flow of 107×10^6 m^3; drainage area 147 km^2) receives most of its water from the Banias Spring ($\sim 67 \times 10^6$ m^3) and the rest from other springs and small runoff components. By using HYMKE (Rimmer and Salingar 2006), Samuels et al. (2010) estimated that snowfall amounts on the Hermon basin for 1970–2000 were 2.4 (1978/9) to 202.8 (1991/2) $\times 10^6$ m^3 with an average of $41 \pm 40 \times 10^6$ m^3 year^{-1}, and Samuels et al. (2009) assessed that evaporation is ~ 20 % of the total annual precipitation.

2.2.2 The Hula Valley

The Dan, Hermon and Snir streams join together near the Yosef Bridge (Fig. 2.1) to form the JR, which for the next 21 km flows through the Hula Valley (Hula, Fig. 2.1). The valley covers 177 km^2 (25 km long by 6–8 km wide), and serves as a
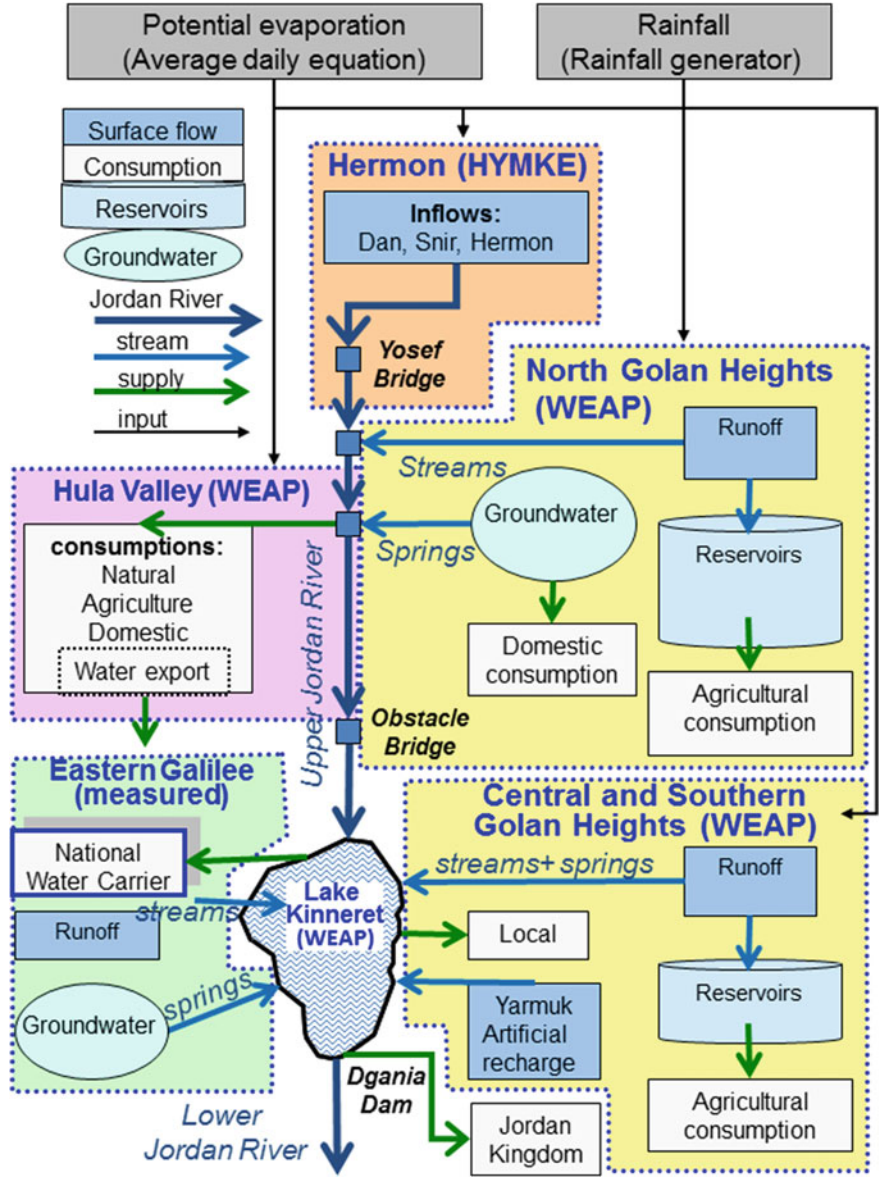
drainage basin to streams and groundwater from the surrounding aquifers. The valley is filled with sedimentary materials of low permeability. An early study of the Hula groundwater (Neuman and Dasberg 1977) claimed that due to the surrounding hydraulic heads there is a significant contribution of deep groundwater flux to the valley. However, based on groundwater measurements in the local aquifer, Litaor et al. (2008) and Sade et al. (2010) found that the shallow water table in the valley is strongly affected by the water level in the JR canals through significant lateral flow in macropores. Litaor et al. (2008) suggested that the component of vertical flow upward is fairly mild. The origin of water in the valley is therefore mainly from the JR, from springs at the margins of the valley, and streams that drain the surrounding mountain. Annual rainfall in the Hula valley varies greatly between ∼400 mm in the south, up to 800 mm in the north, and the contribution to the flow in the JR is considered minor.

2.2.3 The Golan Heights

The Golan Heights (Golan, Fig. 2.1) is a 1,160 km^2 upland region. Its boundaries are the slopes of Mt. Hermon in the north-west, the Rokad River in the east, the Hula Valley and the JR in the west, and the Yarmouk River in the south. It is a basalt-covered plateau, sliced off by deep canyons at its edges. The plateau slopes gently from north to south, descending from 1200 m a.s.l. on its northern edge to 300 m a.s.l. at its southern rim. Average annual rainfall ranges from 1200 mm at the north to less than 500 mm at the southern part. The Golan area may be divided into two hydrological regions: northern (between Sa'ar-Hermon and Gilabun; Fig. 2.1), that drain to the JR, and southern (between Meshushim and Yarmouk Valley; Dafny et al. 2003), that drain directly to Lake Kinneret.

2.2.4 The Eastern Galilee Mountains

The water sources originating from this region are the groundwater and stream flows from all sub-basins west of the JR, the Hula Valley, and Lake Kinneret. It includes the surface water basins of the Ayun stream (∼6×10^6 m^3 year^{-1}) in the north, Dishon (∼4.5 × 10^6 m^3 year^{-1}), Hatzor (∼0.4 × 10^6 m^3 year^{-1}), and down to the Amud (∼1×10^6 m^3 year^{-1}) and Zalmon streams that drain directly into Lake Kinneret (Fig. 2.1). The main groundwater resources of this region are the Einan Springs, located South-West of the Hula Valley, and the Tao spring, about 5 km north of Einan. The annual contribution of all the springs in this region today is only ∼6 × 10^6 m^3 year^{-1}. The average annual precipitation in this region is between 400 mm at the Hula Valley (∼60 m a.s.l) and 740 mm on Mt. Knaan (900 m a.s.l.).

Fig. 2.2 Schematic presentation of the water system in Lake Kinneret watershed, and how it was integrated into the entire IWRM system

2.2.5   The Water System in Lake Kinneret Watershed

The structure of the water system in the LKW (Fig. 2.2) includes fresh water sources (springs, surface streams and wells); the surface runoff reservoir systems (mainly on the Golan Heights); main water supply projects of the "Mekorot" Water Company and local associations (Upper Galilee and Mei Golan); and several reservoirs of treated effluent for agricultural reuse, originating from the sewage of urban and rural communities in the watershed. Some 60×10^6 m^3 year^{-1} is consumed annually for agricultural activity in the Hula Valley, mainly from the northern part of the JR. Additional 23×10^6 m^3 year^{-1}, originating from the Jordan River and local effluent sources is exported from the JR by the Zemer project for agricultural use in the Eastern Galilee Mountains. The Golan Heights with local reservoir volume of 32×10^6 m^3 year^{-1}, consume 34×10^6 m^3 year^{-1}, mostly for agriculture. Direct pumping from the Lake Kinneret (LK) for local consumption is $\sim 75 \times 10^6$ m^3 year^{-1}. Finally, the largest water consumer in the LKW is the National Water Carrier (NWC), which exports on average $\sim 300 \times 10^6$ m^3 year^{-1} from Lake Kinneret to the central and southern parts of Israel.

2.3   Methodology

The heterogeneous hydrological characteristics of LKW require the application of different modeling approaches to different areas of the catchment. The choice of modeling approach is subjective and depends on its goal and the features of the modeled area. In this case, we divided the catchment into the above four regions, namely Mt. Hermon, Hula Valley, Golan Heights and Eastern Galilee. Each region was simulated and calibrated separately using a suitable modeling tool, and then the calibrated units were unified into WEAP to create the simulation for the entire LKW. Short description of WEAP, the modeling procedure of each region, and how they were incorporated together, is explained in the following sections.

2.3.1   WEAP21 General Description and Applications

The Water Evaluation and Planning (WEAP) is an IWRM simulation tool that has been designed to bridge the gap between water management and watershed hydrology. WEAP integrates natural watershed processes together with agricultural, municipal, and industrial water demands. The entire simulation components are set into a sources-sinks network to define an allocation problem. For solving this problem, WEAP supplies the water demands according to priorities and quantities.

Different strategies for representing water sources and water demands are available in WEAP. Water sources can be represented by either time series of flow

data or by a more complex quasi-physical approach that represents rainfall-runoff processes and groundwater-surface-water interactions. Water demands can be assigned as a time series of monitored data. Alternatively, it can be calculated as a function of evapotranspiration and crop coefficients (Kc) for modeling agricultural water demands, or for modeling watershed scale evaporative demands as part of the rain runoff module.

Other simulation capabilities of WEAP include simple in-stream water quality, surface reservoir, hydropower stations, snow temperature index melt model and financial planning. WEAP is by no means an optimization tool, but a simulation tool to calculate regional water balances and support decision making (Yates et al. 2005a, b).

In recent years, WEAP has been applied for various problems including snow-melt modeling under climate change in the hydrological system of California's Sierra Nevada (Young et al. 2009); modeling of transboundary water resources in South Africa (Juízo and Lidén 2008); hydrologic model for the Rio Conchos Basin (Eusebio and Daene 2009) and hydrological modeling and water resources modeling of the Sacramento Basin under climate change.

2.3.2 Simulating Mt. Hermon Streams

This mountainous region (Figs. 2.1 and 2.2) is the source of most of the water in the catchment. On one hand, the "two buckets" conceptual structure of the WEAP groundwater model (see Golan Heights simulations below) is not suitable for modeling the complex karst hydrology of Mt. Hermon. On the other hand, there is fairly small local water consumption in the Mt. Hermon region. Therefore, rainfall-runoff procedure on this area were modeled and calibrated separately with the Hydrological Model for Karst Environment (HYMKE; Rimmer and Salingar 2006). The input to HYMKE is two time series: a. equivalent rainfall on Mt. Hermon, and b. predetermined daily potential evaporation (ET; see Fig. 2.2). The daily output of the calibrated model (i.e., the discharge of the Dan, Hermon and Snir streams) formed the calculated discharge of the JR, and was introduced as monthly input to the WEAP model of the Hula Valley. Local consumption in the Hermon is relevant only to the Snir River in Lebanon, where consumption data are not available to us. Therefore the model was calibrated with monthly flows of the Dan, Hermon and Snir River measured at a gauging station located on the Israel–Lebanon border.

2.3.3 Simulating the Hula Valley

The Hula Valley is mainly an agricultural area. The water balance of the valley was calculated using simple mass balance equation because: (1) the local rainfall- runoff

in the Hula Valley is negligible compared to the external inflows-outflows; (2) large inflows and outflows of the JR are measured directly; (3) on a monthly scale it is assumed that no significant storage change is available in the valley; (4) it is assumed that most of the Hula direct rainfall seeps into the upper soil layer, and later evaporates with very little contribution to the groundwater discharge or surface flow, and thus this component could be omitted. We therefore define the monthly water balance (m^3 $month^{-1}$) equation for the valley as:

$$Q_{out} = Q_{in} + Q_{sp} + Q_{ro} - Q_{ET} - Q_{zemer} \tag{2.1}$$

where Q_{ET} is the evapotranspiration (ET), attributed mainly to water "import" into the valley for irrigation; Q_{in} is the JR natural inflow to the valley (calculated using HYMKE) including the volumes allocated for agriculture; Q_{sp} is the local Hula Valley springs discharge; Q_{ro} is the runoff (unmeasured flow into the valley), Q_{out} is the JR outflow at the obstacle bridge, and Q_{zemer} is the water exported from the valley for agricultural use in the Eastern Galilee (Zemer Project). The Q_{ET} in Eq. 2.1 includes evaporation from open water surface, as well as ET from land following irrigation and from riparian vegetation (Fig. 2.2).

Most of the water (95 %) consumed in the valley is used for agriculture. Only the agricultural consumption was simulated using the FAO crop evaporation method (Allen et al. 1998) which is available within WEAP "Irrigation Demands Only" Method. It allows simulating changes in water demands by man-induced alterations using the "crop coefficient" Kc. The Kc incorporates crop characteristics and averaged effects of evaporation from the soil (Allen et al. 1998). Climate-driven changes are simulated by changing the values of potential input ET (Fig. 2.2).
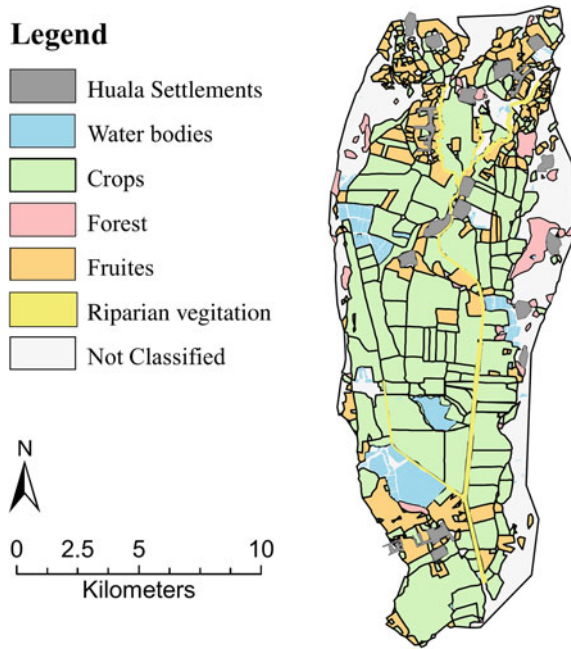
The information on the land-use in the Hula Valley was extracted from maps generated by the Survey of Israel and by the Crop Ecology Laboratory, Migal (Israel). The former was validated and updated with an orthophoto before seven categories of land-use were defined (Table 2.1; Fig. 2.3). For calculation of water demands within the valley, only consumers which directly receive water from the JR were used, i.e., field crops, fruits, water bodies and riparian vegetation. The last two categories, although not irrigated, do receive water directly from the JR and thus they were aggregated into the non-irrigated category.

The land-use changes within a year were estimated with maps that elaborate only part of the area (the Hula Project, a reclamation project conducted over 4000 ha in the south Hula Valley area) between the years 2004 and 2006. These maps are being updated twice a year (March and August) and therefore, could represent general management trends within a year. For the purpose of this work we assumed no land-use changes between years.

The reference ET and the Kc value determine the actual ET (Allen et al. 1997). For the WEAP simulations, we used reference ET from the Israeli Meteorological Service, which was calculated by the Penman Monteith equation using data from the Kefar Blum meteorological station (Fig. 2.1). The crop factors, i.e. Kc values, (Table 2.1) were based on the National Engineering Handbook (NEH 1993).

Table 2.1 Land use area and Kc values used for the Hula Valley and the Golan basins

	Type	Area (km²)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Golan	Citrus	3.73	0.6	0.6	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6
	Olives	3.03	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8
	Orchard	27.62	0.7	0.0	0.0	0.0	0.0	0.0	0.4	0.6	0.9	1.0	1.0	1.0
	Palm	0.41	0.6	0.5	0.4	0.4	0.4	0.4	0.5	0.6	0.6	0.7	0.7	0.6
	Subtropics	5.19	1.1	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.1	1.1	1.1
	Vineyards	9.00	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.7	0.9	0.9	0.8
	Field crops	58.49	0.1	0.2	0.9	0.9	0.9	0.2	0.1	0.2	0.5	0.6	0.3	0.1
	Open area	958.06	–	–	–	–	–	–	–	–	–	–	–	–
	Elev < 600 m	–	0.5	0.7	0.8	1.0	1.0	1.1	1.0	0.4	0.2	0.2	0.2	0.5
	Elev > 600 m	–	0.5	0.5	0.6	1.0	1.0	1.2	1.0	0.6	0.2	0.2	0.2	0.5
Hula	Field crops	96.46	0.1	0.2	0.9	0.9	0.9	0.2	0.1	0.2	0.5	0.6	0.3	0.1
	Fruits	29.78	0.6	0.6	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6
	Water bodies	11.30	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Riparian vegetation	3.20	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Fig. 2.3 Land use map of the
Hula Valley

Legend

- Huala Settlements
- Water bodies
- Crops
- Forest
- Fruites
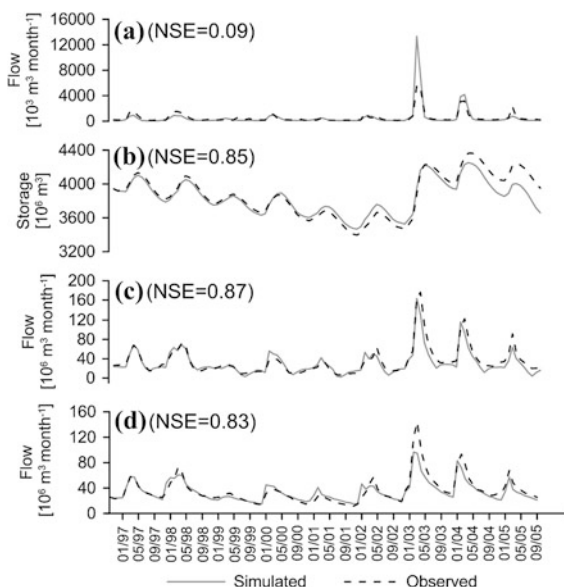- Riparian vegitation
- Not Classified

The FAO crop evaporation does not account for domestic water-use. This part of the simulation was evaluated by per capita calculation. The population size (8300 capita) was taken from the Israeli statistical bureau, and water consumption was assumed to be 250 m^3/(capita × year). The springs and the runoff flow (i.e. Ayun and the Eastern Galilee streams) were used directly as time series data measured by the Israeli Hydrological Service (IHS).

Calibration of the Hula area was performed by comparing the calculated flow at the Obstacle Bridge (Fig. 2.2) to the measured flow (Fig. 2.4c). We calibrated the model by adjustment of the irrigated portion out of the total field crops area for each month. The calibration resulted in an irrigated portion that reached the maximum of 90 % at late spring and early summer, and decreased to 50 % at the end of summer (August, September). This reflects general trends of decreased irrigation towards the end of the summer crop season.

2.3.4 Simulating the Golan Heights

The Golan area consists mainly of non-cultivated open areas (i.e. grazing land, nature reserve, army fire zone). Direct rainfall over the area is the main water source; thus the total water input can be estimated by interpolation of rain records over the Golan. In order to estimate the available water for the region, one must also

Fig. 2.4 The observed and the simulated **a** the Orvim Stream monthly flow; **b** Lake Kinneret storage; **c** the Obstacle Bridge monthly flow; and **d** the JR sources monthly flow. The Nash-Sutcliffe Efficiency (NSE) is shown for each simulation

know the total output of water. This component includes the ET, surface flow and groundwater flow all of which are difficult to estimate. The ET was estimated with the Penman Monteith equation similar to the Hula Valley. The surface water flows through about 15 streams running from east to west into the JR in the north and into the Lake Kinneret in the south (Fig. 2.1), but only five streams are equipped with flow gauges. Moreover, some of the precipitations infiltrate into the basalt aquifer which feeds many small springs located in the large streams and at the western slopes of the Golan (Dafny et al. 2003). Here again, not all springs have flow records. Evidently, no direct measurements of the total input and output in the Golan are available and consequently, the water balance of this area could not be simply completed.

The Golan area was therefore simulated with the rain runoff module (RRM) inside WEAP (Fig. 2.2). In this modeling approach, the hydrological system is treated as a "two bucket system" (Sieber and Purkey 2002). Meteorological records are the forcing variables for the modeled hydrological system. The main watersheds of the Golan area were delineated from a digital elevation model (DEM) (50 m pixel) using ArcMap (ESRI). Since meteorological parameters such as precipitation and temperature are strongly correlated with elevation (Rimmer and Salingar 2006), each watershed was segregated into elevation belts (<0, 0–300, 300–600, 600–900, >900 m. a.s.l.) and meteorological parameters were calculated as a linear function of the mean elevation of each elevation belt.

Since precipitation data show high variability between years, and precipitation is correlated with geographic elevation, we used the monthly time series data of 14 rain gauges (partly shown on Fig. 2.1) to generate the spatial distribution of rain on the Golan. The other meteorological parameters used to force the RRM were air

temperature, relative humidity and wind speed. Their values were based on the monthly averages records from two meteorological stations, one in Kfar Blum (Israeli Meteorological Service) at the elevation of 75 m, and the other in El-Rom (Ministry of Agriculture and Rural Development) at the elevation of 900 m (Fig. 2.1).

The RRM was calibrated for five watersheds with flow gauges at their outlet: Orvim (Fig. 2.4a), Meshushim, Yehudia, Dalyot and Samah. Parameters for calibration were the soil hydraulic parameters (Sieber and Purkey 2002) and the seasonal changes of Kc (Table 2.1) which in this case represent the growing stage of the natural grass that cover most of the open areas on the Golan Heights. The calibrated parameters were then used to run the RRM for the rest of the Golan Heights watersheds.

Using the RRM we evaluated the inflow into the reservoirs on the Golan Heights. The watersheds which include a reservoir were divided into two parts; one part included only the watershed upstream the reservoir and the other part included the watershed downstream. The reservoir overflow was linked to the main stream of each watershed so that the total flow from each watershed was the sum from both parts excluding the reservoir storage.

The agricultural water demands were simulated similarly to the Hula area. Land maps from the local water company (Mei Golan) were used together with Kc (Table 2.1) and ET values as the input for the FAO crop evaporation method inside WEAP.

2.3.5 Simulating the Eastern Galilee

The Eastern Galilee (Fig. 2.1) has minor influence on the catchment water budget because the large springs in the area are pumped into the local water system and runoff occurs only after large rainstorms. Since we have only little information about the consumption in this area, we decided to represent it by monthly time series of the measured flow from all stream gauges at the Eastern Galilee (average of 15×10^6 m^3 year^{-1}; Fig. 2.2). The flow is either to the JR or directly to Lake Kinneret.

2.3.6 Simulating Lake Kinneret Water Balance

When measured variables of the water balances are separated from the unknowns the water balance equation of Lake Kinneret is:

$$Q_s - Q_e = \Delta V_L + \sum Q_{out} - \sum Q_{in} \tag{2.2}$$

where the monthly measured quantities (m^3) at the right hand side of Eq. (2.2) are the change in water volume of the lake (ΔV_L, positive if inflows larger than outflows); the outflows (Q_{out}), including water released to the lower Jordan River through the Degania Dam (Fig. 2.1), the withdrawal of water by pumping to the National Water Carrier (NWC) and by private consumers. The inflows (Q_{in}) include the flow from the upper JR, the runoff from the direct watershed, water diverted to the lake from the Yarmouk River, direct rainfall, and discharge from several gauged saline springs. The monthly-unknown quantities (m^3) at the left hand side of Eq. (2.2) are evaporation loss (Q_e), and the unmonitored contribution of saline springs (Q_s).

The Lake is simulated in WEAP as a reservoir on the JR, and as such, uncertainties in the water balance (Rimmer and Gal 2003) were not taken into account. Following Eq. 2.2, inflows (Q_{in}) were calculated from the cumulative models of the upstream units- the JR and the direct watersheds. The JR includes the Hermon, the northern parts of the Golan Heights (see Sect. 2.2.3) and the Western Galilee, and the Hula Valley. Direct watersheds are the southern parts of the Golan Height and the Western Galilee. The pumped outflows (one part of Q_{out}) were set as monthly measured time series of pumping to the NWC and to private consumers. In Eq. 2.2 both the evaporative loss (Q_e) and the contribution of the saline springs (Q_s) are unknowns of the water balance which are not possible to evaluate with the WEAP built in modules. These unknowns were introduced as calculated time series, based on the long term solution of the water-solute-energy balances (Assouline 1993). The change in water volume of the lake (ΔV_L in Eq. 2.2) was determined by the WEAP simulations, using the Israeli official hypsographic curve (volume-elevation and volume-storage capacity curves) of the lake (Mekorot 2003). Comparison between the simulated and the observed lake storage is presented in Fig. 2.4b.

2.3.7   Scenarios

In this part of the study, we have generated artificial rainfall and ET scenarios in order to evaluate the effects of the changes in precipitation and ET on the water availability in the entire LKW. Note that by combining the four units into the general WEAP-LKW scenario, the priorities of water allocations could be re-examined. For example, the system allows testing how allocations should be determined for both local water consumers and NWC consumers, together with the considerations of maintaining the required water level in Lake Kinneret. The main purpose of this part was to test the performance of the complete WEAP-LKW under various forces, and it is by no means a prediction of climate change scenarios.

Four scenarios (SC) were determined in WEAP: SC1 real daily rain time series in the years 1996–2005 and average monthly ET; SC2—based on SC1, but the rain reduced by a factor of 0.8, and the ET increased by a factor of 1.05; SC3—artificial rain series (see Samuels et al. 2009 base scenario) and average monthly ET.

The SC3 time series represent hypothetical precipitation (no real meaning to dates) with an averaging monthly rainfall as in SC1, but daily and monthly precipitation vary stochastically; SC4—based on SC3, but the rain reduced by a factor of 0.8, and ET increased by a factor of 1.05.

In SC1 we verified that the HYMKE results and the entire LKW inflows and outflows were consistent with the real water system, while SC2 was used to detect the effect of extreme reduction in precipitation and increase in ET. These scenarios served as references for the SC3 and SC4, respectively, used for simulating the same long-term conditions as in SC1 and SC2, but with random climate conditions for each year (Samuels et al. 2009). These four scenarios are used for (1) verifying that the WEAP LKW system is reliable under general trends of climatic forcing, and (2) compare between the results of two scenarios—business as usual (SC1, SC3) and severe drought (SC2, SC4).

2.4 Results

The calibrations of the different parts of the model were good (Fig. 2.4) with Nash-Sutcliffe Efficiency (NSE) values of 0.09, 0.85, 0.87 and 0.83 for the Orvim stream, Kinneret water storage, JR at the obstacle bridge and the sources of the JR, respectively. Moriasi et al. (2007) suggested that a model performance was satisfying if the NSE is greater than 0.5. The NSEs here are well inside this range except for the NSE of the Orvim stream which is low even compared to the NSE of other streams in the Golan, i.e. NSE of 0.58, 0.87, 0.75 and 0.79 for the Meshushim, Yehudia, Dalyot and Semeh, respectively. Thus, overall performance of the model is satisfying for the purpose of this work.
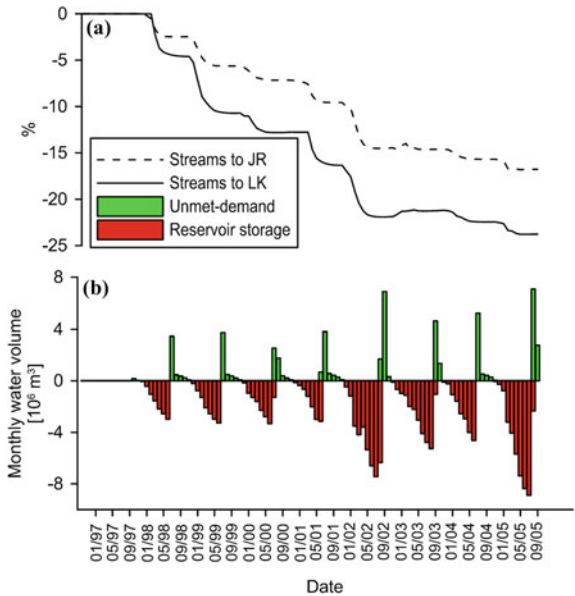
In some cases the non-satisfying WEAP performance in modeling rain-runoff processes and especially peak floods, could be attributed to the time step in the model (Yates et al. 2009). This should be at least as long as the longest resident time in the system (Purkey et al. 2008). Like many others, a monthly time step was used here because only monthly consumption data is available. This choice inherently scales the soil parameters to monthly values (Purkey et al. 2008) and puts a limitation on modeling the rain-runoff process which occurs on shorter time scales, i.e. hours to days. Despite this limitation, the Rain-Runoff method inside WEAP gives good results for the needs of the integrated hydrological system, as it is evident here and in other works (Purkey et al. 2008; Yates et al. 2009; Joyce et al. 2011; Vicuña et al. 2011a, b; Mehta et al. 2013).
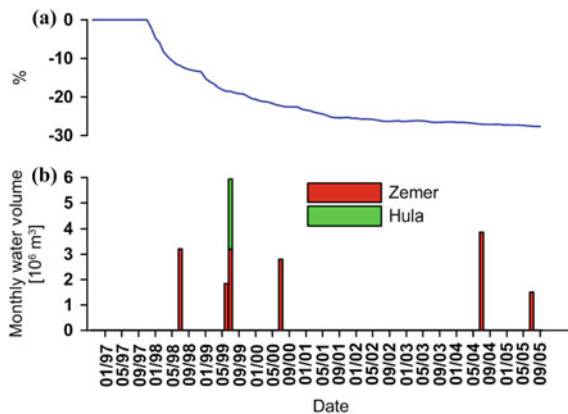
Results of the scenarios are focused mainly on the ability of WEAP to examine the differences between "business as usual" SC3 and drought SC4. Available water in the Golan, in the Hula and in LK is presented and discussed as the difference between SC3 and SC4. The flow from the Golan was aggregated into two components, the flow to the JR in the Hula Valley (north) and the direct flow to LK (south). The decrease in the flows (SC4 compared to SC3) is presented in Fig. 2.5a as the percentage of the accumulated flow of SC3. As expected, SC4 generated less

flow. The decrease is sharper in the direct flow to Lake Kinneret (southern Golan) where it reaches ~ 25 %, compared to only ~ 15 % decrease in the northern Golan. The larger decrease in the southern part is explained by the higher storage volume in this area compared to the north of the Golan Heights, which causes larger percentage of the water to be stored in local reservoirs. The decrease in the available water from SC4 compared to SC3 is seen not only in the discharge but also in the reservoir storage and the unmet demands (the monthly volume of water needed which could not be supplied by the present water system; Fig. 2.5b). The calculated maximal storage in each year is reduced by ~ 4–8×10^6 m^3. The very close similarity between the decrease in storage volume and the increase in unmet demands is due to the high reliance on reservoir storage for irrigation in the Golan.

The results from the simulation of the Hula area are presented in Fig. 2.6. The simulated JR accumulated flow at the Obstacle Bridge under SC4 was reduced by about 30 % with respect to the simulated flow in SC3 (Fig. 2.6a). Most of it is attributed to reduction of stream flow in the JR sources. Although the simulation showed significant reduction in the available water, most of the demand for irrigation in the Hula Valley could still be met (Fig. 2.6b). The reduction in available water in the Hula is reflected in the reduction of the water export through the Zemer project (Fig. 2.6b). In this case the simulation showed 6 summer month of unmet demand. Unlike the local reservoir system on the Golan Height, the water supply to the Zemer project is supported by the entire JR system, and therefore unmet demands occurred only during extreme cases of draught, in the middle of the summer, when large amount of water is needed.

Fig. 2.5 Available fresh water in the Golan. **a** The change in accumulated flow from the Golan in SC4 as percentage of accumulated flow in SC3. **b** The change in storage volume and unmet demands in SC4 compared to SC3
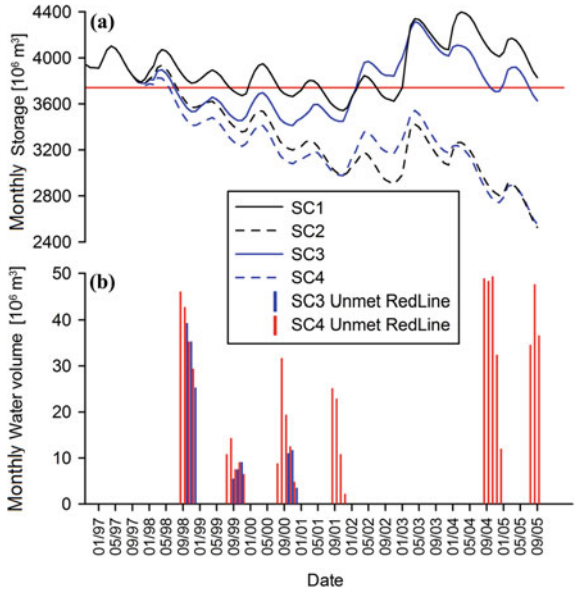
Fig. 2.6 Available fresh water in the Hula. **a** The change in accumulated flow at the Obstacle Bridge in SC4 as percentage of accumulated flow in SC3. **b** Unmet demands of the Zemer Project and of the Hula agricultural area

The storage volume in LK is influenced greatly by the decrease in precipitation (Fig. 2.7a). Similarity can be observed between the steady water storage in SC1 and SC3, compared to the severe reduction in lake storage in SC2 and SC4. These reductions were caused since lake deployment was considered the same for both the regular (SC1, SC3) and drought (SC2, SC4) scenarios. When the operation of the lake is unrestricted, no unmet demands are expected in the NWC (as long as there is water in the lake). However, realistically, the operation of the lake is restricted between the upper red line (flood risk) and the lower red line (operational and environmental risks). Therefore, practically pumping from the lake should not continue when water level is under the lower red line. When SC3 and SC4 were modified to meet the red line restriction (i.e. minimum lake storage of 3660×10^6 m^3) the restrictions created unmet demands in the NWC (Fig. 2.7b), which was given lower priority. Unmet demands were observed in three out of nine years in SC3 but increased to six out of nine years in SC4. The unmet demands reached a maximum of about 50×10^6 m^3 a month, and a total of 148×10^6 m^3 and 649×10^6 m^3 in SC3 and SC4, respectively.
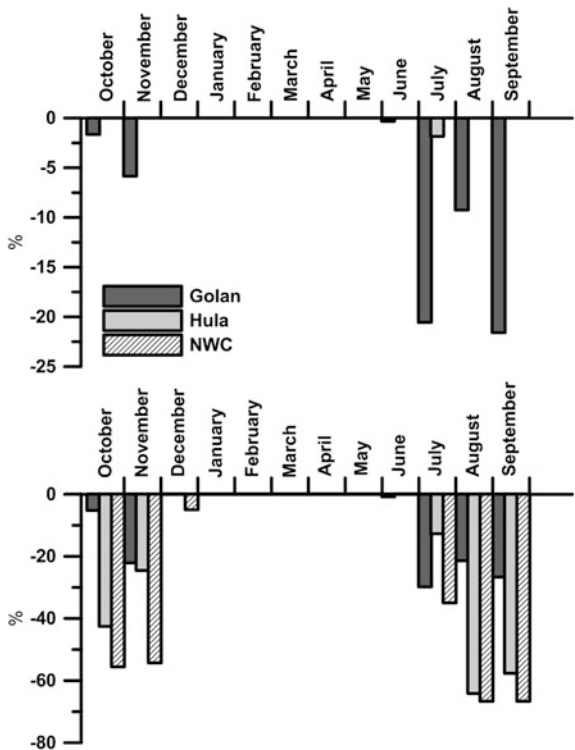
The "coverage" was suggested to be a good estimation of the vulnerability of agricultural area (Vicuña et al. 2011a, b) to changes in available water. It is defined as the ratio between the water demand and water supply. Since all scenarios had the same land use, the changes in coverage reflect the ability of a watershed to sustain current agricultural activity under climatic/operational changes.

The change in monthly average coverage in the SC4 simulation with respect to the SC3 simulation is presented in Fig. 2.8a. In the Golan, during most of the summer and the autumn month, the simulations showed a reduction of the monthly average coverage. This reduction reached to about 20 % in July and September. In the Hula area the reduction in coverage was evident only in July. Thus, we see that

Fig. 2.7 **a** Simulated storage volume in LK in SC1–4; **b** The unmet demands in the National Water Carrier in SC3 and SC4 when storage volume is restrict to above 3660×10^6 m^3

Fig. 2.8 **a** Changes (%) in coverage calculated for SC4 relative to SC3. **b** Changes (%) in coverage calculated for SC4 *Red Line* relative to SC3. The coverage is defined as the ratio between the water demand and water supply. The negative values indicate decrease in coverage

the agriculture in Golan area is more vulnerable to "climate change" then the agriculture in the Hula.

The comparison between the two areas is interesting since they represent two different kinds of water production strategies. The Golan area relies on local reservoir which is nearly fully exploited every year, i.e., there is no long term storage. The Hula area irrigation relies on the supply of water from direct pumping from the JR. The low vulnerability of the Hula area is due to the large volume of water flow in the JR with respect to total water demand in this area.

The regional picture becomes more complicated when we analyze the coverage if the water authorities will change operation rules in the lake, so that the water level is restricted above the red line (Scenario SC4 Red-Line, Fig. 2.8b). In this case the coverage of the Hula area and the NWC is significantly reduced. The reduction of the coverage in the Golan is kept similar to the original SC4. These results imply that the NWC and the Hula area are more vulnerable to the lake operation rules, then to "climate change". The Golan is operated almost autonomously, thus is less vulnerable to the operation rules of the lake.

2.5 Summary

According to the Global Water Partnership (GWP) website (http://www.gwp.org), Integrated Water Resources Management (IWRM) is a "…process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems."

In this study, emphasize was set on one of the IWRM basis: the quantification of finite natural water resources which have many different uses, under scenarios of reduced available water. The integrated model tested how irrigation demands in two locations, are met together with ecological management of Lake Kinneret and its tributaries. Some aspects of IWRM such as economic and social welfare, including trans-boundary water sources and the touristic significance of the Lake Kinneret Watershed, were not included in this project. However, the quantification basis set by this study may lead to farther enhancement of these aspects as well.

Here we used several modeling tools together with detailed databases of monitoring to assemble, test, calibrate and predict simultaneously the water availability within the entire LKW. The system is now in the required form, capable for integrated water resources management in the LKW. Two main aspects of water management were demonstrated in this study:

The first aspect is from a watershed modeling technical point of view - how to incorporate and integrate the main hydrological components of a complicated hydrological system into an IWRM using various, independent models. The central modeling tool was WEAP however, although it was designed to integrate natural watershed processes with various types of water demands, application of this tool alone to complex watersheds such as the LKW was not the preferred choice.

The hydrogeological structures that we tested required an operation of several complimentary modeling tools: (i) HYMKE (Rimmer and Salingar 2006) for the hydrology of the karst Mt. Hermon springs; (ii) Input of monthly time series (lake evaporation and offshore springs discharge) originating from an independent lake water balance calculations (Assouline 1993); (iii) the usage of two different WEAP built in catchment modules- one ("Irrigation Demands Only" Method) for the Hula and one ("Rain Run Off, Soil Moisture" Method) for the Golan Heights; and (iv) Artificial rain series based on stochastic rainfall generation tool (Samuels et al. 2009). It is suggested that in complicated hydrological problems the approach of integrating several independent models and analytical tools into a single modeling system might be more accurate and easier to produce than using a single modeling tool.

The second aspect is from a practical water management point of view. We defined the coverage as a parameter of water availability; we show how to identify vulnerable partial areas inside the watershed, which are more sensitive to extreme conditions; and exemplified how to separate between the effect of "climate change" and the effect of operational decisions on water availability. It is the heterogeneity of the LKW water system that made it possible to demonstrate various types of hydrological approaches and water availability considerations within a single case study.

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