A Model for Multi-Year Combined Optimal Management of Quantity and Quality in the Israeli National Water Supply System

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Research Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Engineering and Management of Water Resources

by
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Submitted to the Senate of the Technion - Israel Institute of Technology

Shvat 5766 **Haifa** **February 2006**

Acknowledgements

The Research Thesis was done under the Supervision of Prof. Uri Shamir in the Department of Environmental and Water Resources, Faculty of Civil and Environmental Engineering, Technion – Israel Institute of Technology.

I was privileged to be supervised by Prof. Uri Shamir and I would like to express my deep thanks and appreciation for the inspiration and the thrilling moments experienced during his guidance which extended far beyond the research subject to many other issues of water management.

I would also like to thank Dr. Joseph Dreizin (former manager of the Planning Division, Water Commission) who strongly encouraged me to study water management and enabled me to combine work and studies.

I'm grateful to Mo Provisor (current manager of the Planning Division, Water Commission) for his encouragement and support.

I wish to thank the Water Commission which participated in financing my studies.

I wish to thank my family for their patience and support, especially my mother who helped with the proof-reading of this thesis.

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Abstract

Israel has entered the desalination era once it became obvious that the natural resources do not suffice to meet the needs of today, and of a sustainable future. The depletion of the natural resources has been exacerbated by deterioration of the groundwater in the main aquifers. With desalination becoming an important addition to the supply system, and water quality gaining increasing importance, it is necessary to develop tools for management of the national water system which consider both quantity and quality of water in the sources and in the supply systems.

Most models for water management operated in the Water Sector were focused on the quantitive aspects of the national water sector almost without addressing the salinity considerations along the system: especially the salinity concentration in the water sources and in the demand zones.

In this work a seasonal multi-year model for management (planning and operation) of both water quantity and quality in the Israeli National Supply System (INWSS) has been developed. For the first time, both quantity and quality (salinity) considerations (water sources, supply system and demand zones) are optimized simultaneously for a long term time horizon (10-20 years and more). The model is called: Multi-Year Combined Optimal Management of Quantity and Quality in the Israeli National Water Supply System (**MYCOIN**).

The model seeks the seasonal operating plan for this time horizon which minimizes a cost function that combines actual operational costs, including the extraction levy placed on production of water from the natural sources, with penalties for not using the full capacity of desalination plants (as per the contracts with the private companies that construct and operate them), a penalty for deficits in supplying the demands, and a penalty for water spilled from the Kinneret.

The operating plan is subject to constraints of various types, including: capacities of the sources and the conveyance system, capacity and removal ratio of the desalination plants, demands to be met and their required salinities, the physical laws of water and salt mass conservation in the aquifers and in the supply system, and limits of levels and salinities in the sources. Sequential seasons are linked through the values of state variables: water levels and salinities in the sources.

While the model deals with the operational plan with a given physical supply system, the optimization yields insights with respect to the planning of the system itself, such as:

- Adequacy of the installed capacity of desalination plants.
- Adequacy of the removal ratio (outlet salinity) of the desalination plants.
- The required 'salinity map' in the supply system which is required to meet salinity constraints at consumer nodes and maintain aquifer salinity limits.
- Installed capacities of production and conveyance facilities.

The solution reports can indicate some of the planning needs ("bottle-necks") by analysis of the results and examination of shadow prices.

The objective function and some of the constraints in the model that has been developed is non-linear. Discontinuous functions have been "smoothed" by a transformation that maintain acceptable accuracy of the smoothed function yet results in a differentiable function that can be handled by the optimization software. The model is solved by LSGRG (Large Scale Generalized Gradient), an off-the-shelf software that uses EXCEL for model formulation.

Two versions of the model have been implemented: an annual model with two seasons, and a multi-year model that covers the coming three years one-by-one, and then two more "Future Reference Years" (FRYs). Each FRY represents a number of years (typically 3-7, but they can be longer), which repeat themselves and bring into the operational model the considerations of a longer time horizon. The multi-year model therefore has 5 annual periods: the first 3 years to come plus two FRYs.

The annual model has 420 decision variables and 156 constraints. The multi-year Model, which covers five years, has 2100 decision variables and 780 constraints (not including upper and lower bounds – 4200 altogether). Its output is presented in schematics of the system, on which are placed flows (seasonal quantities) and their associated salinities, as well as source water levels and salinities, as well as in "management reports" which facilitate comprehension of the results.

The model is considered to be one component in a "Model Hierarchy" (Shamir, 1971, 1972) that is being developed for and utilized by the Water Commission, which range from highly aggregated models of the entire national water system to much more detailed (in space and time) models of regional systems.

The model was developed with available data, not all of which is considered accurate and final. Model results should be viewed accordingly.

The main conclusions from the models' runs are:

1. It is possible to solve jointly by optimization quantity and quality issues.
2. It is possible to solve the quantity and quality problem by off the shelf software (Frontline's Solver).
3. The model is for optimizing the operation – with planning implications.
4. It is possible to:
   a. Prove whether the stated quality and quantity targets can be achieved.
   b. Indicate and test the means for achieving these targets.
5. The solution can change - sometimes quite dramatically - when salinity considerations are imposed.

Concerning management of the INWSS the conclusions are:

1. This is the first time the national system is optimized over a period of many years considering both quantity and quality (salinity).
2. In addition to the regular water management policy there is a need to adopt a water quality management policy, expressed by salinity targets at the demand zones and in the natural sources.
3. The development program should be determined with consideration of the water quality management policy, and may be affected quite substantially by it.

List of Symbols

C_{no}^{t} - The average salinity in node no at season t (mg Cl^{-}/*liter*).

C_{CC}^{t} - The average salinity in Center Coastal Aquifer (mg Cl^{-}/*liter*).

Cin_{n}^{t} - The average salinity entered to the aquifer n (mg Cl^{-}/*liter*).

$Cout_{n}^{t}$ - The average quality of water that exits the aquifer n (mg Cl^{-}/*liter*).

$C_{n}^{t}C_{n}^{t-1}$ - The average water salinity in Aquifer n in season t and t-1 respectively (mg Cl^{-}/*liter*).

C_{r}^{t} - The salinity of each source r=1...R (mg Cl^{-}/*liter*).

Def_{d}^{t} - Deficit of water to demand zone d in season t (MCM).

h_{n}^{t} - Water table in aquifer n in season t (m).

$hmix_{n}$ - Mixing volume coefficient in aquifer n.

hcc^{t} - Water table in CCA (m).

$hmix_{cc}$ - The coefficient of the mixing volume in CCA.

$hspill_{CC}^{t}$ - Spill level above the bottom of the aquifer cell (m).

K_{CC} - The spill coefficient from CCA to the sea (MCM/day).

$\overrightarrow{kdir}^{t}$ - A direction coefficient that gets the value 0 or 1.

$Kinspill^{t}$ - The extent of spills in Kinneret in season t (MCM).

Q_{l}^{t} - Quantity that supplied in pipe l in season t (MCM).

$Qartnode_{no}^{t}$ - Artificial source in node no in season t (MCM).

$Qartmassnode_{no}^{t}$ - Artificial mass in node no in season t (Ton Cl^{-}).

$Qartmass_{cc}^{t}$ - Artificial mass source (Ton Cl^{-}).

$Qartnode_{n}^{t}$ - Artificial source in source n in season t (MCM).

$Qartmzone_{d}^{t}$ - Artificial mass in zone d in season t (Ton Cl^{-}).

$Qdes_{i}^{t}$ - The extent of desalination use in plant i in season t (MCM).

Qin_{n}^{t} - Recharge into natural aquifer n in season t (MCM).

$Qout_n^t$ - Extraction from aquifer n in season t (MCM).

Q_r^t - Replenishment and recharge of water from sources and pipes r=1....R (MCM).

Qp^t - The extraction from aquifer cell in season t (MCM).

RR_i^t - The removal ratio of salt in desalination plant i in season t.

SA_n - Aquifer's n coefficient of storativity (MCM/m).

ΔT - The number of days per season (day).

$\frac{\Delta V_n}{\Delta T}$ - The change in the aquifer's n volume in the period ΔT (MCM/Season).

$\frac{\Delta CV_n}{\Delta T}$ - The change of mass in an aquifer n in the period ΔT (Ton Cl^-/Season).

List of Abbreviations

No.	Abbreviation	Full Text
1	ASL	Above Sea Level
2	AV	Artificial Variable
3	BR	Base Run
4	BWDP	Brackish Water Desalination Plant
5	CA	Coastal Aquifer
6	CAN	Coastal Aquifer North
7	CCA	Central Coastal Aquifer
8	CAS	Coastal Aquifer South
9	FRY	Future Representative Year
10	GA	Genetic Algorithm (GA)
11	GD	Gush Dan
12	GRG	Generalized Reduced Gradient
13	GUI	Geographic User Interface
14	JK	Jordanian Kingdom
16	KY	Kfar Yehoshua
17	LB	Lower Bound
18	LK	Lake Kinneret
19	LP	Linear Programming
20	LKB	Lake Kinneret Basin
21	LSGRG	Large Scale GRG
22	MA	Mountain Aquifer
23	NC	National Carrier
25	NCA	North Coastal Aquifer
24	NPV	Net Present Value
26	NWSS	National Water Supply System
27	OF	Objective Function
28	PA	Palestinian Authority
29	PV	Present Value
30	RR	Removal Ratio
31	RSM	Regional Simulation Model
32	SFWMD	South Florida Water Management District
33	SWDP	Sea Water Desalination Plant
34	TBM	Tri Basin Model
35	TBS	Three Basin System
36	UB	Upper Bound
37	WG	West Galilee

Chapter 1: Introduction

1.1 Preface

The water sector in Israel will face huge changes in the coming decades regarding its structure and in many aspects of managing the Israeli National Water Supply System (NWSS). The main challenges facing the Israeli water sector regarding quantity and quality issues are:

a. Assuring reliability of supply.

b. Restoration and preservation of the natural sources.

c. Managing the water sector for long-term sustainability.

On the basis of the Water Sector Master Plan for the years 2002-2010 (Water Commission, 2002),the government of Israel decided to build sea water desalination plants SWDP with an installed capacity of 315 MCM/Year and to import 50-100 MCM/Year from Turkey. In addition, 50 MCM/Year of brackish water will be desalinated and over 500 MCM /Year of wastewater will be reclaimed by 2010 mainly for agricultural use (Table 1.1). A large part of the desalination program will be carried out by the private sector; this will raise the challenge of efficient regulation and management.

The Israeli NWSS is a relatively small yet complex system to manage and optimize. The system comprises aquifers, a main surface reservoir – Lake Kinneret, desalination plants, a central conveyance system and local distribution systems.

The consumers are urban, industry, agriculture, nature, and commitments under Bilateral Agreements (with the Jordanian Kingdom (JK) and the Palestinian Authority (PA)). The various consumers have different requirements regarding reliability, quality of water supplied and the ability to pay for it.

The conveyance system is limited and the complexity of management, operation and design of the Israeli NWSS will increase when quality considerations are taken into account, especially when sustainable development policy considerations are incorporated in cost–benefit analyses. A sustainable policy means meeting the needs of the present without compromising the ability to meet the needs of future generations.

An example of a sustainable development issue relating to the preservation of the natural resources is the "Salt Balance" issue. It is necessary to define the technical and economic tools for reducing the amounts of salt accumulated in the natural sources, especially in the Coastal Aquifer (CA). One proposal is to remove salts from the reclaimed sewage; another option is to treat the water supplied for domestic use, so that the wastewater has less salt content. Each alternative has its advantages and disadvantages, technically and economically.

Tasks like these lead us to the need for long term (multi-year) multi-quality tools for management of the Israeli NWSS under conditions of uncertainty and subject to a policy of sustainable development. It does not seem feasible, nor desirable, to create one tool that deals with all tasks simultaneously. The preferred option is to use a set of models inter-connected in a well defined hierarchy.

The tool developed in this work can be part of this 'model hierarchy', which is already in use at the Water Commission, and can contribute to strategic planning processes, answering questions concerning operating and planning problems of policy while taking into account the combined considerations of water quantity and quality.

1.2 The Israeli Water Sector and the National Water Supply System (NWSS)

Israel is located in a semi-arid to arid region (Gvirtzman 2002). The natural water sources are replenished by an average of 500 mm of rain per year, ranging from over 1,000 mm/year to 150 mm/year over a distance of some 500 km (see Figure 1.1).

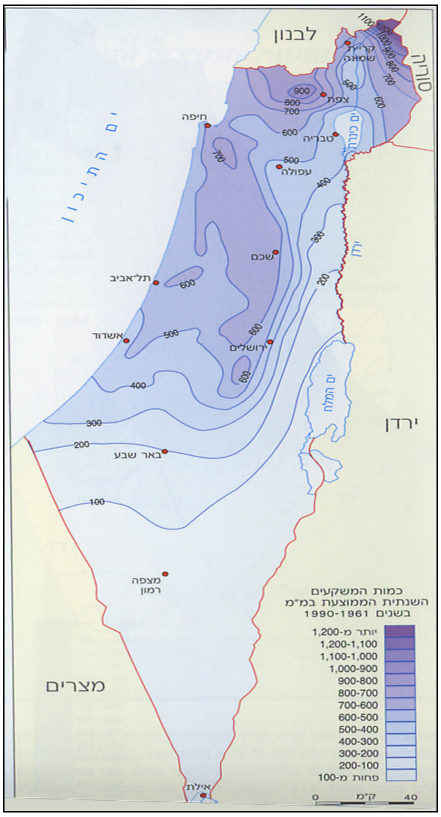

Figure 1.1 – Rainfall Variability in Israel
(Gvirtzman, 2002).

The average annual renewal potential of fresh water is 1555 MCM/Year (Water Commission, 2005) . The main natural sources are Lake Kinneret (LK), the Mountain Aquifer (MA) and the Coastal Aquifer (CA). Most of the supply depends on these three sources, and the national system is therefore called the 'Three Basin System' (TBS). There are some additional natural sources which are connected to the TBS: the Carmel and Western Galilee aquifers, and the Negev. The Arava basin is not connected to the main water system.

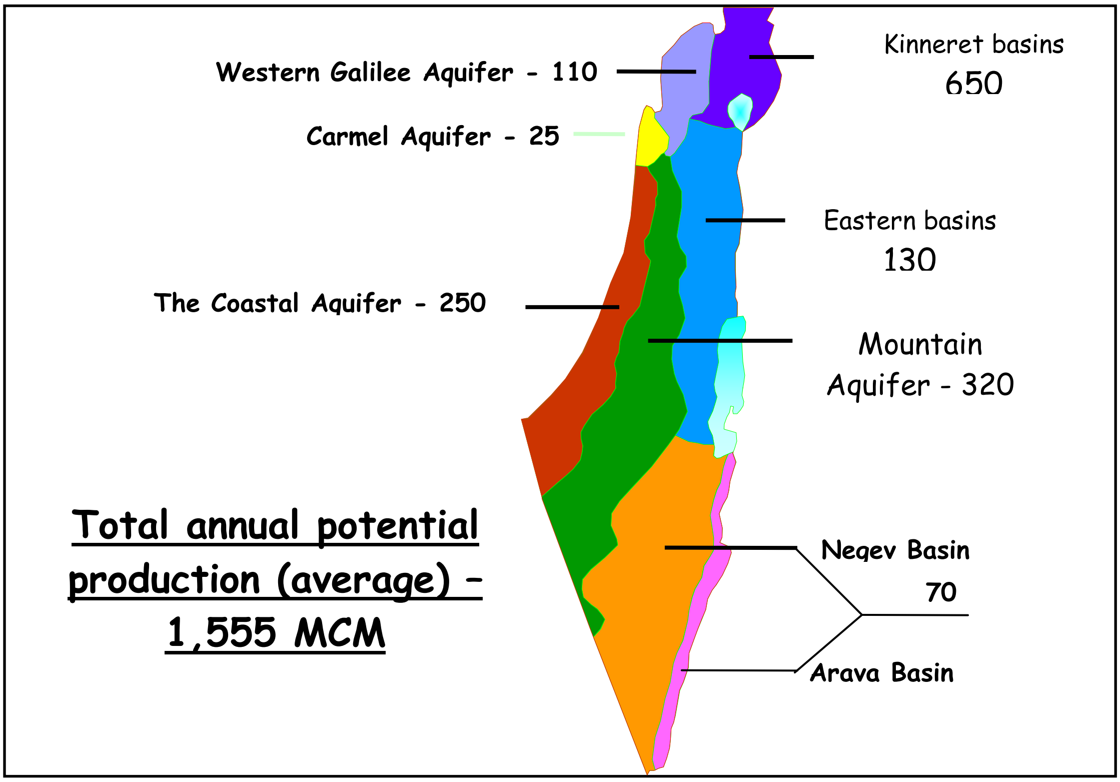

Figure 1.2 – The Main Natural Water Sources and their Average Annual Yield (MCM/YEAR) (Water Commission, 2005).

The difficulty of supplying a reliable quantity of water is due to the high variability of annual replenishment, and the appearance of relatively long sequences of below average years, as can be seen in Figure 1.3. The average over the period 1932-2002 is around 1,457 MCM/Year, with a standard deviation of 458 MCM/Year. It has been as low as 657 (1951) and as high as 3563 MCM/Year (1992).

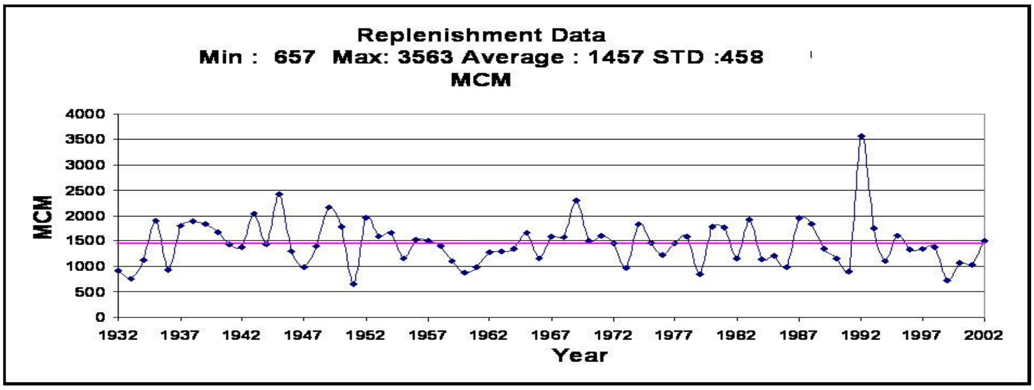

Figure 1.3 – Replenishment Time Series 1932-2002
(Planning Division, Water Commission, 2002).

The Coastal Aquifer (CA) functions as the main over-year reservoir, while the other sources have a lower over-year capacity.

In 2003 the total demand of all sectors for all types of water was 1860 MCM (Figure 1.4, Water Commission, 2004) - 1,377 MCM/Year of potable water and 483 MCM/Year of sub-potable water (reclaimed wastewater and brackish waters). Urban consumption already exceeds 50% of the total potable water use, and keeps rising at a rate of approximately 20 MCM/Year. Potable water use by agriculture is close to the goal set by the government of 530 MCM/Year; this residual agriculture is much less flexible regarding to water shortage.

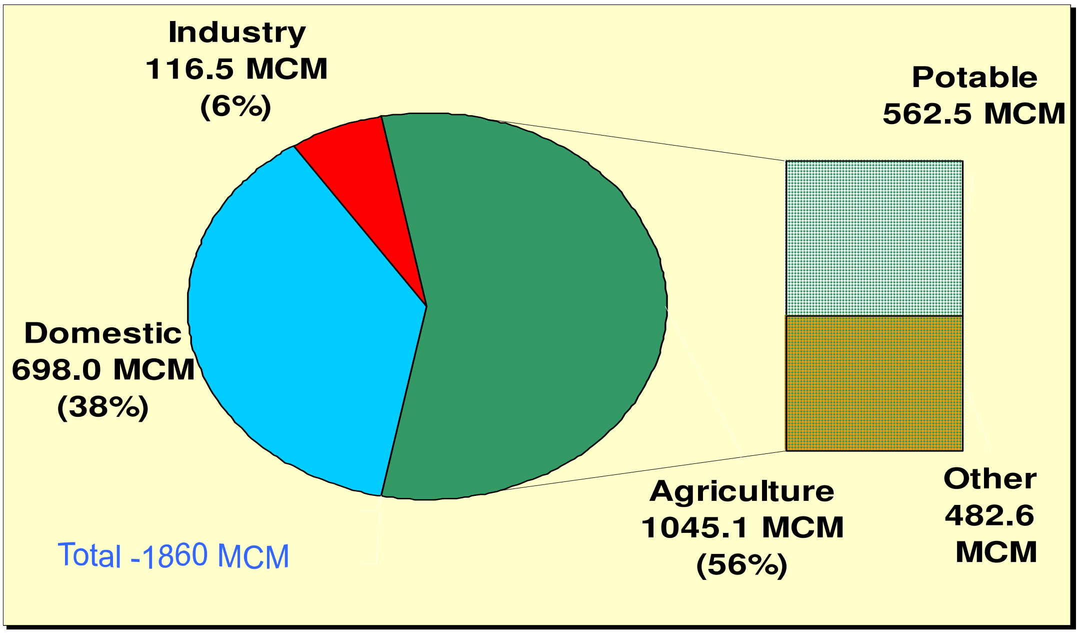

Figure 1.4 – Total Demand by Sectors in 2003
(Consumption Management Division, Water Commission, 2004).

The three main water sources, as well as most of the others, are connected by a conveyance system that covers the country (except the southern parts of the Negev) and supplies water to some 4,000 primary consumers (Water Commission, 2005) from the north (Lake Kinneret Basin) to the south (around Beer Sheva). The main grid, some 130 km long, supplies water to the east and west through dozens of lateral water systems (Figure 1.5).

The main grid comprises pipes, pumping stations, tunnels and operational reservoirs. The water is pumped from Lake Kinneret at an average water level of -212 m (Below Sea Level) to +44 m (ASL) by 4 pumping units. The water is pumped again and conveyed by open canals (16km and 18 km) and tunnels to the Eshkol reservoir (at +150 m). From there the water flows in a 108” pipe for 86 km to Rosh-Ha’Hayin, where the flow splits between the West and East Yarkon lines that rejoin at the Zohar node (Nehora reservoir). From Zohar the water flows to the south through the ‘Yarkon – Negev’ and ‘Zohar–Ze'elim’ lines.

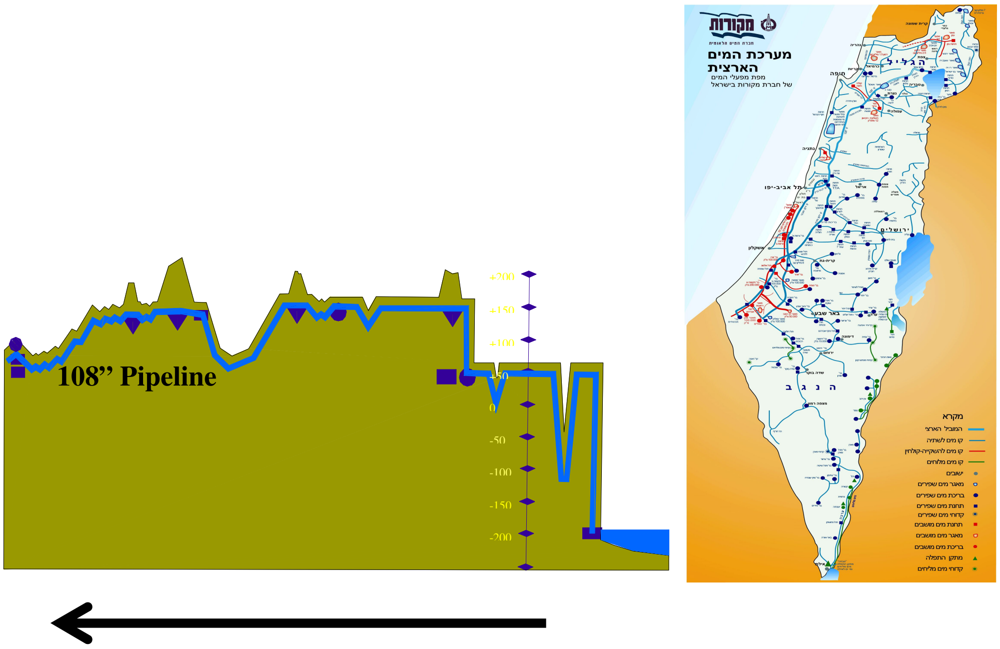

Figure 1.5 – National Water Supply System (Water Commission, 2005)

Beyond the challenge of maintaining reliable supply, there is the quality problem, since large parts of the water in the aquifers (especially in the Coastal Aquifer) are no longer suitable for direct potable purposes, due to contamination by human activities above phreatic aquifers and over extractions for many the years. The average rate of annual salinity increase in the Coastal Aquifer is 2.4 mg Cl^-/*liter*/Year, and the nitrates increase by 0.7 mg NO_3^- per year (Water Commission, 2002) - see Figure 1.6.

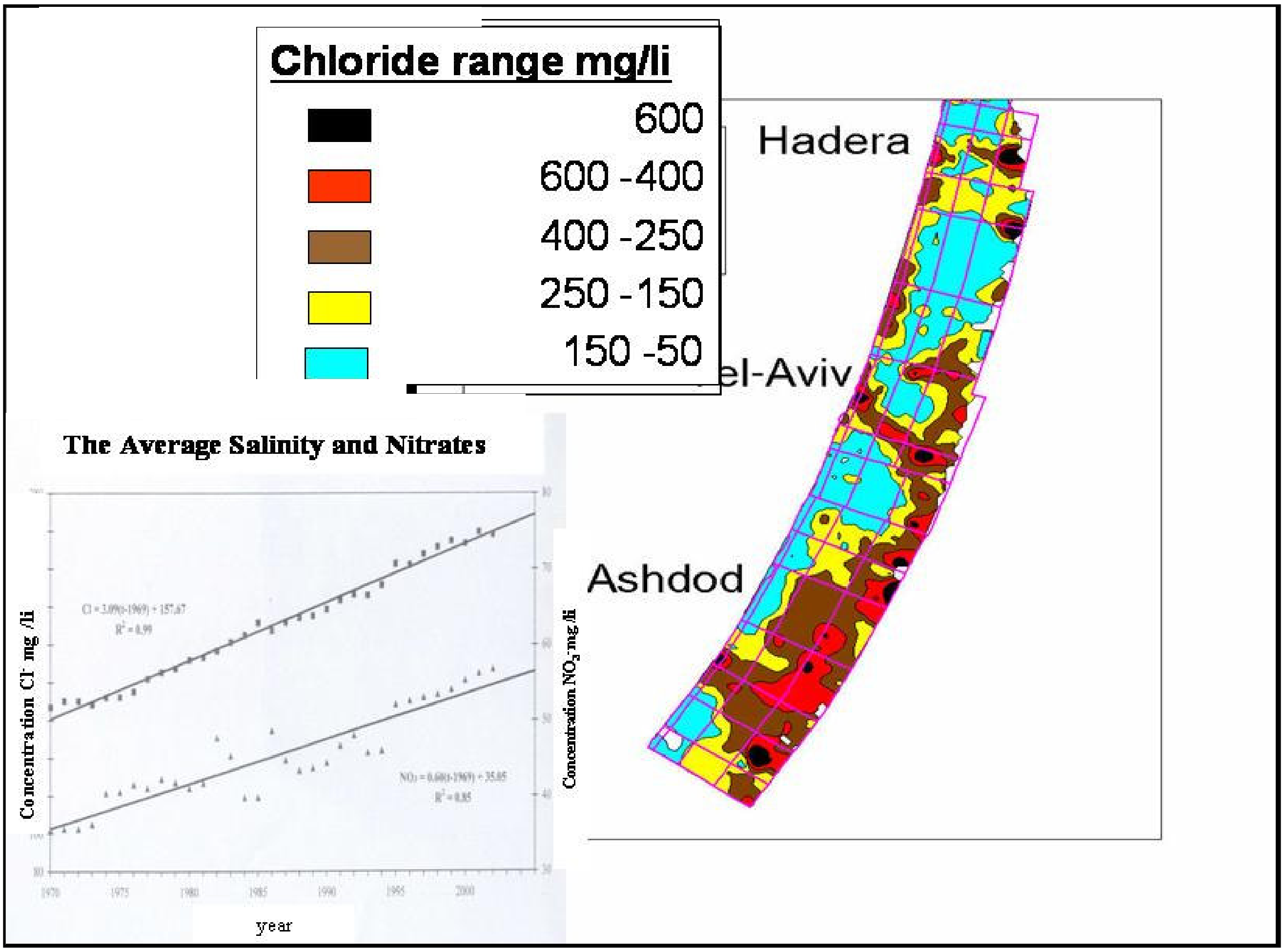

Figure 1.6 – Salinity and Nitrates in the Coastal Aquifer (Hydrological Service, Water Commission, 2002)

The overall water balance of the Israeli water sector is shown in Table 1.1: allocation of water of all types (potable, brackish, reclaimed) to all sectors (urban, industry, agriculture, nature, and neighboring countries), and the available resources at present and in the future (until 2020). This balance indicates the need for developing supplies to meet the consumption under <u>average</u> replenishment conditions. The detailed development program development to 2010 is presented in Table 1.2. The location and size of planned desalination plants is shown in Figure 1.7. The Ashkelon sea water desalination plant is already operating and by the end of 2006 will produce at least 100 MCM/Year directly to NWSS.

Table 1.1 : Water Sector in ISRAEL - National Water Balance* to 2020

Water Sources (MCM)										
Year	Total Population	Potable Water	Brackish Water	Treated Waste Water**	Dan Sewage Reclamation Project ('Shfdan'	Brackish Water Desalination	Sea Water Desalination & Import	Rain Water Harvesting	Additional Water Required	Total Supply
1999	6.312	1,500	166	173	105	0	0	55	-50	1,888
2005	6.902	1,500	170	278	110	15	25	55	64	2,169
2010	7.435	1,500	170	372	120	30	300	55	-116	2,395
2015	8.010	1,500	140	465	130	50	300	55	-9	2,617
2020	8.629	1,500	140	558	140	50	300	55	32	2,773

** not including water from the dan sewage reclamation project

Water Consumption (MCM)																	
		Industry				Agriculture						Bilateral Agreements					
Year	Domestic	Potable water	Brackish water	Treated waste water	Total	Potable Water	Brackish Water	Dan Sewage Reclamation Project ('Shfdan'	Treated Waste Water*	Rain Water Harvesting	Total	PA	Jordan	Syria	Storage Restoration	Scenery and Nature	Total Water Consumption
###	698	84	32	0	116	563	150	138	147	0	998	41	35	0	0	0	1888
###	725	90	40	0	130	583	120	110	240	46	1098	52	35	0	100	30	2169
###	830	95	40	7	142	566	120	120	339	46	1191	63	35	0	100	34	2395
###	948	100	45	13	158	553	94	130	439	46	1261	77	35	0	100	38	2617
###	1079	105	45	20	170	537	94	140	538	38	1346	93	35	0	0	50	2773

* The data is taken from the Planning Division, Water Commission . The data is under ongoing process of updating and it is still not formal to be used elsewhere.

Table 1.2: Development Program to 2010.

	2002	2003	2004	2005	2006	2007	2008	2009	2010
Sea water desalination	-	-	-	40	110	130	140	270	315
Recycle system	-	-	-	-	-	15	35	35	35
Brackish water desal.	1	8	15	20	30	50	50	50	50
Water import	-	-	-	-	-	-	-	-	50
Additional amounts of potable water	1	8	15	60	140	195	225	355	450
Treated waste water	295	332	359	390	441	461	471	491	509

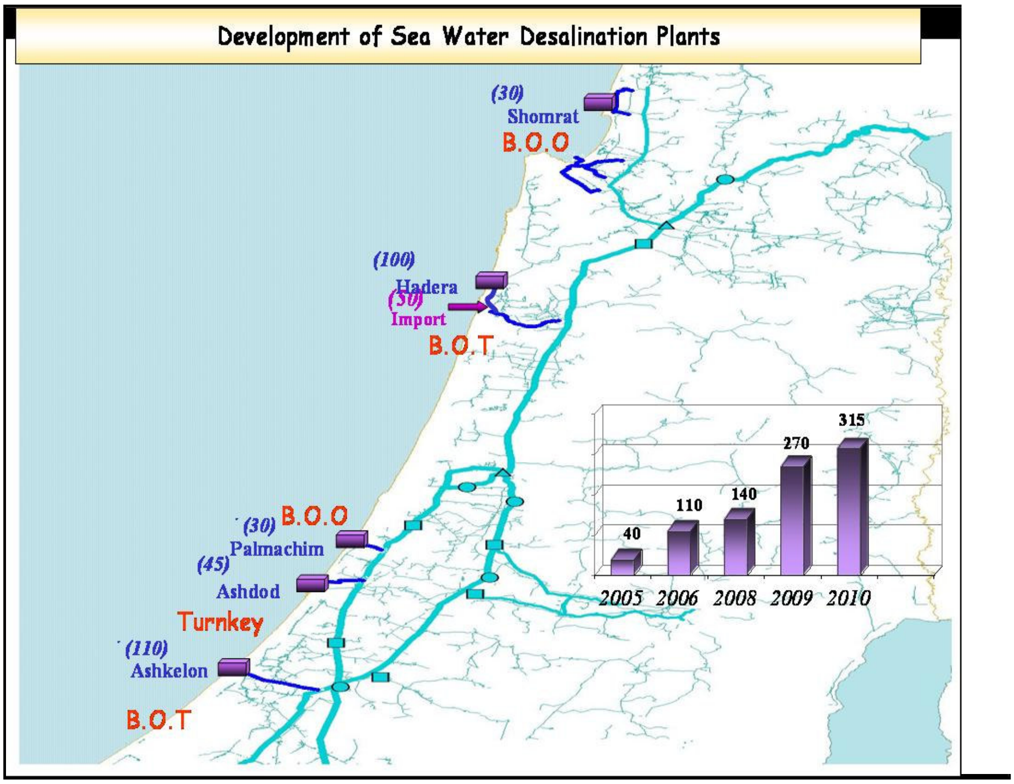

Figure 1.7 – The Development and Deployment of Sea Water Desalination Plants (Water Commission, Planning Division, 2004)

Upon this background it is anticipated that the operation of the NWSS will have to change quite substantially, to incorporate the new facilities and to recognize water salinity as an important component. This work is aimed at developing a model for optimal operation of the Israeli NWSS, over a time horizon of 10-15 years, with each year divided into two seasons.

1.3 Structure of the Work

Chapter 2: Literature Survey: review of related works, concentrating on multi-regional, large-scale water management models. The chapter includes definitions and a 'comparison table' concerning various components of the different models and the way they were addressed in this work.

Chapter 3: The approach taken in developing the management model and the alternatives that were considered while building the model.

Chapter 4: Mathematical formulation of the annual and multi-year models - definition of the time horizon, time periods, decision variables, objective function, and constraints.

Chapter 5: Examples of the model's results – several runs of the annual model and an example of running the multi-year model, followed by analysis of the results and their implications.

Chapter 6: Conclusions and discussion –conclusions concerning technical aspects of the model and strategic conclusions concerning the management of the Israeli NWSS.

Chapter 7: Recommendation for further development of the models and their usage.

Chapter 2: Model Classification and Literature Survey

2.1 Introduction

The model that was built in this work deals with optimal operation of the Israeli National Water Supply System (NWSS) at the level of policy and strategic planning over a time horizon of years. The policy relates to both quality (salinity) and quantity aspects. This chapter includes a survey of the relevant literature, and places our model in the context of the "model world" for optimizing water supply systems at a similar scale in time and space.

Aggregation in time and space of the system in question is always required when a model is constructed. Selecting the proper aggregation is one of the most important aspects of modeling. Our model contains the main fresh water sources (natural and desalination), conveyance system and demand zones, and seeks to determine the least-cost seasonal operation over a time horizon of 10-20 years. There is an implicit assumption that operation at a more detailed scale in time (hours, days, weeks, months) and space, and with the more precise physical laws included explicitly in the model (e.g., hydraulics and aquifer hydrology) would be feasible with the solution given by our model, and the cost would be practically the same as the one calculated by our model. This assumption is not unique to our model; it is always invoked when a high-level model is developed.

Policy objectives such as meeting bilateral agreements with Israel's neighbors, the total amount of fresh water allocated to agriculture, distribution of the population, or the amount of water allocated to nature are external to our model, and are imposed as ‘boundary conditions’, in fact as constraints.

In the past, operational decisions were based mainly on water quantities, and were not limited by quality considerations. More recently, quality has become an important component in operating the supply systems, and in managing the aquifers, not only in Israel. The complexity of managing the Israeli NWSS for both quantity and quality derives from several reasons:

1. The number and variability of components in the system. The Israeli NWSS is composed of: a large surface reservoir and several aquifers divided into "aquifer cells"

of different sizes, pipes ranging from very large to small distribution elements, pumping stations, desalination plants. The size of the system also determines the size of the optimization model that is to be solved.

2. The difference in temporal variation in the natural sources and in distribution systems. In natural sources time is measured in seasons and years whereas supply systems operate with time units of hours, days, month and seasons.

3. The uncertainty of replenishment. Solving a multi-year model with different replenishment scenarios and their associated probabilities increases the difficulty of identifying an optimal solution, sometimes even a feasible one.

4. Introduction of quality into the model creates non-linearities (as will be explained in Chapter 4), which compound the difficulties of solving a large optimization model.

The above make the problem of optimizing the operation of the Israeli NWSS difficult to formulate and to solve by analytic tools, and these considerations are relevant to regional water supply systems around the world.

On the other hand, the advent of advanced optimization software makes it possible to handle larger, more complex, non-linear models of water quantity and quality, as will be demonstrated in this thesis.

Upon this background a review of the relevant literature is presented. The review is divided into two sections:

1. Definitions (sections 2.2-2.5) – definition of the characteristics that are used in placing each model in the ‘model world’. These are:

- Water quality.
- Water quality models and water quality networks.
- Directed networks.
- Water management models.
- Network system models’ scope.

2. Review of water management models (section 2.7) – main related models with their general concept and a comparative table (Table 2.1).

3. The contribution of the current work (section 2.8).

2.2 Definition of Water Quality

The quality of water can be classified into five main categories (Dinus, 1987; Cohen 1988; Ostfeld, 1990):

1. **Independent Conservative Parameters**: Their total mass is conserved, and they do not dissolve nor react with their surroundings (e.g. Chloride $Cl^{-}_{(aq)}$).
2. **Dependent Conservative Parameters**: Parameters that are a function of the independent conservative parameters (e.g., SAR).
3. **Independent Non-Conservative Parameters**: Parameters whose total mass does not remain constant in time (e.g. Chlorine gas).
4. **Dependent Non-Conservative Parameters**: Parameters that do not remain constant in time and space; most water quality elements belong to this group and react with their surroundings (e.g. NH_4^+).
5. **Quality Index:** A combination of quality parameters, used as a more general indicator of water quality.

2.3 Classifications of Water Quality Models and Water Quality Networks

It is possible to classify water quality models into two categories:

1. **Single Water Quality Component Model**: The model deals with water that is assumed to have a uniform quality.
2. **Multi Water Quality Components Model:** The model deals directly with more than one water quality in the solution. This might be done by dividing water into "potable" and "sub-potable", or, more specifically, by considering one or more water quality parameters in the model.

When the distribution system is depicted in the model explicitly, the result is a multi-quality network model, which can be classified (Ostfeld, 1990) into three Categories:

1. **Source–Sink Networks**: Each source is connected to all consumers and there is no connection of the sources with each other, nor of the consumers to each other.

2. **Multiple Networks**: Some sources are connected to the same consumers, but there are no connections within the network. Dilution of waters with different qualities can occur only in the consumer zones.
3. **Dilution Networks**: An inter-connected network is fed by several sources and supplies different consumers. Dilution occurs within the distribution system.

2.4 Classification of Directed Networks.

Networks of water systems can also be characterized by the way in which the direction of flow in the pipes is defined:

1. Directed Network (DN): A network in which the direction flow in all pipes is fixed and known.

2. Undirected Network (UN): A network in which some or all pipes can flow in either direction, which is not known in advance and is revealed only in the solution.

The latter type creates considerable difficulty in solving optimization models, in particular when quality is considered, since the equations are non-linear and some are discontinuous. Since most optimization algorithms, especially the readily available commercial ones, which also have good convergence properties, assume continuous and differentiable equations we resort to "smoothing" techniques (Cohen et al., 2000a- Appendix; also Cohen et al., 2000b, c)

2.5 Classification of Water Management Models

There are three main groups of water management models:

1. **Hydrological Models (HM):** Whose main purpose is to manage the water sources, including the effect of external inputs and pollution loads on them.
2. **Network System Model (NSM)**: Whose main purpose is to manage the system network.
3. **Combined Models (CM):** Whose main purpose is to manage both the sources and the network.

These can be further classified into three sub-groups:

1. **Planning Models (PM):** Whose purpose is to determine the topological layout, policy decisions, overall water balance etc.
2. **Design Models (DM):** Whose purpose is to determine the size of system components, given the overall layout and topology. These models can identify system components which are not required, even though they appear in the model. They cannot, however, "invent" components which have not been included in it in the first place. These models can also help in identifying design bottlenecks.
3. **Operational Models (OM):** Whose purpose is to determine the optimal operation for a certain time horizon, given the design and capabilities of the various operational facilities (pumps, valves, treatment plants).

The three categories are inter-related, since the topology of the system affects the size of the system's components and that affects the optimal operation under a given loading condition. Each type can be built in many versions of aggregation in time and space.

2.6 Classification of Network System Models Scope with respect to Flow, Quality and Hydraulics

It is possible to classify the scope of network system as follows (Cohen et al., 2000a, b, c):

1. **Flow Models (Q)**: Models that function as "transportation systems" or as water balance models, without reference to hydraulic laws, nor to water quality.
2. **Flow–Head Models (Q-H)**: Models that balance flows and consider the hydraulic laws explicitly.
3. **Flow–Quality Models (Q-C)**: Consider the balance of flows and mass of quality parameters, but without explicit inclusion of the hydraulics.
4. **Flow–Quality-Head Models (Q-C-H)**: Consider flow and mass balances, and the full hydraulic laws that govern flows. Q-C-H models combine the capabilities of the Q-H and Q-C models.

Note: If a C model considers more than one quality parameter it should be marked as a MC (multi-quality) model.

2.7 Review of Water Management Models

2.7.1 Scope of the Review

The main attention of this work focuses on models for managing the Israeli NWSS. Therefore, many of the models surveyed here have been developed for the Water Commission. There are only few models in international journals and reports that have relevance to our work, in terms of long-term (years) allocation optimization with various components of water supply, water quality and water system and demand zones for national level decision makers. The models that will be reviewed are: WAS (Fisher et al., 2002, 2005) for managing the water systems of Israel, potentially jointly with its neighbors; CALVIN and CalSim (Jenkins et al., 2004 and Draper et al., 2004) for the California system; the South Florida Water Management Model (SFWMM), originally developed by the staff of the South Florida Water Management District (SFWMD) in the late 1970's (South Florida Water Management District, 1997) and improved recently (South Florida Water Management District, Draft Report, 2005) in a new model called Regional Simulation Model (RSM).

Some network models that are used for a more detailed analysis (operation over hours to days) will be mentioned in their relevance to incorporation of quality (Cohen et al., 2000).

At Mekorot and the Water Commission there are several models whose purpose is to manage a single source (e.g. Lake Kinneret, Mountain Aquifer etc.). We will not include these models in the current review.

2.7.2 Management Models

The most aggregative tool for management the Israeli water sector is the so called in Hebrew 'Mecholel Mazanym Arzi' (MMA). The basic model was developed (using VBA – EXCEL) originally by TAHAL (1998) for the Planning Division, Water Commission and was upgraded by Hoshva (2005).

The model performs simulations of the total national water balance on the basis of 12 inter connected regions. The basic idea of the model is to enable decision makers in the water sector to get a dynamic insight on the national and in main regions water balances using a Decision Support System (DSS). The water balances are subject to changes in the basic planning assumptions such as: growth rate of the population, water consumption per capita, supply in various water types (potable, brackish, waste water) and general policy factors such as: min total agriculture at each region and in national level.

Table 1.1 and Figure 2.1 are examples of some of the various reports that are created by the model.

The main characteristics of this model are:

- The regional and national water balances are taking into account all sectors (agriculture, industry, domestic, nature and scenery and Agreements with neighboring countries).
- The water balance refers to 6 types of water (potable, brackish, 4 levels of waste water quality)
- The user can work in 'Top-Down' or in 'Bottom Up' modes - by changing the national data and assumptions and see the outcome results in the regions, alternatively changing the regional data and assumptions and view the way they some up in the national level.
- The time horizon for the water balance is technically unlimited where limitations concerning the time horizon are only on the accuracy of the future data available.
- The water balance is solved by simulation (without any optimization).
- The storage capacity is not analyzed in this model. The water balance can be computed under various supply data (per region or nationally)
- No reference to water quality (yet there is reference to different water types)
- The supply system is highly aggregated.

The replenishment of natural water and its variability over time, together with the storage capacity available in the national system (Kinneret and aquifers) determine the development program of the artificial sources (mainly sea water desalination plants).

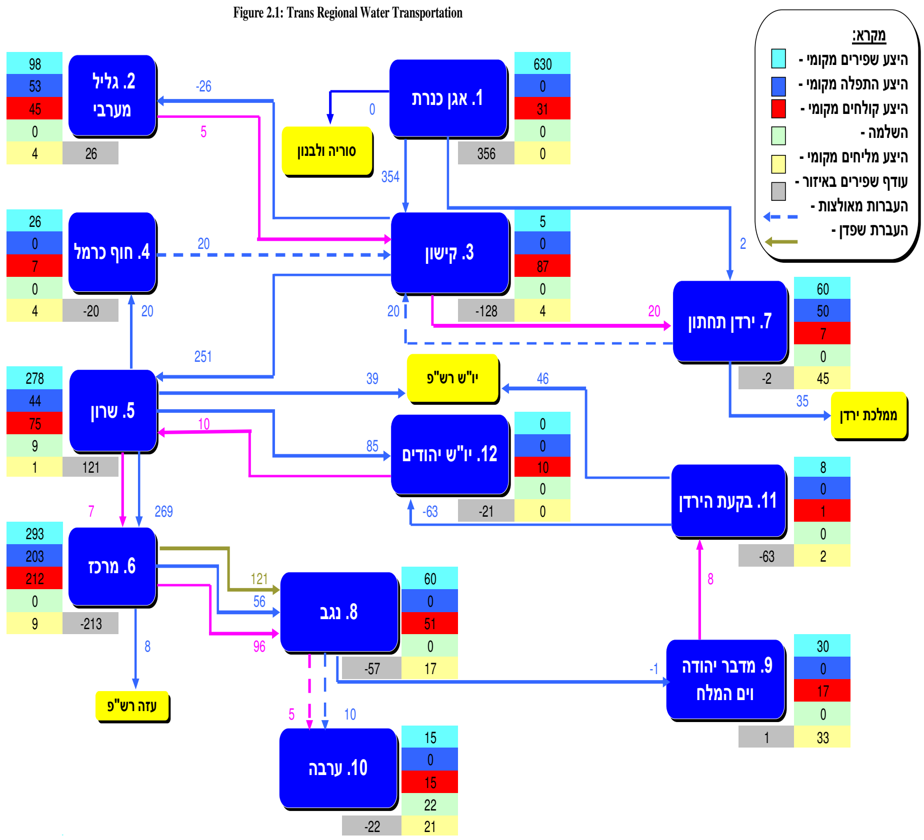

Figure 2.1: MMA – Inter Regional Water Flows in Israel

(Planning Division, Water Commission, 2005)

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A model for potable water was developed by Schwartz at al., (2002) for the Water Commission. The Model was called ‘Aggregative Model’. All main potable water in the TBS is aggregated as coming from a single source (Figure 2.2.), which represents the whole ‘Three Basin System’ (TBS). The model enables multi-year simulation and analysis of many replenishment time series which are solved simultaneously.

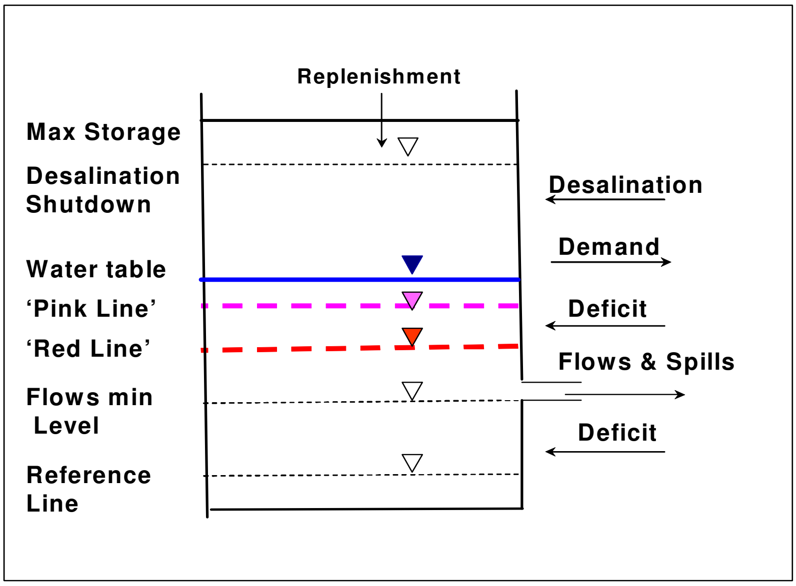


Figure 2.2: Schematic Representation of the 'Aggregative Model' (Planning Division, Water Commission, 2005)

The main characteristics of this model are:

- It produces statistical reports resulting from using the historical time series of potable water replenishment.
- Only potable water
- There is no reference to water quality
- The conveyance system is not represented in the model
- Conveyance capacities of the supply system are neglected
- Solved by simulation (without any optimization)

Shamir and Meyers (1982) solved a linear transportation model for the Israeli NWSS. The model is solved for one year with internal periods of 12 months. The objective function is minimization of operational cost (energy). The decision variables are the quantities of pumping from the aquifers which are represented as cells and the quantities of transportation in links of the main system. The constraints are continuity of mass at nodes (no quality) and continuity of head (energy) lines. The linearity is applied in two ways:

(a) By linearizing the Hazen Williams equation (Rubin, 1992) for head loss in the main system.

(b) The description of the head–flow curve for pumps is made by choosing specific working points on the curve.

The quality issues are taken care of in a limited way, where there are constraints that restrict the quantity supplied because of quality reasons.

Remarks:

1. There is no reference to long term considerations.
2. The solution is not driven by quality considerations.

Schwarz at al. (1981, 1987) developed a chain of transportation models for the Israeli NWSS called 'TKUMA' (in Hebrew: Tichnun Kavi Meshek Ha'Maim). The model operates as a transportation network, and is for both quality and quantity. It is multi-year model and the time unit is divided into periods. Each period represents a 'Typical Year'in the future. The purpose of the model is to analyze development, design and operation of the system.

The objective function of the model is:

(2.1) $$MinZ \left\{ Cost_q^t \cdot Q \right\}$$

$Cost_q^t$ - cost vector (p* = parameter)

Q - flows in pipes (dv = decision variable)

Constraints:

Quantity Conservation (continuity at nodes):

(2.2) $$\sum_{in=1}^{n} Q_{in}^{t} = \sum_{out=1}^{u} Q_{out}^{t}$$

Mass Conservation

(2.3) $$\sum_{in=1}^{n} Q_{in}{}^{t} \cdot C_{in}^{t} = \sum_{out=1}^{u} Q_{out}^{t} \cdot \overline{C}^{t}$$

Equation (2.3) is non-linear. To maintain linearity of the model (LP is easier to solve), this equation is introduced into the model by a linearized form, solved by successive approximations:

(2.4) $$\sum Q^{t-1} \cdot C^{t} + \sum Q^{t} \cdot C^{t-1} = Q^{t} \cdot C^{t}$$

With the values Q^{t-1}, C^{t-1} taken from one or more previous solutions of the LP, which is solved successively until $Q^{t} \cong Q^{t-1}$ and $C^{t} \cong C^{t-1}$ to within accepted accuracy. The process normally converges in 2-4 iterations.

$Q_{in}{}^{t}$ - Inflow to node *in* in season *t* (dv).

$Q_{out}{}^{t}$ - Outflow from node *out* in season *t (dv).*

C_{in}^{t} - Water quality carried by pipe *in* (dv).

$\overline{C}^{t}$ - Average water quality at the exit node (dv).

Conveyance Capacity

(2.5) $$Q_{l}^{t} \leq con\max Q_{l}$$

Q_{l}^{t} - The seasonal quantity that flows in pipe *l* (dv).

$con\max Q_{l}$ - The maximum capacity of pipe *l* (p*).

Quality limitations

(2.6) $$C_{l}^{t} \leq C_{MAX}$$

C_{MAX} - The maximum quality at the exit node (p*).

Continuity of water volume between successive years:

(2.7) $$V_{n}^{t} = V_{n}^{t-1} + \frac{\sum Q_{in,n} - \sum Q_{out,n}}{\Delta t} \ , \ \forall n$$

V_{n}^{t-1}, V_{n}^{t} - The volume of the reservoirs in the years t-1, t respectively (dv)

$Q_{in,n}, Q_{out,n}$ - flows in and out of the source respectively (dv)

The quality in sources is known (and does not change due to the operation)

(2.8) $$C_n^t = const$$

<u>Remarks:</u>

1. The quality in the sources is known (doesn't change due to operational conditions).
2. The removal ratio of salinity – is not mentioned as a component in the objective function but as a given constant by the user.
3. The model is solved by LP with successive approximation applied to the non-linear quality equations.
4. It has not been proven theoretically that the solution of this method is converging (Schwarz at al., 1986). Yet, experiments showed that the method works well.
5. The topology was examined with larger aggregation than is needed for future challenges.
6. The methodology used is effective for small scale systems. It is not mentioned what happened when used in large scale systems if ever.

Schwartz et al. (2000) developed a new version of the TKUMA model for the Water Commission. The model is an annual optimization of the Israeli NWSS in the TBS for quantity only, with seasonal (4 seasons) and annual decision variables, and multi-year simulation. The water storages in all sources at the end of the year are the state variables that connect between successive years. The network is directed (flow directions are fixed) transportation model. It consists of 5 demand zones, 8 water sources, 4 main nodes and 4 sea water desalination plants. The topology of the current version is given in Figure 2.2. The contribution of this model is multi-year simulation (of all decision variables) with annual optimization with the year is divided into four seasons, the introduction of sources management policy and the use of a chosen deterministic replenishment series for drawing a conclusion for the time horizon. The model is undergoing these days continued development at the Water Commission.

Remarks:

1. The model does not include long term considerations when it solves the annual optimization.
2. Quality is not included in the optimization, although it can be tracked over time in the simulation. (This will be one of the improvements that will be introduced in the new version).

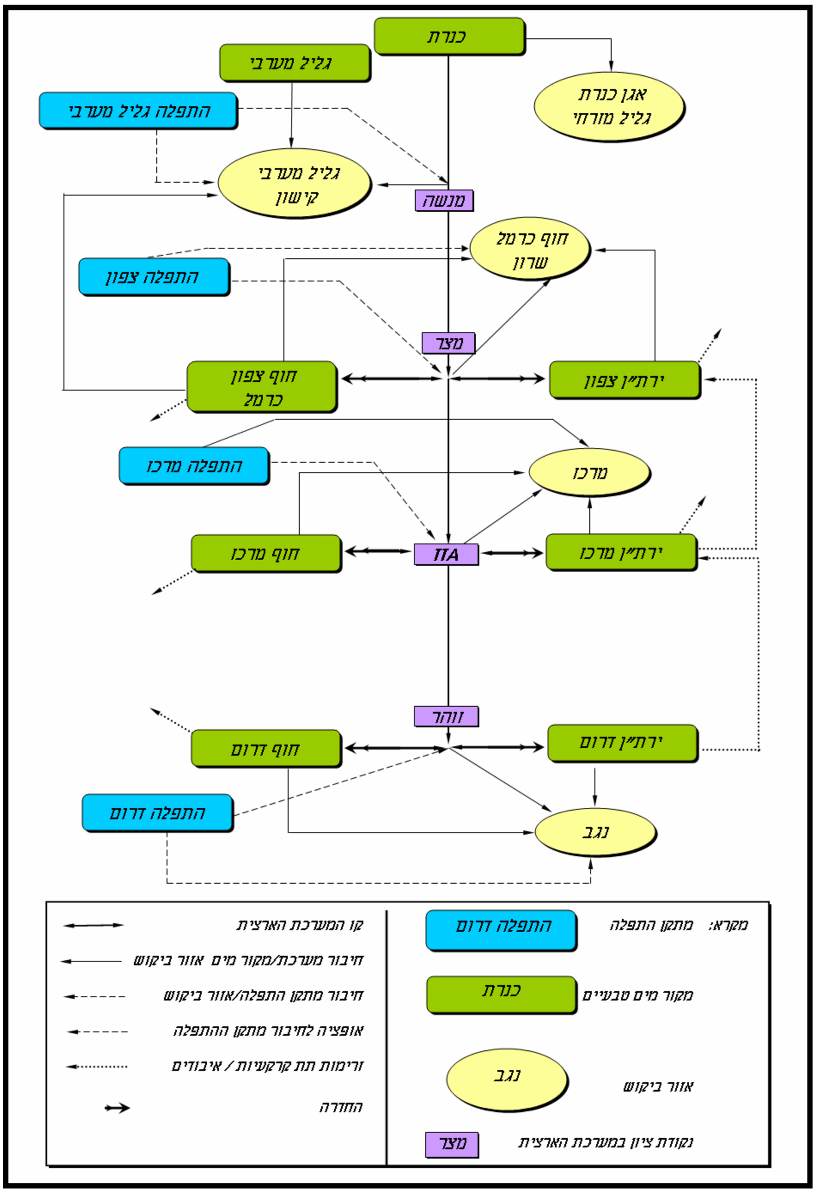


Figure 2.3: Topology of the TBS Model

(Planning Division, Water Commission, 2005)

In the framework of checking the operation of the national water carrier with the introduction of sea water desalination plants, TAHAL (2004) used a network solver for the main grid of the supply system from the Eshkol reservoir to the Zohar node. The objective was to determine whether the system can function under several hydrological and development scenarios.

Fisher et al. (2002, 2005) developed and applied, in a combined US, Dutch, Palestinian, Jordanian and Israeli team, a model called Water Allocation System (WAS) that takes into account not only the operation of the supply system but also the demand side, by incorporating the ability/willingness of consumers to pay for water (demand functions). The model was applied by Israeli, Palestinian and Jordanian teams to their water sectors. In its application to Israel, the country is divided into districts, each with its own demand curve.

WAS is an annual model. It allocates water to maximize the total net benefit (benefit from the use of water minus costs of supplying it) over all consumer sectors in all districts. WAS accepts a defined water supply system, which can be the existing one or with any proposed future changes/additions, and computes the annual operation of the sources and conveyance systems under a prescribed hydrological condition, given the quantities of recharge into the various natural sources. Runs can be made with different recharge scenarios. The model is run under sets of constraints, representing physical laws (e.g., continuity in sources and network nodes; hydraulics are not included) and administrative/political ones (e.g., minimum amounts to be provided to specific consumers).

The model can be applied to part of one country, to the entire country, or to the area of two or more neighboring countries. In all cases, it is the total net benefit to the entire area covered that is maximized.

<u>Remarks:</u>

1. Maximizing social net benefit is considered much more difficult than minimizing operational costs, due to the lack of information concerning the demand function, especially so for future years.
2. WAS is (currently) a single year model and does not take into account long term considerations. It has been reported that it is currently being expanded into a multi-year model (MYWAS).

3. There is no reference to water quality except through the definition of a few water types (reclaimed sewage, potable, brackish etc), which are considered separately. Therefore, the supply system does not function as a dilution system.
4. There is no reference to the sources state (water levels) along time.
5. Quality aspects of the sources are neglected.

Jenkins et al. (2004) developed a large scale economic-engineering model of California's water supply system called CALVIN. The model incorporates the willingness-to-pay together with the conventional engineering aspects. The model comprises a set of tools: data management and solvers that altogether serve as a DSS tool under a unified framework.

The model covers 92% of California's population 88% of the irrigated land. 51 surface reservoirs, 28 groundwater basins 19 urban demand zones. The model allocates water in order to maximize the statewide agriculture and urban economic value.

The model runs subject to historical time series on a single loading condition, as a result various statistical computations are made (similar to the 'Aggregative Model' Concept).

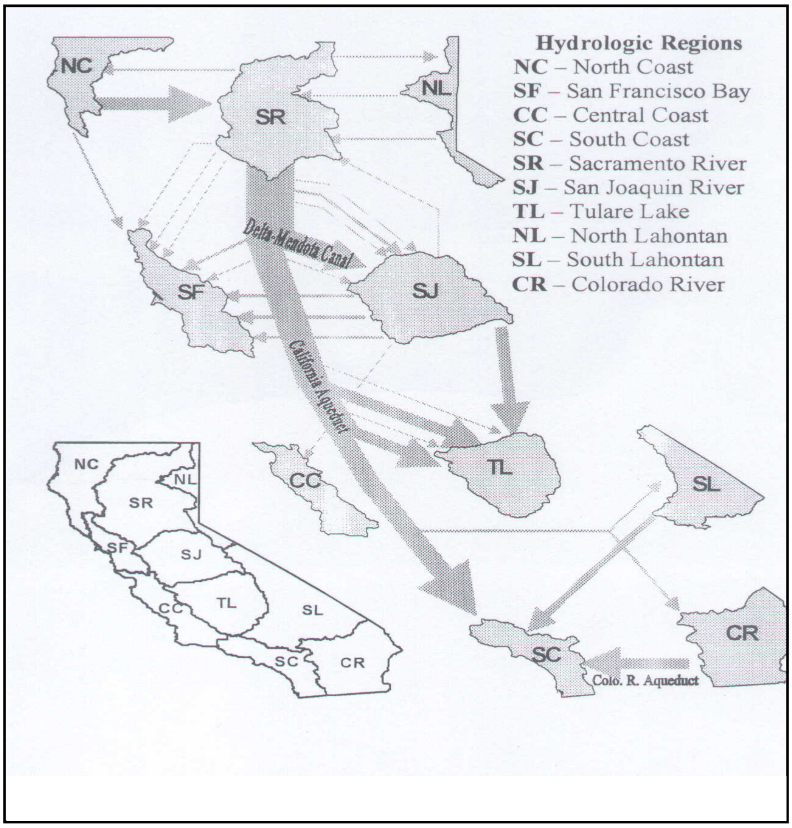


Figure 2.4: CALVIN – Inter Regional Water Flows In California.
(Jenkins et al., 2004)

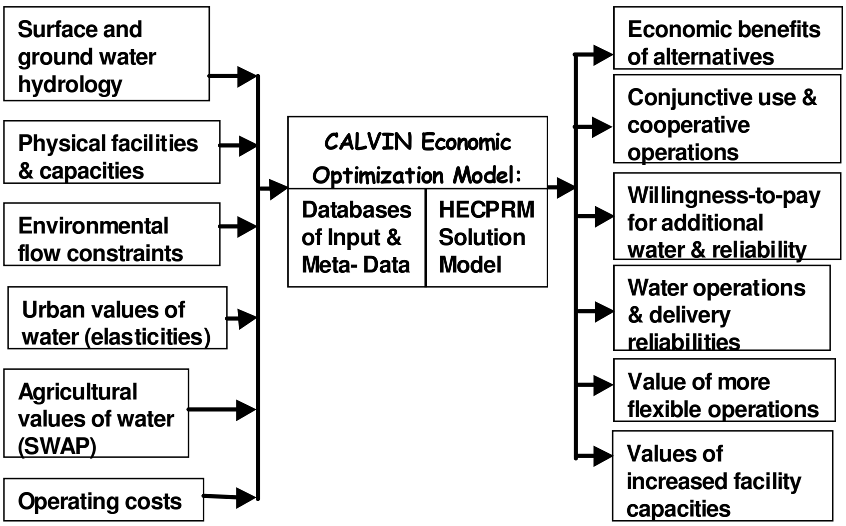


Figure 2.5: Data flow in the Calvin Model.
(Jenkins et. al, 2004)

Remark:

- The model is very large and is solved only for water quantities.
- The model is solved each time for a single loading condition which indicates that future needs are not taken into account in the solution.

Draper et al. (2004) developed a general-purpose reservoir-river basin simulation model for planning and management of the State Water Project and the federal Central Valley Project in California. The model is called California Water Resources Simulation Model (CalSim). Model users specify system objectives as input to the model, while system description and operational constraints are specified with a water resources engineering simulation language. A mixed integer linear programming (MIP) solver routes water through the system network, given the users priorities or weights. Simulation cycles, at different temporal scales, allow for successive layering of constraints. The model uses an external module that uses an Artificial Neural Network to estimate the flow-salinity relationship. The model is a single time step optimization, while simulation is used to follow the system operation over a sequence of monthly periods. Month-to-month system objectives are specified using a mix of weights on decision variables and penalties on deviations from specified target values. Constraints may be conditional on the state of the system.

Remarks:

1. The quality considerations are not taken into account intrinsically in the model.
2. The optimization is myopic and does not refer to long term considerations.
3. There are no economic considerations.
4. The MIP algorithm does not allow a large number of binary integers and is difficult to solve.

Another model that deals with large region water management is the South Florida Water Management Model (SFWMM) which is a regional-scale computer model that simulates the hydrology and the management of the water resources system from Lake

Okeechobee to Florida Bay. It covers an area of 19,455 km^2 using a mesh of 3.2 km x 3.2 km cells. The SFWMM was originally developed by the staff of the South Florida Water Management District (SFWMD) in the late 1970's (South Florida Water Management District, 1997). Since then, the SFWMM has undergone numerous modifications .The model simulates the major components of the hydrologic cycle in south Florida including rainfall, evapotranspiration, infiltration, overland and groundwater flow, canal flow, canal-groundwater seepage, levee seepage and groundwater pumping. It incorporates current or proposed water management control structures and current or proposed operational rules. The SFWMM simulates hydrology on a daily basis using climatic data for 30 years period.

An improvement of the model has been developed recently (South Florida Water Management District, Draft Report, 2005) with a new model called Regional Simulation Model (RSM). The RSM is a regional hydrologic model developed principally for application in South Florida, although it can be applied as a framework to a range of hydrologic situations. The RSM computes the coupled movement and distribution of groundwater and surface water throughout the model domain, using a Hydrologic Simulation Engine to simulate the natural hydrology and a Management Simulation Engine to capture operational options. The RSM has been implemented in several projects in South Florida and currently is being applied on an area-wide basis, as part of the South Florida Regional Simulation Model.

Remarks:

- The SFWMM is a hydrological model and there is relatively little reference to management and economic considerations.
- The RSM attempts to optimize through simulation rules, and is, in this repect, better than the SFWMM model.
- There is no reference to quality which is solved simultaneously with the quantity considerations.

Watkins at al. (2004) introduced a screening model called the South Florida Systems Analysis Model (SFSAM) to support the Central and South Florida Project

Comprehensive Review Study (Restudy). The objective of the Restudy, preformed by The Jacksonville District of the U.S Army Corps of Engineers and the South Florida Water Management District, was to recommend a plan for improving environmental quality and urban and agricultural water supply reliability affected by the Central and South Florida water management project. SFSAM was limited in scope and was used primarily to assist analysts in the development alternatives and specially in operating policies.

SFSAM is a model and special application of HEC-PRM (The Hydrologic Engineering Center - Prescriptive Reservoir Model). The model is deterministic optimization that represents a multi-period water management problem as a minimum cost generalized network flow problem, with water conveyance and storage facilities are represented as arcs in the network. Goals of and constraints on system operation are expressed through functions that imposed penalties (costs) for various levels of flow on the network arcs. Analyses were preformed using 300 monthly time steps (25 years).

Yates et al. (2005a, 2005b) introduced a model called WEAP21 (Water Evaluation and Planning, Version 21). The model integrates water supplies generated through watershed-scale hydrologic processes with a water management model driven by water demands and environmental requirements, and is governed by the natural watershed and physical network of reservoirs, canals and diversions. This version (WEAP21) extends an earlier WEAP model (Raskin et al., 1992) by introducing demand priorities and supply preferences and using LP. The scenarios are evaluated with regard to supply sufficiency and cost of delivery (the costs are not in the objective function directly). WEAP21 adopts a broad definition of water demand while taking into account surface-atmosphere interconnections (evapotranspiration). WEAP21 has a hydrologic (one dimensional) module that considers evapotransipration, surface runoff, sub-surface runoff (interflow) and pecolation. It includes the interconnections between an aquifer and the surface above and a stream at the base of the watershed. It also includes a temperature-index snow-melt model and heat budget equations. A surface water quality module is included with the impact of point source pollutants that represent the impact of wastewater on receiving waters. The water quality parameters are constituents that are conservative or decay according to an exponential decay function, Dissolved Oxygen (DO), Biological Oxygen Demand (BOD) and in-stream water temperature. The demand allocation is made by the LP, in which the priorities are entered by the user. The consumers are divided into Equity Groups, and the objective function in the LP is formulated such that demand centers with the same priority are supplied equally as percentage of their total demand. The model has a user-friendly drag and drop GUI (Graphic User Interface) template to build the model of the topology and functions of the water system.

Remarks:

1. It is mainly hydrologic model and less a long-term management model.
2. Water quality is not included in the optimization model.
3. Water quality in the aquifer is not considered. Quality refers only to surface interactions.
4. Flow directions are pre-determined, and follow a top-down direction.
5. Some of the parameters that are needed for running the model (e.g. total rate of BOD removal) are very hard to estimate for large and diverse inter-connected watersheds.
6. Allocations are made according to user-specified that are independent of source state and of conveyance costs.

Note: Yates et al. (2005a, 2005b) appeared after this thesis was completed

Ostfeld and Shamir (1993a, 1993b) solved for optimal operation policy of a multi-quality network, which consists of the following elements: sources, reservoirs, pipes, pumping stations, treatment plants and consumption nodes. The objective function was to minimize the total operational cost of water. Three types of models were developed: steady-state, quasi-steady-state and an approximate unsteady state. The solution was obtained with GAMS/MINOS (General Algebric Modeling System / Modular In Core Nonlinear Optimization System).

Cohen et al. (2000a, 2000b, 2000c) optimized the operation of a multi-quality network under steady-state flow conditions. The Q-C-H (flow-quality-head) is divided into two sub-problems - hydraulic (Q-H) and quality transport (Q-C) - which are solved separately and then ombined into a comprehensive Q-C-H model, which uses the shared flow (Q) vector. The purpose of this decomposition is to tackle the non-linearities that appear in the Q-C-H problem.

The Q-C model minimizes the costs of treatment, conveyance and costs of damage due to poor quality at the supply nodes. It is non-linear in the objective function and in constraints and is not differentiable, due to two conditions that relate to flow directions:

1. The dilution equations at nodes.
2. The cost of transportation depends on the absolute value of the flow.

In order to overcome these obstacles the authors introduces a smoothing function that enables to solve an undirected network (for details see Equation 4.5-4.7 in Chapter 4). The Q-H model is based on continuous representation of the flow-head relations in links and of the power-flow functions of the pumping stations, which results in a continuous non-convex optimization model. It is solved in a sequence of iterations. In each, the flow is fixed and the heads are determined by the optimization. The results are used to determine (by the projected gradient method) a direction for changing the "circular flows" (maintaining continuity) such the objective function will be improved. These "circular flows" have been introduced by Alperovits and Shamir (1977) as "decoupling variables" in optimizing the design and operation of hydraulic networks. The Q-C-H model combines the two sub-models into one that optimizes the operation with both hydraulic and quality considerations.

Tu et al. (2005) developed quality-quantity (called ‘multi-commodity’) flow model to optimize water distribution and water quality in a regional water supply system, with sources of different qualities. The model can accommodate two-way flow, represented by two opposite directed arcs. Blending requirements are specified at certain control nodes within the system to ensure that users receive the desired water quality. The optimization model is nonlinear and solved by a hybrid genetic algorithm (GA) using the commercially available optimization software LINGO. The GA is first used to globally search for the directions of all undirected arcs. Then a generalized reduced gradient algorithm (GRG) embedded in the GA is used to optimize the objective function for fitness evaluation. This method is used with successive iterations until a stopping criteria is reached in the GA algorithm. The model is monthly, with a six-month time horizon and therefore does not consider hydraulic constraints. The methodology was applied to the regional water distribution system of the Metropolitan Water District of Southern California. The district serves a population of 17 million in a service area of 13,462 km^2.

Remarks:

1. There is practically no reference to: multi-year considerations, to treatment plants and to quality in the sources.
2. There is no reference to the type of quality, and it is assumed to be a conservative component.
3. There is no reference to the advantages of the smoothing method of Cohen et al. (2000a, 2000b, 2000c), which overcomes the problems of undirected links.

Forteen models, plus ours (number 15) are listed and characterized in Table 2.1, which is followed by explanations of all entries and symbols used in the table. Table 2.1 contains a comparison of these models according to a set of characteristics, which are given symbols in order to simplify the tracking of the comparison.

Note: The RSM is not included in Table 2.1.

Table 2.1: Summary Table of National (or large regional) Level Models

Strategic Models		Water Supply System Models (Operational Models)	
Water Balance Models	Demand Management Models	Transportation Models	Network Models

	Subject \ Model	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	**Model Initials**	**MA**	**MMA**	**SFSAM**	**WAS**	**CALVIN**	**MSTA**	**TKUMA**	**Me-Sh**	**HGA**	**CalSim**	**WEAP21**	**EZ**	**OOMQSS**	**OO MDS**	**MY-COIN**
2	**Developed For**	WC	WC	SFWMD HEC	MEWP	A	WC	WC	A	A	CDWR	SEIB	WC	A	A	WC
3	**Model Coverage**	INWSS	INWSS	CSFWMP	INWSS	CWSS	INWSS	INWSS	INWSS	MWD	CWSS	LN	INW SS	LN	LN	INWSS
4	**System Components**	AQ,CS CZ,R	CS CZ,WCS	AQ,R, WCS,CS	CS,WCS CZ	CS, R,WCS	AQ,CS, WCS,CZ	AQ, CS WCS	PS WCS	AQ,R, WCS	AQ,CZ, WCS,R	AQ,CS,CZ. WCS,R,HE	CS, WCS PS	PS,CS,R,WT F	PS, CS,R WCS	AQ,CS, WCS,CZ, WTF CZ
5	**Model Scope**	Q*	Q	Q	Q*	Q –H	Q	Q-C	Q-H	Q-MC	Q	Q-MC	Q-H	Q-MC-H	Q-MC-H	Q-C
6	**Model Type**	G	G	G	G	OP	OP	OP	OP	OP	OP	OP	OP	OP	OP	OP
7	**Time Unit**	Y	Y	M	M	M	S	Y	Y	M	M	H,D,M,S	H	H	H	S

8	**Time Horizon (Years)**	40	20	25	1	1	20	20	1	0.5	1	100	GLC	GLC	GLC	10-20
9	**Objective Function (OF) Formulation**	NR	NR	MinDev	Max	Min	Min	Max	Min	Min	MinDev	MinDev	NR	Min	Min	MIN
10	**OF Components**	NR	NR	F	WSB, CC, RC	C,D	OC, DC DesC,RMC	EC,	OC	OC,DC ,RMC	D	D	NR	OC	OC	OC,DF, TC,DesC,R MC
11	**Main Decision Variables**	QS, Def	Def	QS	QS, D, PR	QS,D	CON,Def WT,Des	CON, Def WT Des	QS	QS,C, DEF	QS	QS	QS , H	QS,C,CF	QS,C	QS,C, Def,RR, WT,WC,De s
12	**State Variables**	WT	NR	WT	NR	U	WT	WT	H	WT,W Q	WT	WT	NR	H	H	WT,WQ
13	**NO. Loadings Conditions**	>1	1	>1	1	U	1	1	1	1	>1	1	1	>1	>1	1
14	**Approach To Stochastic Variables**	EF	DTS	EF	DTS	DTS	DTS	DTS	U	DTS	EF	DTS	NR	NR	NR	DTS
15	**Flow Direction**	NR	UD	D	U	UD	D	D	D	UD	U	D	D	UD	UD	UD
16	**Method of Solution**	Sim	Sim	O&S	LP	U	O&S	SLP	U	GA GRG	LMIP,GP ANN,O& S	O&S	S	IO GM	U	GRG
17	**Software Used**	E	E	HP	GM	HP O	EL	LP iterative	U	L	WRESL HEC-DSS	O	E	O	GM	ES

NR - Not Relevant; U – Unknown; * Using a "typical" year in the future; O-Other

2.7.3 Table 2.1 – Abbreviations

1. Models Names and Authors

1. **MA** – ’**M**odel **A**ggregativy’, (TAHAL, 2002).
2. **MMA** – ‘**M**echolel **M**azanym **A**rtsy’ (TAHAL, 1998, Hoshva 2005).
3. **SFSAM**- ‘**S**outh **F**lorida **S**ystem **A**nalysis **M**odel’ (Watkins et al., 2004)
4. **WAS**- '**W**ater **A**llocation **S**ystem’ (Fisher et al., 2002).
5. **CALVIN** - Optimization of California's Water Supply System (Jenkins et al., 2004).
6. **MSTA**- ‘**M**odel **S**imulatazya **T**lat **A**gany’ (TAHAL, 2003).
7. **TKUMA** –‘**T**ichnun **K**avi **M**eshek Ha’**MA**im’ (TAHAL, 1981,1986).
8. **Me-Sh**- “Optimal annual operation of a water supply and distribution system” (**Me**yers S. and **Sh**amir U., 1982)
9. **HGA** – “Optimization of Water Distribution and Water Quality by **H**ybrid **G**enetic **A**lgorithm” (Tu et al.,2005).
10. **CalSim** – **C**alifornia Water Resources **S**imulation Model (Draper et al.,2004).
11. **WEAP21**- **W**ater **E**valuation and **P**lanning Version 21 (Yates et al., 2005).
12. **EZ** - '**E**shkol – **Z**ohar' - Net Work Simulator, (TAHAL, 2003).
13. **OOMQSS** - '"**O**ptimal **O**peration of **M**ulti **Q**uality water **S**upply **S**ystems III: The Q-C-H Model - (Cohen et al. 2000c).
14. **OOMDS** - “**O**ptimal **O**peration of **M**ulti quality **D**istribution **S**ystems (Ostfeld, and Shamir 1993a, 1993b).
15. **MYCOIN** – **M**ulti-**Y**ear **C**ombined **O**ptimal management of quantity and quality in the **I**sraeli **N**WSS (This work).

2. Developed For

A = Academic institution; MEWP = The Middle East Water Project (combined academic and institutional); WC = Israeli Water Commission; CDWR=California Department of Water Resources; SEIB = Stockholm Environment Institute – Boston;

SFWMD = South Florida Water Management District; HEC = Hydrologic Engineering Center.

3. Model Coverage

CWSS = California Water Supply System; CSFWMP = Central and South Florida Water Management Project; INWSS = Israel National Water Supply System; LN = Local Network (or watershed); MWD= Metropolitan Water District of Southern California System.

4. System Components

AQ = Aquifers; CS = Constant Sources; CZ = Consumption Zones; PS = Pumping Stations; WCS = Water Conveyance System; R = Reservoirs; WTF = Water Treatment Facilities; HE = Hydro-Electric facilities.

5. Model Scope

Q = Quantity ; Q*= several water types without mixing; Q-C = Flow -Quality; Q- MC = Flow-Multi-Quality; Q-H = Flow–Head; Q-MC-H = Flow-Multi-Quality-Head.

6. Model Type

G = General (Planning Models)**;** D = Design; OP = Operation.

7. Model Time Unit

Y = Year; S = Season; M = Month; D = Day; Hr = Hour.

8. Model Time Horizon

The number of years that are covered by the model.

GLC=Given Loading Conditions; UL = Unlimited.

9. Objective Function Formulation

Max = Maximum (net) benefit; Min = Minimum cost; MinDev = Minimize Deviations from specified values.

10. Objective Function Components

CC = Capital Cost; DC = Deficit Cost; OC = Operational Cost; RC = Recycling Cost; RMC = Reservoir Management Cost; DesC = Desalination Cost; TC = Treatment Cost; WSB = Water Supply Benefit; D = Demand; F = Flows; O = Other

11. Main Decision Variables

QS = Quantity Supplied; PR = Percent of Recycling; CF = Circular flows; H = Head at nodes; C = Quality at nodes; WT = Water level (table) in the aquifer; WC = Water quality in aquifers; Des = Desalination capacity; Def = Deficit of supply; RR = Removal ratio (% removal) in treatment plants

12. State Variables

WT = Water level (table); WQ = Water Quality; H = Head.

13. Number of Loading Conditions

The number of loading condition that the model can handle (solve) simultaneously.

14. Approach to Stochastic Variables

DTS = Deterministic time series; EF = Ensemble Forecasting

15. Flow Direction

D = Directed flow (direction of flow fixed and known in advance); UD = Undirected flow (determined by the solution).

16. Method of Solution

GRG = Generalized Reduced Gradient; GA = Genetic Algorithm; OGM = Other Gradient Methods; Disaggregation-Aggregation (Inside-Outside); LP = Linear Programming; Sim = Simulation; SLP = Sequential Linear Programming; O&S = Combination of Optimization & Simulation; LMIP= Linear Mixed Integer Programming; GP= Goal Programming; ANN = Artificial Neural Network.

17. Software Used

E = Excel; E&L = Excel & Lindo; ES = Excel Solver (Frontline); GM = GAMS/MINOS; HP =HEC-PRM; L=Lingo; WRESL = Water Resources Simulation Language; HEC-DSS = Hydrologic Engineering Center's Data Storage System; O = Other.

2.8 Contributions of the Current Work

1. MYCOIN and TKUMA are the only attempts to incorporate quality considerations into an optimization model of the Israeli NWSS, albeit at very different levels of detail and processes.
2. The model integrates long term (years) considerations (objectives, constraints) of both quantity and quality in the sources and the distribution system into the short term (seasons) operational decisions.
3. Salinity removal ratios at desalination plants are decision variables.
4. Shadow prices are provided when the optimal solution is reached.
5. The level of detail with which the Israeli NWSS is described in the model is more extensive than in most (possibly all) of the existing models at the national level.
6. The solution is obtained with an existing optimization software package - LSGRG from Frontline Systems. This is not an innovation in itself, but there are several aspects of the implementation that are worth mentioning:
    a. Non-linear and discontinuous functions (relating to flow directions for modeling quality and to aquifer overflows) are converted into smooth functions, which enable solution of the model with the GRG software.

b. The input is prepared on an Excel table, in formats which make it relatively easy to develop the model, identify mistakes and errors, and explain its structure and modify it.

c. The output is presented in easy-to-follow schematics and condensed "management reports", which enable clear and (relatively) easy comprehension of the results and their significance.

3. Methodology

3.1 Introduction

The work's main objective is to build a tool for long term (multi-year) seasonal operation of the Israeli National Water Supply System (NWSS) with respect to quantity and quality, subject to constraints imposed by the supply system, development program, consumers' demand and natural sources. It is a model for Multi-Year Combined Optimal Management of Quantity and Quality in the Israeli National Water Supply System (**MYCOIN).**

The model is designed to assist in analyzing key questions in the planning and management of the water sector such as:

a. What will be the quality distribution in the National Carrier (NC) with the connection of new sea water desalination plants?

b. What will be the effect of reducing salinity in Lake Kinneret (LK) on the NC?

c. What will be the effect of a very dry year / rainy year on that distribution?

d. What should be done in order to supply better quality water to certain demand zones?

e. What would be the consequences of increasing or reducing the salinity of the desalination plants' product?

f. What will be the salinity of the reclaimed wastewater, as determined by fresh water supplied?

g. Is it possible to affect the Coastal Aquifer salinity by operational means?

h. Is it possible to preserve the quantity and quality of the Coastal Aquifer in the long run?

i. Should the government encourage additional desalination of wastewater? In case the answer is positive, then when and to what extent?

j. Is the development policy of the system (desalination capacity, salt removal ratio in the desalination plants, conveyance capacity) sufficient for achieving sustainable conditions?

k. What are the consequences of possible water agreements with Israel's neighbors on natural resources (with respect to both quality and quantity)?

Answering these and similar strategic planning issues with models is complex, for several reasons. Among them:

1. The considerations are multi-objective, where the objectives compete with each other (e.g. long term considerations vs. short term considerations)
2. The weight of each objective in the final decision is subjective and is not always quantified explicitly by the decision makers (e.g. salinity deterioration, reliability). The weights can be determined also by sensitivity tests.
3. There is a large number and variability in the system components.
4. There is a difference in the time unit used in analyzing each component of the system (e.g. network flows change in terms of hours, while aquifer water levels change with seasons and the salinity changes over seasons and years).
5. Uncertainty in the replenishment of the natural sources (stochastic inputs) and in demand forecasting.
6. Insufficient and/or inadequate hydrological and system data.
7. The need for incorporating sustainable development considerations in the short-term planning.
8. The models (software and hardware) available to analysts and for decision makers.

   It is important to emphasize that there is no model that takes all considerations into account simultaneously. The model that was built in this work attempts to strike a compromise among the issues mentioned above, and is intended to be part of a set of tools to manage the water sector (‘model hierarchy’).

The chapter includes some of the main methodology issues that affected the considerations of the mathematical formulation presented in chapter 4.

3.2 Optimization in Water Resources Management

The use of optimization is possible in cases where problems: (1) are clearly defined by quantifiable objectives, (2) are describable by a reasonably credible mathematical model, (3) have a sufficient amount of available data to characterize the effects of alternative solutions, and (4) are without an obvious best alternative (Jenkins at al., 2004), and have more than one solution.

As is the case in all real-world systems, developing and operating Israel's NWSS has objectives that compete with each other; also, the objectives of water management policy are subjective, are modified in an iterative process under the influence of many forces, and change over time. Still, optimization can identify a “best alternative” at a given time, for stated objectives and subject to given constraints; it can help in eliminating poor solutions and indicate the sensitivity to data variability and to the relative weight of objectives. A specific advantage of using optimization is the ability to estimate what will be the benefit if a constraint is relaxed by one unit (its shadow value).

3.3 Hierarchy of Models

Management of Israel's NWSS is complex due to the large number of components and the consideration of water quantities and quality in its multiple sources, including the installed and planned desalination plants, and the increasing importance of water quality in the distribution systems. Management decisions are made over a wide range of levels in space and time: from hour-by-hour operation of local systems to long term (annual, multi-year) considerations of preserving the aquifers. The operating rules of the system range from hourly operational decisions to multi-annual operational decisions.

It is impossible and technically unreasonable to build a detailed model that takes both short-term objectives and long-term considerations into account. For example, the decision regarding how much to pump from Lake Kinneret (LK) this month is almost irrelevant to the condition (water level and quality) of the coastal aquifer (CA) in another 20 years. Yet many such successive decisions eventually influence long term considerations.

Shamir (1971, 1972) analyzed the management of the Israeli NWSS and described an approach to its optimization by using a ‘Hierarchy of Models’. The complexity is tackled by decomposing the management issues and using a series of inter-connected models, which have different scales in time and space and "feed" each other with information and results. The models are embedded in a general framework and related to each other by their constraints and objective functions. The model developed here is intended to be one of the models in such a hierarchy which is being developed at the Water Commission. The location of our model in the hierarchy is somewhere “in the middle”, not too detailed and not too aggregated.

This hierarchy of models can be described as follows. A "top" and general model is designed to determine the general plan of the system, capacity expansion of its main components, including desalination plants, and main topology of the system; it does not have to consider the detailed hydraulics, and therefore treats the conveyance system as a "transportation network". This model should take into consideration the stochastic nature of natural replenishment and possibly of the demands as well, and operate in a "scenario testing" or "ensemble forecasting" mode. In the former mode, different scenarios are tested individually, to evaluate the robustness of a proposed plan. In the latter, ensembles of future scenarios, each with its assigned probability, are used jointly in a stochastic optimization model.

Once the general topology, development plan, demand management policy, and reservoir management policy are given, and the long term replenishment series is assumed known, the operational variables are optimized subject to the systems’ constraints (on both quantity and quality). The model developed in this work is of this type. Its results should be further examined with detailed models in time and space including simulation by a network solver, in which the hydraulics appears explicitly.

3.4 Model's Scope

The objective of this work is to develop and apply a model for optimal seasonal operation of NWSS, combining both quantity and quality (salinity) considerations, over a time period of 10-20 years ahead. While its decision variables are operational – seasonal quantities to be taken from each source, treatment levels in the desalination plants, and the quantities to be conveyed in each link of the system, over a period of 10-20 years – the model is an effective tool for identifying bottle-necks in the system and for evaluating proposed development plans.

3.5 Elements of the Methodology

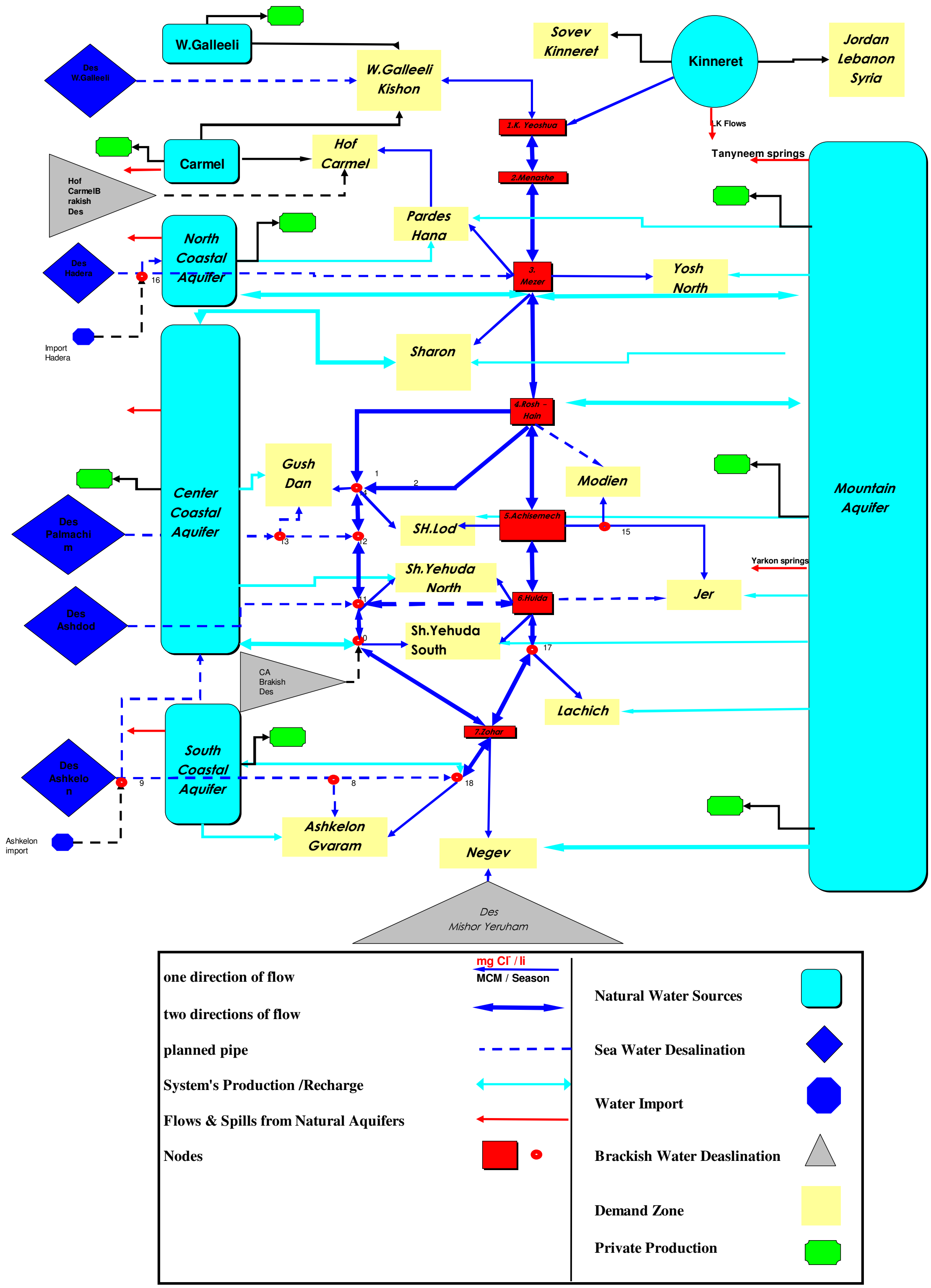
The schematic of the system being modeled appears in Figure 3.1. A larger version of this figure is used for displaying models results, in Chapter 5.

3.5.1 Policy Principles

The model is a 'Transportation Model' of the Q-C type: flows (Q=seasonal quantities) and water quality (C=salinity). It is a dilution network, in which total mixing occurs at nodes, for a single conservative quality parameter. The hydraulics of the conveyance system is represented as a seasonal conveyance capacity for each link, and its associated conveyance cost.

3.5.1.1 Demand Policy – the total demand in each zone is a summation of all sectors (domestic, industrial, agriculture and nature, scenery, recreation). The demand policy is expressed by a deficit cost for water not supplied, which can vary between demand zones and between seasons. A very high deficit cost (as compared with other costs) means the specified demand will be supplied fully, unless there is a physical constraint, for example, when a link has reached its maximum capacity, or there is not enough water in the sources.

Figure 3.1 : Model Scheme



This approach implies that water cost does not affect the demand, either because water prices are not pegged to costs, or because within the range of prices that are set equal to costs the consumption does not change appreciably with price. The latter is true for urban and industrial consumption, and may be true also for the high-value agriculture that will be provided with fresh water in the future, which will either be able to pay the full cost or be provided with direct subsidies from the government.

Another parameter of the demand policy is the salinity of supplied water. In the model, the salinity supplied to the zone is the weighted average of the salinities from all its sources. Constraints imposed on this average should reflect the quality management of supply. In addition, constraints can be imposed on the salinity at a network node, which allows further control of salinity throughout the system.

3.5.1.2 Development Policy – The development policy refers to several components of the system: size of the desalination plants and the feasible range of water salinity they produce, size of the import facilities (at Ashkelon and Hadera), and capacities of links in the conveyance system. The values of all these variables, for all time periods, are fixed in the model. Once a model run is made, full utilization of a component's capacity indicates the need for expanding this component, and the shadow value of the capacity constraint indicates the benefit of such expansion. On the other hand, a desalination plant or the expanded capacities of some other component that are introduced into the model and are not fully utilized indicate that it was not necessary to develop them in the first place.

The water sources include sea water and brackish water desalination plants and import of water. They are divided into two groups: sources which are constant in time and are not a decision variable, for example import of water from Turkey, and sources whose capacity is installed but their actual operation is a decision variable in the model.

The quality management policy (operation and development) can be controlled by several means:

1. By constraints on the removal ratios of the desalination plants; the assumption is that once the desalination plant was constructed the removal ratio range is fixed (it is part of the installed plant capacity).
2. By constraints on the salinity at nodes of the supply system.

3. By constraints on the salinity of the aquifers.

- The replenishment components are: rain, wastewater and potentially inflows from other sources. The wastewater reclamation is external to the solution of the potable transportation problem. The replenishment‘s salinity of each component can be defined externally.

- The change in salinity of the Coastal Aquifer cells is due to many factors, such as human activities on the land surface, sea-water intrusion and saline inflows from the east. There is a time lag (years) between the replenishment of a selected year (chosen from the historical time series data) and the salinity that enters the aquifer in the year that is under consideration, mainly because of the low transmissivity of the aquifer. The assumption in this work is that the time lag can be defined and is entered by user. In addition, the time lag is not dependent on the operation of the system. If it had been incorporated in the model, it would have become much more complicated.

- The salinity of water pumped from LK, of imported water and of brackish water desalination plants are not decision variables (they are given constants).

3.5.1.3 Sources Management Policy – Management of the aquifers is implemented by an 'extraction levy' that is dependent on the water level in the aquifer: the levy is increased as the water level drops, to indicate the increasing cost of scarcity. The levy can be different among the aquifers. The extraction levy represents a management policy of the reservoirs, or taken as the shadow prices of the sources, if they are known.

Notes:

- Part of the production from the natural sources is considered fixed (not a decision variable): production by the private sector and the extractions by the Palestinian Authority.
- Quality management of the sources is defined by imposing constraints on the minimum and maximum salinity in the aquifer at specified times.

3.5.2 Aggregation and Simplification

The need for analyzing policy decisions concerning the operation of the whole system and the need of taking into account long-term considerations binds the user to make concessions and simplifications in all modeling aspects of the system. Aggregation and simplification of the system components was made in time and in space. The model can be defined as a ‘long term operational model’ (multi-year); it is not intended to be a real-time (minutes, hours, days) operational model. Since the model represents almost the entire Israeli NWSS it is impossible to represent all pipes, consumers, nodes etc. Therefore the model contains the main features, as shown in Figure 3.1: conveyance system and its main nodes, consumer demand zones, sources.

The sources are represented by cells which contain a volume of water. The cells are able to lose water (e.g. flows to the sea, when their level is above a threshold) and to be replenished (rain, irrigation by fresh water and wastewater). The Mountain Aquifer (MA) is defined as one unit whereas the Coastal Aquifer was divided into three cells.

The basic time unit of the model is a hydrological year, divided into two seasons: a "winter” of ~275 days (October - June) and a "summer" of ~90 days (July – September), and the model deals with average values for the season. The seasons are not equal, so as to observe the consequences of the consumption variability between the seasons. The peak consumption is in the summer, and that is when the operation of the NWSS system is tested under relatively difficult (or extreme) conditions. It is important to divide the year into at least two seasons: the high demand ‘Summer’ and the rest of the year; i.e. ‘Winter’.

3.5.3 Optimization vs. Simulation

The use of optimization demands more simplifications than does simulation, due to the greater difficulty of solving an optimization model, in particular a non-linear one. Several approaches can be taken to tackle a long-term optimization model:

1. Using a one period (e.g. one year) model and running it with present data and future data, as has been done with the WAS model (Fisher et al., 2002). The comparison of the results is then made externally. This method is a kind of the Decomposition–Aggregation technique (Shamir 1971, 1972). The model that is

solved for a single period is simpler than a multi-period one. The main disadvantage of that is that there is no consideration of developments over time.

2. Combination of optimization and simulation: long-term simulation, in which at each time period the system is optimized, given the values of the state variables that resulted from the previous period's optimization. This maintains the "memory" of the system, as has been done with the Tri-Basin Model (TBM) (Water Commission, 2000). This approach is simpler than a multi-period optimization, and its main advantage is the ability to see future consequences of ongoing decisions. However, present decisions are in a sense "myopic", since they do not anticipate these consequences and therefore do not take them into consideration in neither the constraints nor in their effect on the objective function.

3. Solving simultaneously all periods of the time horizon, which ensures that all present and future considerations and constraints are taken into account in the operation of all time periods. This is a "clairvoyant" approach, which "sees" all time periods jointly.

   The main disadvantages of this approach are:

   a. Future conditions are not easy to anticipate. The “real world” tends not to act in this manner, since the time horizon of the decision makers is usually quite short. Still, if this is the case, then immediate goals can be given a higher weight, while the future is left to be considered in further decisions. So, this is really not a shortcoming of the approach.

   b. The model is technically hard to develop and to solve since it is large. The chance of errors in formulation and in data grows faster than linearly with the size of the model (some say exponentially), and the software that is normally available has much more difficulty in reaching a solution that is stated to be (at least near to) optimal.

   c. These challenges increase when incorporating stochastic considerations.

Representing the current and immediate future in greater temporal detail, while the future is introduced as a small number of “Typical Periods”, each representing a number of time periods which are considered to be identical to each other. The advantage of this approach is that it reduces the size of the model, while keeping the effect of future periods in the model. This is the approach taken in this work (section 3.5.4.2).

3.5.4 Incorporating Sustainability Considerations

3.5.4.1 Prescribed System States at Selected Times - Since the model is multi-year, considerations of sustainability can be incorporated into it, by imposing constraints on water quantity and quality in the sources at selected times in the future, and in particular at the end of the entire planning horizon. An additional means is to impose a penalty on levels and qualities which do not meet specified targets; using this device avoids the possibility of an infeasible solution being identified by the optimization model, due, for example, to overall shortage of water. The targets should be generated by models that above ours in the model hierarchy.

3.5.4.2 Time Horizon and Time Representation - The basic cornerstone of the multi-year model is one hydrological year divided into two seasons: Season 1 ~275 days ("winter": October- June) and Season 2 ~90 days ("summer": July-September). The seasons and years are interconnected serially through the ‘state variables’ of the water sources, namely water levels and water salinity in each source.

There are altogether 10 periods (seasons) which are solved simultaneously.

In order to manage and analyze the system under a policy of sustainable development, the time horizon of the model should be at least 15-25 years, with the presumed needs of the next generation incorporated at appropriate time points by constraints and possibly penalties, as described above. In this work the model was built for 10-15 years (but can be extended to a longer time horizon).

The multi-year model is solved simultaneously for 5 annual time periods: 3 consecutive years and 2 Future Representative Years (FRY), which represent a ‘typical year’ in the future, beyond the first 3 years (2004-2006, see Figure 4.1). These appear in the multi-year model as 2 single years, each representing a period of several years. The first represent a period of 4 years (2007-2010, called "2010") and the second a period of 5 years (2010-2015, called "2015"). The time horizon in our current model is therefore 3+4+5 = 12 years.

It is reasonable to determine the FRY as a cluster of 3–5 years which are assumed to be close enough or identical. The range can be widen to (3-7, or even more) but the FRY will be less “accurate” as we increase the future period. This total added period of 2 x (3 - 5) = 6 -10 or 2 x (3 - 7) = 6 - 14 years is incorporated into the multi-year model so as to include an adequately long future. The justification for not including this period year-by-year is that the resulting model would be too large, while this future period cannot be forecasted anyway with sufficient accuracy to justify a year-by-year model, beyond the first 3 years.

The total reasonable time horizon covered by the model thus represents a period of some 10-15 years, and can be stretched to longer, if the FRYs are assumed to represent more years at each period.

3.5.4.3 Incorporating Uncertainty Considerations - The main stochastic parameter in our case is the natural replenishment of water sources. In this work the time series of replenishment is selected by the analyst (deterministic approach): it can be extracted from the historical record or be a synthetic sequence that is generated by a statistical model fit to the historical data.

Obviously, the model can be run for different replenishment sequences (including extreme sequences with low probability), and the results of the various runs analyzed external to the model itself. If each sequence has an associated probability, then the results of the different runs can be assigned the corresponding probabilities.

The main characteristic of this method is that the more extreme the situation the more expensive is the solution (if the solution is feasible). It is associated also with the time horizon of the model. The NPV (Net Present Value) of the deficit (amortized value) gets smaller when it happens in the distant future.

3.5.4.4 Reliability - There is a trade-off between reliability and cost, therefore the reliability should be defined properly and be quantified. Reliability can be defined as the numbers of periods (or years) that the demand zones (in aggregate) were supplied with less than the prescribed demand (possibly combined with the magnitude of the deficit).

3.5.4.5 Calibration - Calibration of a model of this size and complexity is not possible, in the sense that its results cannot be compared to real historical data and its parameters adjusted to achieve a good fit. Still, there is the possibility to enter data from the past and adjust coefficient values according to expected results.

3.6 Model's Structure and Input

The model includes, in 16 aggregated zones, all the consumers that are connected to the potable water system of the Israeli NWSS. For 14 of them the supply is a decision variable The seven sources of the so called Three Basin System (TBS) system are: LK (Lake Kinneret, Sea of Galilee), the 'Yarkon-Taninim' part of the Mountain Aquifer (MA), three parts (cells) of the Coastal Aquifer (CA), and the sources in West Galilee and Carmel Coast. The CA was divided into three cells because of the low hydraulic transmissivity between them and the difference in their characteristics. West Galilee and Carmel Coast are constant sources (the water levels in these aquifers are not decision variables in the model).

The water supply system includes the conveyance system that is already in place, plus the main development elements that are already planned, including sea-water and brackish water desalination plants.

Overall management of the Israeli water sector includes integration of reclaimed wastewater, primarily for agriculture. There is a partial trade-off between fresh water and reclaimed wastewater: the more effluents are used the less potable water has to be supplied to fulfill the agricultural demand, up to the point where the residual agriculture must have fresh water.

The model does not refer to reclaimed wastewater directly, but it does consider reduction of potable water use over time in case of increasing reclamation. An important consideration is, however, that the reclaimed water adds salt to the aquifer. The model takes this into account in calculating of the salt mass balance in the aquifer.

Note: The data used in the model is "close to reality", in the sense that the best available data has been used. However, it should be noted that since this is a research thesis, there is no claim that these are the real and accurate data. See Chapter 7 for further discussion of this matter.

3.6.1. Supply Data

3.6.1.1 Replenishment - The replenishment of all sources is described by both quantity and quality. The replenishment data is of three different water types: natural replenishment (rainfall), reclaimed wastewater, and "other" (e.g. in the southern cell of the Coastal Aquifer there is an entrance of saline water from the east in addition to natural replenishment from rain and wastewater).

The division of replenishment between the sub-sources is made by spatial coefficients. The division of replenishments between the two seasons is made by seasonal coefficients. The coefficients are determined by aggregation of monthly data of replenishment taken from "Development Program for the National Water System and Developing Simulation Model" final report (Water Commission, 2000).

3.6.1.2 Water Sources Data - For all non-constant sources there are hydrological data such as: storativity, area, flows and spill coefficients to the sea and rivers respectively. In addition, characteristics of each aquifer cell include:

- Physical dimension: surface area, depth, maximum and minimum water levels;
- Storativity (m of water/m of aquifer thickness);
- Spill level (above which spill begins) and spill coefficient;
- Dilution volume coefficient (between 0 and 1, defining which part of the aquifer thickness is assumed to participate in mixing waters of different salinities. When the coefficient equals 1 it means full mixing;
- Initial conditions: water level and salinity.

Note: most of the sources quantity data for this section are based on a model used in the Planning Division, Water Commission (Water Commission, 2000) . The quality data is based on the Hydrological Service annual status report (Water Commission, The Hydrological Service, 2003).

3.6.2 Demand Data

There are 16 demand zones, based on aggregation of nodes in the network solver used in the Water Commission, Planning Division (Water Commission, 2004). The zone demand is the sum of all sectors: urban, industry, agriculture and environment. All forecasts and demand are made externally to the model. The division of the demand between the two seasons is made by coefficients on the annual demand. The coefficients are based on a simulation model of NWSS used in the Planning Division, Water Commission (Water Commission, 2000).

For three areas the demands are fixed, and their supply is not a decision variable:

1. Obligation to the Jordanian Kingdom (JK) from LK.

2. The consumption around LK.

3. The private production (not supplied by 'Mekorot') - defined for each source separately. These are the consumers who extract their water by direct pumping from the aquifers based on water rights and administrative allocation. These are considered constant in time (prescribed only by regulation) and not dependent on the operation policy of the Israeli NWSS.

Extraction by the Palestinian Authority from the Mountain Aquifer is added to the demand in the zones. In case one considers this allocation as fixed, and not a decision variable, due to bilateral agreements, it is possible to add it to the 'local production'.

The demand management tools are: deficit costs, average water salinity criteria of supply to demand zones.

3.6.3 Conveyance System Data

Conveyance system capacity is based on the maximum hourly conveying capacity operated in the past or known as the hourly installed capacity, multiplied by the number of hours at each season. The cost of conveyance is based on the average cost of production, pumping the water to the required elevation and energy losses in the conveyance system. The data is based on reports mentioned above (Water Commission, 2003, Water Commission, 2004).

3.6.4 Sources Management Data

The reservoirs management tools (for each season) are: the Extraction Levy (in Hebrew: 'Hetel Hafaka') and limits (upper and lower bounds) on water level and water salinity in the natural sources. These are given only for those sources whose water level and quality are decision variables.

3.6.5 Development Policy Management Data

The development policy management tools are:

1. Conveyance capacity - the system conveyance limits define the seasonal capacity of pipes; it can represent the existing system and also planned capacity expansion over time. The data is based on reports (Water Commission, 2003., Water Commission, 2004) and other data in the Planning Division, Water Commission.

2. Desalination development policy: the capacity of seawater desalination plants (SWDP) along the shore can be increased over time, to represent the capacity expansion program. The maximum salinity removal ratio (for both existing and planned plants) is another parameter of the SWDP.

3.6.6 Initial Values

The user must enter the initial values of state variables: water salinity and water level for all sources.

3.7 Model Output

One of the reasons for choosing the software which was used is the ability to view the results of the runs directly in an electronic sheet (Excel). The results are organized in tables and system flow charts for both quantity and quality.

The main groups of the model's output are:

1. Flows distribution along the system (MCM/Season).
2. Water quality distribution at the system's nodes (mg Cl^- / *liter*).
3. Water levels in natural sources (m).
4. Water balance of natural sources (MCM/Season).
5. Water quality in natural sources (mg Cl^- / *liter*).
6. Mass balance of natural sources (Ml ton Cl^- / Season).
7. Desalination capacity used (MCM/Season).
8. Removal ratio required in the desalination plants (%).
9. Supply deficits in consumer zones (MCM/Season).
10. Kinneret spills (MCM/Season).
11. Seasonal and multi-year operational cost of the system (also the NPV values – MUS$ / Season).

3.8 Optimization Method and the Software Used

The optimization method is LSGRG – Large Scale General Reduced Gradient. The model is non-linear in the objective function in two terms: cost of the removal ratio and the extraction levy, as well as in the dilution constraints (see chapter 4). The LSGRG finds optimal solutions to problems where the objective and constraints are all smooth functions of the variables. For this class of problems, the Solver normally can find a local optimum, if one exists – but this may or may not be the global optimum.

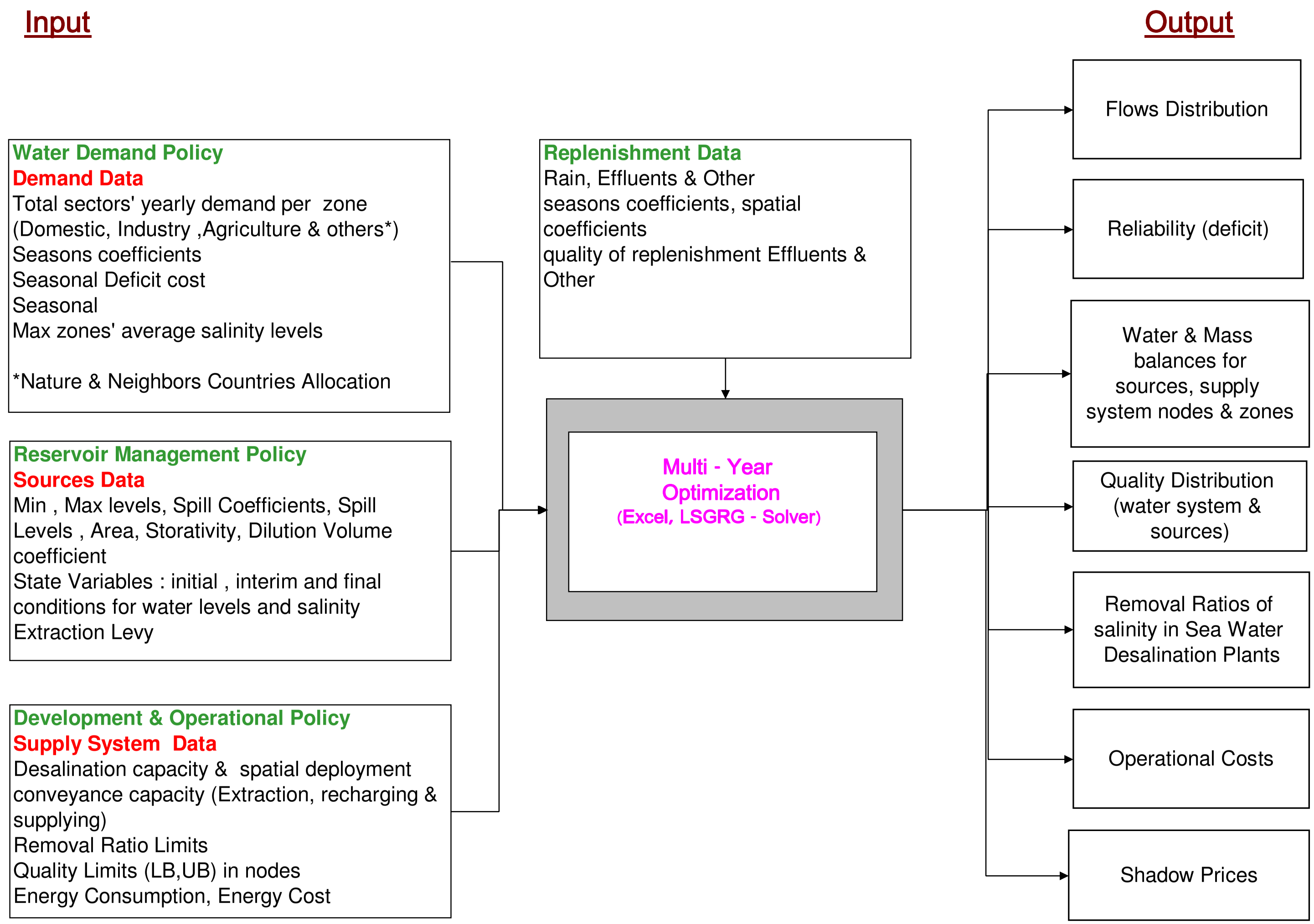
The spill functions (Equation 4.4, Chapter 4) are basically non-smooth functions, which are rendered continuous by the transformations defined by equations 4.5-4.7. This alleviates some of the difficulties associated with solving the model with discontinuous functions.

In practice, the software may hang up at a point that is not even a local optimum due to computational or numeric difficulties. Several runs with the same data, from different starting points, should help in increasing the probability that the solution obtained is global, or at least the best local optimum that could be found. Yet there is no guarantee that the optimum is global.

The software used is Frontline's LSGRG Solver whose interface is the *Premium Solver Platform , V 5.5 - for use with Microsoft Excel* (Frontline Systems, 2003).

Frontline's LSGRG Solver is designed to solve smooth nonlinear problems much larger than the 500 variable limit imposed by the built-in nonlinear GRG Solver. LSGRG is offered in two versions, one capable of solving problems of up to 4,000 variables and 4,000 constraints, the other capable of handling large problems of up to 12,000 variables and 12,000 constraints.

Figure 3.2 : Summery of the Model's Input and Output



4. Mathematical Formulation of the Model

4.1 Introduction

The model was developed in two phases, both for technical and conceptual reasons, first as an annual model and then the annual model was expanded to a multi-year model. The annual model served both as a “test model” and also as the cornerstone for the multi–year model.

This chapter describes the mathematical formulation of the model and its dimensions, its time periods and time horizon, decision variables, constraints, formulation of assumption and the aggregation that was made.

4.2 Model Dimensions

The multi-year model is solved simultaneously for 5 annual time periods: 3 consecutive years and 2 Future Representative Years (FRYs), which represent a ‘typical year’ in the future, beyond the first 3 years (see Figure 4.1). These appear in the multi-year model as 2 single years, each representing a period of several years.

The first FRY represents the years 2007- 2010 and the second FRY represents the years of 2011-2015. The multi-year model in its current application thus covers 3+4+5 = 12 years.

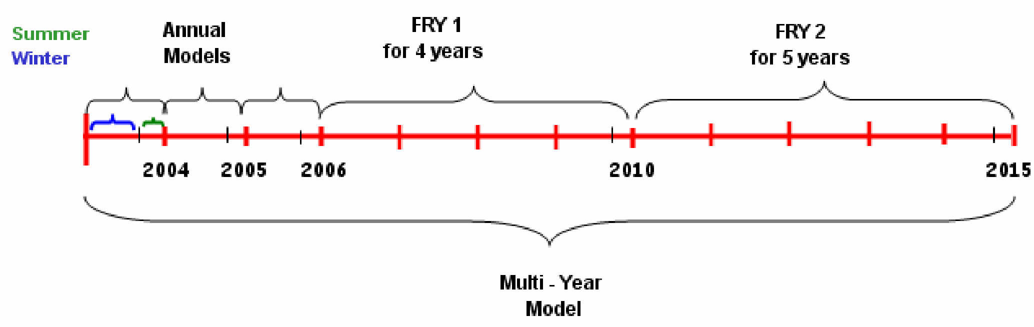


Figure 4.1: Time Scheme for the Multi–Year Model.

Each year has two seasons: Season 1 ~275 days ("winter": October- June) and Season 2 ~90 days ("summer": July-September). The seasons and years are interconnected serially through the 'state variables' of the water sources, namely water levels and water salinity in each source. Each season has:

78 constraints and 210 decision variables (plus 420 upper bounds and lower bounds)

For a 12-year model, covering the period 2004 to 2015 (3 years + 2 FRYs, one representing 4 years and the other 5 years) for a total of 5 linked annual models, covering 10 seasons, the corresponding numbers are: 780 constraints and 2100 decision variables (plus 4200 LB and UB).

4.3 Decision Variables

Q_l^t -Quantity supplied in pipe l in season t (MCM / Season). $\forall l, \forall t, t \in T$

t is the season in year T. There are 82 decision variables of this type per season.

h_n^t - Water level in aquifer n in season t (m). $\forall n, \forall t,\ t \in T$

The levels are measured from the aquifer's bottom. There are 5 decision variables of this type per season.

$Qdes_i^t$ - The amount of desalination produced in plant i in season t, out of the operational capacity installed (MCM/Season) in plant i. There are 10 desalination plants in the model, 5 of them are Sea Water Desalination (SWD) plants represented as decision variables and the rest (Brackish Water Desalination (BWD) plants) supply fixed amounts (which can be changed over time). $\forall i, \forall t,\ t \in T$

RR_i^t - The removal ratio of salt in SWD plant i in season t. $\forall i, \forall t,\ t \in T$

RR is the degree of salinity reduction from the origin seawater salinity. The RR range is theoretically between 0-100%, yet practically it is confined to the range of 99.75-99.95 % (approximately equivalent to reducing the seawater salinity from 27,000 to below 200 and down to 20 mg Cl^-/*liter*). In order to reduce scaling problems (Cohen et al., 2001) the units in percentage are converted to the range 0-10,000 points. Thus, the removal ratio range shown above is 9975-9995.

Def_d^t - Deficit of water to demand zone *d* in season *t* (MCM/Season). There are 16 demand zones, while only 14 of them are decision variables (Sovev Kinneret and JK & Syria are not decision variables). $\forall d, \forall t$, $t \in T$

$Kinspill^t$ - Spills from Lake Kinneret (MCM/Season). $\forall t$, $t \in T$

There is one decision variable per season.

C_{no}^t - The average salinity at node *no* in season *t* (mg Cl^-/*liter*). $\forall no, \forall t$, $t \in T$

There are 18 nodes in the water supply system and 3 zones that function as dilution nodes as well, together 21 nodes.

C_n^t - The average salinity in source *n* in season *t* (mg/*liter*). There are 9 water sources; in 4 of them the salinity is a decision variable. In LK the salinity is not a decision variable but can change over time (mg Cl^-/*liter*). $\forall n$, $n \in 1...4$, $\forall t$ $t \in T$.

A set of artificial variables are added in the model, to avoid mathematical infeasibility while the model is being developed and tuned, and later to identify real problems in the system. The artificial variables are given a high penalty in the objective function, so they are removed from the optimal solution – if at all possible. Once the model is a true representation of reality, then if an artificial variable appears in the mathematical solution this indicates a location where the system, as described in the model, cannot meet the requirements placed on it, pointing to the need to take real steps in the field to make it feasible. An infeasible solution which indicates an error may appear if wrong data and/or constraint parameters (right hand side) were entered into the model in the first place. The main reasons for real infeasibilities include: lack of water to meet the regional water demand, quality limits which can not be met, and lack of conveyance capacity.

The artificial variables are placed in the model according to the potential of encountering an infeasible solution .Some of them were embedded into the equations (and into the model) in "pairs" - one with a (+) sign and the other with a (-) sign since there is a constraint (4.4.5) that all variables are non-negative.

There could be some resemblance to the use of artificial variables in Goal Programming, where artificial variables are used to approach the feasible solution from the infeasible region. In our model the reason for using them is to identify and locate problems of model formulation and later of real infeasibilities.

There are 73 artificial variables per season (out of 210 decision variables per season), that are associated with several types of elements in the model as follows:

$Qartnode_{no}^{t}$ - Artificial source at node *no* in season t (MCM/Season) 18 variables $\forall no, \forall t$, $t \in T$

$Qartmassnode_{no}^{t}$ - Artificial salt mass in node *no* in season *t* (ton/Season): 18 variables. $\forall no, \forall t$, $t \in T$.

$Qartsource_{n}^{t}$ - Artificial source at source *n* in season *t* (MCM/Season): 8 variables. $\forall n, \forall t$, $t \in T$.

$Qartmassource_{n}^{t}$ - Artificial salt mass in source *n* in season *t* (ton/Season): 8 variables. $\forall n, \forall t$, $t \in T$.

$Qartzone_{d}^{t}$ - Artificial source in zone *d* in season *t* (MCM/Season): 6 variables. $\forall d, \forall t$, $t \in T$

$Qartmzone_{d}^{t}$ - Artificial mass in zone *d* in season *t* (ton/Season): 14 variables. $\forall d, \forall t$, $t \in T$

Indices:

$t \in T$, season t in year T= Year, In the multi year model T = 2004, 2005, 2006, period 2007-2010, period 2011-2015

t=1,2 for "winter" - Season 1 ,and "summer" - Season 2, respectively

t = t (s) – in each year t the variable 'X' with index t has two values: $X^{t(1)}, X^{t(2)}$

$n \in OA$, *OA* = 5 Operational sources: 1 = Coastal Aquifer–North (CAN); 2 = Coastal Aquifer–Center (CAC); 3 = Coastal Aquifer–South (CAS); 4 = Mountain Aquifer (MA); 5 = Lake Kinneret (LK).

$i \in I$, *I* = 5 Sea water desalination plants: 1 = West Galilee (WG); 2 = Hadera; 3 = Palmachim; 4 = Ashdod; 5 =Ashkelon.

$f \in FAS$, FAS= 5 Fixed Artificial Sources, 3 Brackish Water Desalination Plants (BWDP), 2 Import Intakes (Im)

$b \in BDW$, BWD = 3 Brackish Water Desalination Plants:

1 = BWD-Hof Carmel ; 2=BWD-Gat ; 3= BWD – Mishor Yeruham (MY)

$im \in \text{Im}$, Im=2 Import Intakes: 1. Import Hadera; 2. Import Ashkelon.

$d \in D$, D = 14 Demand Zones: 1 = WG– Kishon; 2 = Hof–Carmel; 3 = Pardes-Hana; 4 = Yosh–North; 5 = Sharon; 6 = Gush-Dan; 7 = Modi'in; 8 = Shiflat Lod; 9 = Shiflat Yehuda North; 10 = Jerusalem; 11 = Shiflat Yehuda South; 12= Lachish; 13 = Ashkelon–Gvaram; 14 =Negev.

$no \in Nodes$ =18 nodes on the conveyance system. The main nodes are: 1 = Kfar Yehoshua (KY); 2 = Menashe; 3= Mezer; 4 =Rosh–Hayin; 5 = Achisemech; 6 = Hulda; 7 = Zohar. The rest: 8-18 = points on the conveyance system

$f \in l \in L$, L – all pipes in the model.

4.4 Constraints

The 78 constraints per season represent groups of constraints.

4.4.1 Hydrological Constraints

Lake Kinneret (LK) is a surface reservoir, while the other natural sources are aquifers; however the hydrological constraints in the model refer to all sources as “cells” of water with different characteristics. Therefore, the term “aquifer” is sometimes used also for LK in defining the mathematical formulation.

The difference between the replenishment from all sources and the water usage from an aquifer (water balance) is equal to the change in the aquifer volume during the season. The mathematical definition of that principal is:

(4.1) $$\sum Qin_n^t - \sum Qout_n^t = \frac{\Delta V_n}{\Delta T} = SA_n \cdot (h_n^t - h_n^{t-1}) \quad \forall n, \forall t,\ t \in T, n \in OA$$

There are 5 constraints of this type, one for each source.

The mass balance for the quality component (salinity) in each source is represented by the non-linear equation:

$$(4.2)\quad \sum Cin_n^t Qout_n^t - \sum Cout_n^t Qout_n^t = \frac{\Delta CV_n}{\Delta T} = C\frac{\Delta V_n}{\Delta T} + V_n\frac{\Delta C_n}{\Delta T} = SA_n \cdot \left(C_n^t \cdot h_n^t - C_n^{t-1} \cdot h_n^{t-1}\right)$$

$\forall n, \forall t,\ t \in T, n \in OA$

To represent a "mixing volume" in the aquifer, which allows mixing to occur in part of the aquifer thickness, a coefficient $0 < hmix_n \le 1$ is defined, such that when $hmix_n = 1$ dilution occurs in the entire thickness (depth) of the aquifer. This modifies the preceding equation as follows:

$$(4.3)\quad \sum Cin_n^t Qin_n^t - \sum Cout_n^t Q_n^t = \frac{\Delta CV_n}{\Delta T} = C\frac{\Delta V_n}{\Delta T} + V\frac{\Delta C_n}{\Delta T} = SA_n \cdot hmix_n \cdot \left(C_n^t \cdot h_n^t - C_n^{t-1} \cdot h_n^{t-1}\right)$$

$\forall n, \forall t,\ t \in T, n \in OA$

Where:

Qin_n^t - Recharge into *n* in season *t* (MCM).

$Qout_n^t$ - Extraction from aquifer *n* in season *t* (MCM).

$\frac{\Delta V_n}{\Delta T}$ - Change in water volume of aquifer *n* during the period ΔT (MCM/Season).

SA_n - Storativity of aquifer *n* (between 0 and 1 MCM /m).

h_n^t, h_n^{t-1} - Average water level in aquifer *n* (above the bottom) in season *t* and *t-1*, respectively (m).

Cin_n^t - Average salinity of the replenishment of the aquifer (mg Cl^-/*liter*).

$Cout_n^t$ - Average salinity of the water extracted form the aquifer (mg Cl^-/*liter*).

$\frac{\Delta CV_n}{\Delta T}$ - The change of mass in aquifer *n* cell during time period ΔT (Tons of Cl^- /Season).

$C_n^t C_n^{t-1}$ - The average water salinity in aquifer *n* in seasons *t* and *t-1* respectively (mg/*liter*).

Notes:

- Salinity in Lake Kinneret is constant. Therefore there are only 4 constraints of type (4.3).

▪ Both sides of equation (4.3) express the change in total mass of salts per season.

An example for the mass balance is given for the Central Coastal Aquifer:

$$(4.4)\quad \sum_r C_r^t \cdot Q_r^t - C_{CC}^t \cdot \sum_p Qn^t - Kcc \cdot \Delta T \cdot \overrightarrow{kdir}_{cc}^t \cdot C_{CC}^t \cdot \left(hcc^t - hspill\right) + Qartmass_{cc}^t =$$
$$SAc \cdot hmix_{CC} \cdot \left(C_{CC}^t \cdot h_{cc}^t - C_{CC}^{t-1} \cdot h_{cc}^{t-1}\right)$$
$$\forall t, r \in R \;\; t \in T, n \in OA$$

Where:

Q_r^t - Natural replenishment and recharge of water from sources and pipes r=1....R (MCM/Season), each having its own salinity.

C_r^t - The salinity of water source *r*=1...*R* (mg Cl^-/*liter*).

Qn^t - The production from aquifer cell *n* (MCM/Season)

C_{CC}^t - The average salinity in the Central Coastal Aquifer (CCA) (mg Cl^-/*liter*).

K_{CC} - The spill coefficient from CCA to the sea (m^2/day)

ΔT - The number of days per season (day)

$hspill_{CC}^t$ - Spill level above the bottom of the aquifer cell (m).

hcc^t - Water level in CCA (m).

$hmix_{CC}$ - The thickness of the mixing volume in CCA (m).

$Qartmass_{cc}^t$ - Artificial mass source (MCM/Season) – used to guarantee mathematical feasibility; is given a large penalty coefficient in the objective function.

$\overrightarrow{kdir}_{cc}^t$ - A direction coefficient that takes on the value 0 or 1 according to the sign of the expression $\left(hcc^t - hspill\right)$, so as to zero out the term if the water level is below the spill level. To avoid an “If statement” which is a non-smooth function, the value of the direction coefficient $\overrightarrow{kdir}^t$ is determined by a "direction equation" and the spill value by a "smoothing function" (Cohen et al, 2000a), defined by the flowing expressions.

(4.5) $$\vec{k}dir^{t} = \frac{1*\exp(k\mathrm{x}^{*}) + 0*\exp(-k\mathrm{x}^{*})}{\exp(k\mathrm{x}^{*}) + \exp(-k\mathrm{x}^{*})} = \left\{ \begin{array}{l} = \ 1 \quad when \quad \mathrm{x} >> 0 \\ \\ = \ 0 \quad when \quad \mathrm{x} << 0 \end{array} \right\}$$

Where the spill to the sea given by:

(4.6) $$\mathrm{x} = Q^{t}_{n-sea} = k_{CC} \cdot \left(h^{t}_{CC} - hspill^{t}_{cc}\right)$$

With a large enough value of *k*, the expression (4.5) takes on the value 1 if the water level in the aquifer is above the spill level, and is 0 otherwise, in which case there is no spill. The actual flow to the sea is given by a relaxation function:

(4.7) $$Q^{t}_{n-sea}* = X^{*} = \frac{Q^{t}_{n-sea}}{\sqrt{\left(\left(Q^{t}_{n-sea}\right)^{2} + \varepsilon\right)}} \approx \pm 1$$

$k = 100$
$\varepsilon = 10^{-3}$

$Q^{t}_{n-sea}{}^{*}$ rises from 0 at $Q^{t}_{n-sea} = 0$ and tends to 1 quickly as Q^{t}_{n-sea} increases.

The value of *k* is large enough to drive the negative exponential to zero, while the small value ε is used to avoid division by zero.

When - $\vec{k}dir^{t}$ tends to 1 the water / mass loss for the year T in aquifer n is computed

When - $\vec{k}dir^{t}$ tends to 0 the water / mass loss for the year T in aquifer n is zero.

Note:

- k , ε determines the of "softness" for the transition from one direction to the other.
- At his stage, the coefficient $\vec{k}dir^{t}$ is calculated yearly (according to the value of Q^{t}_{n-sea} in the winter due to simplification considerations in the multi year model)
- As a result of these definitions the direction indicator *kdir* takes on the following values:

$$x >> 0 \rightarrow, \quad X^* \Rightarrow 1 \rightarrow, \quad kdir \Rightarrow 1$$
$$x << 0 \rightarrow, \quad X^* \Rightarrow -1 \rightarrow, \quad kdir \Rightarrow 0$$

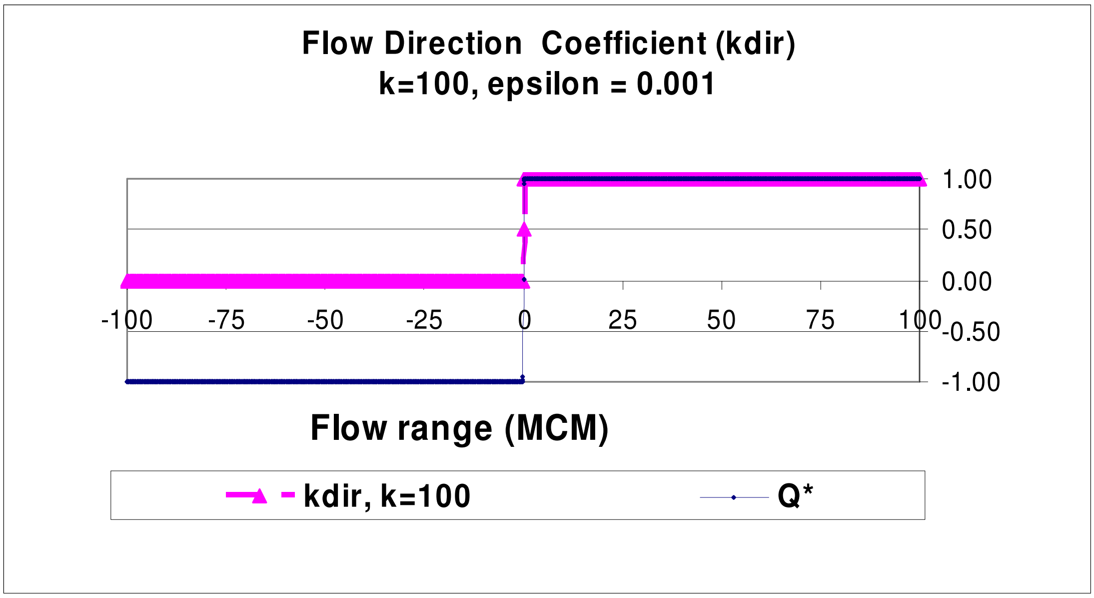


Figure 4.2: Flow Direction Coefficient.

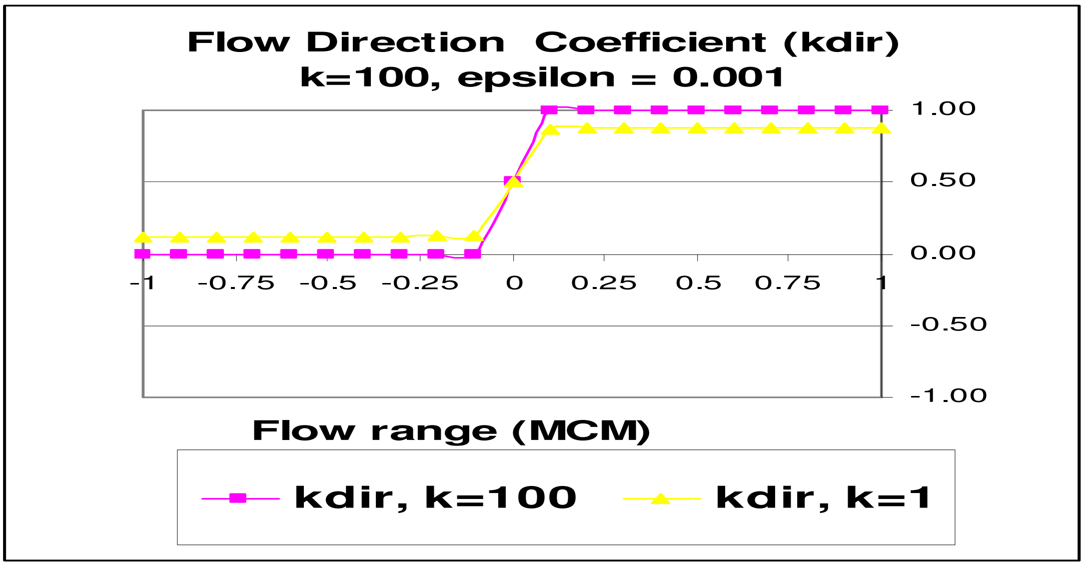


Figure 4.3: Sensitivity of the approximation with respect to the coefficient k.

4.4.1.1 Water Level Constraints

(4.8) $h\min_n^t \leq h_n^t \leq h\max_n^t \quad \forall n, \forall t, t \in T \;, \; n \in OA$

There are 5 constraints of this type for each season.

Where:

$h\min_n^t$ - Minimum seasonal required level in aquifer n (m)

h_n^t - Average water level in aquifer n in season t (m)

$h\max_n^t$ - Maximum seasonal allowed level in aquifer *n* (M)

4.4.1.2 Aquifer Salinity Constraints

(4.9) $C\min_n^t \le C_n^t \le C\max_n^t \quad \forall n, \forall t, t \in T \;, \; n \in 1...4$

$C\min_n^t$ - Minimum seasonal average salinity required in aquifer *n* in season *t* (mg Cl^-/*liter*).

C_n^t - Average concentration in aquifer *n* in season *t* (mg Cl^-/*liter*).

$C\max_n^t$ - Maximum seasonal average concentration allowed in aquifer *n* in season *t* (mg Cl^-/*liter*).

4.4.1.3 Spills in Lake Kinneret

Spills from Lake Kinneret are decision variables, which satisfy:

(4.10) $Kinspill\min^t \le Kinspill^t \le Kinspill\max^t \quad \forall t, t \in T$

Notes:

- There is one constraint per season (part of the UB and the LB constraints).
- The UB and LB could be changed each season, but were fixed in this version of the model.

4.4.2 Demand

4.4.2.1 Minimum Demand in Consumer Zones

The demand constraint at zone *d* is defined as:

(4.11) $\sum_{l=1} Q^t{}_{ind} + Def_d^{\,t} \ge D_d^{\,t} \quad \forall d \;\; d \in D \,, \; \forall t \;\; t \in T$

There are 14 constraints of this type for each season.

Where:

$Q^{t}{}_{ind}$ - The total amount of water supplied to zone *d* in season *t* from all pipes connected to the demand zone (MCM/Season)

$D_d{}^t$ - The demand for water in zone *d* in season *t* (MCM/Season).

$Def_d{}^t$ - The deficit of water resulting in zone *d* (MCM/Season).

4.4.2.2 Prescribed Quality of the water supplied to Consumer Zones

The weighted average salinity in the water supplied to demand zone *d* in season *t*.

(4.12) $\overline{C_d^t} = \dfrac{\sum Q_{l-d}^t \cdot C_l^t}{\sum Q_{l-d}^t} \quad \forall d \;\; d \in D\,, \;\; \forall l \;\; l \in l-d \;\; ,\forall t \;\; t \in T$

Must be below the maximum allowed value

(4.13) $\overline{C_d^t} \le Cps\max{}_d^t$

There are 14 constraints from that type.

Where:

$\overline{C_d^t}$ **-** The weighted average salinity supplied to zone *d* in season *t* (mg Cl^-/*liter*).

$Cps\max{}_d^t$ - The maximum weighted average salinity allowed in zone *d* in season *t* (mg Cl^-/*liter*).

4.4.3 Conveyance System

4.4.3.1 Conveyance Capacity

(4.14) $0 \le Q_l^t \le con\max Q_l^t$

There are 82 constraints of this type per season.

Where:

Q_l^t - The seasonal quantity that flows in pipe *l* (MCM/Season).

$con\max Q_l^t$ - The installed conveyance capacity of pipe *l* (MCM/Season).

Note:

- Development plans of pipe capacities are expressed by changing $con\max Q_l^t$.

4.4.3.2 Quantity Conservation

$$(4.15)\quad \sum_{in=1}^{l} Q_{in-no}^{t} + a_{in-no}^{t} = \sum_{out=1}^{u} Q_{no-out}^{t}$$

$$\forall l \;\; l \in in\,,\ \forall u \;\; u \in out\,,\ \forall no \;\; no \in nodes\ ,\ \forall t \;\; t \in T$$

a_{in-no}^{t} **-** Artificial variable

4.4.3.3 Mass Conservation

$$(4.16)\quad \sum_{in=1}^{l} Q_{in-no}^{t} \cdot C_{in-no}^{t} + ma_{in-no}^{t} = \sum_{out=1}^{u} Q_{no-out}^{t} \cdot \overline{C}_{no}^{t}$$

$$\forall l \; l \in in\,,\forall u \; u \in out\,,\forall no \; no \in nodes\,,\forall t \;\; t \in T$$

There are 21 constraints of each type per season.

Where:

l,u - Pipes.

no – node in the supply system.

in - All pipes that convey water into node *no*.

out - All pipes that convey water out of node *no*.

nodes – All nodes of the supply system.

$\sum_{in=1}^{l} Q_{in-no}^{t}$ - The sum of water from all pipes that convey water to node *no* in season *t* (MCM).

$\sum_{out=1}^{u} Q_{no-out}^{t}$ - The sum of water from all pipes that convey water out of node *no* in season *t* (MCM).

a_{in-no}^{t} - Artificial variable (water - MCM).

C_{in-no}^{t} - Water quality in pipe in-no (mg Cl^-/*liter*).

$\overline{C}_{no}^{t}$ - Weighted average water salinity computed at node *no* (mg Cl^-/*liter*).

ma_{in}^{t} - Artificial variable (mass - Ton).

The salinity of the water supplied to demand zones is controlled, by placing upper and/or lower bounds on salinity at the nodes:

(4.17) $\overline{C}\min_{no}^{t} \leq \overline{C}_{no}^{t} \leq \overline{C}\max_{no}^{t} \quad \forall no \;\; no \in nodes, \forall t \;\; t \in T$

4.4.3.4 Desalination Capacity

(4.18) $des\min_{i}^{t} \leq Qdes_{i}^{t} \leq des\max_{i}^{t} \quad \forall i \;\; i \in des, \forall t \;\; t \in T$

(4.19) $Qdesshut_{i}^{t} = des\max_{i}^{t} - Qdes_{i}^{t} \quad \forall i \;\; i \in des, \forall t \;\; t \in T$

Where :

des - Seawater desalination plants.

$Qdes_{i}^{t}$ - Quantity of water desalinized in plant *i* in season *t* (MCM/Season).

$des\min_{i}^{t}$ - Minimum operational capacity in plant i (MCM/Season).

$des\max_{i}^{t}$ - Maximum operational capacity in plant i (MCM/Season).

$Qdesshut_{i}^{t}$ - Operational shutdown of the desalination plant *i* in season *t* (MCM/Season).

Notes:

- Usually $des\min_{i}^{t} = 0$ and $des\max_{i}^{t} =$ installed capacity of plant *i*.
- The value $des\max_{i}^{t}$ can be changed with time, to express the desalination development policy.

There are 5 constraints of this type per season, one for each SWD plant.

4.4.3.5 Desalinated Water Quality

(4.20) $Cdes_{i}^{t} = Cn_{i} \cdot \dfrac{\left(10000 - RR_{i}^{t}\right)}{10000} \quad \forall i \;\; i \in des, \forall t \;\; t \in T$

(4.21) $RR\min_{i}^{t} \leq RR_{i}^{t} \leq RR\max_{i}^{t} \quad \forall i \;\; i \in des, \forall t \;\; t \in T$

Where:

$Cdes_i^t$ - Water salinity in the outlet of desalination plant *i* in season *t* (mg Cl^-/*liter*).

Cn_i - The salinity in source *n* of plant *i* - mg Cl^-/*liter*. In this model it refers to the Mediterranean Sea salinity, which is 27,000 mg Cl^-/*liter*.

RR_i^t - Percentage removal by plant *i* in season *t* (converted from % to the range 0-10,000, to avoid scaling difficulties); it is a decision variable.

$RR\min_i$ - Minimum *RR* in plant *i* (0-10,000)

$RR\max_i$ - Maximum *RR* in plant *i* (0-10,000)

There are 5 constraints from that type per season, one for each desalination plant.

Note:

- In the current version of the model RR_i^t is determined according to the first season of the first year, but is subject to all constraints of all subsequent years due to simplification of the multi-year model. It can be explained as the development plan needed (for salinity removal) to be implemented in the first year of the model in order to comply with demand in the future constraints as well.
- The prescribed range for the RR in the current model is 9980-10000.

4.4.4 State Variables

The state variables are the water levels (h_n^t) and salinities in the aquifers (C_n^t)

They are the initial values for each season and each year. They function as continuity variables between the years and the season and represent the "memory" of the water system over time. For the first year and first season the water level and the water salinity is entered by the user.

In order to compute the initial level at the beginning of the FRY we multiply the last year change of the state variable by the number of the years (e.g. 2-5) till the start of the FRY in the representative period. We add the delta computed to the previous value of the state variable to get the final FRY initial value. The calculation can be computed by the expression:

(4.22) $X_n^{t-1}(T) = X_n^t + \Delta T \cdot \left(X_n^t - X_n^{t-1}\right)$

$\forall X_n^t \ \ h_n^t, C_n^t \in X_n^t, \forall t \ \ t \in T$

Where:

T – Final year of the FRY

ΔT - The number of years between the beginning of FRY and the last computed year in the model

$X_n^t(T)$ - State variable of natural aquifer *n* in season *t* - salinity mg Cl^-/*liter* or water level (m).

Note:

- See figure 4.1 for the extrapolation made in the multi- year model.

4.4.5 Non Negative Variables

All decision variables are Non Negative.

$0 \le X^t$

4.5 Objective Function

The objective of the multi-year model is to minimize the total cost of operation over the planning horizon, which is made of 3 consecutive years and 2 FRYs in the future, a total of 10 seasonal time periods. The components of the (<u>non-linear</u>) objective function are:

a. Operational cost of pumping and recharge.

b. Operational cost of conveyance.

c. Cost of regional deficits.

d. Operational cost of desalination plants.

e. Cost (penalty) for not using the full capacity of desalination plants.

f. Cost of spills from the Kinneret (loss of water).

g. Extraction levy from the sources.

h. Penalty on artificial variables (this term becomes zero when a feasible solution is attained).

$$(4.23)\quad MinZ=\sum_{t=1}^{T}\frac{\sum_{S(t)=1}^{2}\left(\begin{array}{l}\sum_{l} CE_{l}^{s,t}\cdot Q_{l}^{s,t}+\sum_{n=1}^{OA} EL_{n}^{s,t}(h_{n}^{s,t})\cdot Q_{l,n}^{s,t}+\\ \sum_{i=1}^{des}\left(Cdes_{i}^{t}(RR^{t},E_{i}^{t})\cdot Qdes_{i}^{s,t}+Cdesshut_{i}^{t}\cdot Qdesshut_{i}^{s,t}\right)+\\ \sum_{d=1}^{D} Cdef_{d}^{s,t}\cdot def_{d}^{s,t}+Ckinspill^{t}\cdot Kinspill^{s,t}+far\,\mathrm{var}^{t}\cdot\sum_{j=1}^{AV} ar\,\mathrm{var}_{j}^{s,t}\end{array}\right)}{(1+r)^{t}}$$

$$\forall i\ \ i\in des,\forall t\ \ t\in T\quad \forall d\ \ d\in D,\ \ \forall j\ \ j\in av\ ,\ \forall S(t)$$

$S(t)$ - is the specific season (1 winter, 2 summer) of a year t.

The objective function is non-linear in two terms: the extraction levy $E_{Ln}(h_n)$ and the salinity removal cost at the desalination plants - $Cdes_i^t(\mathrm{RR}^t, \mathrm{E}_\mathrm{i}^t)$.

The present value of the objective function calculates the Net Present Value (NPV) of the operational cost by using a discount rate on a series of yearly operational costs in the future:

$$(4.24)\quad NPV(r,t)=\sum_{t=1}^{T}\frac{values^{t}}{(1+r)^{t}}$$

r – Annual interest rate.

t - years

Where:

Z - The objective function value - million US $.

$Kinspill^t$ - The amount of spills in Kinneret in season *t* (MCM/Season).

$CKinspill$ -The cost of spills from the Kinneret $\left(\$/m^3\right)$.

$Cdes_i^t(\mathrm{RR}_\mathrm{i}^t, \mathrm{E}_\mathrm{i}^t)$ - Operational cost of desalination plant *i*, which includes capital recovery, energy, maintenance and the percentage removal $\left(\$/m^3\right)$.

$Cdef_d^t$ - Deficit cost in region d in season t $\left(\$/m^3\right)$.

$far\,\mathrm{var}$ - Artificial Variables (AV) cost $\left(\$/m^3\right)$.

4.5.1 Definition of the Conveyance Cost

(4.25) $CE_l^t = E_l \cdot EC_l^t \quad \forall t \;\; t \in T \quad \forall l \;\; l \in L$

(4.26) $E_l^t = \dfrac{(\Delta H_T + \Delta H_l \cdot L + \Delta H_p^t)}{200 \cdot 0.736} \quad \forall t \;\; t \in T \quad \forall l \;\; l \in L$

CE^t - Cost of supply (pumping and transporting) $\left(\$/m^3\right)$.

E_l - Energy consumption $\left(Kw/m^3\right)$.

EC^t - Energy cost in season t $\left(\$/Kw\right)$

ΔH_T - Topographic lift (m).

ΔH_l - Hydraulic energy loss ($\%_{o}$)

L - Length of pipe (km)

ΔH_p^t - Supply head required (m)

Note: The coefficients 200 is derived from units conversion, where 1 Hp = 0.736 Kw

4.5.2 Extraction Levy

(4.27) $EL_n^t = \left[1 - \dfrac{\left(H\,\text{int}_n - \overline{h_n^t}\right)}{H\,\text{int}_n}\right] \cdot MaxEL_n^t \quad \forall n \;\; n \in N \quad \forall t \;\; t \in T$

(4.28) $H\,\text{int}_n^t = h\max{}_n^t - h\min{}_n^t \quad \forall n \;\; n \in N \quad \forall t \;\; t \in T$

(4.29) $\overline{h_n^t} = h\max{}_n^t - h_n^t \quad \forall n \;\; n \in N \quad \forall t \;\; t \in T$

Where:

EL_n^t - Extraction Levy from aquifer *n* in season *t* ($\$/m^3$)

$MaxEL_n^t$ - Maximum Extraction Levy on aquifer *n* in season *t* ($\$/m^3$)

$H\,\text{int}_n^t$ - Operational range in aquifer *n* in season *t* (m)

$\overline{h_n^t}$ - Unsaturated thickness in aquifer *n* in season *t* (m)

h_n^t - Water level in aquifer *n* in season *t* (m)

$$(4.30)\quad EL_n^t = \begin{Bmatrix} MaxEL_n^t & h_n^t \Rightarrow h\min_n \\ \\ EL_n^t & h_n^t \Rightarrow h\max_n \end{Bmatrix} \quad \forall n \;\; n \in N \;\; \forall t \;\; t \in T$$

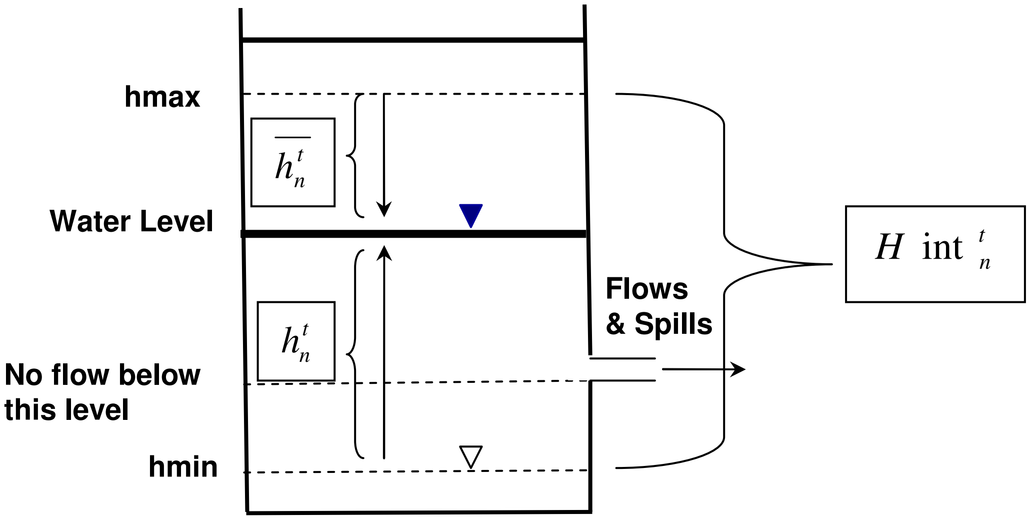


Figure 4.4: Definition sketch for the Extraction Levy

4.5.3 Desalination Cost

(4.31) $\text{Cdes}_i = \text{CdesE}_i + CRR_i \quad \forall i \;\; i \in des, \forall t \;\; t \in T$

(4.32) $CRR_i^t = \dfrac{1}{\left(10000 - RR_i^t\right)^a} \quad \forall i \;\; i \in des, \forall t \;\; t \in T$

(4.33) $RR\min_i^t \le RR_i^t \le RR\max_i^t \quad \forall i \;\; i \in des, \forall t \;\; t \in T$

Where:

CdesE_i - Cost related to capital energy and operation without the removal of additional salinity at SWD i ($/m^3)

CRR_i^t - Cost related to removal of salinity in SWD plant i ($/m^3)

$RR\min_i$ - Minimum *RR* in plant *i* (0-10,000)

$RR\max_i$ - Maximum *RR* in plant *i* (0-10,000)

a = constant t- years

Note: Incase there is no data to differentiate between the costs CdesE, CRR_i it possible to degenerate one of the costs and to put all the cost in the value Cdes_i . RR will be calculated just as a result of the quality demand constraints.

5. Examples of the Model's Results

5.1 Introduction

In this chapter some of the model's results will be presented and analyzed. The results are presented in two sections:

1. Results for one year runs (two seasons), using the annual model.
2. Results for long-term runs (3 successive years and two FRYs to represent two future periods of several years each) – using the multi–year model.

The results are presented in flow charts and in tables. These are designed as 'management reports' in the sense that the information has been condensed into formats that should be easy to comprehend. There is a color schematic of the entire system, upon which the season's results are displayed. It depicts the main components (detailed in section 4.3, Figure 3.1) of the national water system: desalination plants, natural sources, consumption zones and the main pipes of the conveyance system. For each pipe there is an arrow which indicates the direction of flow, and there is a pair of numbers which give the model's solution: salinity (mg Cl^-/*liter*) on top (in red) and quantity (MCM/Season) below (in black). Each main node in the supply system is numbered and represented by a red circle or box with the node's name inside. At the top of each source there a pair of numbers: the average water level per season (m-ASL – in blue) - and the average salinity per season (mg Cl^-/*liter* – in red).

The description of model's results both for the annual model and the multi year model will be presented in this chapter where the main focus will be analyzing the runs' results. General conclusions and strategic conclusions based on these runs and future development needed as a result - will be presented in the next chapters.

5.2 Results of the Annual Model

5.2.1 Base Run

The main information for the Base Run (BR) is:

<u>a. Time horizon and time units</u>

One year with two seasons - season 1, "Winter" ~ 275 days, season 2 "Summer " ~ 90 days.

b. Development program:

1. Desalination: no sea water desalination available. Most of the supply is from the natural sources, supplemented by 13 MCM/Year of brackish water desalination.

2. Conveyance System: a few lines of the full model where eliminated: line 11-6 (from node 6 (Hulda) to node 11– in both directions), MA (Mountain Aquifer water source) to Yosh-N (consumption zone), 10- CC (Recharge from node 10 to the Costal Aquifer Center), TTA – Mod (from Rosh Ha'Ain to Modi'in). These assumptions are made in order to represent the "current" development phase of the system better and to simplify the runs at this stage.

c. Sources management policy:

Extraction levy ('Hetel Hafaka'): the levies reflect the current order of using the sources first from Lake Kinneret (max levy=0 US$/m^3), next from the Mountain Aquifer (max levy=0.05 US$/m^3), and finally from the Coastal Aquifer (max levy=0.13 US$/m^3).

There are no set of targets (constraints values) on water level and water salinity in the end of the summer (season 2 – the end of the annual run).

d. Demand management policy:

The full demand should be supplied. The price of water shortage is high enough to prevent shortages (the deficit cost is two orders of magnitude higher than the average water supply cost).

e. Quality management policy:

1. The max salinity prescribed for supply to demand zones is 400 mg Cl^-/*liter*.

2. The salinity of Lake Kinneret is 250 mg Cl^-/*liter* (constant).

f. Replenishment:

1. The CA annual replenishment has two "active" components (out of three possible in the model): replenishment from reclaimed wastewater used for irrigation (~ 50 MCM/Year and 350 mg Cl^-/*liter*) and replenishment from annual precipitation (250 MCM/Year and 250 mg Cl^-/*liter* which include the salts which are "pushed" from the unsaturated zone into the groundwater).

2. The MA annual replenishment has two components: replenishment from reclaimed wastewater used for irrigation (~ 20 MCM/Year and 350 mg Cl^-/*liter*) and

replenishment from annual precipitation (360 MCM/Year and 140 mg Cl^-/*liter* which include the salts which are "pushed" from the unsaturated zone into the groundwater).

g. Initial conditions: are summarized in Table 5.1.

Note: Artificial variables are not expected to remain in the solution, since the introduction of penalties for not meeting demands makes it possible to find a feasible solution.

Table 5.1: Initial Conditions for the Annual Base Run.

No.	Source Name	Range of allowed change of water level	Initial Water level above bottom of base line	Range of allowed change of salinity	Initial Water Quality (Salinity)
		[m ASL]	**[m ASL]**	**[mg Cl^-/*liter*]**	**[mg Cl^-/*liter*]**
1	Lake Kinneret	-208.9 - -213	- 211.9	250*	250
2	Coastal Aquifer – North (CN)	+30 - -10	+3.5	250-250	150
3	Coastal Aquifer – Center (CC)	+10 - -10	+3.5	150-250	150
4	Coastal Aquifer – South (CS)	+30 - -10	+2	150-250	150
5	Mountain Aquifer (MA)	+22 - +12	+15	140-250	140

* Constant

5.2.2 Scenarios Description

The scenarios are presented in Table 5.2.

Table 5.2: Annual Model - Scenarios List.

No	Scenario's Name	Scenario's Description
1	Base Run (BR)	Two seasons, no desalination, initial conditions presented in Table 5.1
2	BR+1m in the Mountain Aquifer	Same as BR + a constraint of level above + 1m in the Mountain Aquifer (MA) at the end of the 2nd season.
3	BR + 150 MCM/Year in Lake Kinneret Basin	Same as the BR + the consumption in the Lake Kinneret Basin (LKB) was increased by 150 MCM/Year.
4	BR + 100 MCM/Year Negev	Same as BR + the consumption in the Negev zone was increased by 100 MCM/Year.
5	BR +150 mg Cl^-/*liter* to Gush–Dan + 45 Des-Pal	Same as the BR + a constraint on the maximum salinity of 150 mg Cl^-/*liter* in the second season (instead of the original 400 mg Cl^-/*liter*) was imposed on the supply to Gush Dan. A sea water desalination plant was installed in Palmachim with a capacity of 45 MCM/Year.
6	BR +150 mg Cl^- in Gush–Dan + 45 Des Pal + quality limit at KY	Same as Scenario 5 + minimum salinity was imposed at 'Kfar Yehusha' (KY, Node 1) of minimum 250 mg Cl^-/*liter*

5.2.3 Analysis of the Results

The main results of these scenarios are summarized in Table 5.3 and in Figures 5.5-5.17. Each figure contains the main seasonal values placed on the model's topology. Description and analysis of the results are presented in the following section.

<u>Scenario 1: Base Run (BR) – Figure 5.1-5.2</u>

There is no deficit. The difference between the total replenishment and demand (95 MCM/Year, Table 5.3) is supplied from storage in natural sources and from the existing desalination plants of brackish water (13 MCM/Year). There are no sea water desalination plants.

At the end of the year there is a rise in water table in Lake Kinneret (LK), (+0.23 m) and in the North Coastal Aquifer (NCA)-(+0.13 m). In the rest of the natural water sources there is a decline in the water levels. The Mountain Aquifer (MA) was completely depleted and reached its 'red line' (+12m ASL). The salinity of all aquifers (in all cells) deteriorated by the end of the one year run. The salinity of the MA was raised by 0.53 mg Cl^-/*liter* and in CA by 1.26 mg Cl^-/*liter*. In the CA the deterioration in quality is higher which is associated with the fact that there is more intensive reclamation above the aquifer and salinity of replenishment from precipitation is higher.

The objective function (OF) value is 100.1 MUS$/Year. The only "active" components of the OF are conveyance cost (73%) and extraction levies (27%).

Scenario 2: BR + 1m in the Mountain Aquifer- Figure 5.3-5.4

The water table in MA at the end of the 2^{nd} season is prescribed to be 1m above the "red line". The water level result is as was expected (+13 ASL – 1 m above the + 12 ASL level in BR). The reduction in the extraction of water from MA was compensated mainly by extracting water from LK. The OF went up by only 2.8 MUS$/ Year. The active components of the OF are the same as in the BR.

The addition in conveyance costs (+5.9 MUS$/Year) is explained by increasing conveyance from a more expensive source (because of the addition of transportation length) while this extra expense was compensated by a lower extraction levy (-3 MUS$/ Year) since the extraction levy in LK is 0.

Scenario 3: BR + 150 MCM/Y in the Lake Kinneret Basin - Figure 5.5-5.6

The increase in consumption in the Lake Kinneret Basin (LKB) by 150 MCM/Year turned out to be a "local change" considering the results of the whole water system. In comparison with the BR the OF value did not change. The main change was in the water level in LK. In the BR, the water level in LK at the end of the run (2^{nd} season) was 0.89 m higher than in this run (0.23-(-0.67)). The product of the LK storativity (=1, since it is a lake) times the water level change (0.89m) and the area of the Kinneret (167 km^2) provides the additional demand.

There was no extraction levy on the increased demand (it is considered 'local production'); therefore this component in the OF did not change and therefore the total value of the OF did not change.

<u>**Scenario 4: BR + 100 MCM/Y to the Negev- Figure 5.7-5.8**</u>

In this run the OF had another 'active' component which is the Deficit Cost. The local source (MA) of the Negev demand Zone was fully utilized and was depleted again. The consumption in the Negev was increased by 100 MCM/Year but there is a remaining deficit of 6.4 MCM (all in the 2nd season) as a result of the limitation on the conveyance capacity in the second season from Zohar (node 7) to the Negev demand zone. In the first season the conveyance constraint to the Negev was not binding and the addition of consumption caused the conveyance cost component in the OF to rise from 47.6 MUS$/Season to 59.2 MUS$/Season. In the 2nd season the limitation in capacity and the relatively high cost of deficit caused the OF to peak up to 436 (MUS$/Year).

Scenario 5: BR + 150 mg Cl^-/*liter* to Gush Dan + 45 MCM/Year Desalination in the Palmachim Plant - Figure 5.9-5.10

The maximum (weighted average) salinity allowed for supply to Gush Dan (GD) in the 2nd season was reduced from 400 mg Cl^-/*liter* in the BR to 150 mg Cl^-/*liter*. A SWD plant with an installed capacity of 45 MCM/Year was installed in Palmachim. It was expected that most water will be supplied from the SWD plant due to the quality restriction and the relatively high initial level of salinity in the aquifers (according to the Base Run there is no need for desalination due to the wide (non-restrictive) quality constraints and sufficient water in terms of water quantity).

The SWD plant worked but added only 5.5 MCM (out of the 45 MCM/Year installed) in the 2nd season (18 MCM desalinated in total). The range of salinity in the outlet of the SWD was confined to the range of 0 mg Cl^-/*liter* (RR = 100%) to 50 mg Cl^-/*liter* (RR = 99.80%) from origin sea water salinity of 27,000 mg Cl^-/ li. The resulting salinity in the outlet of the desalination plant was 34.4 mg Cl^-/*liter* (R.R. = 99.87%).

The model met the maximum weighted average salinity constraint in Gush Dan (in the 2nd season only) by diluting water from Lake Kinneret (LK) in the West Galilee

(WG) demand zone. Water from LK is the most saline but cheaper than SWD plant. The water was supplied to WG through the Kfar Yehoshua (KY) node. The supply exceeded the demand by 15.65 MCM. The addition of water to WG is explained by the need to dilute the water before it reaches Gush Dan (GD).

The dilution happened in WG since the water salinity there is low (~50 mg Cl^-/*liter*). The water that came from LK with 250 mg Cl^-/*liter* came out of the KY node with 224.9 mg Cl^-/*liter*. The water was conveyed south through the National Carrier (NC) and was diluted again with water from the MA to the level of 170 mg Cl^-/*liter* just before entering the GD demand zone. Finally, the weighted average of all sources to GD was 150 mg Cl^-/*liter* - as was prescribed. In the BR the water supplied to GD was with salinity of 201 mg Cl^-/*liter*.

This run indicates how quality considerations can make a substantial – and somewhat unexpected – change to the entire production and conveyance scheme.

Scenario 6: BR + 150 mg Cl^-/*liter* to Gush Dan + 45 Desalination in the Palmachim Plant + Kfar Yehoshua 250 mg Cl^-/*liter* - Figure 5.11-5.12

The dilution of water in WG that occurred in Scenario 5 is in reality not feasible with the current state of the system. There is no pipe (nor boosters) that can convey the water from Western Galilee (AG) back to the Kfar Yehoshua (KY) node. To test how the system would operate without this connection, we can devise two options:

1. Remove the pipe from WG to node KY

2. Adopt a different policy of dilution: eliminate the dilution at node KY by raising its lower bound on salinity from 0 mg Cl^-/*liter* to 250 mg Cl^-/*liter*. This makes it possible to convey LK water further south without mixing at KY.

In this run the second option was adopted. The water was conveyed with higher salinity in the NC beyond KY, and was not mixed with water from WG. Instead, the water was diluted further south with water from the Mountain Aquifer (MA). In addition, the SWD plant in Palmachim supplied more water (+2.9 MCM/Season) with low salinity to Gush Dan (GD). The Objective Function (OF) was raised by only a small amount (+0.4 MUS$) as compared to Scenario 5, since there is a tradeoff between various OF components.

Table 5.3 : Annual Model - Main Results

#	Scenarios	Unit	Base Run (B.R) 1 season 1	1 season 2	1 Total	B.R. 1m in MA 2 season 1	2 season 2	2 Total	B.R.+150 MCM LKB 3 season 1	3 season 2	3 Total	B.R.+100MCM Negev 4 season 1	4 season 2	4 Total	B.R. +150 mg Cl⁻ li Gush Dan+ 45 des Pal 5 season 1	5 season 2	5 Total	B.R. +150 mg Cl⁻ li Gush Dan+ 45des Pal+KY 250mg Cl- 6 season 1	6 season 2	6 Total
1	**Total Replenishment***	MCM	1,296.2	151.8	1,448	1,296.2	151.8	1,448	1,296.2	151.8	1,448	1,296.2	151.8	1,448	1,296.2	151.8	1,448	1,296.2	151.8	1,448
2	**Total Demand**	MCM	1,002.6	539.9	1,543	1,002.6	539.9	1,543	1,100.1	592.4	1,693	1,066.7	574.4	1,641	1,002.6	539.9	1,543	1,002.6	539.9	1,543
3	**Water Supply**	MCM	1002.6	539.9	1,543	1002.6	539.9	1,543	1100.1	592.4	1,693	1066.7	568.5	1,635	1002.6	555.5	1,558	1002.6	539.9	1,543
4	**Deficit**	MCM	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	6.4	6	0.0	0.0	0	0.0	0.0	0
5	**Desalination & Artificial Sources**	MCM	6.5	6.5	13	6.5	6.5	13	6.5	6.5	13	6.5	6.5	13	6.5	12.0	18	6.5	14.9	21
6	**Water Extraction**	MCM	918.1	491.4	1,410	918.1	491.4	1,410	1015.6	543.9	1,560	982.1	519.9	1,502	918.1	485.9	1,404	918.1	483.0	1,401
7	**Kinneret**	MCM	409.2	202.7	612	438.9	237.8	677	506.7	255.2	762	486.4	217.4	704	437.8	151.6	589	437.8	154.1	592
8	**Mountain Aquifer (MA)**	MCM	372.4	207.9	580	342.7	170.8	514	372.4	207.9	580	359.3	221.0	580	343.9	236.4	580	343.9	236.4	580
9	**Coastal Aquifer (CA)**	MCM	136.5	80.8	217	136.5	82.8	219	136.5	80.8	217	136.5	81.6	218	136.5	97.8	234	136.5	92.4	229
10	**Water Recharge**	MCM	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
11	**Flows & Spills**	MCM	65.0	20.6	86	65.0	20.5	86	65.0	20.6	86	65.0	20.5	86	65.0	20.1	85	65.0	20.3	85
12	**Storage Change**	MCM	235.0	-402.2	-167	235.0	-402.1	-167	137.5	-454.7	-317	171.0	-430.7	-260	235.0	-396.2	-161	235.0	-393.4	-158
13	***Water level change***	m																		
14	**Kinneret**	m	1.25	-1.02	0.23	1.07	-1.23	-0.16	0.67	-1.34	-0.67	0.79	-1.11	-0.32	1.08	-0.72	0.36	1.08	-0.74	0.35
15	**Mountain Aquifer (MA)**	m	0.04	-3.04	-3.00	0.48	-2.48	-2.00	0.04	-3.04	-3.00	0.24	-3.24	-3.00	0.47	-3.47	-3.00	0.47	-3.47	-3.00
16	**Coastal Aquifer (CA)****	m	0.19	-0.25	-0.06	0.19	-0.28	-0.09	0.19	-0.25	-0.06	0.19	-0.27	-0.08	0.19	-0.44	-0.25	0.19	-0.38	-0.19
17	***Quality Change***	mg Cl⁻ / li																		
18	**Mountain Aquifer (MA)**	mg Cl⁻ / li	0.39	0.13	0.53	0.39	0.13	0.53	0.39	0.13	0.53	0.39	0.13	0.53	0.39	0.13	0.53	0.39	0.13	0.53
19	**Coastal Aquifer (CA)****	mg Cl⁻ / li	0.94	0.31	1.26	0.94	0.31	1.26	0.94	0.31	1.26	0.94	0.31	1.26	0.94	0.31	1.26	0.94	0.31	1.26
20	**Objective Function*****	MUS$	**64.6**	**35.5**	**100.1**	**65.9**	**37.0**	**102.9**	**64.6**	**35.5**	**100.1**	**75.6**	**360.3**	**435.9**	**72.6**	**44.3**	**116.9**	**72.6**	**44.7**	**117.3**
21	**Conveyance Cost**	MUS$	47.6	25.0	72.6	50.3	28.1	78.5	47.6	25.0	72.6	59.2	29.0	88.2	50.2	20.8	71.0	50.2	20.5	70.7
22	**Sea Water Desalination Cost**	MUS$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3	4.3	0.0	6.5	6.5
23	**Kinneret Spill Cost**	MUS$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	**Demand Zone's Deficite Cost**	MUS$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	320.0	320.0	0.0	0.0	0.0	0.0	0.0	0.0
25	**Total Artificial Variables Cost**	MUS$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	**Production Levy**	MUS$	17.0	10.5	27.5	15.6	8.9	24.5	17.0	10.5	27.5	16.4	11.3	27.6	15.6	14.1	29.7	15.6	13.4	29.0
27	**Sea Water Desalination Shutdown Cost**	MUS$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.8	5.1	11.9	6.8	4.2	11.0

* Including replenishment in WG & Hof Carmel
** Average of all 3 cells
*** Without amortization

Figure 5.1-Base Run (BR)

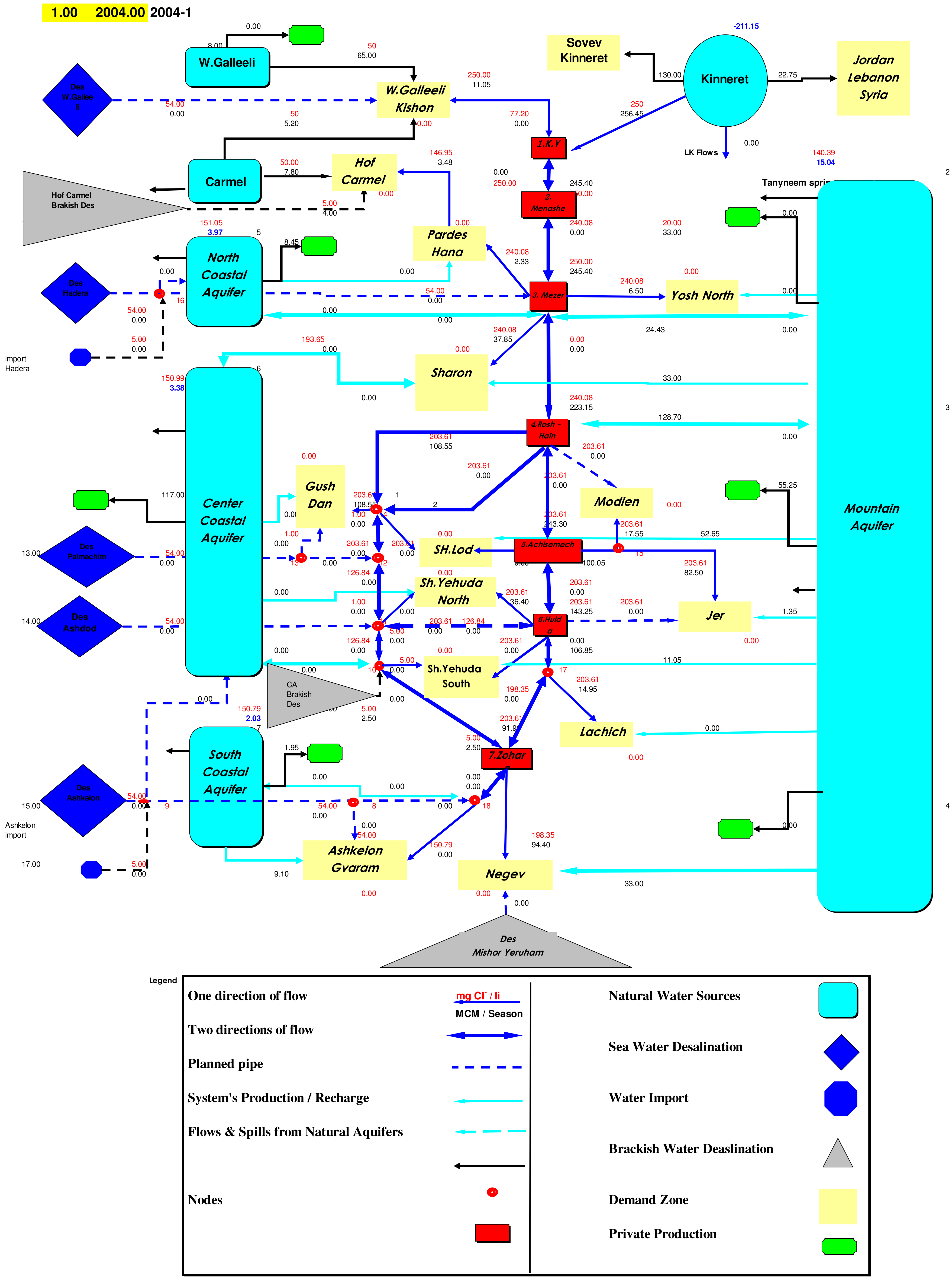


Figure 5.2:Base Run (BR)

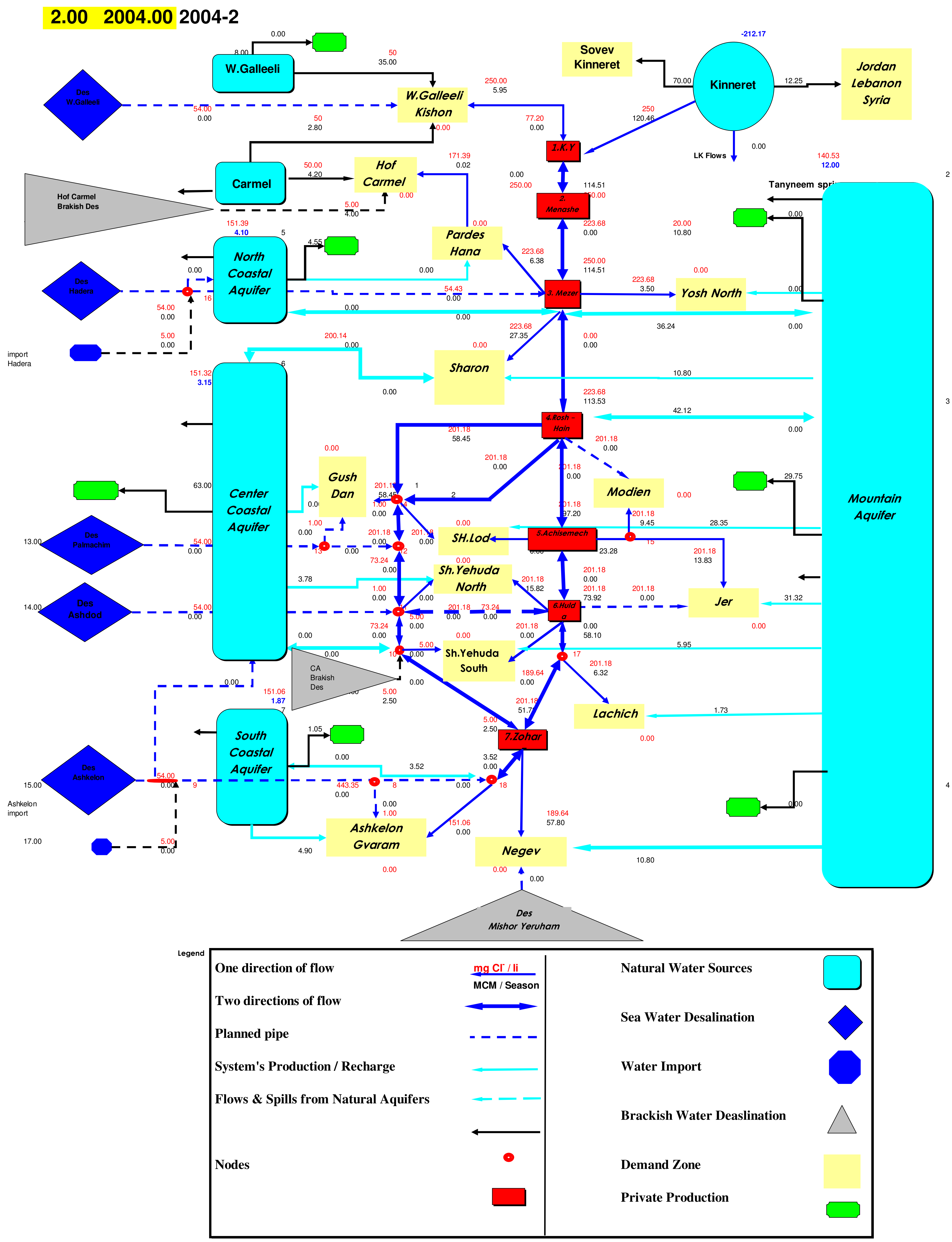


Figure 5.3: B.R.+1m in the Mountain Aquifer

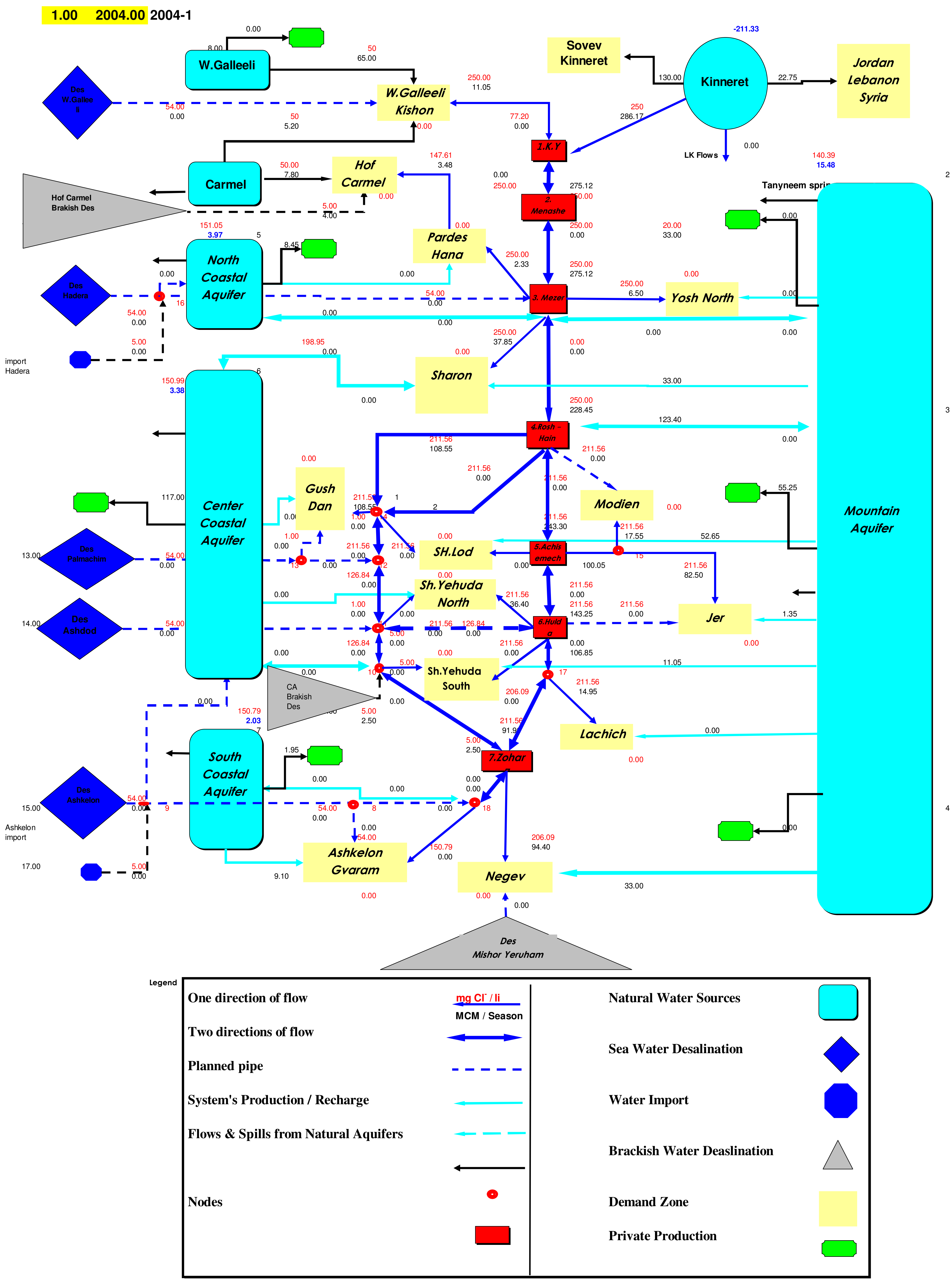


Figure 5.4: B.R.+1m in the Mountain Aquifer

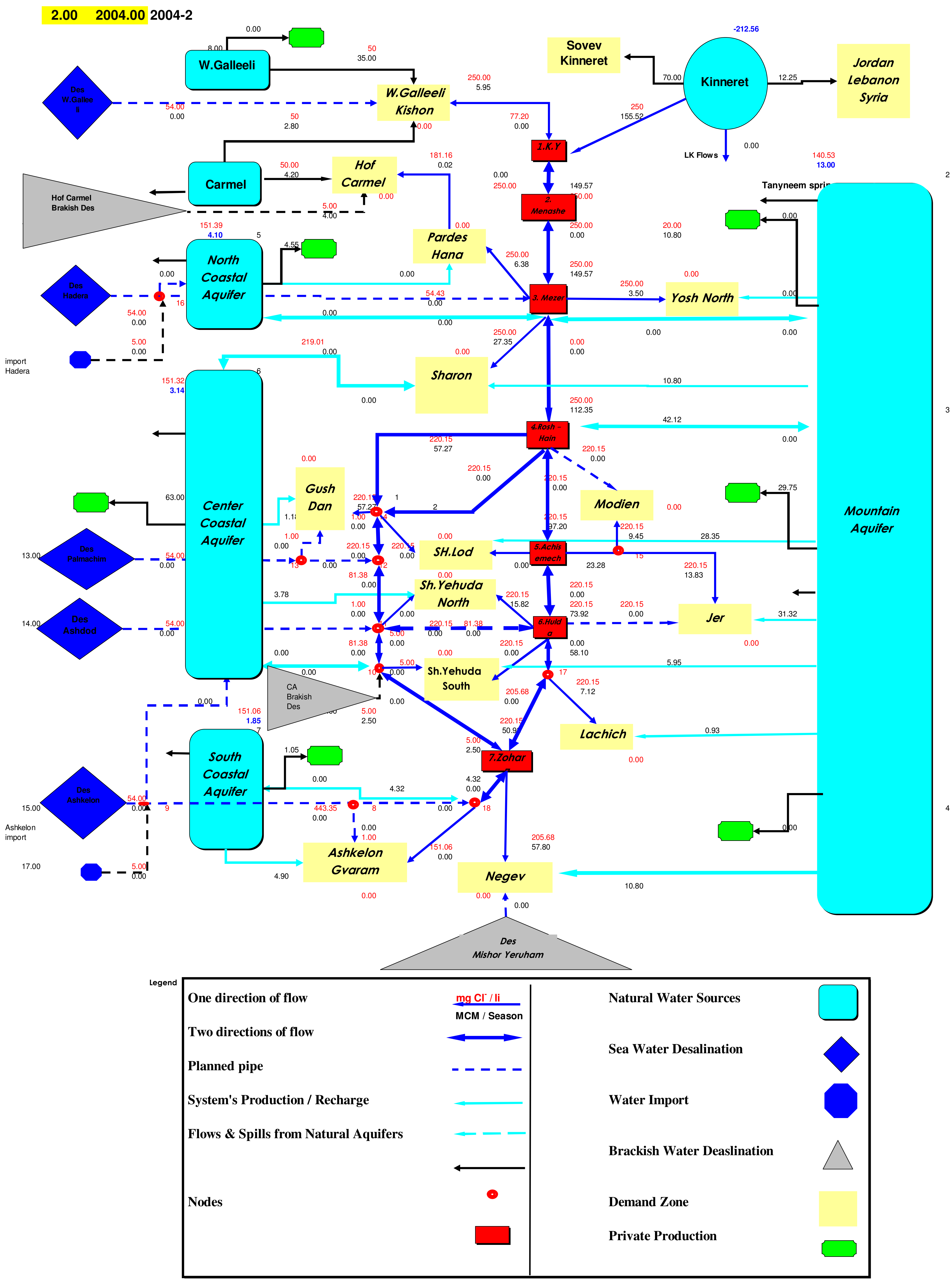


Figure 5.5: B.R + 150 MCM/Year in the Lake Kinneret Basin

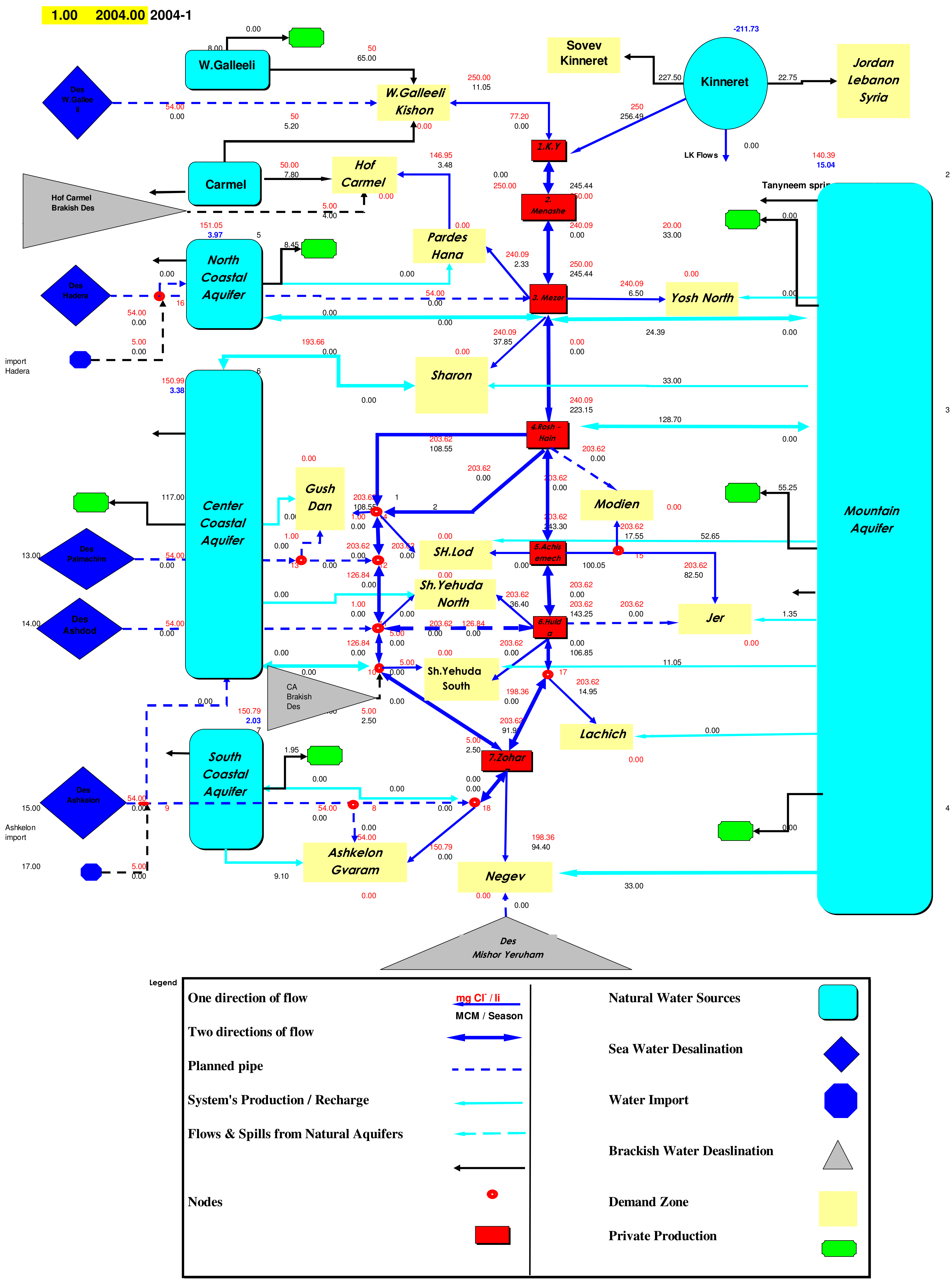


Figure 5.6: B.R +150 MCM/Year in the Lake Kinneret Basin

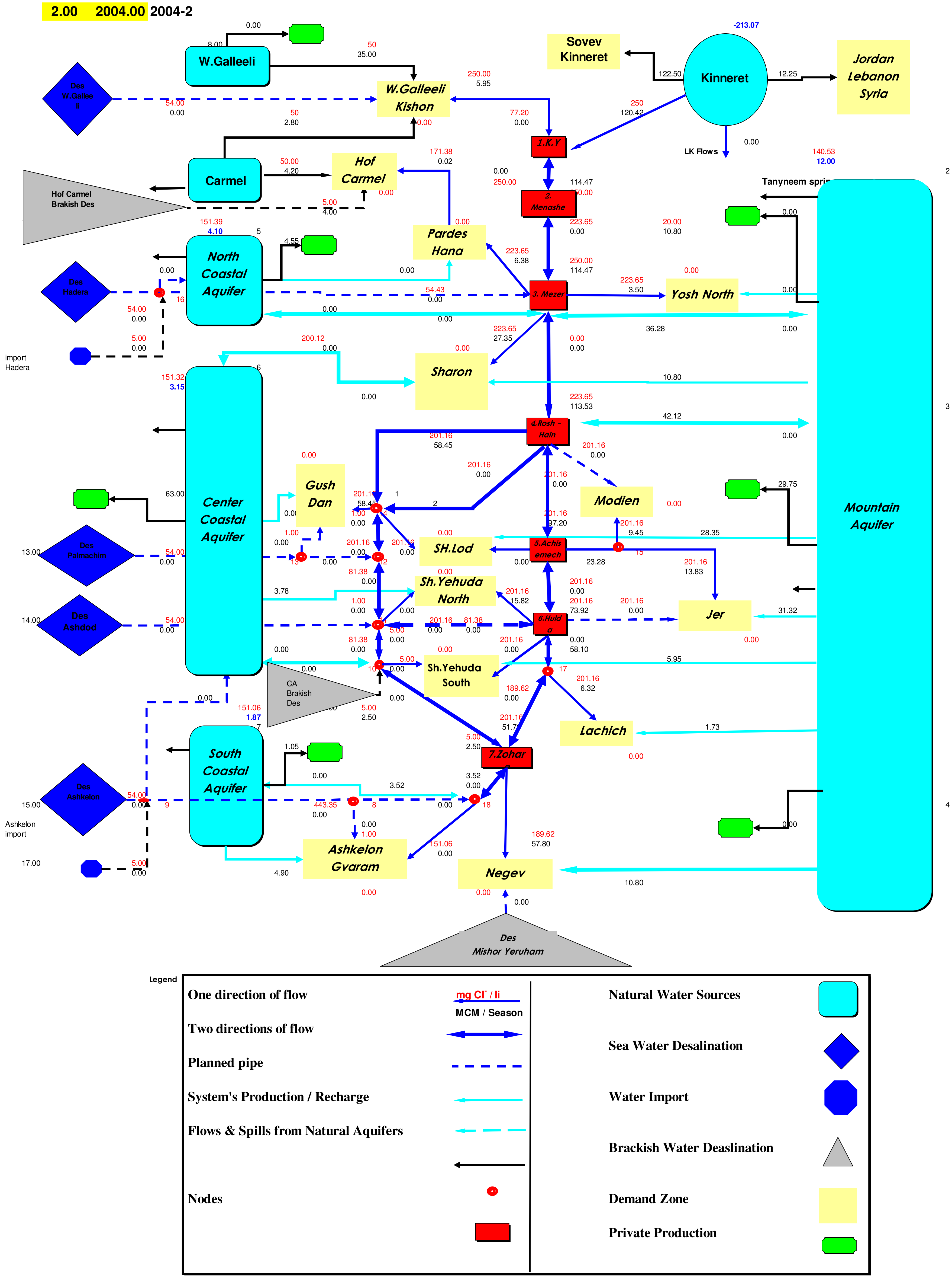


Figure 5.7: B.R +100 MCM/Year to the Negev

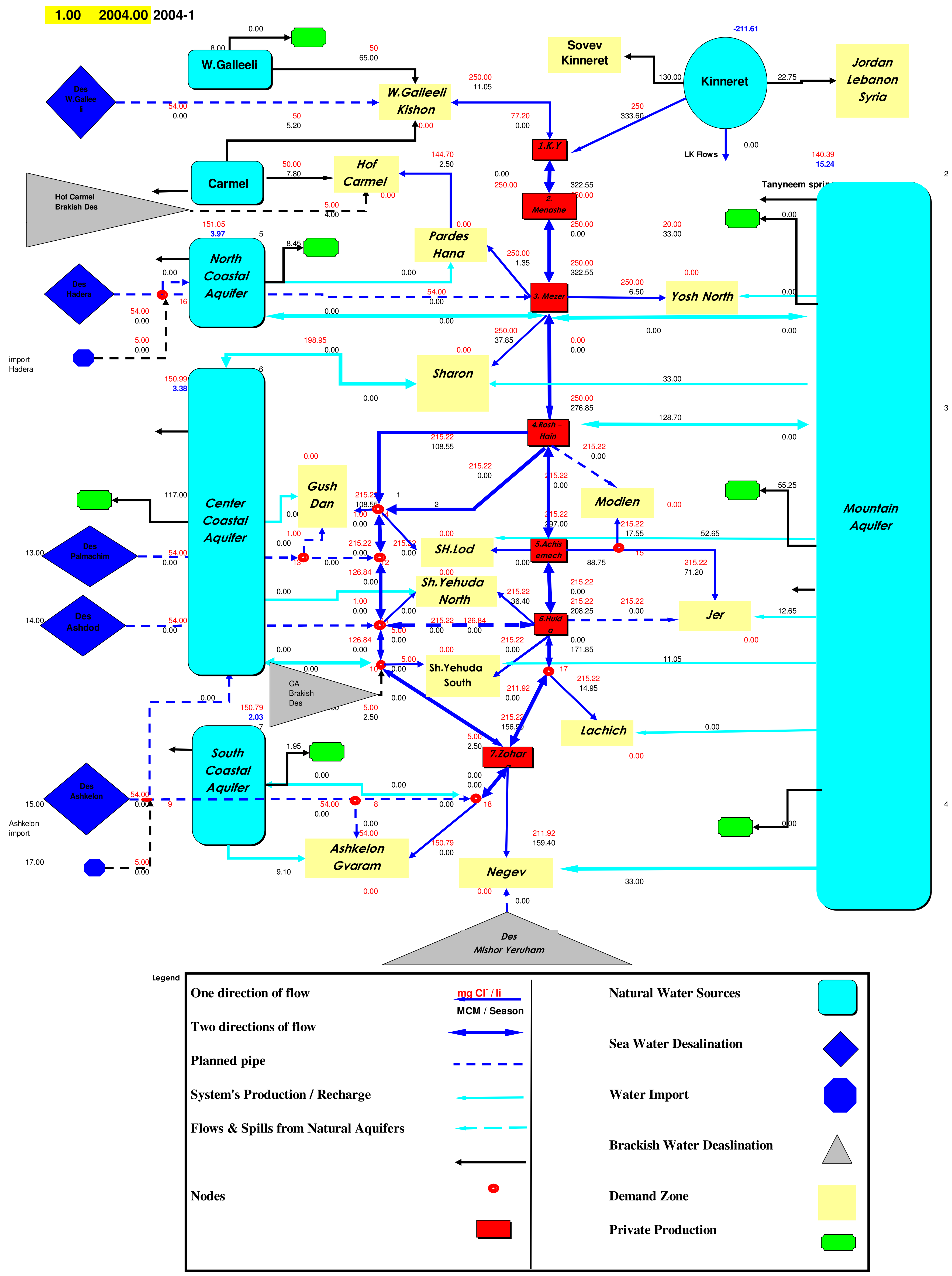


Figure 5.8: B.R +100 MCM/Year to the Negev

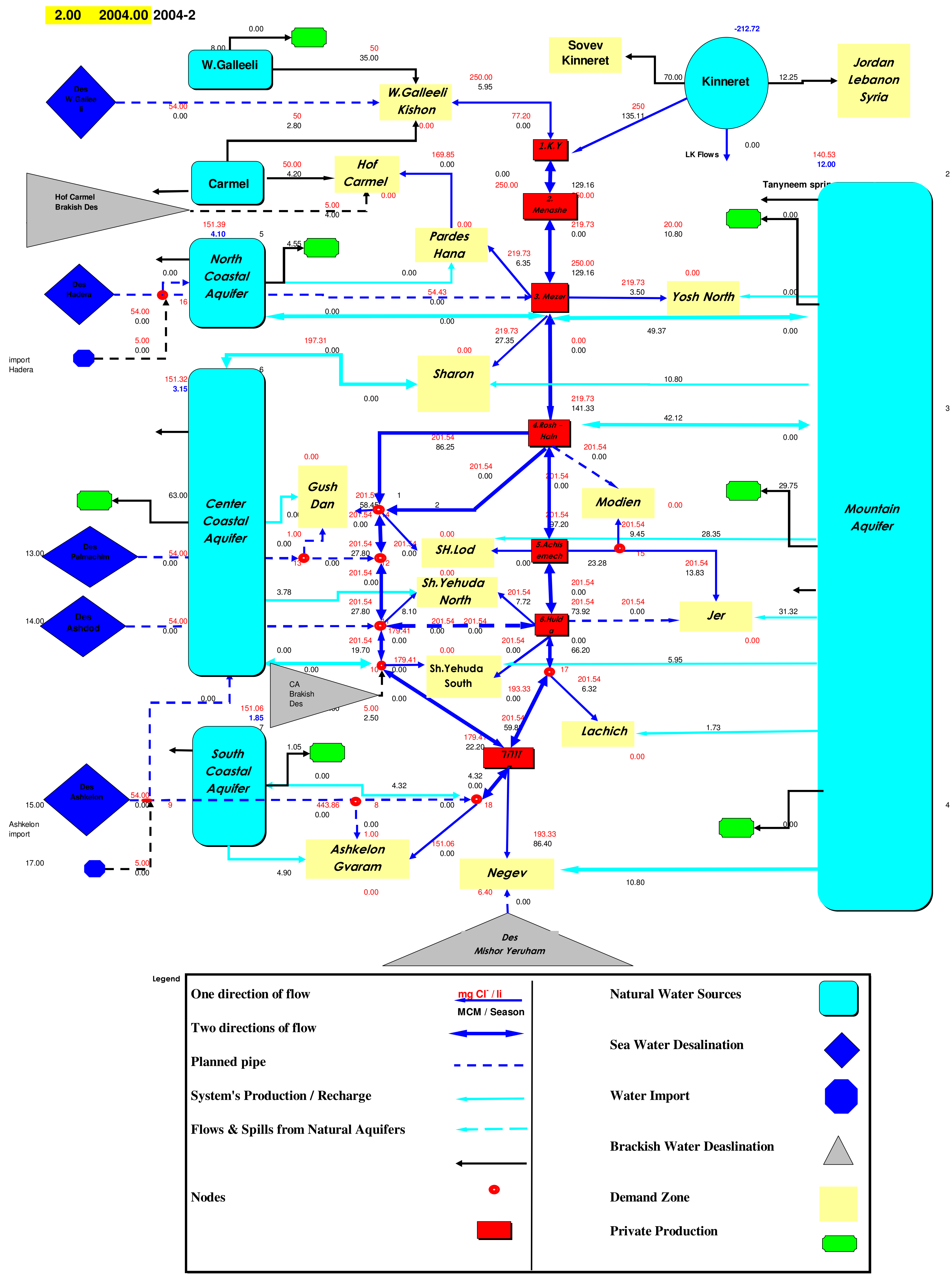


Figure 5.9:BR + 150 mg Cl-/liter to Gush Dan + 45 MCM/Year Desalination in the Palmachim Plant

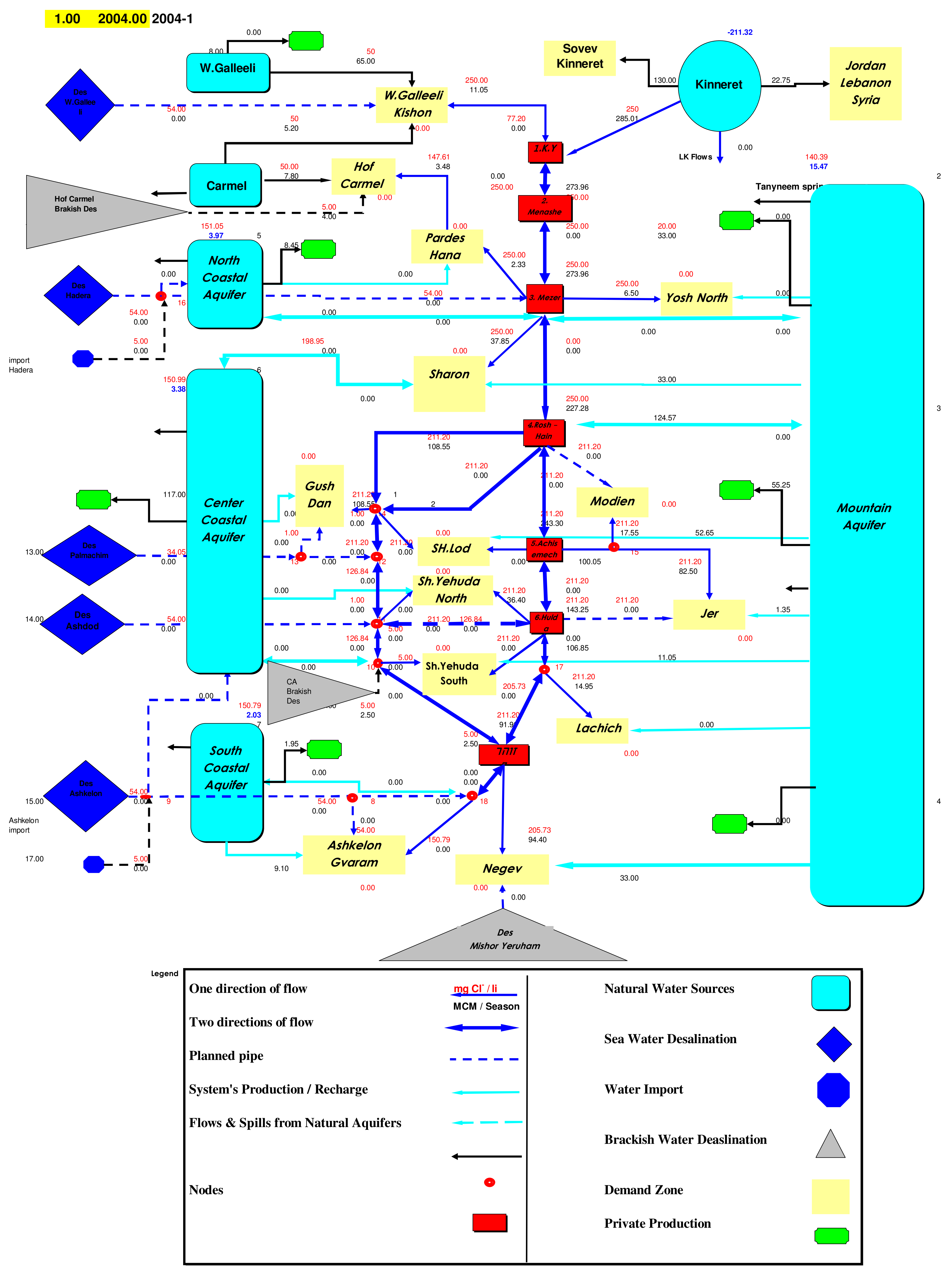


Figure 5.10:BR + 150 mg Cl-/liter to Gush Dan + 45 MCM/Year Desalination in the Palmachim Plant

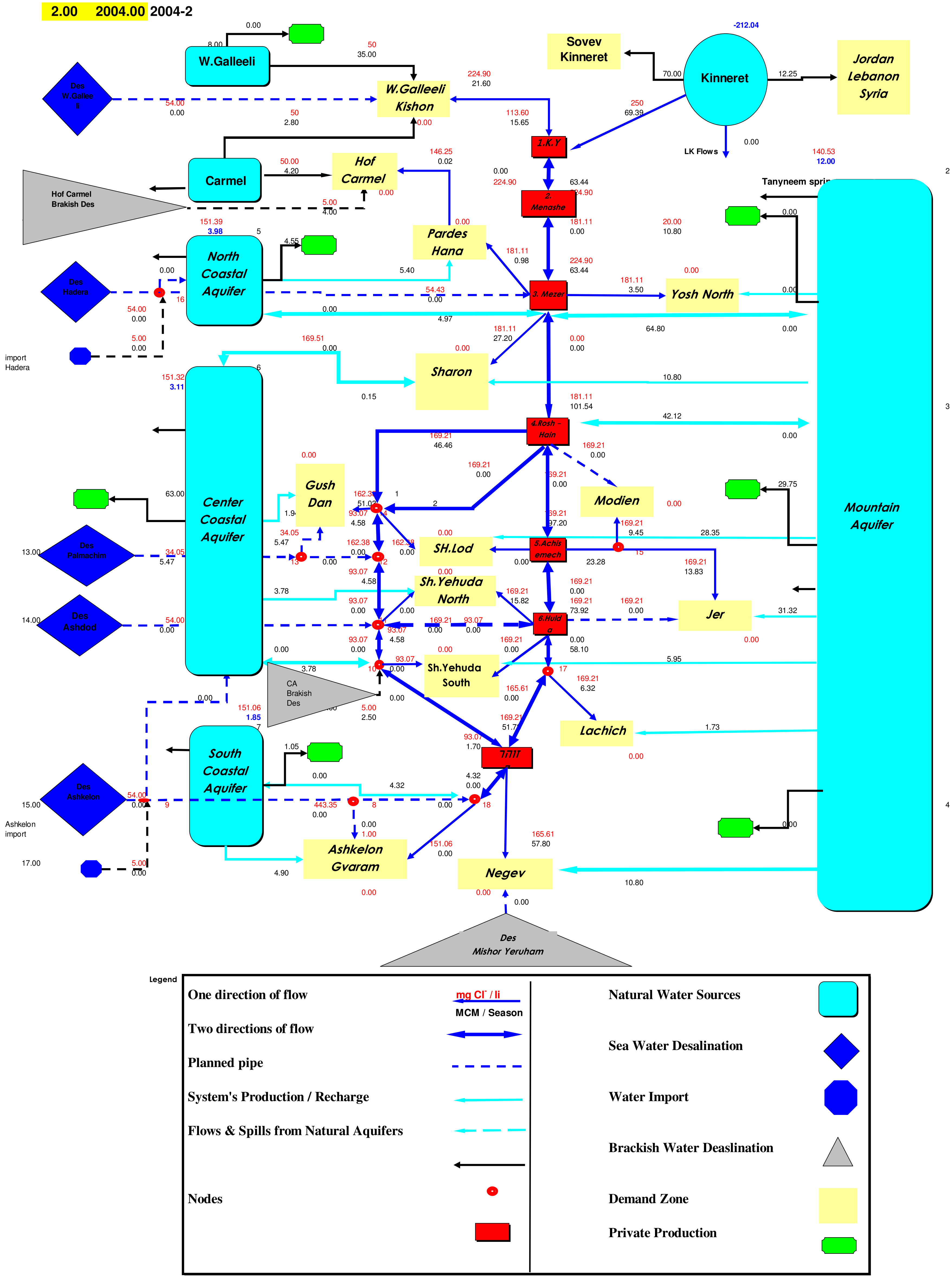


Figure 5.11:BR + 150 mg Cl-/liter to Gush Dan + 45 Desalination in the Palmachim Plant + Kfar Yehoshua 250 mg Cl-/liter

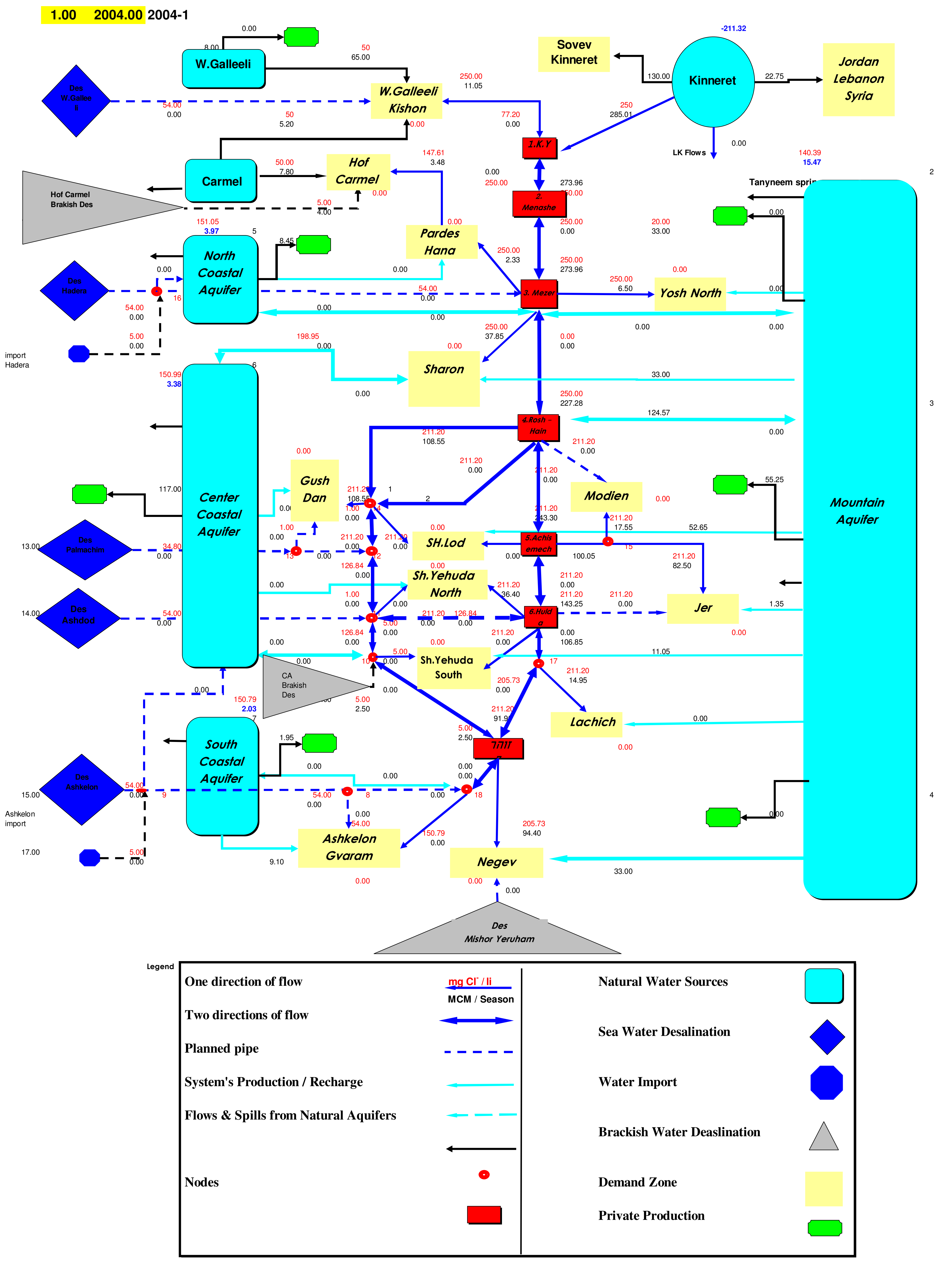
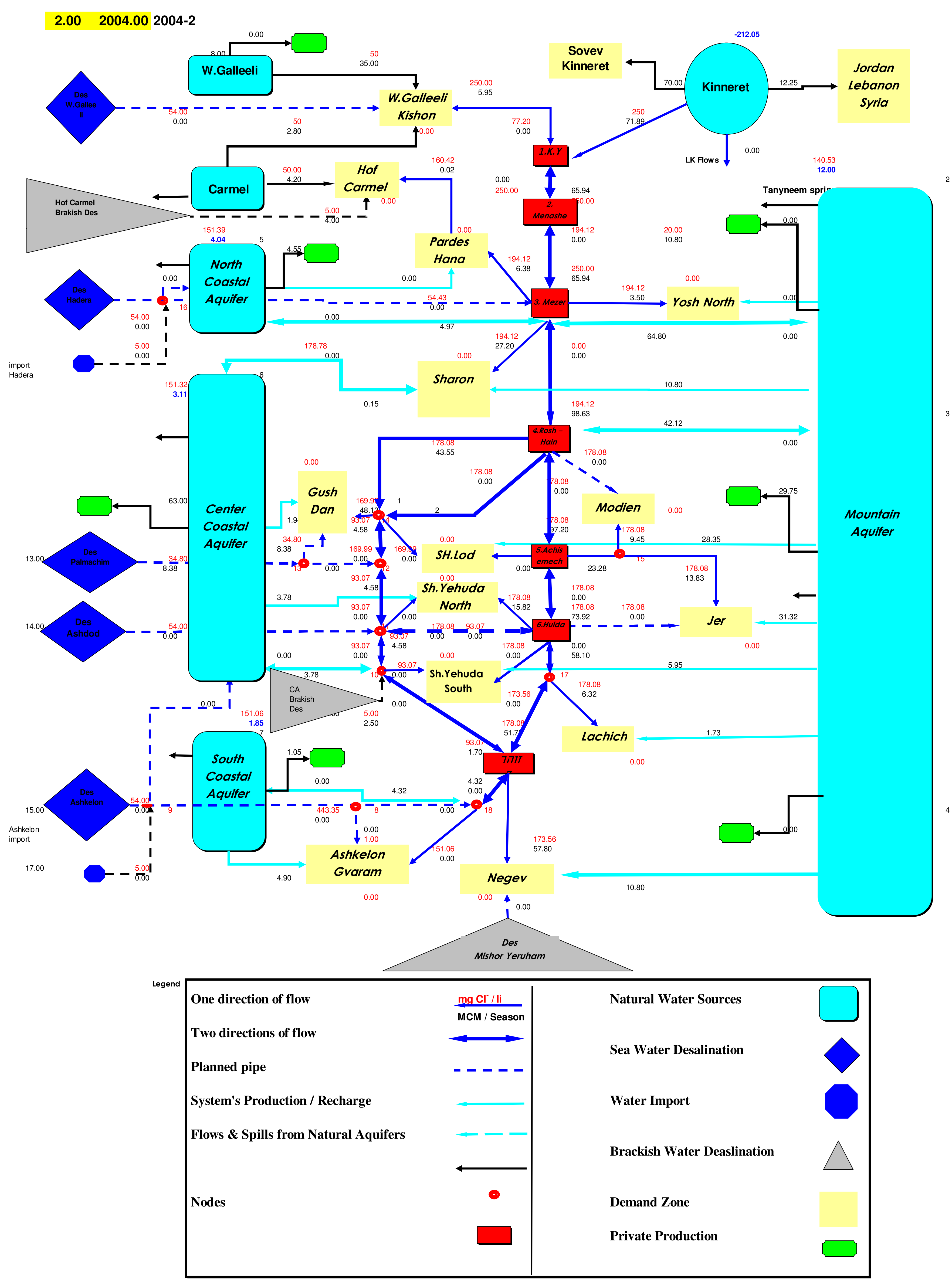


Figure 5.12:BR + 150 mg Cl-/liter to Gush Dan + 45 Desalination in the Palmachim Plant +   Kfar Yehoshua 250 mg Cl-/liter



5.3 Multi–Year Run

The multi-year run covers a sequence of five years, three successive years and two groups of future years - FRYs. Jointly they represent a time horizon of 12 years: 2004, 2005, 2006, 2007-2010 (4 years, called jointly "2010"), and 2011-2015 (5 years, called jointly called "2015") - all solved simultaneously.

The years data and assumptions for each year are almost identical to the annual run's data presented in section 5.2 with few assumptions and simplifications:

1. The demand is kept constant for all years.
2. The supply development program is as presented in Table 5.4

Table 5.4: Multi–Year Run - Development Program (MCM/Year).

Year	*2004*	*2005*	*2006*	*2010*	*2015*
Total Artificial	250	250	250	250	620
Total Sea Water Desalination	250	250	250	250	500
Des Westen Galilee	50	50	50	50	100
Des Hadera	50	50	50	50	100
Des Palmachim	50	50	50	50	100
Des Ashdod	50	50	50	50	100
Des Ashkelon	50	50	50	50	100
Import Hadera	0	0	0	0	50
Import Ashkelon	0	0	0	0	50
Des Hof Carmel	0	0	0	0	10
Des Gat	0	0	0	0	10
Des Mishor Yeruham	0	0	0	0	0

The results of Multi-Year Model runs are presented in: Table 5.5, Figures 5.13-5.17.

5.3.1 Review of the Results

The OF value for the entire time horizon covered (12 years) is 1121.9 MUS$ (Table 5.5). This is the accumulated value of the OF (before calculating the present value (PV) of the stream of the annual cost. The active components of the OF are costs of: conveyance, SWD plants, Extraction Levy and SWD plants shutdown cost.

In total there is a little use of artificial variables - 1.8 MUS$ which is 0.16% of the total sum. This amount can be neglected, as it is the product of a large fine (cost) by a very small value of the artificial variables (~ 0.001MCM).

Figures 5.13-5.17 show that the levels in the Mountain Aquifer (MA) and LK decline, and at the end of the last period (2015) reach the 'red lines' (as defined in the input data). The Central Coastal Aquifer was extracted to below sea level (~ -3 m ASL) since in this specific run the limitations on the production from the CA were ”lifted”.

The model preferred extracting water from the aquifer rather than to desalinate sea water due to the relatively high cost of desalination. This means that the Extraction Levy was too small to force desalination. To eliminate this result it is possible to increase the Extraction Levy and / or to raise the lower bound on the water table in this part of the aquifer, so there is less groundwater available for use.

In the north and south part of the CA the water levels are almost steady with a slight rise in the water level.

The quality (salinity) of all sources is deteriorating. The rate of salinity accumulation in the CA is higher than in MA due to the intensive use of wastewater, which has high salinity, above the aquifer and the higher salinity of replenishment from precipitation. The balance of salt mass in the CA, between the addition from replenishment and discharge into the sea, is not enough to maintain a steady state concentration in the aquifer.

There is almost a constant rate of SWD use along the years (Figure 5.16). This should be expected, due to the constant demand and water available in the natural sources. In the last year (FRY = 2015) there is an increase in the use of the SWD plant in Ashdod into its full capacity which was enlarged in that year by 100% relative to its capacity in FRY = 2010.

The conveyance system operates with no significant change over time, and the development program is constant. The SWD shutdown cost is almost constant as well. The appearance of a SWD Shutdown cost means there is an over development of the desalination plants. This is explained by the constant demand level and over extraction from the aquifer.

The desalination plant in Ashdod is the only one that is operated. Its capacity was used fully even when the plant's capacity was increased (second season of 2015).

Table 5.5: Multi–Year Model – Components of the Objective Function.

Objective Function - MUS$											
	2004-1	2004-2	2005-1	2005-2	2006-1	2006-2	2010-1	2010-2	2015-1	2015-2	Total
Convayance	55.2	28.2	41.3	27.8	50.2	26.9	55.2	25.8	36.1	26.4	373.0
Desalination	17.5	5.4	17.5	17.5	17.5	17.5	17.5	17.5	17.5	35.0	180.5
RR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kinnret Spill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zone's Defficit	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A.V. Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A.V. Aquifer Mass	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A.V Node Water	0.0	0.0	0.0	0.0	0.6	0.0	0.6	0.0	0.6	0.0	1.8
A.V Node Mass	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Production Levy	30.2	19.7	46.6	17.5	36.1	18.4	30.2	20.0	46.2	10.4	275.3
S.W.D Shutdown	23.2	28.7	23.0	23.4	23.1	23.4	23.3	23.6	53.4	46.2	291.4
Total	126	82	128	86	127	86	127	87	154	118	1121.9

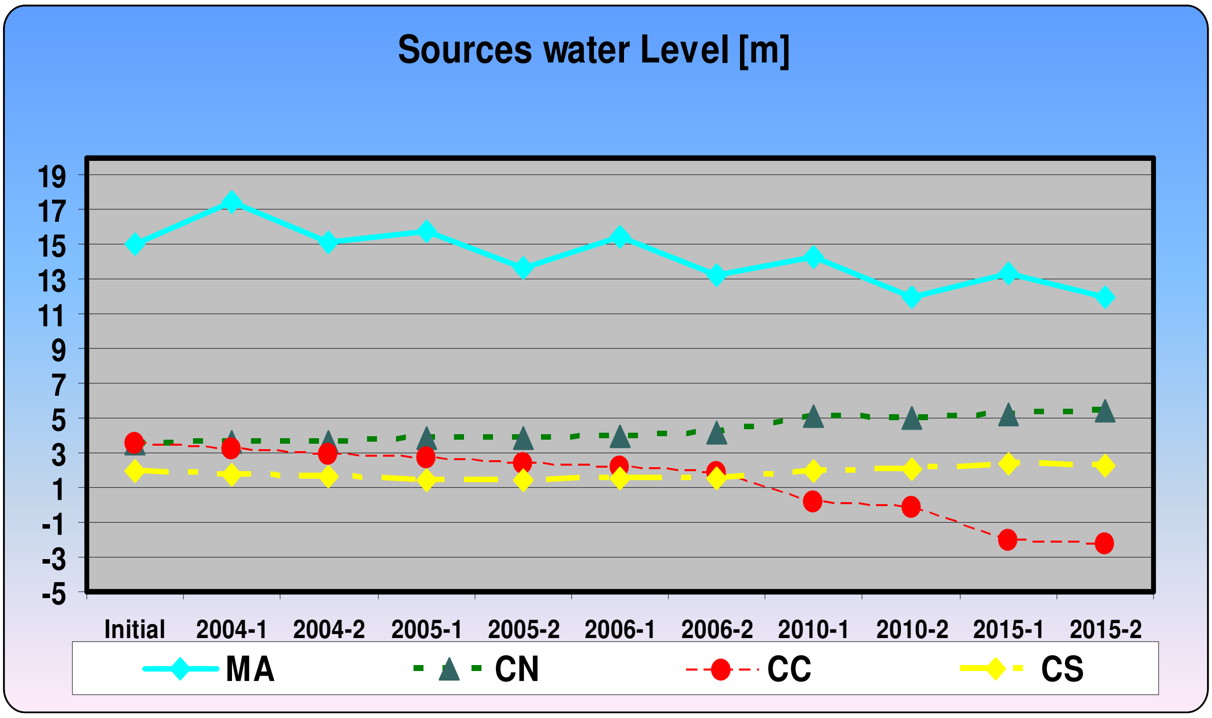


Figure 5.13- Multi -Year Model - Sources Water Level.

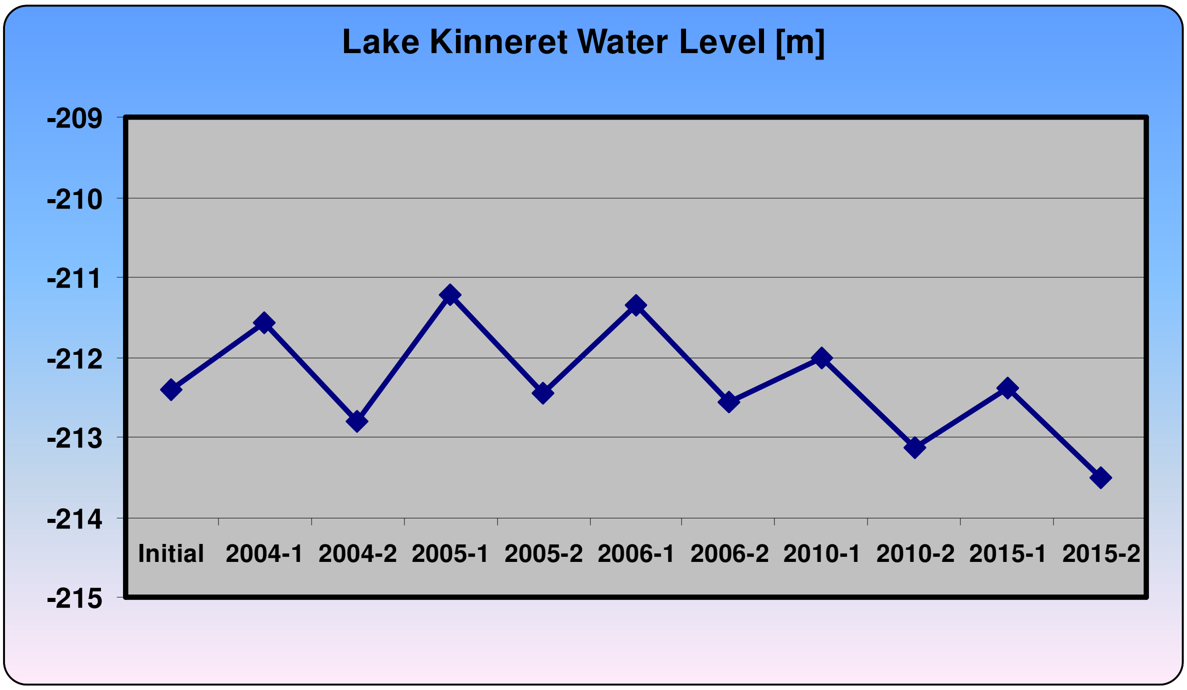


Figure 5.14- Multi-Year Model – Lake Kinneret Water Level.

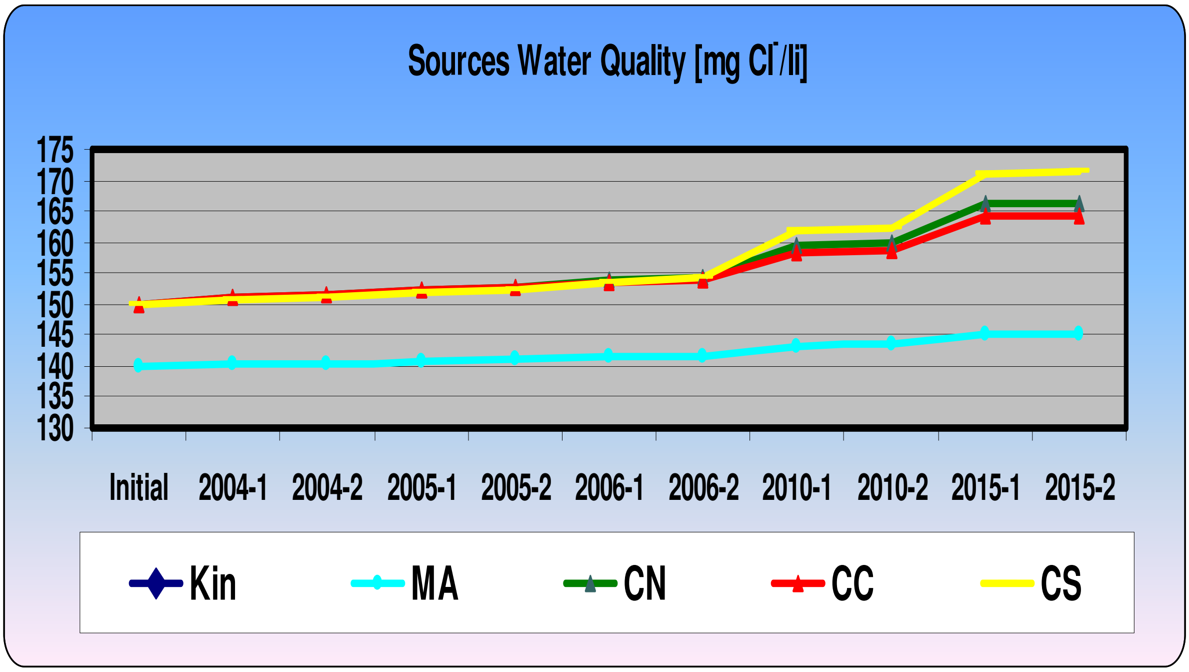


Figure 5.15- Multi-Year Model – Salinity in the Water Sources.

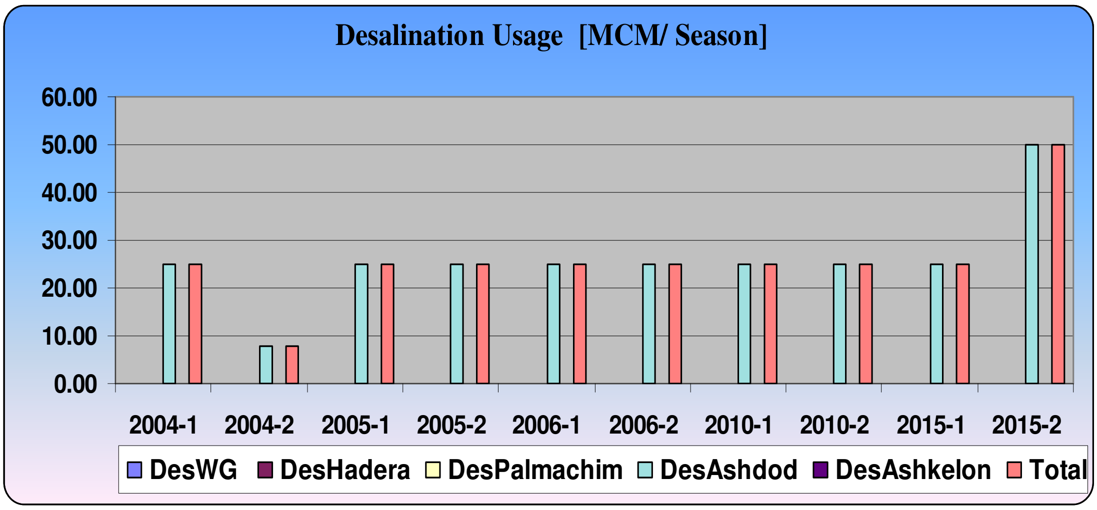


Figure 5.16- Multi-Year Model – Desalination Usage.

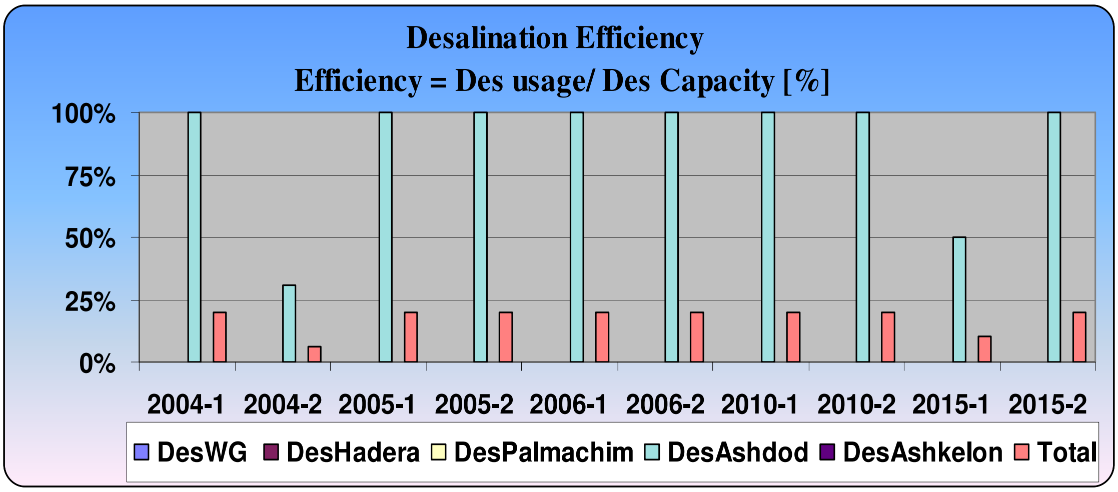


Figure 5.17- Multi-Year Model – Desalination Efficiency.

5.4 Conclusions Drawn from the Annual and Multi-Year Runs

The main conclusions from running the annual model and the multi-year model are:

- The results demonstrate that the model reaches results that can be explained through the logic of the physics and economics incorporated in it.
- Still, some results were not expected in advance. This is seen to result from inclusion of quality considerations. These results demonstrate that quality aspects can have significant and sometimes quite unexpected consequences for operating the Israeli NWSS.

- In the real world it is not recommended to let the water level in the aquifers drop below sea level. On the contrary, the recommendations are to raise the water levels above sea level, so as to maintain a stock for years of low replenishment. It is expected that adding constraints to raise water levels or changing the extraction levy above the CA will cause the SWD facilities to be operated more fully (provided that the conveyance system can distribute the water to the demand zones).
- There is still much work that should be done to present the “real world” in the model.
- While the model is not fully realistic, general conclusions can be derived from using it regarding the management (planning and operating) of the Israeli Water Sector – as summarized in Chapter 6.

6. Conclusions and Discussion

The outcome of the process of developing a model for both quantity and quality and the results of the runs that have been made and analyzed point to three sets of conclusions:

1. Modeling and General Conclusions: mainly technical remarks, concerning the process of building such a model, running it etc.
2. Strategic Conclusions: conclusions relating to the operation and planning of the Israeli NWSS.
3. National Planning Implications: lessons learned from model runs with respect to certain general planning issues of the Israeli NWSS.

6.1 Modeling and General Conclusions

The main conclusions are:

- This is the first time the national system is optimized over a relatively long period of successive years, considering both quantity and quality (salinity).
- It is possible to solve the quantity and quality problem by off-the-shelf software (we used Frontline's Solver LSGRG – Large Scale Generalized Reduced Gradient).
- The model optimizes the operation; while at the same time indicating planning implications (see section 6.3).
- The model assists in:

  1. Determining whether is it possible to achieve the quality and quantity targets.

  2. Indicating the best (in the sense of the objective function) means for achieving these targets.
- The main disadvantage is that the solution obtained may be a local optimum, which depends on the initial values of the decision variables. To overcome this, "wise" initial values for the decision variables are needed. Learning by trial, and many runs with different initial points (multi-start method) can assure that the optimum is in good probability also the global optimum. There is also the option of using other solver engines on the same platform of software to ensure the optimum solution and to verify that we reached global solution.

- Verification of the model is a tedious process, with considerable trial-and-error, but also generating much insight.
- Analysis of the results of a large model (many variables & constraints) requires a very good interface of presentation for the model results. The ability to analyze large amounts of information is limited. Therefore tools for pre- and post-processing are essential for running large scale models.
- The model is a first prototype and much work has yet to be done in refining the data, the topology and the economic functions in the model for applying on the national system.
- There can be more than one set of operational answers for the same value of the objective function, due to the tradeoff among system components and costs.
- The ability to "grab the problem" of such a complex challenge like management of the NWSS is limited with only one model. A 'Hierarchy of Models' connected in their boundaries conditions with different kind of emphasis in each model.
- Some scenarios which are analyzed have development program consequences therefore an external computation should be made in order to analyzed the full problem with all the engineering and economic insights.(section 6.4)
- Aggregation is always a compromise of the 'real world' and there is a tradeoff between the details needed to solve this program and the technical obstacles.
- A feasible solution in terms of season and even months is not necessarily in terms of hours that should be proved with detailed models.
- The model reached feasible solutions for all the scenarios that were defined in Chapter 5. Yet there could be situations were unfeasible solution errors might appear if wrong initial data and constraint parameters were entered into the model in the first place. As mentioned in section 4.3, artificial variables were introduced in order to identify and correct these situations.

6.2 Strategic Conclusions

Although the data used so far are not fully verified to match reality, nor is the system description final, it is still possible to draw from the runs that were made some interesting conclusions that are believed to be realistic for the Israeli NWSS, regarding both quantity and quality. Some of these conclusions are believed to change substantially the view of managing the system, once quality has been introduced into the main considerations. The main highlights are:

- Simultaneous application of the quality and quantity objectives and constraints changes -- sometimes dramatically -- the optimal solution based on quantity considerations alone.
- A quality management policy should be adopted, to manage:
  - Quality of water supplied to demand zones – the quality supplied to each demand zone should be defined as a goal that should be met and not merely a result of the quantities transported by the system from the various sources.
  - Water quality targets (constraints) in the aquifers – these should be set as goals, and force the operation to meet them.
  - Quality at selected strategic nodes in the system – some nodes can be used as strategic nodes, where water quality is forced to be within specified limits. These can also be used for meeting the previous goal – supplying the demand zone water with a desired quality.
- This quality management policy also helps to identify a development plan, of both the desalination plants and the conveyance system, which supports the quality management plan.

6.3 National Planning Implications

The model cannot solve all planning problems but can contribute, with few modifications in model data or structure, to various national planning challenges such as:

- The capacity and the outlet salinity needed from sea water and brackish water desalination plants.
- The operational requirements for the desalination plants, i.e. the temporal variation in operating the plants.
- Operational, development and economic consequences of reducing Lake Kinneret salinity or available quantity.
- The benefits of Coastal Aquifer rehabilitation, its salinity and available operational storage.
- Salt removal from wastewater effluents versus reducing the salinity of the supply.

7. Recommendation for Future Development

1. Incorporating stochastic considerations into the model. It can be made, for example, by solving with a few replenishment sequences, possibly with their associated probabilities. The probabilities and the addition of variables should be incorporated both into the objective function and constraints formulas. This obviously increases the size of the model and the difficulty in obtaining a solution.
2. Incorporating more economic considerations into the model, in particular demand functions (consumers' willingness-to-pay) which transforms the model from minimum cost to maximum net benefit.
3. Decomposition of the problem and solving the model with smaller time units and / or fixing variables which will be constant at the inter-annual boundaries.
4. Incorporating design variables as decision variables into the model, for example the carrying capacity of some selected critical conveyance lines. This transforms the model into one of design and operation simultaneously.
5. Adding more quality substances and transforming the model to a multi-quality model.
6. Adding hydraulics constraints into the model.
7. Increasing the time horizon and solving for a longer time period, by adding more FRYs and/or making them longer.
8. Adding the wastewater network and monitoring its salinity as a function of the potable water supplied to the domestic sector and also adding plants for salinity removal from the effluents.
9. Adding simulation of detailed operational cost along the system.
10. Incorporating Min-Max optimization techniques.
11. Refining the model topology, data, c onstraints and objective function by :
    a. Adding benefits/incentives for supplying better quality water than requested.
    b. Redefining the cost functions of the salinity removal in the sea water desalination plants.
    c. More detailed definition of the supply system
    d. Disaggregating the sources (e.g. dividing the MA into three cells).

e. Adding seasons: four instead of two, for a better definition of its temporal operation.
f. Adding desalination plants placed on the aquifer outputs, to serve as so called “artificial kidneys” which treat the water extracted from local aquifers.
g. Using a time-varying removal ratio of the desalination plants.
h. Imposing the proposed rehabilitation plans for the coastal aquifer.
i. Improving the method for computing flows to sea.
j. Allowing levels in the sources to drop below the prescribed "red line", while imposing a high penalty for doing so.
k. Connecting between the salinity of waste water replenishment and the salinity supplied.
l. Improving the Graphic User Interface (GUI).

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המתבקש מאי-קיומם. לשמירת מקורות המים משיקולי היצע הכמות נוסף תפקיד של מיהול מי התהום במים אחרים, להשגת יעדי אספקה.

12.3 יש להגדיר תחומי מליחות דרושים בצמתים נבחרים של מערכת ההולכה. התכנון, הפיתוח והתפעול העתידיים יידרשו לעמוד בהם , או לפחות לשלם את הקנס המתבקש מאי-קיומם. לתפקידה של מערכת ההולכה להעביר כמויות מים נוסף התפקיד של מיהול מים בעלי מליחויות שונות, על מנת לעמוד ביעדי האספקה.

13. בהיבט התכנוני מסייע המודל לבחון חלופות במספר נושאים, ביניהם:

13.1 היקף מתקני ההתפלה הדרוש, ופריסתם.

13.2 יחס הרחקת המלחים הדרוש במתקני ההתפלה.

13.3 שימוש משתנה בזמן של מתקני ההתפלה: שינויים בכמות ובאיכות המים המיוצרים במשך עונות השנה ועל פני השנים.

13.4 המשמעות של הקטנת העלייה של מליחות מי אקוויפר החוף או הקטנתה.

13.5 המשמעות של הורדת מליחות מי הכנרת.

13.6 התועלת מסילוק מלחים מן הקולחים.

המודל מוזן בנתונים המייצגים בקירוב את המציאות הנוכחית, ונותן תוצאות בעלות משמעות מעשית. עם זאת, תידרש עבודה נוספת בהגדרת בסיס הנתונים, הגדרת הפונקציות הכלכליות, עידון בהגדרת מקורות המים ומערכת ההולכה – לפני שניתן יהיה להמליץ על יישום הלכה למעשה של תוצאות המודל.

4. המודל מסייע במקביל לשני יעדים: (א) בחינת האפשרות לסגור את משוואות המאזן עבור חלופה תכנונית – תפעולית נתונה, הן בהיבט של כמות והן בהיבט של איכות (קרי: האם ניתן למצוא מציאת פתרון אפשרי), ו-(ב) אם קיימת אפשרות כזו (כלומר: יש פתרון אפשרי) מהם האמצעים להשגת פתרון זה באופן אופטימלי.

5. הכנסת שיקולי איכות למערכת משנה לעיתים לחלוטין את פתרון בעיית ניהול הכמות בלבד.

ב. מסקנות טכניות

6. הפתרון המתקבל עלול להיות מקומי (לוקאלי). המודל לא-ליניארי והפתרון תלוי בנקודת ההתחלה. הרצת המודל ממספר נקודות התחלה (הדבר אפשרי הן באופן ידני והן במתכונת אוטומטית הכלולה בתוכנה), וזה מגדיל את הסיכוי למצוא פתרון אופטימלי גלובלי. ניתן לבחון את הפתרון המתקבל גם במנועי אופטימיזציה אחרים.

7. לעיתים ייתכנו מספר פתרונות בעלי ערך זהה (לפחות דומה) של פונקצית המטרה, עקב התחלופה בין מרכיבים שונים של המערכת.

8. יש לראות את המודל כמרכיב ב"היררכיה של מודלים" עבור משק המים, הנבדלים זה מזה ברמת הפירוט בזמן ובמרחב, ובהתייחסותם לאקראיות של ההעשרה הטבעית. בכל מודל יש רמה מסוימת של אגרגציה בזמן ובמרחב, המותאמת לבעיית הניהול עבורה פותח המודל.

9. את תוצאות המודל שלנו יש לבחון באמצעות מודלים מפורטים יותר.

10. המודל גדול יחסית, וקשה לעקוב אחר נתוני הקלט ובמיוחד אחר התוצאות. לכן ניבנו מימשקי קלט להכנת המודל, ומתכונות פלט, הכוללות סכמות גרפיות שעליהן מוצגות כל התוצאות הרלבנטיות וטבלאות המהוות "דיווחי מנהלים".

11. המודל מכסה אמנם את מערכת אספקת המים הראשית של ישראל, אבל הוא אב-טיפוס, הדורש עבודה רבה נוספת לאימות מבנהו ונתוניו, לפני שניתן יהיה לקבל את התוצאות כהנחיה למדיניות מיושמת.

ג. מסקנות אסטרטגיות באשר לתפעול ותכנון המערכת הארצית בעתיד

12. הממצאים מצביעים על הצורך לאמץ מדיניות של ניהול משולב של כמות ואיכות במערכת אספקת המים משק המים במספר היבטים:

12.1 יש להגדיר את יעדי מליחות המים המסופקים בכל אזור ביקוש. התכנון, הפיתוח והתפעול העתידיים יידרשו לעמוד בהם, או לפחות לשלם את הקנס המתבקש מאי-קיומם.

12.2 יש להגדיר את תחומי וספי מליחות המים במקורות בנקודות זמן נבחרות בעתיד התכנון, הפיתוח והתפעול העתידיים יידרשו לעמוד בהם, או לפחות לשלם את הקנס

המודלים השנתיים מקושרים בינהם ע"י <u>משתני מצב</u> שהם המפלסים והמליחויות במאגרי המים בסוף השנה. מפלסי המים והאיכויות במקורות המים ניתנים בתחילת הריצה כתנאי התחלה. במהלך הריצה ובסופה כפופים מפלסי המים והאיכויות לאילוצים המבטאים את מדיניות ניהול משולבת של כמות ואיכות המים במקורות. בנוסף, כפופה מדיניות ניהול המאגרים להיטלי הפקה עונתיים.

במודל השנתי שתי עונות, כאשר בכל עונה 210 משתני החלטה ו-78 אילוצים. המודל הרב-שנתי מורכב משרשור של חמישה מודלים שנתיים, בעלי 2 עונות כל אחת, סה"כ 2100 משתני החלטה ו-780 אילוצים (לא כולל אילוצי תחום על משתני ההחלטה– Upper and Lower Bounds, במודל יש 4,200 מסוג זה). למודל ניתן השם:

Multi-Year Combined Optimal Management of Quantity and Quality in the Israeli National Water Supply System (**MYCOIN**).

המודל נפתר באמצעות תוכנת מדף Large Scale Generalized Reduced Gradient - LSGRG (של חברת Frontline) המבוססת על גיליון אלקטרוני (ECXEL) ומאפשרת הכנת נתוני הקלט והצגת תוצאות הפלט בקלות יחסית.

כאשר מושג פתרון אופטימלי, הוא כולל ערכי צל של האילוצים, המהווים מכשיר חשוב בהצבעה על צרכים לפיתוח המערכת והצדקתם הכלכלית וכן באפשרותו לכלול בדיקות רגישות נוספות.

עקב הכללת נושא האיכות במודל יש בו פונקציות לא-חלקות ולא-רציפות. על מנת לאפשר שימוש בתוכנת האופטימיזציה, המשתמשת בנגזרות, בוצעה "החלקה" של פונקציות אלה, בשיטה המאפשרת שליטה במידת הקירוב של הפונקציה החלקה ל"מדרגה" של אי הרציפות.

העבודה מכילה מספר הרצות של המודל השנתי, שמטרתן לבחון את נכונותו של המודל וההיגיון של תוצאותיו, וכן להצביע על מסקנות הנובעות מהרצתו. לאחר מכן מובאת הרצה של המודל הרב-שנתי וניתוח של התוצאות.

הממצאים העיקריים של ביצוע עבודת המחקר ובניית המודל מתחלקים לשלוש קבוצות של מסקנות. להלן המסקנות על פי שלושת הקבוצות:

<u>א. מסקנות כלליות</u>

1. לראשונה נפתרה בעיית ניהול אופטימלי רב-שנתי משולב של כמות ואיכות במערכת אספקת המים הארצית הקיימת והמתוכננת.
2. ניתן לפתור את המודל באמצעות תוכנת מדף (LSGRG).
3. המודל פותר את בעיית התפעול, ובאותה עת מאפשר ניתוח של מגבלות במערכת הקיימת ו/או חלופות תכנוניות.

ידועה (ולכן לא יהיו משתני החלטה במודל), שיכולה להשתנות על ציר הזמן): חוף כרמל, גת ומישור ירוחם . בנוסף, יש שני מקומות לשילוב יבוא מים בעתיד במערכת האספקה: בחדרה ובאשקלון.

- <u>אזורי הביקוש</u>

הוגדרו 15 אזורי הביקוש במערכת התלת-אגנית. בנוסף, יש העברות לגורמי חוץ (מדינות שכנות).

- <u>מערכת ההולכה</u>

במודל מיוצגת מערכת ההולכה המרכזית, מן הכנרת, האקוויפרים ומתקני ההתפלה לאזורי הביקוש.

בעבודה שולבו לראשונה באופן בו-זמני וברמה הארצית שיקולי הכמות והמליחות. פותח ויושם מודל אופטימיזציה רב-שנתי (10-20 שנה) המבוסס על מודולים שנתיים המחוברים ביניהם. המודל השנתי מחולק לשתי עונות: "חורף" - אוקטובר עד יוני, ו"קיץ" - יולי עד ספטמבר. החלוקה לשתי עונות (בלבד) מביאה לכלל ביטוי את השוני הבין-עונתי בלי לסבך את המודל מעבר לדרוש על מנת לביצוע ניתוח רב-שנתי.

פונקצית המטרה (שהינה לא-לינארית) היא להביא למינימום את עלות התפעול של מערכת הארצית על פני אופק התכנון, כאשר משתני ההחלטה (העונתיים) העיקריים הם: ההפקה והחדרה במקורות המים הטבעיים, כמות הייצור במתקני ההתפלה, כמות המים המובלים בכל מובל במערכת הארצית, מליחות המים המים במוצא מתקני ההתפלה , ההולכה של מים לאזורי הביקוש והיקף המחסורים (המבטאים את אמינות אספקה) .

המודל נפתר תוך עמידה באילוצי המערכת השונים, כאשר האילוצים העיקריים הם: כושר ייצור מותקן של מיתקני ההתפלה ותחומי הרחקת המלחים האפשריים בהם, כושרי הולכה בקווי המערכת, מפלסי מינימום ומקסימום במקורות המים, איכויות דרושות באקוויפרים ויעדי איכות באזורי הביקוש.

על מנת לאפשר פתרון כל אופק התכנון סימולטנית לתקופה ארוכה ולהביא בחשבון את "שיקולי העתיד" בתפעול הנוכחי אופק הזמן של המודל הרב שנתי הוגדר כדלקמן: שלוש השנים הראשונות (הבאות) מיוצגות אחת-אחת. אחריהן מופיעות שתי "שנים מייצגות עתידיות". כל "שנה" כזו מייצגת קבוצה של שנים (בין 3 ל-7, ואפשר גם יותר), הנחשבות דומות זו לזו מבחינת נתוני ההעשרה, הצריכה והמערכת הפיסית, אך השפעתן על מצב המערכת (מפלסי מאגרים ומליחותם) מצטברת (השפעת שנה אחת כפול מספר השנים שאותה מייצגת השנה). במודל שנפתר במסגרת העבודה, אופק התכנון היה מ-2004 עד 2015. כל אחת שלוש השנים הראשונות, כלומר השנים 2004-2006, מיוצגת בנפרד. התקופה של השנים 2007-2010 (ארבע שנים) יוצגה ע"י שנה מייצגת אחת. התקופה של השנים 2011-2015 יוצגה ע"י השנה המייצגת השנייה (חמש שנים) כך שאופק התכנון כולו מקיף 3+4+5 = 12 שנים (המודל פותר למעשה רק חמש תקופות שנתיות).

מערכת המים הראשית בישראל מחברת את שלושת מקורות המים המרכזיים - הכינרת, אקוויפר ההר אקוויפר החוף - ונקראת 'המערכת התלת-אגנית', אם כי קשורים אליה גם כמה מקורות נוספים, כולל אקוויפר הגליל המערבי וחוף כרמל. מערכת האספקה כוללת את: המוביל הארצי, מפעלי אספקה רוחביים מהצפון ועד הדרום (צפון הערבה), ובעתיד הלא-רחוק סדרה של מתקני ההתפלה ויבוא מים המוקמים על חוף הים אשר יספקו מים למערכת הארצית. בנוסף ישנם מיתקנים אזוריים להתפלת מים מליחים – גם הם יתרבו לצרכי שלילת מלח ושמירה על מקורות המים הטבעיים.

מטרת העבודה הנוכחית הינה לפתח מודל לניהול ארוך-טווח (10-20 שנה) של המערכת הארצית תוך שילוב שיקולי כמות ואיכות (מליחות).

ברור כי לא ניתן (וייתכן גם שלא צריך) להכיל את כל השיקולים והאלמנטים בכלי אחד לקבלת החלטות. אתגר זה הוביל לפיתוח הגישה של יצירת 'היררכיה של מודלים' לקבלת החלטות (שמיר 1971,1972). המודלים מאורגנים בהיררכיה כאשר כל מודל מתמקד בפירוט אחר (בזמן ובמרחב) של הבעיה הכוללת העומדת על הפרק. אם ניתן לסווג את הכלים על בסיס יחידת הזמן הניפתרת והפירוס במרחב ניתן לומר כי בראש ההיררכיה יהיו מודלים עם רזולוציה נמוכה במרחב (אגרגציה גבוהה של המערכת) ויכולת ניתוח רב-שנתי עם פרקי זמן של חדשים, עונות, ושנים, מודלים הכוללים התייחסות מפורטת לאקראיות של ההעשרה. בתחתית ההיררכיה יהיה אוסף מודלים עם רזולוציה גבוהה במרחב, פרקי זמן קצרים (שעה, יום,שבוע), הפועלים למימוש אופטימלי של ההנחיות המתקבלות מן המודלים ש"מעליהם" בהיררכיה.

גישה זו מאומצת למעשה באגף התכנון בנציבות המים. באגף מופעלים כלים לקבלת החלטות כאשר הכלי המפותח בעבודה זו הינו חלק מאותה היררכיה של כלים שנבנו באגף בעיקר בעשור האחרון. הכלי המפותח בעבודה זו אמור להיות ממוקם אי-שם 'באמצע ההיררכיה'. מודלים אלה ודומים להם המופיעים בספרות מוצגים בפרק 2.

הטופולוגיה של המודל ניבנתה כך שיוכל להיות מקושר לכלים אחרים באגף ברמת בסיס הנתונים והמידע הדרוש להפעלתו. המודל מתאר את המערכת ה'תלת אגנית' (ציור 3.1) במתכונת הבאה:

- <u>מקורות המים הטבעיים</u>

חמישה מאגרי מים טבעיים אופרטיביים: הכינרת, אקוויפר ההר ושלושה תאים באקוויפר החוף, כל אחד עם התכונות הפיזיקליות היחודיות לו (אגירות, שטח, גלישות וכו'). ניהול כמות ואיכות המים במאגרים אלה מהווה חלק מרכזי במדיניות המופקת על ידי המודל. בנוסף גליל מערבי וחוף כרמל – המספקים כמות ידועה (ולכן לא יהיו משתני החלטה במודל), שיכולה להשתנות על ציר הזמן).

- <u>מקורות מים מלאכותיים</u>

חמישה מתקני התפלה (הנחשבים קיימים, אך ניתן להשביתם בעת הצורך,תוך תשלום קנס): גליל מערבי, חדרה, פלמחים, אשדוד ואשקלון. שלושה מתקני התפלת מים מליחים, המספקים כמות

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מיקי זיידה

תקציר

הצורך ביציאה מן המשבר של הידרדרות הכמות והאיכות במקורות המים בסוף שנת 2001 ובהגדלת היצע המים ושיפור איכותם על מנת לנהל את משק המים על בסיס בר-קיימא הוביל להכנתה של תוכנית אב 2002- 2010 (נציבות המים, משרד התשתיות, יוני 2002). על בסיס תוכנית זו ובהתאם להחלטות הממשלה שבאו בעקבותיה, הוחלט על שילוב של מיתקני התפלה במערכת הארצית בהיקף של כ–315 מלמ״ק/שנה עד 2010. רוב מתקני ההתפלה יוקמו ע״י גופים פרטיים.

השלמת המוביל הארצי באמצע שנות השישים הביאה לכך שמים שפירים מובלים מהכינרת בצפון לנגב בדרום, אך עם השנים הצריכה לאורך המוביל גדלה, בעיקר באזור מישור החוף. כניסת מי ההתפלה למערכת תוביל לשינויים מהותיים הן באיכות המים במערכת והן בכיווני הזרימה שלהם ולכן תשפיע על החלטות תכנוניות ותפעוליות כאחד. אחד הגורמים החשובים ביותר הינו מליחות המים, אם כי יש כמובן גם משמעות לרכיבים נוספים המאפיינים את איכות המים. שיקולי האיכות בניהול המערכת כוללים הן את העמידה בדרישות האיכות של צרכנים והן את ניהול המליחות של מאגרי המערכת, משיקולים של שימורם במסגרת מדיניות בת-קיימא. שילוב גורמים פרטיים במערכת ייצור המים מעלה את אתגר ניהול המערכת הסבוכה ממילא. ניהול בר-קיימא מחייב הבאה בחשבון של שיקולים ארוכי-טווח (20 שנה לפחות).

על מנת לסייע בתכנון ותפעול של מערכות מים מקובל להעזר בארץ ובעולם בכלים לקבלת החלטות (DSS – Decision Support Systems). הכלים המרכזיים שפותחו עד כה לניהול המערכת הארצית לטווח ארוך לא התייחסו למרכיב האיכות (למעט אחד – מודל ״תקומה״ – ואף זאת רק חלקית, יחסית למודל שפותח בעבודה זו) . הדבר נבע מן החשיבות הנמוכה יחסית שהייתה בעבר לשיקולי איכות המים בניהול המערכת ברמה הארצית. סיבה נוספת לכך הינם קשיים טכניים בבניית מודל המתייחס גם לאיכות, שכן שילוב שיקולי איכות (במקרה שלנו מליחות) במודלים מגדיל את נפח המודל וגורם להכנסת פונקציות לא-ליניאריות, מה שמקשה על פתרון המודל.

קושי אחר בבניית ופתרון מודלים לניהול לטווח ארוך של מערכות מים קשור באי-הוודאות של סדרות ההעשרה הטבעית. עם קושי זה לא מתמודדת ישירות עבודה זו. הגישה להתמודדות איתה תהיה על ידי ניצול האפשרות להריץ את המודל (הדטרמיניסטי) עם סדרות שונות של העשרה למאגרים הטבעיים, על מנת לבחון את רגישותו של הפתרון האופטימלי המתקבל לסדרות שונות והסקת מסקנות מניתוח התוצאות.

רשימת טבלאות

רשימת איורים

תוכן העניינים (המשך 2) עמוד

תוכן העניינים (המשך) **עמוד**

תוכן העניינים

עמוד

הבעת תודה

המחקר נעשה בהנחיית פרופ' אורי שמיר ביחידה להנדסת סביבה, מים וחקלאות, הפקולטה להנדסה אזרחית וסביבתית במסלול להנדסה וניהול משאבי מים.

זכיתי ללמוד בהנחיתו של פרופ' אורי שמיר. אני רוצה להודות מקרב לב על ההשראה , החוויה והרגעים המרתקים שהיו מנת חלקי במהלך פגישותינו אשר גלשו פעמים רבות מעבר לנושא מחקר זה, לנושאים שונים הקשורים לניהול משאבי מים.

תודה מיוחדת לדר' יוסף דרייזין (המנהל לשעבר של אגף תכנון,נציבות המים) שעודד אותי ללמוד ניהול משאבי מים ואיפשר לי לשלב את הלימודים במהלך עבודתי.

ברצוני להודות למו פרוביזור (מנהל אגף תכנון, נציבות המים) על התמיכה והעידוד.

אני מודה לנציבות המים על ההשתתפות במימון השתלמותי.

אני רוצה להודות למשפחתי על הסבלנות והתמיכה ובמיוחד לאימי על עזרתה בהגהה הראשונית של עבודה זו.

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חיבור על מחקר

לשם מילוי חלקי של הדרישות לקבלת התואר
מגיסטר למדעים בהנדסה וניהול של משאבי מים

מיכאל זיידה

הוגש לסנט הטכניון – מכון טכנולוגי לישראל

תשס"ו　　　　חיפה　　　　פברואר 2006

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מיכאל זיידה