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The Arab Center for the Studies
of Arid Zones and Dry Lands
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Damascus, Syria
www.acsad.org

FEDERAL REPUBLIC OF GERMANY
Federal Institute for Geosciences
and Natural Resources
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BGR Bundesanstalt für
Geowissenschaften
und Rohstoffe

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Management, Protection and Sustainable Use of Groundwater and Soil Resources in the Arab Region

www.acsad-bgr.org

Development and Application of a Decision Support System (DSS) for Water Resources Management in Zabadani Basin, SYRIA and Berrechid Basin, MOROCCO

By

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CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ABHBC	Agence du Bassin Hydraulique de Bouregreg et de la Chaouia (Basin Agency of Bouregreg and Chaouia), Benslimane, MOROCCO
ACSAD	Arab Center for the Studies of Arid Zones and Dry Lands, Damascus, SYRIA (www.acsad.org)
API	Application Programming Interface
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Ressources), Hannover, GERMANY (www.bgr.bund.de)
C_	Catchment
CROPWAT	A Decision Support System developed by the Land and Water Development Division of FAO (http://www.fao.org/nr/water/infores_databases_cropwat.html)
DAWSSA	Damascus City Water Supply and Sewerage Authority, Damascus, SYRIA
DSS	Decision Support System
E	East
FAO	Food and Agricultural Organization of the United Nations (www.fao.org)
GDBAB	General Directorate of Barada and Awaj River Basin (Water Resources Directorate Rural Damascus Area), Haresta, SYRIA (belonging to the MoI)
GIS	Geographical Information System
GMS	Groundwater Modelling System
GUI	Graphical User Interface
GW	Groundwater
MAAR	Syrian Ministry of Agriculture and Agrarian Reform
masl	meters above mean sea level
MLAE	Syrian Ministry of Local Administration and Environment
MoHC	Syrian Ministry of Housing and Construction
MoI	Syrian Ministry of Irrigation
N	North
S	South
SWAP	Soil-Water-Atmosphere-Plant, agrohydrological model (www.swap.alterra.nl)
USGS	United States Geological Survey (www.usgs.gov)
W	West
WEAP	Water Evaluation and Planning System (www.weap21.org)
WRIC	Water Resources Information Center, Dummar, SYRIA (belonging to the MoI)

1 ABSTRACT

Within the framework of the technical cooperation project “Management, Protection and Sustainable Use of Groundwater and Soil Resources” jointly carried out by the Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD) and the German Federal Institute for Geosciences and Natural Resources (BGR) a Decision Support System (DSS) for water resources management was developed and applied in two pilot areas.

The DSS consists of three major components, a project database, a groundwater flow model (MODFLOW2000) and a user-friendly water evaluation and planning software (WEAP, www.weap21.org). The modelling components MODFLOW and WEAP are dynamically linked so that for each time step results of one model are transferred as input data to the other. MODFLOW calculates groundwater heads, storage and flow, whereas WEAP calculates groundwater recharge, river stage, irrigation demand and the remaining water balance components. Through the WEAP interface the user can manipulate inputs and evaluate and compare results of various current as well as future scenarios in the target area, such as:

- Human activities (population growth, urbanization, domestic demands)
- Agriculture activities (land use, crop types, irrigation practices)
- Climate impacts (climate change models, regional climate cycles)
- Network characteristics (transmission link losses and limits, well field characteristics, well depths)
- Additional resources (artificial recharge, waste water reuse)

The results are visualized as graphs, maps and tables (hydraulic heads, water balances, etc.) and support the decision making process among the relevant stakeholders and decision makers.

In two pilot areas, Zabadani Basin, Syria, and Berrechid Basin, Morocco, the DSS was tested and applied. These applications proved the strengths of the DSS tool especially considering the impacts of climate change, changes in demand and supply, waste water reuse and artificial recharge scenarios on water availability. The DSS has been giving the local stakeholders, institutions and decision makers a valuable base for their current and future water management planning.

Thus, the developed DSS and its software components have been approved to be a user-friendly, inexpensive, efficient and easily shareable tool for water resources management.

2 INTRODUCTION

The situation of Water Resources in the Middle East and North Africa (MENA) is characterised by scarcity and at the same time by increasing demands caused by rapid population growth and inefficient use of water especially by the agricultural sector. The groundwater extractions often exceed the natural recharge volumes, resulting in a decline of the groundwater table and in a deterioration of the soil and water qualities (e.g. salinization). In several countries of the MENA region groundwater flow models exist for some areas, but are often not updated and most commonly basin or administrative "basin" water balances are calculated on very rough assumptions. A comprehensive tool for surface and groundwater management and decision support has been missing up to now in the region.

Therefore, the objective of the technical cooperation project "*Management, Protection and Sustainable Use of Groundwater and Soil Resources*" has been to develop a user-friendly, efficient, inexpensive and easily sharable instrument for water resources management (Decision Support System, DSS), to apply it in two pilot areas (Zabadani Basin, Syria and Berrechid Basin, Morocco), and to distribute it with regard to a more integrated water resources management among the MENA countries and beyond.

The DSS has been built by the combination and linkage of three components, a project database, a groundwater flow model (MODFLOW2000) and a user-friendly water evaluation and planning software (WEAP, www.weap21.org). As most MENA countries of the region rely on groundwater as the main water resource the incorporation of a spatial groundwater flow model is a must for the DSS. MODFLOW2000 was utilized to calculate the groundwater heads, storage and flow. WEAP calculates groundwater recharge, river stage, irrigation demand and the remaining water balance components. By a dynamic link, results of one model are transferred as input data to the other for each time step. Via the WEAP interface the user can manipulate inputs and evaluate and compare results of various current as well as future scenarios in the target area, such as human and agricultural activities, climate and climate change impacts, network characteristics and the mobilisation of additional resources.

3 DSS-CONCEPT

The DSS itself is a software product that gives the user the capability to calculate and visualize the effects on a hydraulic system over time, if one or many of the system's parameters change. DSS users can easily build scenarios of those changes in a Graphical User Interface (GUI) and directly view the results.
It consists of three components (Figure 1):

- Database
- Groundwater Flow Model (MODFLOW2000)
- Water Evaluation and Planning System (WEAP21)

A database is used to store all relevant data; as each institution and region applies its own database system, queries, links or downloads can be applied to input respective data sets into the modelling components.

The modelling components are a combination of two existing software products that are dynamically linked to and affecting each other. MODFLOW calculates groundwater heads, storage and flow, whereas WEAP calculates groundwater recharge, river stage, irrigation demand and the remaining water balance components. WEAP holds the Graphical User Interface for the DSS and acts as a “remote control” for MODFLOW, which is running in the background. As its name implies, it is designed as a tool that supports persons involved in certain decision-making processes rather than being a holistic system that substitutes them.

3.1 WEAP21

The Water Evaluation and Planning System (WEAP, refer to www.weap21.org for more details) has been developed by the Stockholm Environmental Institute (SEI) as a planning tool for water resources management and is distributed free-of-charge for government and non-profit organizations in developing countries.

The program calculates groundwater and surface water balances and current and future demands (irrigation and others) at a catchment, sub-catchment or land use class scale level. For the soil water balance and irrigation demand calculations the user can choose from three different built-in algorithms or enter own expressions:

- FAO crop requirements only (input parameters: reference crop evapotranspiration, crop coefficient, irrigation efficiency, effective precipitation),
- FAO rainfall runoff method (input parameters: like above plus the runoff fractions to ground and surface water)),
- Soil moisture method (input parameters: detailed crop, climate, soil, slope and irrigation parameters).

Its graphical user interface (GUI) is easy to use and setting up model constraints is straightforward. Physical dependencies between modelling units can be defined, re-ordered or removed by drag and drop operations on a drawing surface. Modelling data can easily be changed or updated either directly within the GUI, by importing spreadsheet-data or by linking WEAP to an external database management system using WEAP’s Application Programming Interface (API).

Based on a reference year multiple development scenarios can be designed (incorporating prediction data or functions) and the respective water balance results can be visualized, compared and evaluated as graphs or tables by the user and then support respective decisions for the best or most likely planning scenario.

3.2 MODFLOW

MODFLOW is a computer program developed by the U.S. Geological Survey (USGS), which numerically solves the three-dimensional groundwater flow equation for a porous medium by using a finite-difference method. It is one of the most popular and comprehensive deterministic groundwater models available. The basic model uses a block-centered finite-difference grid that allows variable spacing of the grid in three dimensions. Flow can be steady state or transient. Layers can be simulated as confined, unconfined, or a combination of both. Aquifer properties can vary spatially and hydraulic conductivity (or transmissivity) can be anisotropic. Flow associated with external stresses, such as wells, natural recharge, evapotranspiration, drains, and rivers, can also be simulated using specified head, specified flux, or head-dependent flux boundary conditions. There are several commercially available pre- and post-processing packages; some of these operate independently of MODFLOW, whereas others are directly integrated into reprogrammed and (or) re-compiled versions of the MODFLOW code. More details are available from McDonald & Harbaugh (1988) and Harbaugh & McDonald (1996) and Harbaugh et al. (2000).

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3.3 Dynamic link between MODFLOW and WEAP

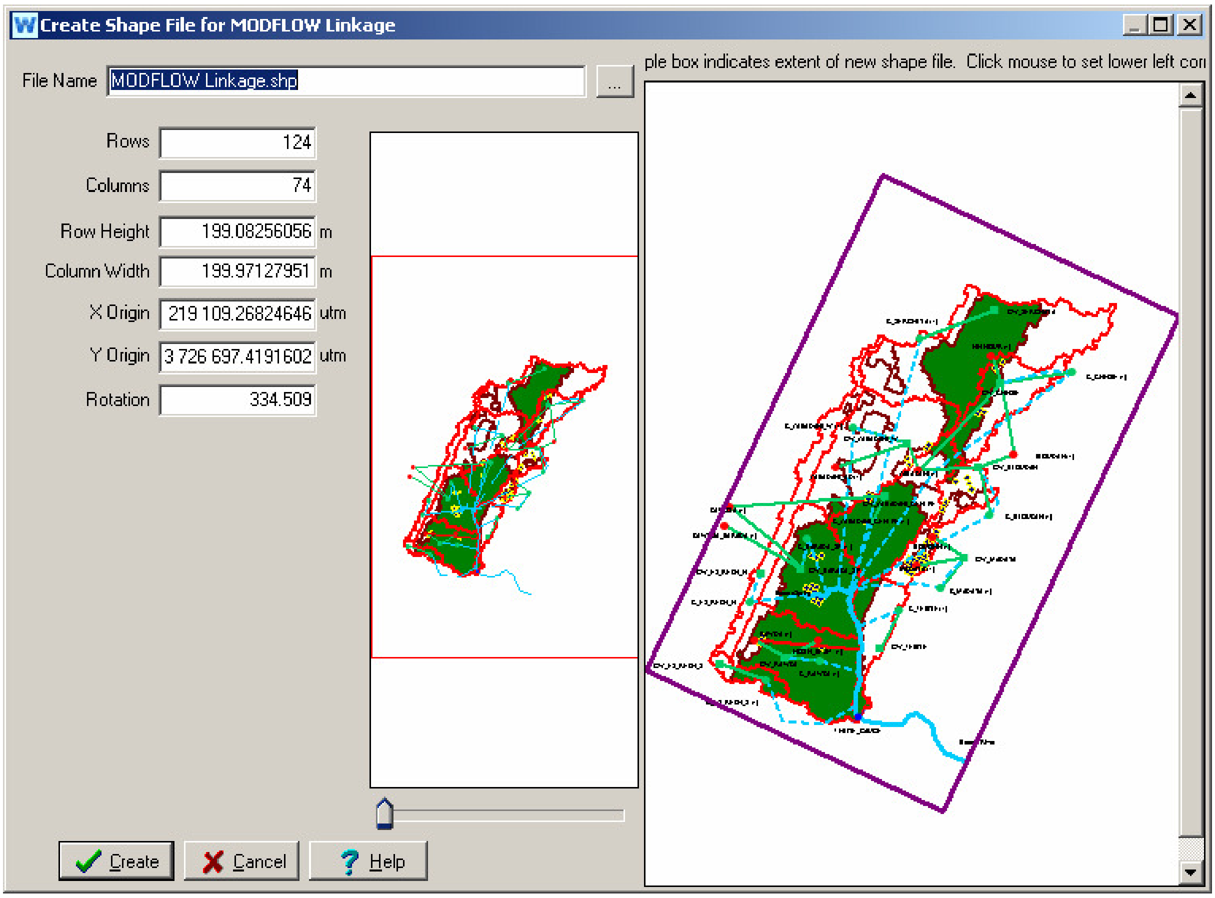
The modelling components MODFLOW and WEAP are dynamically linked so that for each time step results of the one model are transferred as input data to the other. MODFLOW calculates groundwater heads, storage and flow, whereas WEAP calculates groundwater recharge, river stage, irrigation demand and the remaining water balance components.

Contrary to MODFLOW, WEAP does not take into account any spatial relationship between its interior model elements like groundwater nodes, sub-catchments, land use classes or rivers. In order to ensure that WEAP results address the correct MODFLOW grid cells as well as that MODFLOW results are assigned to its corresponding WEAP-elements, the link has to contain information of both models and act as a dictionary between them.

This has been achieved by designing a “linkage-shapefile” (link-file) which consists of rectangular polygons that are identical to the MODFLOW grid cells. All polygon features are enumerated in the same order as MODFLOW internally enumerates its cells and have this enumeration stored as specific row-and-column values. This address acts as a unique identifier to each polygon. Additionally, each polygon holds values of WEAP-elements like sub-catchments’ names. The outlines of sub-catchments and land use classes (spatial units in WEAP) are then spatially intersected with the MODFLOW grid/ link-file polygons to assign the respective WEAP attributes.

3.3.1 Creating the link-file

The link-file can be created within WEAP directly (Figure 3-1) or by a standalone program (ModflowToShape) based on the grid geometry stored in the MODFLOW data set. By overlying GIS-layers of the model area (sub-catchments, land use classes, demand sites, rivers, springs, wells) the required attributes can be assigned to the respective grid polygons using standard GIS-functions.



Create Shape File for MODFLOW Linkage

ple box indicates extent of new shape file. Click mouse to set lower left cor

File Name: MODFLOW Linkage.shp

Rows: 124

Columns: 74

Row Height: 199.08256056 m

Column Width: 199.97127951 m

X Origin: 219 109.26824646 utm

Y Origin: 3 726 697.4191602 utm

Rotation: 334.509

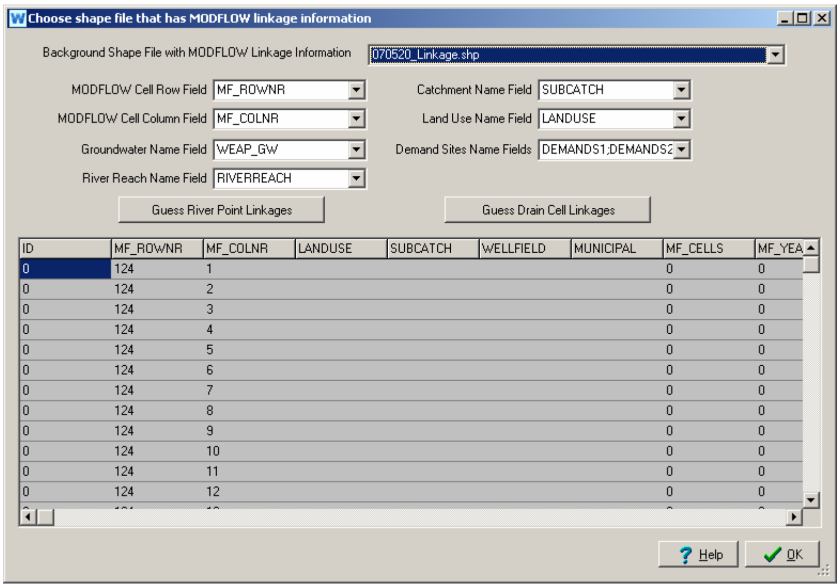
Figure 3-1: Creating the link-shape-file within WEAP

3.3.2 Setting up the dynamic link

After the link-file has been created and all necessary information has been assigned to it, the link-file has to be copied together with the MODFLOW model files underneath the WEAP areas' subdirectory and be loaded as a vector layer in the GUI's "Schematic" view. Now that the link-file is added as a background layer and the MODFLOW name file is specified, MODFLOW and WEAP are ready to be linked by activating the "Link to MODFLOW Groundwater Model" screen.

If WEAP does not find the link layer automatically, it has to be selected manually. WEAP will further try to guess which fields, based on their names, contain information for MODFLOW rows and columns and WEAP groundwater, river reach, catchment, land use branch, demand sites and pumping layers, based on the names of the fields in the link-file's attribute table and will display its contents in the grid below. If WEAP does not correctly guess any of the fields, these have to be chosen manually. For the choice of demand site fields, more than one field might be selected. This would be necessary in cases where multiple demand sites withdrew or returned water to the same cells.

As a convenience for models that include the MODFLOW river (RIV) and drain (DRN) packages, WEAP can try to guess which WEAP river reaches correspond to each river or drain cell, based on proximity to the digitized rivers in the schematic view. There are two buttons on the context screen (“Guess River Point Linkages” and “Guess Drain Cell Linkages”) that make WEAP guess the respective river reach and write its name into the link-file field specified by “River Reach Name Field” (Figure 3-2). It is strongly advised to check back, if the guessing was correct. The easiest way to do this is to display the MODFLOW river cells on the “schematic”-view, labelled by the linked WEAP reach.



Background Shape File with MODFLOW Linkage Information: 070520_Linkage.shp

MODFLOW Cell Row Field: MF_ROWNR

MODFLOW Cell Column Field: MF_COLNR

Groundwater Name Field: WEAP_GW

River Reach Name Field: RIVERREACH

Catchment Name Field: SUBCATCH

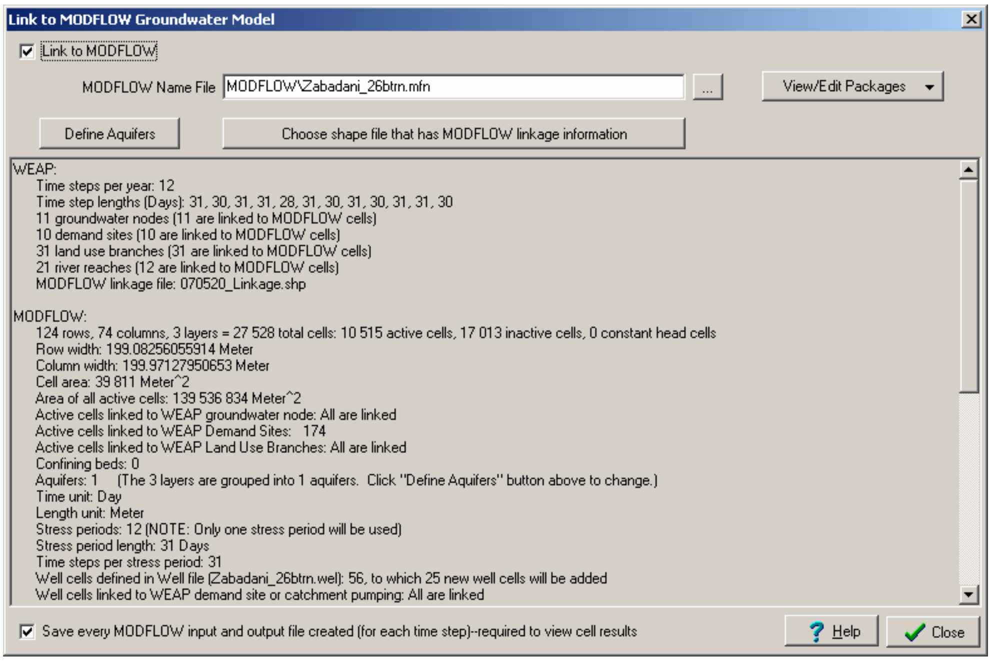
Land Use Name Field: LANDUSE

Demand Sites Name Fields: DEMANDS1;DEMANDS2

ID	MF_ROWNR	MF_COLNR	LANDUSE	SUBCATCH	WELLFIELD	MUNICIPAL	MF_CELLS	MF_YEA
0	124	1					0	0
0	124	2					0	0
0	124	3					0	0
0	124	4					0	0
0	124	5					0	0
0	124	6					0	0
0	124	7					0	0
0	124	8					0	0
0	124	9					0	0
0	124	10					0	0
0	124	11					0	0
0	124	12					0	0

Figure 3-2: The link setup window inside WEAP

After the link-file has been chosen and the fields within it containing the linkage information have been specified, WEAP will be able to link the MODFLOW cells to the WEAP items and returns an on-screen report about the linkage status. For multi-layer MODFLOW models the user can specify by pressing the “Define Aquifers”, button which MODFLOW layers correspond to the respective aquifers, so that WEAP can calculate for each aquifer separate water balances (Figure 3-3).



☑ Link to MODFLOW

MODFLOW Name File: MODFLOW\Zabadani_26btrn.mfn

```
WEAP:
    Time steps per year: 12
    Time step lengths (Days): 31, 30, 31, 31, 28, 31, 30, 31, 30, 31, 31, 30
    11 groundwater nodes (11 are linked to MODFLOW cells)
    10 demand sites (10 are linked to MODFLOW cells)
    31 land use branches (31 are linked to MODFLOW cells)
    21 river reaches (12 are linked to MODFLOW cells)
    MODFLOW linkage file: 070520_Linkage.shp

MODFLOW:
    124 rows, 74 columns, 3 layers = 27 528 total cells: 10 515 active cells, 17 013 inactive cells, 0 constant head cells
    Row width: 199.08256055914 Meter
    Column width: 199.97127950653 Meter
    Cell area: 39 811 Meter^2
    Area of all active cells: 139 536 834 Meter^2
    Active cells linked to WEAP groundwater node: All are linked
    Active cells linked to WEAP Demand Sites:   174
    Active cells linked to WEAP Land Use Branches: All are linked
    Confining beds: 0
    Aquifers: 1     (The 3 layers are grouped into 1 aquifers.  Click "Define Aquifers" button above to change.)
    Time unit: Day
    Length unit: Meter
    Stress periods: 12 (NOTE: Only one stress period will be used)
    Stress period length: 31 Days
    Time steps per stress period: 31
    Well cells defined in Well file (Zabadani_26btrn.wel): 56, to which 25 new well cells will be added
    Well cells linked to WEAP demand site or catchment pumping: All are linked
```

☑ Save every MODFLOW input and output file created (for each time step)--required to view cell results

Figure 3-3: MODFLOW-linkage report in WEAP.

4 PILOT AREA I, ZABADANI BASIN, SYRIA

4.1 Background

The Zabadani Basin is located in the Antilebanon mountains covering an area of about 140 km². Geomorphologically it can be subdivided into three NNE-SSW trending units: the Chir Mansour Mountain range in the W reaching up to 1884 m a.s.l., the Zabadani and Serghaya grabens ranging from 1080 m a.s.l. to 1400 m a.s.l. and the Cheqif Mountain range in the E reaching up to 2466 m a.s.l. The basin is drained by the only perennial stream of the region, the Barada River, which has its source at the Barada Spring at 1095 m a.s.l. (Figure 4-1 and Figure 4-3). The mean annual rainfall is about 700 mm. About 48 000 people living permanently in the area, however during summer especially in Zabadani and Bloudan the population doubles or triples by the number of tourists (Table 4-1).

Table 4-1: Population data in the Zabadani Basin.

Population Census in	**1994**	**2004**
Zabadani	21049	26285
Madaya	8649	9371
Rawda	2825	4536
Bloudan	4685	3101
Ein Hour	1583	1974
Bouqein	1746	1866
Hosh Bejet	429	604
TOTAL	**40966**	**47737**

Source: Syrian Central Bureau of Statistics

There is already a water competition in the area between drinking water suppliers of the area, Damascus water supply authority and agricultural and touristic activities. In dry years Barada Spring (average discharge 3.8 m³/s) ceases completely during the summer months, raising conflicts between the farmers relying on the river discharge and the Damascus City Water Supply and Sewerage Authority (DAWSSA), which is operating a major well field next to Barada Spring.

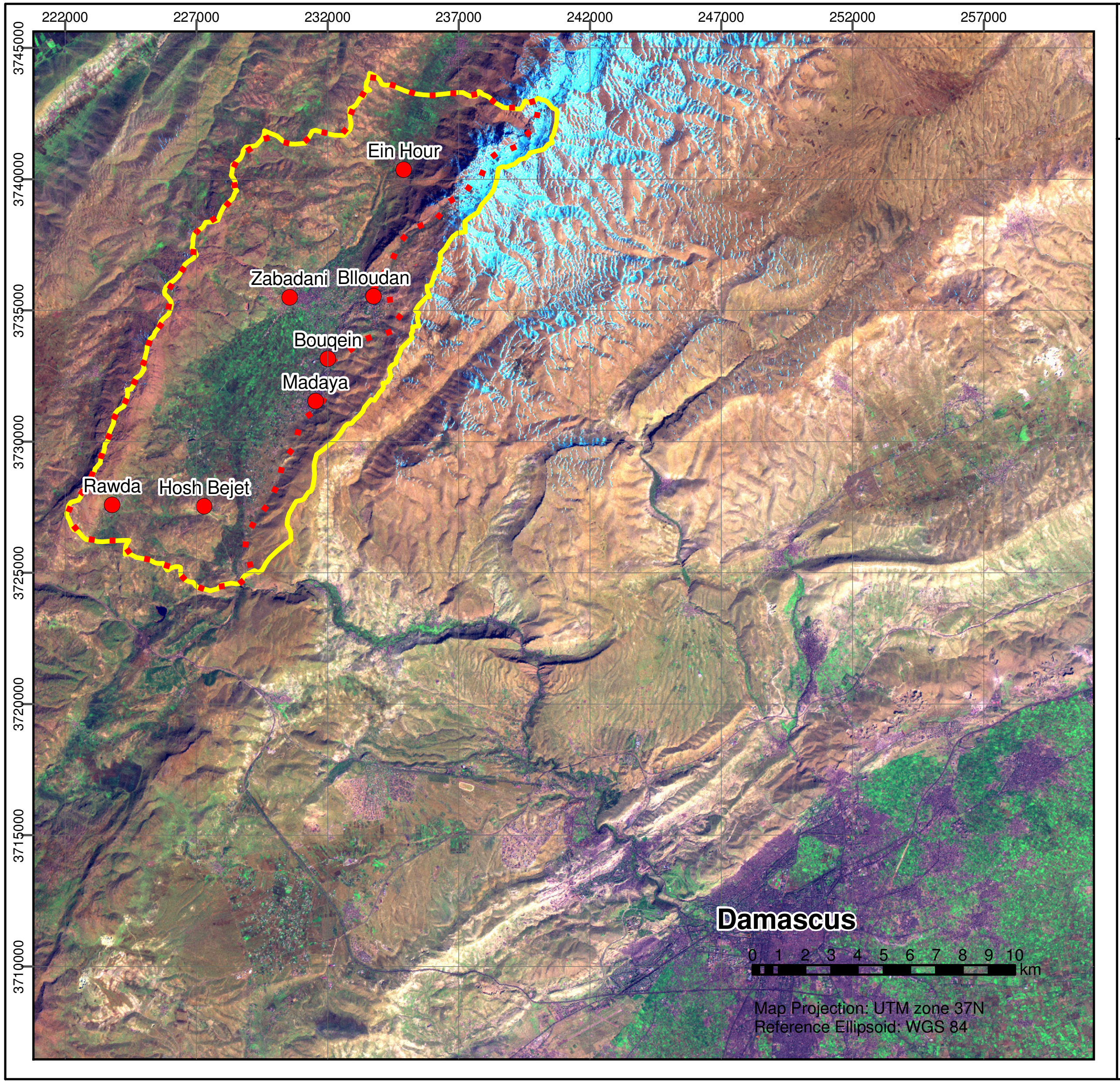
Since the very beginning of the project a steering committee has been set up, integrating all the relevant stakeholders into the DSS development, data acquisition and future scenario planning. The respective institutions are:

- Ministry of Irrigation (MoI), Directorate of Water Resources Management,
- General Directorate of Barada and Awaj Basin (GDBAB of MoI),
- Water Resources Information Center (WRIC of MoI),
- Damascus City Water Supply and Sewerage Authority (DAWSSA),
- Drinking Water Supply Authority for Rural Damascus (DRA of the Ministry of Housing and Construction, MoHC),
- Ministry of Agriculture and Agrarian Reforms (MAAR), main and regional offices,
- Zabadani Municipality,
- Ministry of Local Administration and Environment (MLAE).

Arab-German Technical Cooperation

Management, Protection and Sustainable Use of Groundwater and Soil Resources

Decision Support System Zabadani Basin



Location of the Zabadani Basin

● Cities & Villages

▭ Surface Watershed

⬚ Groundwatershed (estimated)

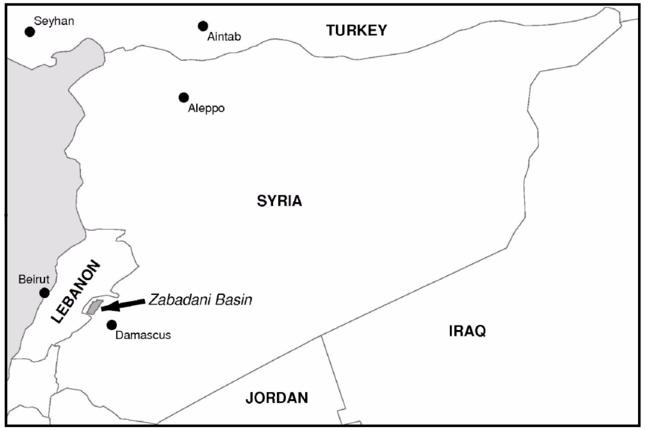


Figure 4-1: Location of the Zabadani Basin

- basemap: ETM+ Landsat scene 174/37, bands 7-4-1, image date: 8.3.2002

compiled by J. Wolfer 7/2006

N

1:250,000

The Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD)
Federal Institute for Geosciences and Natural Resources (BGR)

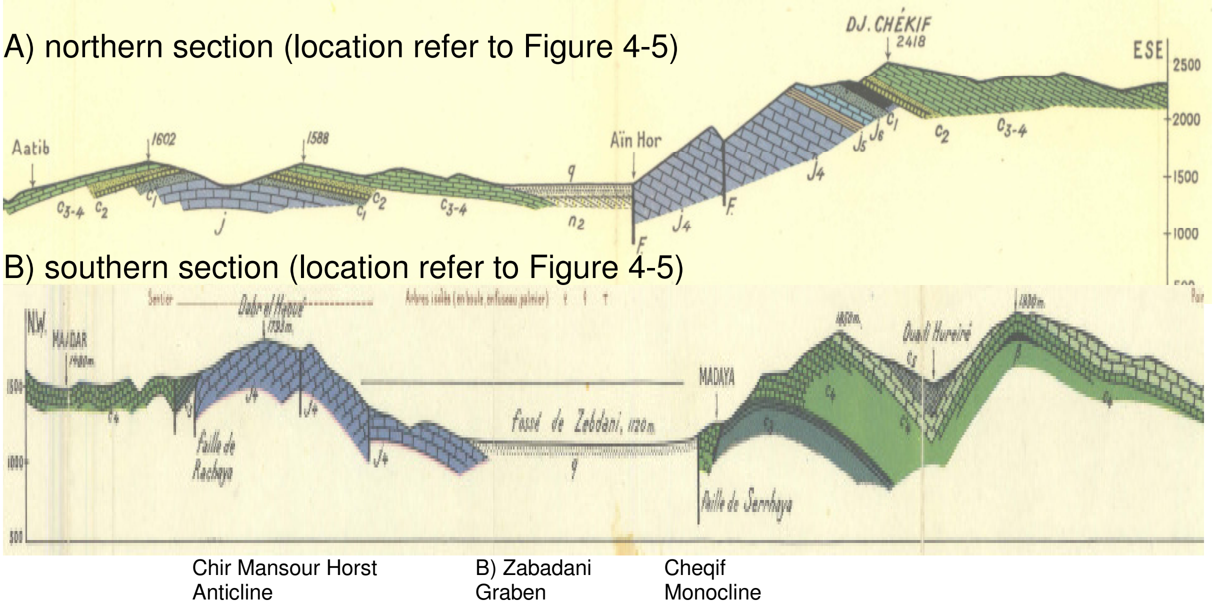
4.2 Hydrogeology and Hydrology

4.2.1 Hydrogeology

The Zabadani Basin is located in the Antilebanon mountain range, which is mainly built of Jurassic and Cretaceous limestones, minor basaltic, sandstone and claystone intercalations at the base of the Cretaceous, Neogene conglomerates and Quaternary alluvium (Figure 4-5).

The regional tectonic pattern of the Antilebanon mountains is very complicated as the major branches of Red Sea – Dead Sea transform fault system are cutting the area. In the study area the Serghaya fault is not only a normal fault separating the Zabadani graben from the Cheqif Mountain range, with an offset of more than 2 km, but also represents a major branch of the sinistral transform system with an offset of tens of kilometres (DUBERTRET & VAUTRIN 1950). Figure 4-5 shows the major folds and faults and geologic cross sections are presented in Figure 4-2, and Figure 4-8.

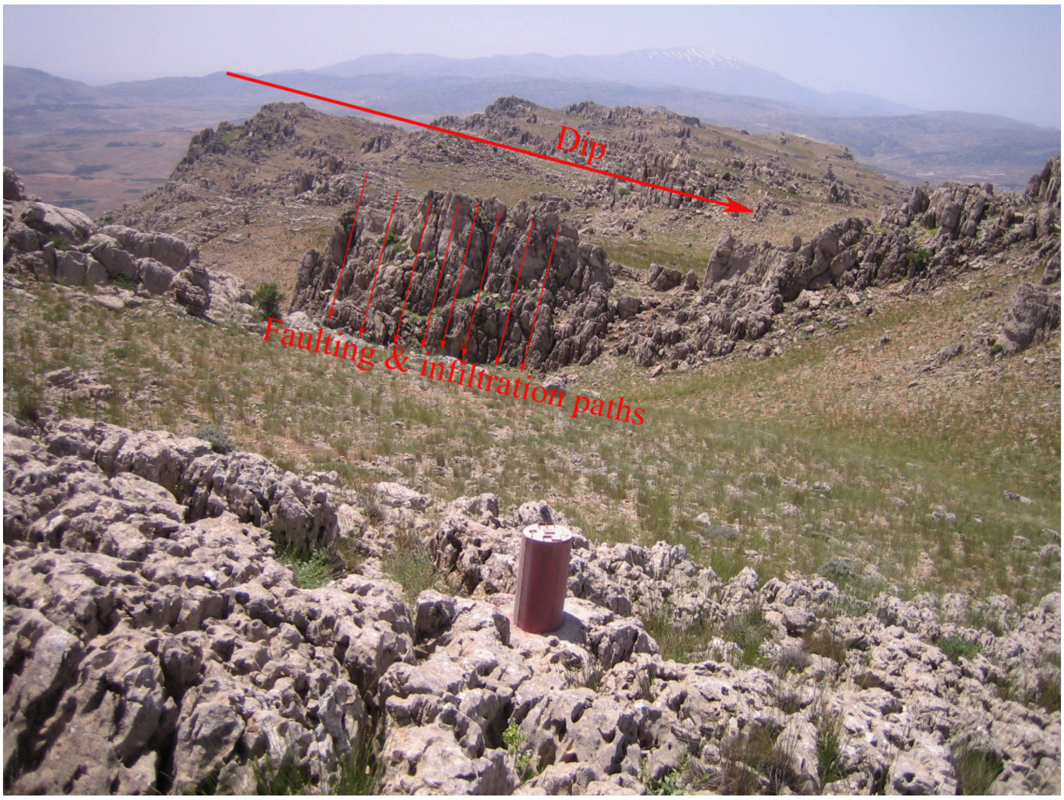
From NW to SW the area can be subdivided into 3 tectonic blocks: the Chir Mansour Horst-Anticline (Chir Mansour mountain range), the Zabadani Graben and the Cheqif Monocline (Cheqif mountain range). The patterns of these blocks are described in more details in the following chapter.


A) northern section (location refer to Figure 4-5)

B) southern section (location refer to Figure 4-5)

Figure 4-2: Geologic Cross Sections NW – SE (DUBERTRET & VAUTRIN 1950).

Figure 4-3: Tectonic map of the study area.



A: View SSW from the summit of Chir Mansour Range showing the SW-dip direction, narrow faulting and the karstification in the Jurassic limestones.

B: View NNW from Wadi Manshura (Cheqif Range) showing narrow NNW-striking jointing/faulting and the karstification in the Jurassic limestones.

Figure 4-4: Jurassic outcrops.

Figure 4-5: Hydrogeologic blocks in the Zabadani Basin.

Figure 4-6: Contours of the top Cretaceous in the Zabadani graben.

4.2.1.1 Hydrostratigraphy

Table 4-2 shows the relative hydraulic properties of the outcropping formations in the Zabadani Basin. The main aquifers of the area are:

- the Jurassic aquifer (karstified limestones)
- the Cretaceous aquifers:
    - -the Aptian aquifer (ferruginous sandstones)
    - -the Cenomanian-Turonian aquifer (karstified limestones and dolomites)
- the Neogene and Quaternary deposits in the Zabadani and Serghaya grabens are forming local aquifers of minor yields

Local perched aquifers:

- the clay rich facies of the pre-upper Aptian caused a massive mudflow and a large debris cone deposit between the villages of Bloudan and Zabadani forming there local perched aquifers, proven by various spring outlets in the area
- the same pre-upper Aptian facies and a local basalt facies form further North along the W slope of Cheqif mountain the basis of a perched aquifer proven by several springs emerging at its contact.

Beside the lithological aspect, the degree of fracturing and karstification controls the hydraulic properties significantly (s. next chapter).

Table 4-2: Hydrostratigraphy of the outcropping formations in the Zabadani Basin.

system	**unit**	**map**	**thickness [m]**	**lithology**	**Permeability:** - low/ +++ high -/+ vary depending on facies
QUATER NARY	recent	Q_4	>5	recent alluvial and proluvial deposits, loams, sands, "Zabadani Mudflow" debris	perched aquifers in the Zabadani Mudflow area
	middle	Q_3	10-15	cemented boulder, pebble conglobreccia	
	lower	Q_1	<50	lacustrine limestones (only downstream of Tekkiye),	
NEO GENE	Pliocene	N_2a	100-700	conglomerates	**+/-**
PALEO GENE	Upper Eocene	Pg_{3-2}	15-45	marbled limestone	**-**
	Middle Eocene	Pg_{2-2}	260-360	limestones, marls, flints, conglomerates	**-**
	Lower Eocene	Pg_{1-2} p	220	limestones, marls, flints, conglomerates	**-**
	Palaeocene-Lower Eocene	Pg_{1-1} / Pg_{1-2} ar	40-70	green clay marls and chalky white marls	**-**
CRETACEOUS	Danian	Cr_2m-d	70	white chalky limestones, marls and clays	**-**
	Upper Campanian	Cr_2cpb	20-30	upper calcareo-siliceous unit, chalky limestones & flint)	**-**
	Lower Campanian	Cr_2cpa	65-80	lower calcarous unit(white chalky limestones),	**-**
	Coniacian, Santonian	Cr_2cn+st	70-120	thick bedded white, chalky argillaceous limestones	**-**
	Lower Coniacian	Cr_2cna	77-115	upper part: limestones lower part: dolomitic limestones, Sst. 77-115m	**-**
	Lower Touronian	Cr_2t_1	20-60	light grey - soft white shaly limestones	**+**
	Upper Cenomainan	Cr_2cmb	60-70	dark grey granular dolomites, dolimitic limestones	**++**
	Lower Cenomanian	Cr_2cma	550	limestones and marls	**+**
	Albian	Cr_1al	110-120	limestones, marly limestones and marls, yellowish-green, lumpy structure	**+**
	Upper Aptian	Cr_1ap_2	70-150	upper part: ferruginous quartz sandstone 50-100m lower part: white limestones 20-50m	**+**
	Pre-Upper Aptian	Cr_1aap_2	10-203	rusty-brown quartz sandstone upper section occurring argillaceous sandstone, sandy clay (Bloudan 10m, Chekif 35m) - Basalts	**+ /-**
JURASSIC	Tithonian	J_3t	25-40	yellowish-grey pelitomorphic limestones alternating with thick, massive clastic limestones 20 m	**+++**
	Kimmeridgian	J_3km	60-70	massive, steep cliff forming, light colored thick bedded (2m) grey pelitomorphic limestones	**+++**
	Upper Oxfordian	J_3ox_2	35-50	dark grey clay-marls and argillaceous, organogenous limestones	**++**
	Lower Oxfordian	J_3ox_1	90-102	coarse detrital, massive and fine detrital, thin-platy limestones, grey	**++**
	Callovian	J_3cl	>688	limestones - beds; dolomitic limestones, limy dolomites lower and middle section, reddish brown - dark grey	**+++**

based on Kurbanov, Zarjanov & Ponikarov, 1968 & Russian Study, 1986

4.2.1.2 Hydrogeologic Blocks

The Zabadani Basin was subdivided into three hydrogeological and tectonic blocks based on their hydrogeologic and hydraulic properties (Table 4-3 & Figure 4-5):

A) Western Block, Chir Mansour mountain range consisting mainly of Jurassic and Cretaceous limestones and some Cretaceous sandstones

B) Central Zabadani and Serghaya Graben: filled by Neogene and Quaternary Deposits (conglomerates, marls, gravel)

C) Eastern Block, Cheqif mountain range consisting of Cretaceous, Jurassic and in the SE also Neogene rocks

Table 4-3: Geologic and hydraulic pattern of the different tectonic blocks.

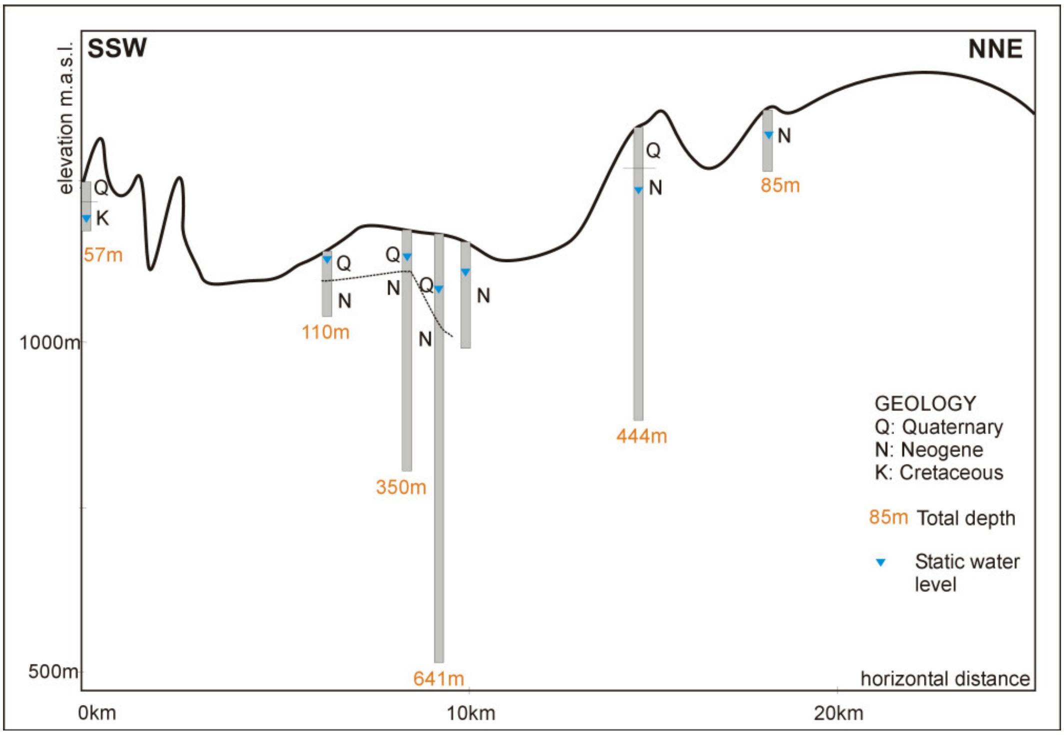
Jurassic outcrops are shown in Figure 4-4

Block	**A) Chir Mansour Range**	**B) Zabadani Graben**	**C) Cheqif Range**
location	NW	CENTER	SE
major geology	Jurassic limestones	Neogene conglomerates	Cretaceous limestones
thickness (outcrop units)	Jurassic: 1000m	Neogene: Max. > 600m	Cretaceous: > 2000m
strike	NNE-SSW	NNE-SSW	NE – SW
dip	WNW	unknown	SE
faulting	Chir Mansour is an uplifted Horst with intensive block faulting brittle deformation	step faults & fault zones	beginning of Qalamoun Range, ductile deformation in mainly Cretaceous rocks
deformation style	brittle (in Jurassic rocks)	unknown	ductile (in Cretaceous rocks)
folding	anticline structure	unknown	monocline/ anticline structure
karstification	intensive	not	minor
aquifers	one aquifer system through intensive faulting proven by some deep drillings (RUSSIAN STUDY, 1986)	one aquifer system, hydraulically connected to Jurassic/ Cretaceous.	Jurassic and Cretaceous aquifers are separated by basalt/tuff or clay and marl layers representing a special facies of the lower Cretaceous there. Local springs emerging at the base of the Cretaceous.
transmissivity	+++	+	++
boundary of groundwater-shed versus surface watershed	assumed to be identical with surface watershed due to intensive vertical jointing, however there might be additional groundwater inflow from S	identical to surface watershed	groundwatershed due to E dipping formations possibly located W of surface watershed

This subdivision was digitized, based on the Geological maps 1:50000 (KURBANOV, ZARJANOV & PONIKAROV, 1968) and 1: 100 000 (RUSSIAN STUDY, 1986) taking also into account borehole logs and pumping test data of the RUSSIAN STUDY (1986). The faults separating the different blocks are supposed to be vertical – although in reality multiple step faults with various dips and offsets are present.

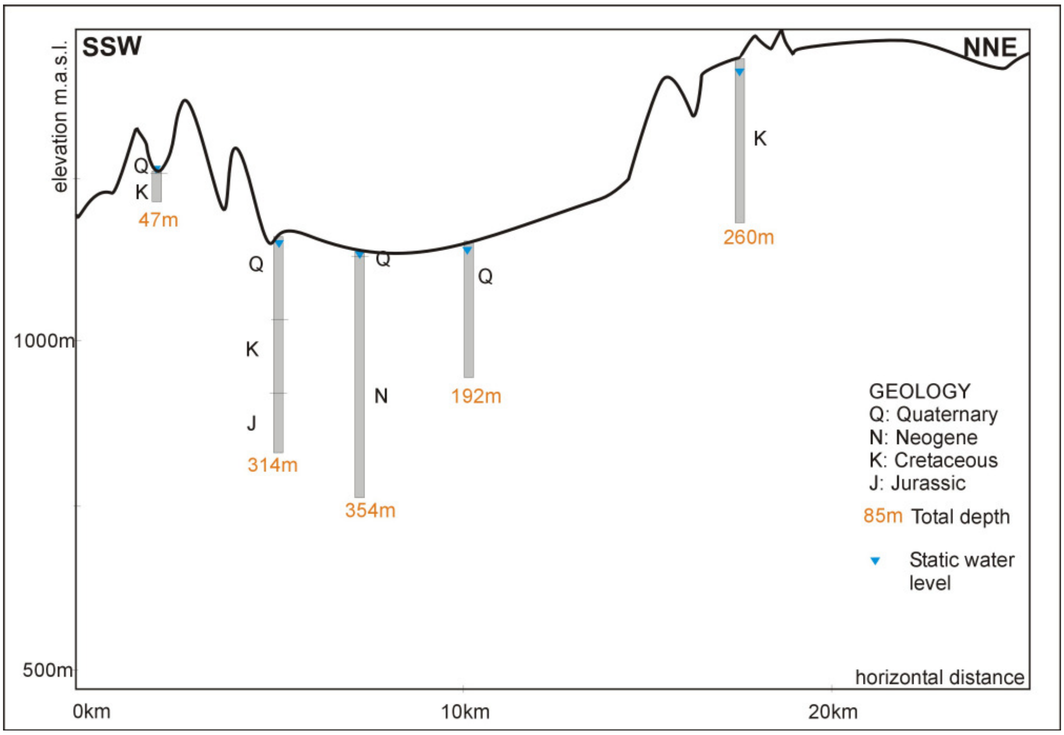
Whereas the Western and Eastern Blocks are assumed to be of great thickness (Jurassic + Cretaceous > 3 km) the thickness and morphology for the Neogene and Quaternary graben fill, was determined only by using the results of the geoelectrical and seismic soundings (RUSSIAN STUDY, 1986) having the top Cretaceous as a key horizon (Figure 4-6). There are no boreholes reaching the Cretaceous in the graben; the borehole 118AK with a total depth of 641 m remained still in Neogene deposits (Figure 4-7). The maximum thickness of Neogene and Quaternary deposits is about 700 m.

Several deep drillings (> 1 km) and hydraulic tests within the Zabadani Basin have proven that it is one aquifer system with hydraulic connections between the different lithological units and the similar hydraulic heads (RUSSIAN STUDY, 1986). In general the local transmissivities are strongly dependent on the local degree of fracturing and karstification. The Eastern Block C) is hydrogeologically still poorly understood as there are some perched aquifers overlaying and due to the lack of deep boreholes the Eastern limit of the groundwatershed remains unknown.



Cross section I, location see Figure 4-5 (borehole data from RUSSIAN STUDY, 1986).

Figure 4-7: Geological sketch I, SSW – NNE through the Zabadani Basin.,



Cross section II, location see Figure 4-5, (borehole data from RUSSIAN STUDY, 1986).

Figure 4-8: Geological sketch II, SSW – NNE through the Zabadani Basin

4.2.1.3 Transmissivity Zones

As there is no sufficient spatial coverage of pumping test data, transmissivity zones were determined according to the hydrogeology and the available pumping test data of the RUSSIAN STUDY (1986). The pumping test data show high variability within the zones depending on the degree of fracturing, however taking into account the cell size of the groundwater model, an average number is expected to be sufficient.
Following zones could be differentiated (Table 4-4 & Figure 4-9):

Table 4-4: Transmissivity classes in the Zabadani Basin.

Transmissivity [m²/d]		**Geology**	**Reference**
Range	Average		
< 50	10	Neogene Conglomerates (SE margin)	GDBAB & private drilling data
2-150	40	Neogene & Quaternary Graben fill	Pumping Test Data, RUSSIAN STUDY (1986)
70-340	150	Aptian Sandstones (W-Block)	Pumping Test Data, RUSSIAN STUDY (1986)
25-300	275	Cretaceous, E-Block Zabadani Basin	GDBAB estimation
250-300	275	Cretaceous, W-Block Zabadani Basin	Pumping Test Data, RUSSIAN STUDY (1986) & GDBAB estimation
>1000	1500	Jurassic Limestones	Pumping Test Data, RUSSIAN STUDY (1986)

Figure 4-9: Transmissivity Zones of the Zabadani Basin.

4.2.1.4 River – Groundwater – Interaction

In the RUSSIAN STUDY (1986) detailed investigations regarding the groundwater – Barada River interaction have been undertaken. Along two sections (Ramleh and Tekije) several boreholes have been drilled and the water levels in the boreholes and the Barada River have been monitored through the seasons, showing different hydraulic conditions.

Ramleh (1km downstream from Barada Spring): groundwater levels in the shallow Quaternary aquifer are always above the river level and therefore recharging the Barada River. The lower aquifer is confined and recharges the upper shallow Quaternary aquifer by upward leakage. The hydraulic head of the lower aquifer is always above the upper aquifer and in spring even artesian conditions prevail (Figure 4-10).

Tekijeh (7km downstream from Barada Spring): groundwater levels stay always below the river level, indicating no connection between the groundwater and the river. The river discharge shows that the river bed is sealed yielding only minor infiltration from the river into the groundwater. Groundwater level is always 10 -20 m below the river level (Figure 4-11).

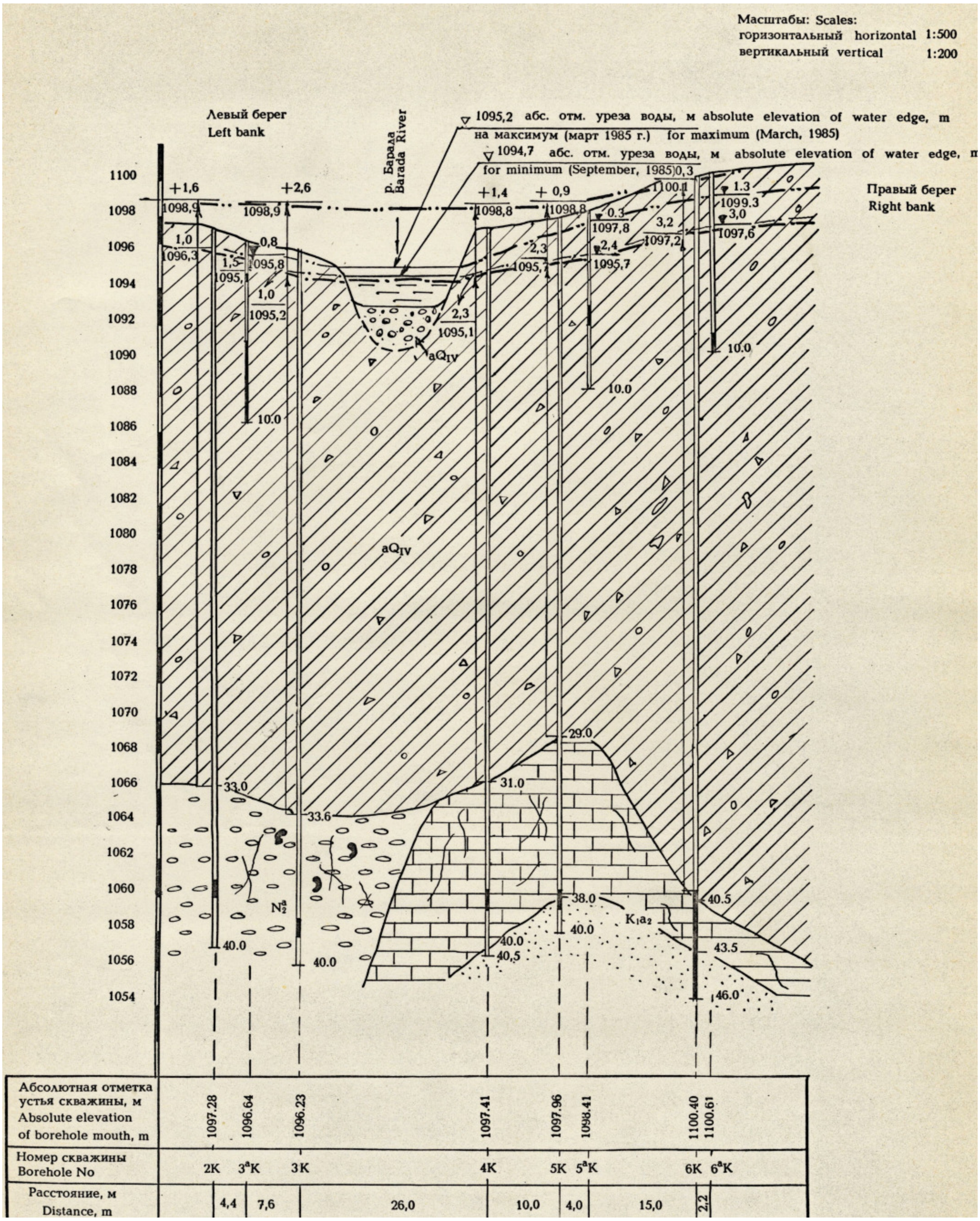


Figure 4-10: Hydraulic conditions in the Ramleh area (Russian Study,1986)

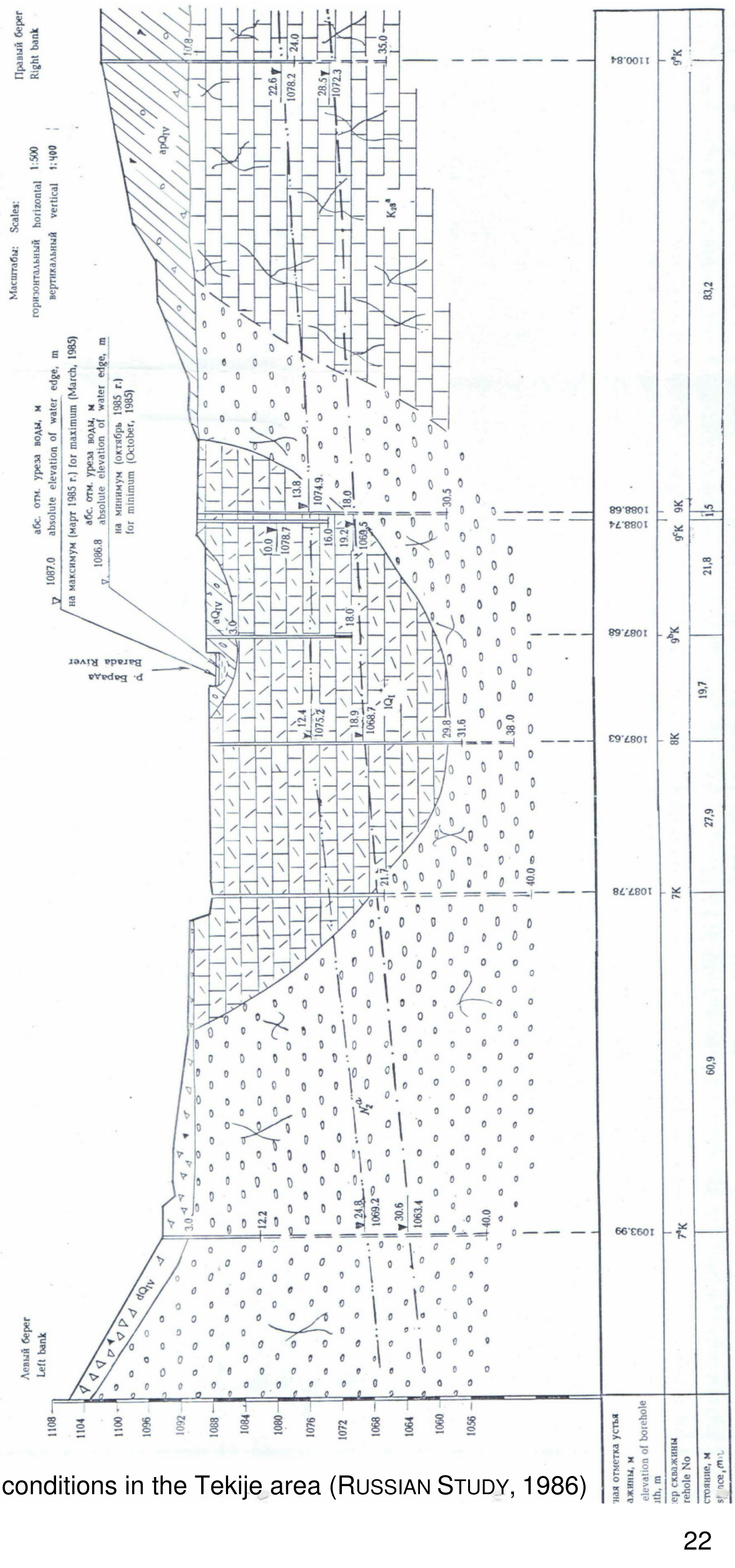


Figure 4-11: Hydraulic conditions in the Tekije area (RUSSIAN STUDY, 1986)

4.2.1.5 Initial Groundwater levels

A reference map for initial groundwater levels (Figure 4-12) for spring 2005 was produced using the following resources:

- RUSSIAN STUDY, 1986
- ACSAD, 2002
- Monitoring data of the General Directorate of the Barada and Awaj River Basin (GDBAB)
- Water level survey by the ACSAD-BGR-Project 05/2006

Through the groundwater flow modelling process and discussions with local farmers and well-drillers the following differences between the surface and groundwater catchments have been assumed:

- the top of the eastern block is assumed to be a perched aquifer and the boundary was estimated by the contact Jurassic/Cretaceous and the trace of the Chir Mansour monocline/ anticline axis (Figure 4-12).

- significant groundwater inflow from SW and most likely also at a minor scale from W through the Jurassic aquifer (Figure 4-12).

4.2.2 Hydrology

As mentioned above due to the highly developed karstification in the limestone formations of the area, surface runoff plays only a minor role. The Barada River is the only permanent surface water stream of the area and is fed mainly by groundwater discharge through Barada Spring.

The table below shows the comparison between Barada Spring and Barada River discharges (6 km downstream of the source) at Tekije where the Barada River leaves the Zabadani Basin. In between the wastewater inflow (through respective wastewater canals) and the surface runoff from the riparian municipalities is either used before directly for irrigation/ infiltration or evaporation - or pumped from the river as mixed water back to the fields for the same purpose (Table 4-5). The records indicate that there is only in January and February a significant surface runoff from the area to Barada River and a minor inflow in April and May due to snow melting.

Figure 4-12: Groundwater contour map of Zabadani Basin.

Table 4-5: Barada Spring and River discharges for the reference year 2004/2005.

month	Barada Spring discharge [Mm³/month]	Barada River at Tekiye discharge [Mm³/month]	River water balance [Mm³/month]
10/2004	2.42	2.97	**0.55**
11/2004	5.6	4.74	**-0.86**
12/2004	4.53	4.41	**-0.12**
01/2005	4.43	8.27	**3.84**
02/2005	7.52	17.54	**10.02**
03/2005	13.07	12.49	**-0.58**
04/2005	9.52	11.29	**1.77**
05/2005	5.77	8.5	**2.73**
06/2005	7.47	7.47	**0**
07/2005	4.16	4.22	**0.06**
08/2005	1.88	1.56	**-0.32**
09/2005	1.78	1.64	**-0.14**
yearly total	**68.15**	**85.10**	**16.95**

4.2.3 Climate

The Climate of the Antilebanon Mountain Range, is a Mediterranean climate with precipitation occurring between October and May. As the main fronts move in from the west and southwest there is a decrease to the east and on the leeward side of the high mountains. For the reference year 2004/2005 the range of precipitation was between 400 and 1000 mm with an average of 714 mm. In the winter months December to March snow falls and accumulates above elevations of about 1600 m.

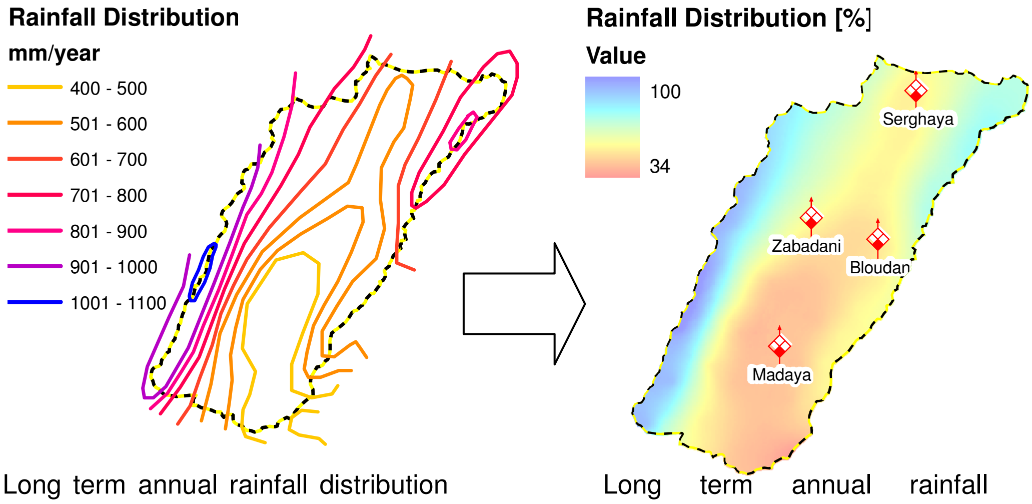
In chapter 4.4.6 more information on the monthly distribution of precipitation, wind, temperature and humidity are given. In the following the regionalization method for rainfall station data is described.

Due to the scarcity and inconsistency of the available data sets an interpolation approach was applied to calculate the spatial rainfall distribution in the study area. The long term annual rainfall distribution pattern (Russian Study 1986) was digitized and based on this a grid of the long term annual rainfall distribution percentage was calculated (max. value 1100mm).

The 4 stations with reliable long term records (Madaya, Bloudan. Zabadani and Serghaya) inside the Zabadani Basin where then used as reference stations and their respective mean values were used to calculate a monthly rainfall distribution grid:

$$\mathbf{GridPrecip_{monthly} = (M+B+Z+S\ /\ 4)\ /\ (M\%+B\%+Z\%+S\%\ /\ 4)\ X\ GridPrecip_{distribution\%}}$$

$GridPrecip_{monthly}$:	*monthly precipitation grid [mm]*
M, B, Z, S:	*measured monthly precipitation at Madaya (M), Bloudan (B), Zabadani (Z) and Bloudan (B) stations [mm]*
M%, B%, Z%, S%:	*long term precipitation distribution percentage at the Madaya (M%), Bloudan (B%), Zabadani (Z%) and Serghaya (S%) stations [%]*
$GridPrecip_{distribution\%}$.	*long term precipitation distribution grid [%]*



Long term annual rainfall distribution (based on Russian Study, 1986)

Long term annual rainfall distribution as percentage grid

Figure 4-13: Rainfall distribution maps.

4.2.4 Basin Boundary

Initially the watershed of the Zabadani Basin was assumed to be identical for the surface and groundwater. In the Serghaya plain this was proven by a groundwater level campaign in May 2006 showing that the shallow groundwater table (2-3 m below surface) follows the surface watershed in the plain area. The influence of the basalt in the subsurface of the plain remains unknown. Along the western margin the intensive fracturing and jointing of the Jurassic limestones indicate that there is no dip-dominant flow direction of the groundwater (otherwise the groundwatershed would be E of the surface watershed). Along the eastern margin of the basin the situation is more uncertain as the fracturing and jointing there are not so intensive in the Cretaceous limestones and a more dip-dominant groundwater flow direction may be expected shifting the groundwatershed probably further W. For the DSS and its sub-models the SE part of the basin was neglected as this area is most likely a perched aquifer system and not linked to the main aquifer. Therefore the groundwatershed in the SE was assumed to follow the anticline/ monocline axis.

4.3 Groundwater Flow Model (MODFLOW)

4.3.1 Conceptual Model

The conceptual model has been designed according to the prevailing hydrogeological and geological conditions as described above and the lessons learnt from a previous groundwater model in the Zabadani Valley (ACSAD, 2002). The regional aquifer has been subdivided into three layers (Table 4-6), which have different hydraulic properties but are hydraulically connected.

Table 4-6: Hydrogeologic blocks and layers as applied in MODFLOW.

relative permeability: - low, + intermediate, ++ high, +++ very high

W - Block	Graben	E – Block	k-ranges [m/d]
Cretaceous/ Jurassic +++ 400-600m	Neogene - 400-600m	Neogene/Cretaceous/ Jurassic +++ 400-600m	0.010 – 60.000
Cretaceous/ Jurassic ++ 200-300m	Neogene/ Cretaceous/ Jurassic - 200-300m	Cretaceous/ Jurassic ++ 200-300m	0.005 – 1.500
Jurassic + 200-300m	Cretaceous/ Jurassic + 200-300m	Cretaceous/ Jurassic + 200-300m	1.000

All boundary conditions have been considered as no flow boundary (groundwater divide), except the surface water outlet of the basin, which is a specified-head boundary.

As mentioned above there is a significant groundwater inflow from the southwest and probably also from the west. These inflows have been modelled as additional recharge along the respective boundary sections. A more reliable estimation of the amount and seasonal pattern of groundwater inflows to the basin requires further investigations. Table 4-7 shows the preliminary water balance of the Zabadani Basin for the hydrological year 2004/2005 used as a reference year.

Table 4-7: Preliminary Water Balance for the Zabadani Basin.

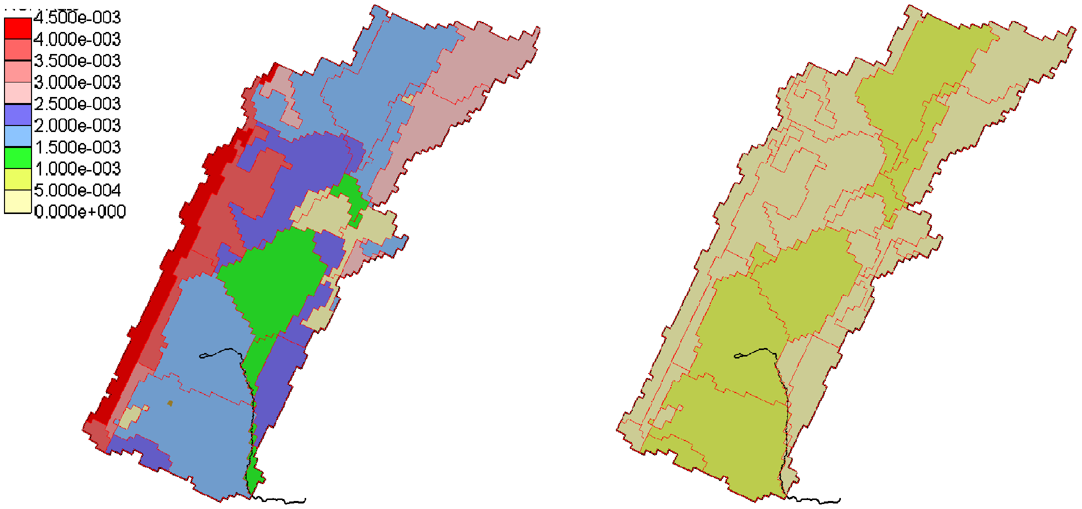
Month	**GW-Abstraction / Spring discharge**				**Rainfall**	**Recharge**	**BALANCE**
	Barada Spring	**Irrigation**	**Domestic**	**SUM**			
10/2004	2.42	4.085	4.559	11.064	1.261	1.113	-9.951
11/2004	5.6	0.000	4.101	9.701	29.943	7.350	-2.351
12/2004	4.53	0.000	3.87	8.400	7.003	7.487	-0.913
01/2005	4.43	0.000	3.228	7.658	21.381	9.301	**1.643**
02/2005	7.52	0.000	0.766	8.286	27.494	11.408	**3.122**
03/2005	13.07	0.000	0.766	13.836	3.928	9.980	-3.856
04/2005	9.52	0.000	0.766	10.286	5.61	6.552	-3.734
05/2005	5.77	0.000	0.766	6.536	3.772	3.758	-2.778
06/2005	7.47	2.884	0.766	11.120		1.793	-9.327
07/2005	4.16	14.218	2.038	20.416		1.299	-19.117
08/2005	1.88	2.670	3.593	8.143		1.066	-7.076
09/2005	1.78	7.488	3.952	13.220		0.914	-12.306
SUM	**68.15**	**31.345**	**29.171**	**128.666**	**100.393**	**62.022**	**-66.644**

All units in Mm^3, irrigation and recharge volumes calculated in WEAP

4.3.2 Input Data

All the stresses on groundwater have been entered in map module as different layers.

- Recharge: the respective groundwater recharge values have been calculated for each land use class by WEAP, applying the “soil moisture method” and then evenly assigned to respective model cells (positive recharge). In general the Jurassic outcrops receive the highest groundwater recharge from rainfall, whereas the graben area receives lower recharge from rainfall, however some additional recharge from irrigation return flow (Figure 4-14).



Jan 05

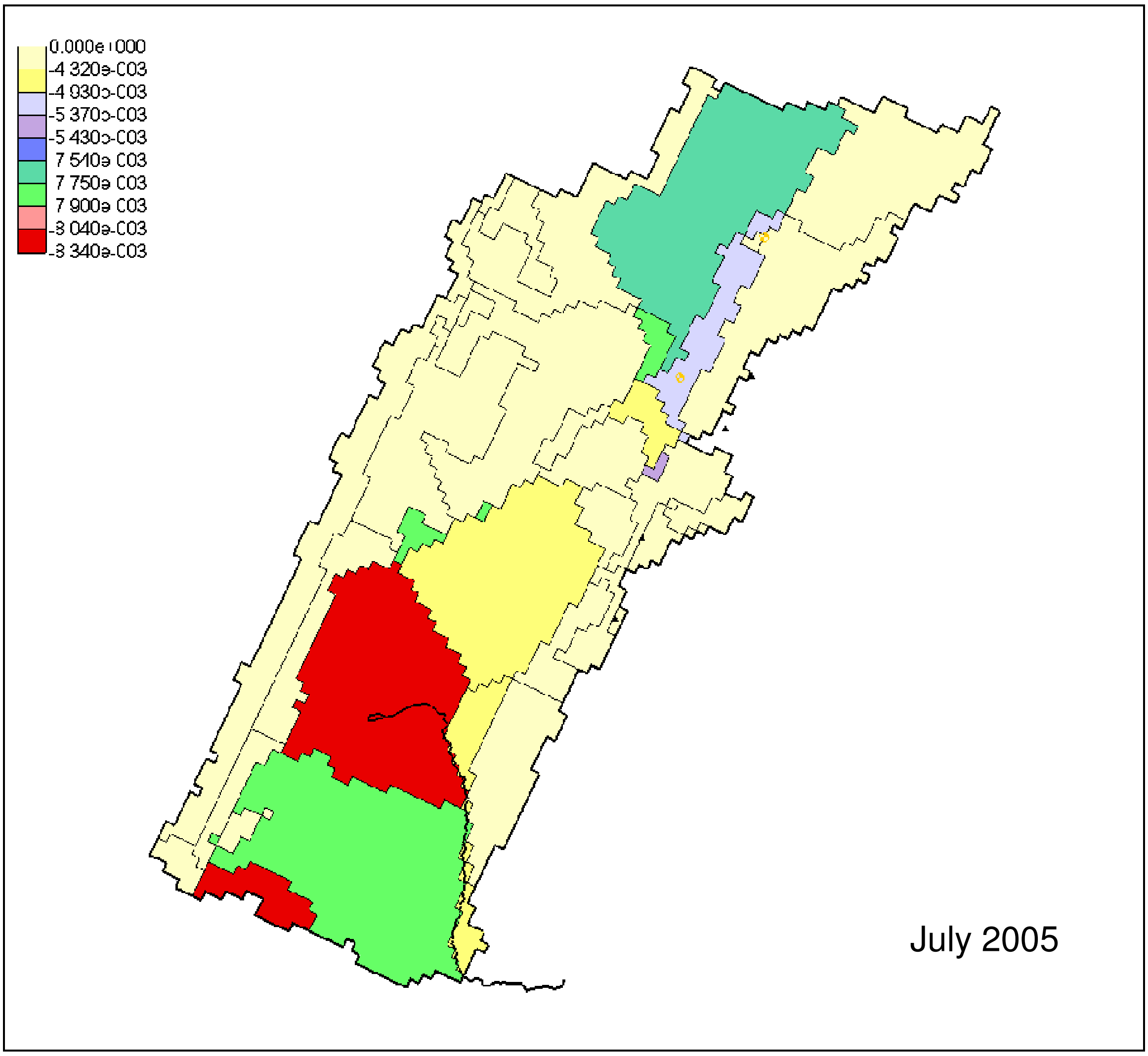
July 05

Values calculated by WEAP and entered to MODFLOW (in m/d).

Figure 4-14: Seasonal groundwater recharge (m/d).

- Domestic groundwater abstraction: the respective well field (Figure 4-23) abstraction rates have been assigned to respective model cells (wel-file).

- Irrigation groundwater abstraction: the respective groundwater abstraction data have been calculated for each land use class by WEAP, applying the “soil moisture method” (s. chapter 4.4.8.6) and then evenly assigned to respective model cells as negative recharge (Figure 4-15).

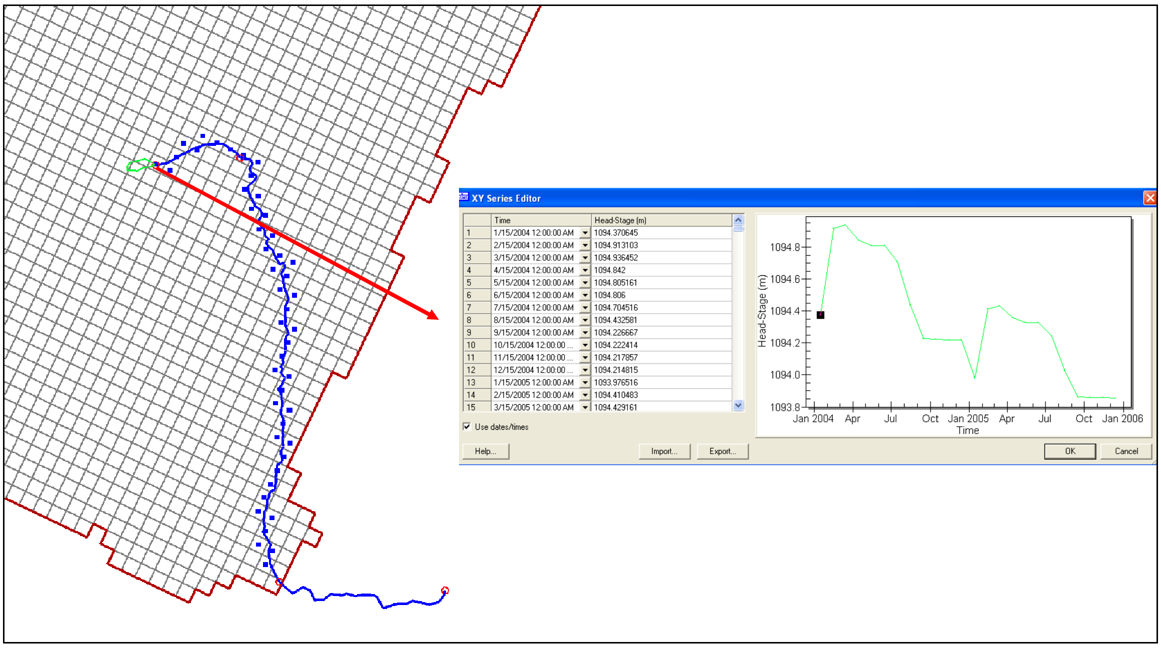


Values calculated by WEAP and entered to MODFLOW (in m/d).

Figure 4-15: Irrigation abstraction distribution in July 2005 (in m/d).

- Barada Spring discharge: the spring area has been modelled as drainage, assigning respective model cells as DRAIN-cells, where the bottom of each cell is equal to the spring outlet elevation varies from 1094 to 1095.4 m.a.s.l. The discharge of Barada Spring has also been used as a calibration target, giving a conductance value of 300 m^2/d/m as a result

- Barada River stage (river package input): The stage of the river was taken from the measured values at Ramleh and Tekije stations and interpolated by GMS to change linearly between these stations.



	Time	Head-Stage (m)
1	1/15/2004 12:00:00 AM	1094.370645
2	2/15/2004 12:00:00 AM	1094.913103
3	3/15/2004 12:00:00 AM	1094.936452
4	4/15/2004 12:00:00 AM	1094.842
5	5/15/2004 12:00:00 AM	1094.805161
6	6/15/2004 12:00:00 AM	1094.806
7	7/15/2004 12:00:00 AM	1094.704516
8	8/15/2004 12:00:00 AM	1094.432581
9	9/15/2004 12:00:00 AM	1094.226667
10	10/15/2004 12:00:00 ...	1094.222414
11	11/15/2004 12:00:00 ...	1094.217857
12	12/15/2004 12:00:00 ...	1094.214815
13	1/15/2005 12:00:00 AM	1093.976516
14	2/15/2005 12:00:00 AM	1094.410483
15	3/15/2005 12:00:00 AM	1094.429161

Figure 4-16: Barada River cells (blue dots) and assigned stages.

- The water balance deficit was balanced by assigning a groundwater inflow from outside the basin as extra recharge to the respective model cells and to calibrate the model using the Barada Spring discharge (however the sensitivity of spring discharge to change of extra recharge values was relatively low, which indicates the need to use "out of the model" method to estimate the extra discharge more accurately, i.e., through field investigation).

- Hydraulic properties of the layers: this was the most difficult part of the modelling work because of the complex hydrogeology and the data scarcity at the mountains and mountain slopes. The layers were divided into several hydraulic conductivity (k) zones according to hydrogeology, tectonics and available pumping test data. The k values range from 0.1 to 100 m/day in the top layer (most permeable layer, Figure 4-17). The values of k vary according to the type of formation, density of lineaments, dipping of the formation, and expected groundwater gradients. The high value of 100 m/d in the fractured area around the spring represents the equivalent porous media conductivity. The k values and zones were refined during calibration of the model but it should be clear that these values of k are valid under the assumptions of the conceptual model and should be revised again and modified in prior to any further utilization of the model.

- Starting groundwater head: the groundwater levels in May 2005 have been used as starting heads (Figure 4-12).

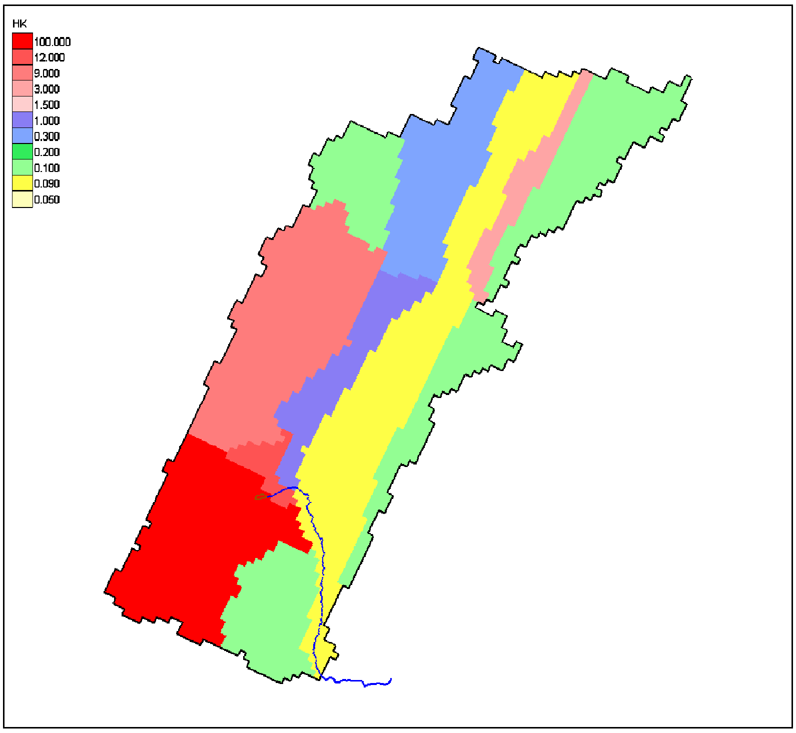


Figure 4-17: Hydraulic conductivity zones for the first layer (m/d)

4.3.3 Numeric Model

The Zabadani Basin numerical model grid consists of 124 rows, 74 columns, and 3 layers (Table 4-6), i.e. 27528 cells, with 200m grid length and width respectively (Figure 4-18). The Groundwater Modelling System GMS 6 (www.ems-i.com/GMS/gms.html) was used as pre-processor of Modflow2000. The model was first calibrated in steady state, and then the parameters have been used as starting values for the transient model and further refined.

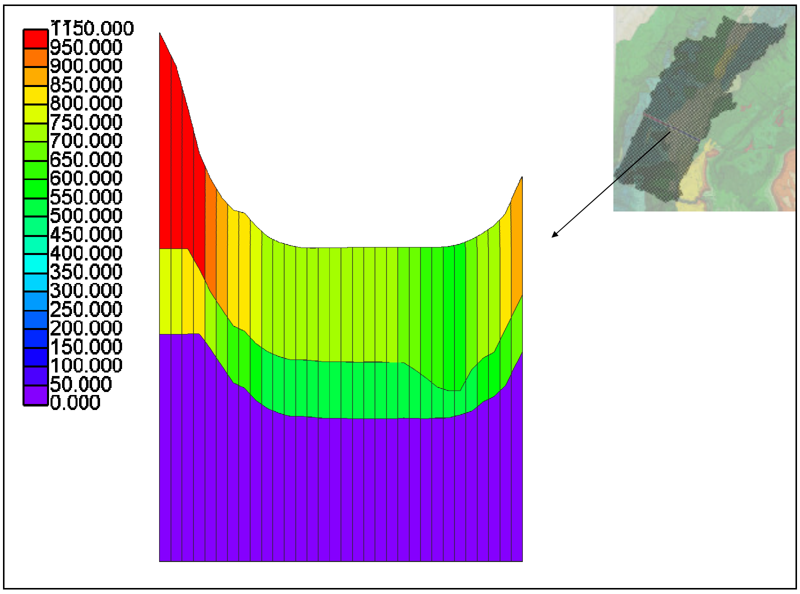


Figure 4-18: Cross section of the 3-layer grid in MODFLOW

4.3.4 Results

Steady state: It was assumed that the year 2004/ 2005 was at steady state as it was an average precipitation year with full recovery of the groundwater levels after the winter rains, and similar heads at the end of the irrigation seasons in November 2004 and November 2005. Using this assumption the model was run under steady state conditions and the hydraulic parameters have been calibrated and the water balance balanced (lateral in- and outflows, Table 4-8).

As illustrated above, it is expected to have a considerable groundwater inflow from the south towards the Barada Spring. This was modelled as extra recharge polygons on the S-SW border of the model (Figure 4-19). Due to lacking observation wells in the area with continuous monitoring records, the amount of this extra recharge was estimated through calibration targeting on the measured spring discharge. However, it is necessary here to mention that these values should be verified through further survey campaigns.

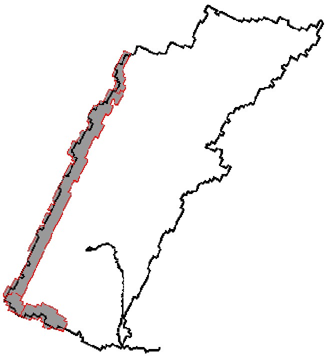


Figure 4-19: Location of the “extra recharge polygons”.

The calculated groundwater balance for the steady state conditions shows that the spring discharge was 66 Mm³/y (the measured value was 68 Mm³/y). The extra recharge value added to represent the lateral flow was 76.2 Mm³/y.

Table 4-8: Steady state groundwater balance (MODFLOW) for 2004/ 2005.

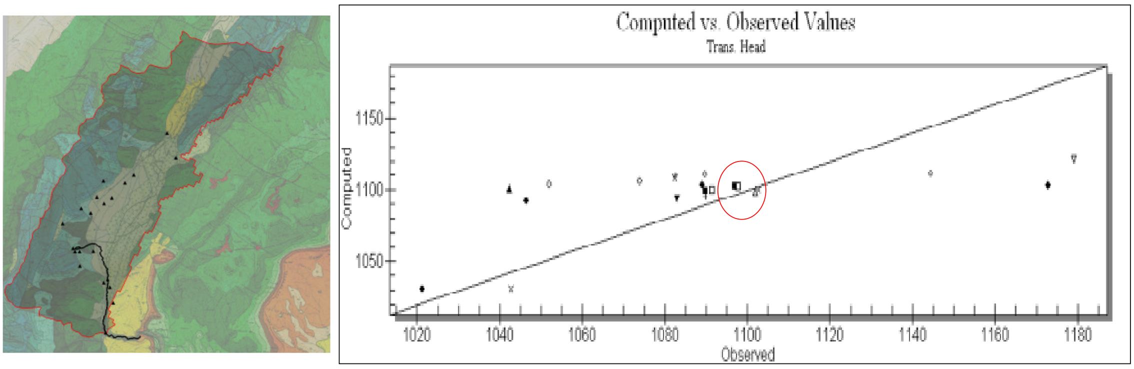
Steady state balance in Mm³/y	inflow	outflow	calculated abstractions as negative recharge
Storage	0.00	0.00	
Constant Head lateral GW-outflow	0.00	15.85	
Wells (here minor springs only)	0.00	2.12	
Drains (Barada Spring)	0.00	66.23	
River Leakage	2.88	13.63	
Recharge (net sum of cell values)	127.04	32.10	domestic 27.55, irrigation 31.18
TOTAL	**129.92**	**129.91**	

Transient state: The steady state calibration was then utilized to run a transient state model with a monthly time step for the hydrologic year 2004/ 2005. The respective water balance is shown in Table 4-9.

Table 4-9: Transient state groundwater balance (MODFLOW) for 2004/ 2005.

Transient state balance in Mm³/y	**inflow**	**outflow**	**calculated abstractions as negative recharge**
Storage	40.88	36.86	
Constant Head lateral GW-outflow	0	13.43	
Wells (here domestic abstractions)	0	29.56	
Drains (Barada Spring)	0	66.71	
River Leakage	0.85	8.52	
Recharge (net sum of cell values)	137.36	28.49	irrigation abstraction 31.43
TOTAL	**179.09**	**183.57**	

The number of observation wells which have some measurements in model period is very low (around 20 located mainly in the graben, Figure 4-20) and the ones with records for the whole model period are even less (approx. 6). The readings of some of the wells are contradictory and some times odd. This makes the calibration more complicated and uncertain. However, the area surrounding Barada Spring has several wells, where the measured hydrographs match reasonably good with the computed ones (Figure 4-20).



Location of observation wells

Circle indicates the good match in the Barada Spring area

Figure 4-20: Observed versus computed hydraulic heads.

Comparing computed versus the measured spring discharges (Figure 4-21) indicates that the yearly volume was calculated correctly (the calculated value was 66.71 Mm3/year). Only the monthly values show some differences indicating rapid and slow moving components feeding the Barada Spring, typically for a karstic system, which cannot be exactly modelled at this stage. Future studies in delimitating the exact groundwater catchment area and respective rainfall and infiltration data will improve the spring discharge and groundwater flow model.

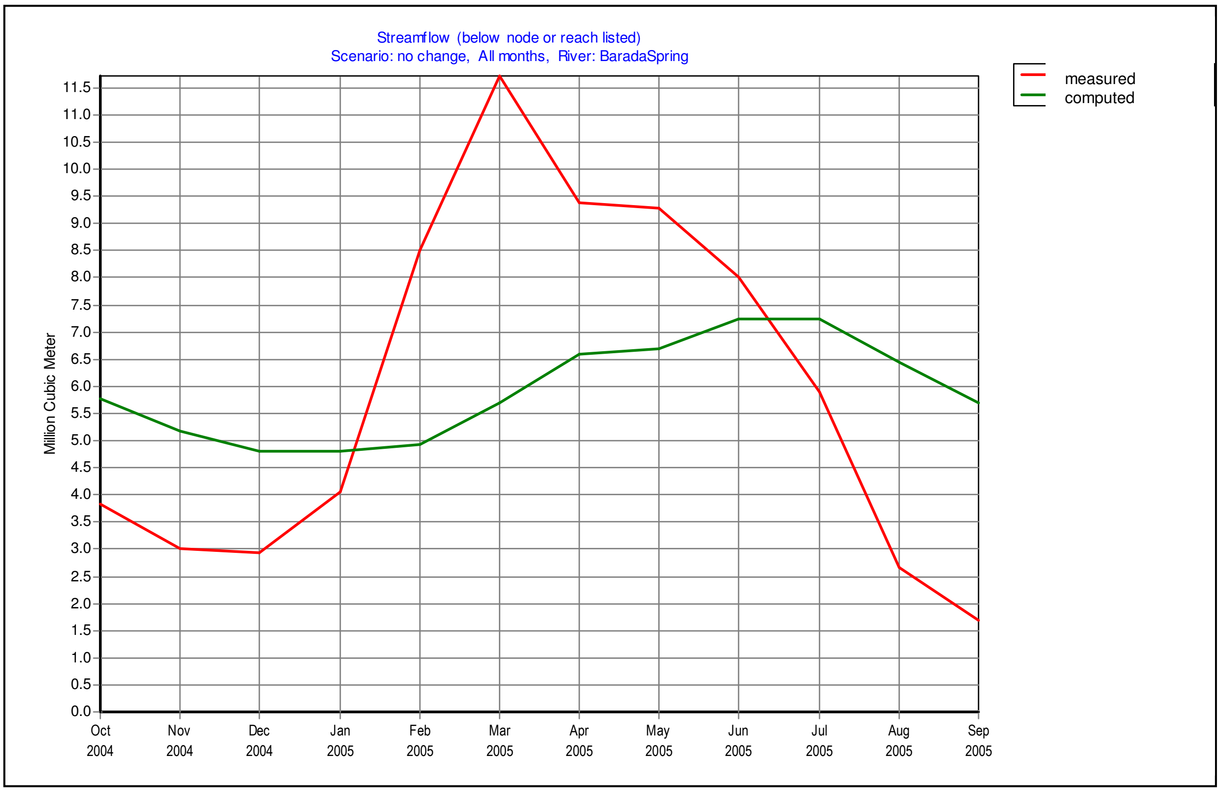


Figure 4-21: Computed versus measured discharge of Barada Spring.

Concerning the computed hydraulic heads, the residuals are within 5 m in the plain area of Zabadani, towards the north and to the margins they increase significantly (Figure 4-22). With the available data and hydrogeologic model this was the best obtainable match so far. In cooperation with the local institutions, drillers and farmers more data need to be collected in order to get a better understanding of the system and to refine the model towards a higher accuracy. The main abstraction and water competition area is the area adjacent to Barada Spring and the Zabadani valley, so even at this stage the model is considered as a valuable and fairly accurate tool to model groundwater flow, head and spring discharge for this region.

Figure 4-22: Computed versus measured heads in the Zabadani Basin.

4.4 WEAP Model

The WEAP21 (www.weap21.org) software was used to build a planning and evaluation model, which is linked to a MODFLOW groundwater flow model (developed by the Stockholm Environmental Institute SEI) as component of the DSS.

For this approach spatial integrity between the models is very important and spatial units in WEAP must follow the outlines of the MODFLOW cell boundaries.

Together with the members of the DSS steering committee the Zabadani Basin was subdivided into 11 sub-catchments, being crucial to the water management planning. Their outlines have been determined by aggregating the major drinking water well fields and if possible follow surface watersheds (Figure 4-23).

Inside WEAP21 the "one bucket" soil moisture method was chosen to calculate the soil water balance, groundwater recharge and the irrigation demand. The hydraulic year 2004/2005 was used as a reference year.

4.4.1 Sub-catchments

As shown in the table below and in Figure 4-23 and Figure 4-24 eleven sub-catchments have been delimitated inside WEAP:

Table 4-10: Sub-catchments and Groundwater Nodes in the Zabadani Basin

SUB-CATCHMENT	GROUNDWATER	AREA [ha]
C_BARADA_SP	GW_BARADA_SP	1684.00
C_BLOUDAN	GW_BLOUDAN	445.88
C_CHEQIF	GW_CHEQIF	1015.18
C_EX_RECH_N	GW_EX_RECH_N	935.55
C_EX_RECH_S	GW_EX_RECH_S	262.75
C_MADAYA	GW_MADAYA	314.51
C_RAWDA	GW_RAWDA	1811.39
C_SERGHAYA	GW_SERGHAYA	3069.41
C_TEKIYE	GW_TEKIYE	692.71
C_ZABADANI_CENTRE	GW_ZABADANI_CENTRE	1660.11
C_ZABADANI_W	GW_ZABADANI_W	2062.20

Beside area, climate data are assigned at the sub-catchment level. Each sub-catchment is then divided into respective land use classes where respective irrigation, crop and soil parameters are assigned.

Figure 4-23: Drinking water wells and well fields.

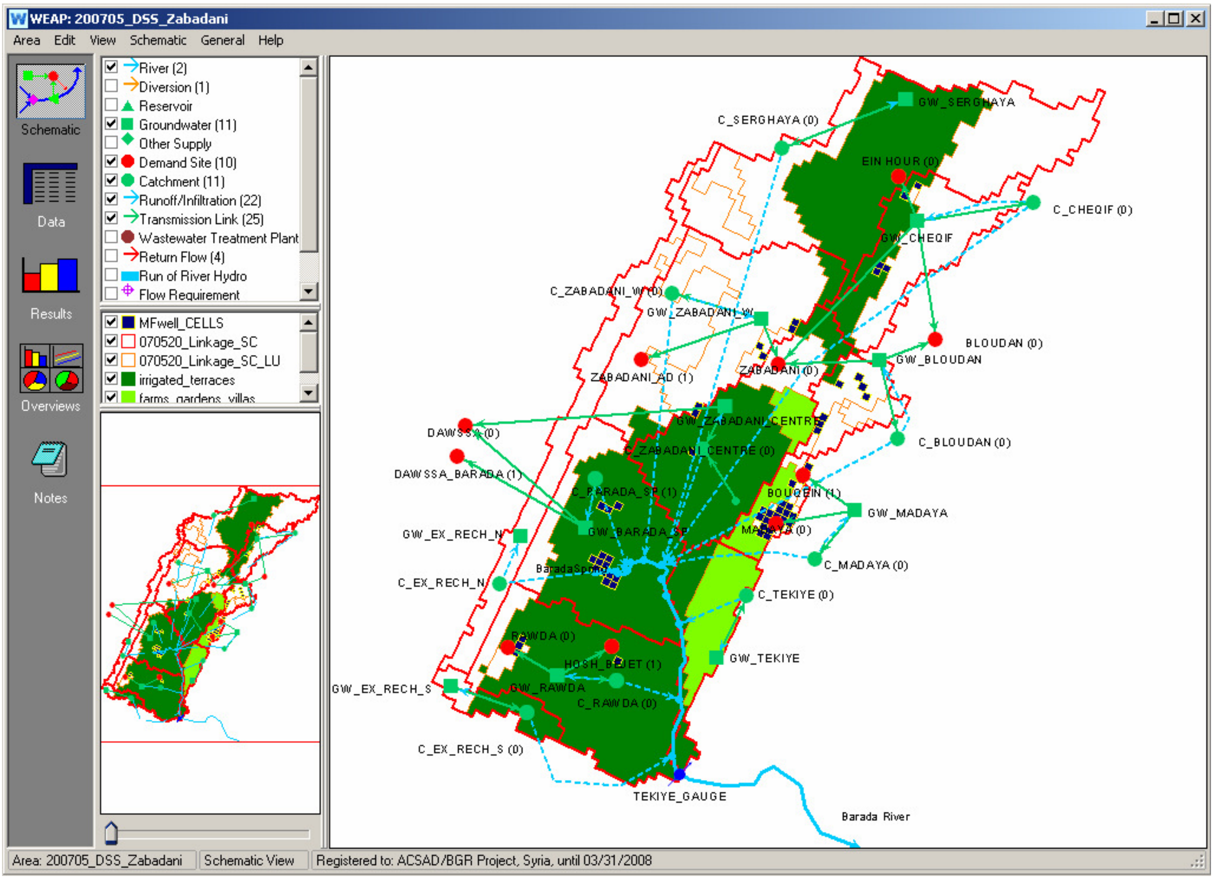


Figure 4-24: WEAP schematic model.

4.4.2 Land Use Classes

On the basis of high resolution aerial photos (GOOGLEEARTH), geological information (geological map 1:50000) and information from the Ministry of Agriculture and local farmers regarding the irrigation practices seven different land use classes have been mapped (Table 4-11 and Figure 4-25).

Table 4-11: Land use classes in the model area.

Land use	Area [ha]	Irrigated Area fraction [%]
Cretaceous Neogene undeveloped	88	0
densely built up	752	0
forest	104	0
Jurassic undeveloped	3806	0
unirrigated planted terraces Cretaceous	1895	0
gardens villas farms	776	0
irrigated terraces	6533	100

Figure 4-25: Land use map.

By intersecting these land use classes with the eleven sub-catchments thirty-one spatial units have been assigned in WEAP (sub-catchment | land use class, s. Table 4-12).

Table 4-12: Land use classes in the respective sub-catchments

Sub-catchment | Land use Class	Area [ha]
C_BARADA_SP|irrigated terraces	1373.47
C_BARADA_SP|Jurassic undeveloped	310.52
C_BLOUDAN|Cretaceous Neogene undeveloped	87.58
C_BLOUDAN|densely built-up	250.81
C_BLOUDAN|forest	91.56
C_BLOUDAN|irrigated terraces	15.92
C_CHEQIF|densely built-up	11.94
C_CHEQIF|irrigated terraces	314.51
C_CHEQIF|Jurassic undeveloped	688.73
C_EX_RECH_N|Jurassic undeveloped	843.99
C_EX_RECH_N|unirrigated planted terraces Cretaceous	91.56
C_EX_RECH_S|irrigated terraces	183.13
C_EX_RECH_S|Jurassic undeveloped	79.62
C_MADAYA|densely built-up	119.43
C_MADAYA|forest	11.94
C_MADAYA|gardens villas farms	183.13
C_RAWDA|densely built-up	51.75
C_RAWDA|irrigated terraces	1624.28
C_RAWDA|Jurassic undeveloped	135.36
C_SERGHAYA|irrigated terraces	1365.51
C_SERGHAYA|Jurassic undeveloped	951.48
C_SERGHAYA|unirrigated planted terraces Cretaceous	752.42
C_TEKIYE|gardens villas farms	449.86
C_TEKIYE|irrigated terraces	242.85
C_ZABADANI_CENTRE|densely built-up	242.85
C_ZABADANI_CENTRE|gardens villas farms	143.32
C_ZABADANI_CENTRE|irrigated terraces	1273.95
C_ZABADANI_W|densely built-up	75.64
C_ZABADANI_W|irrigated terraces	139.34
C_ZABADANI_W|Jurassic undeveloped	796.22
C_ZABADANI_W|unirrigated planted terraces Cretaceous	1051.00

4.4.3 Demand Sites

Inside WEAP the domestic demand sites have been integrated as nodes and respective annual water use rates have been assigned (Figure 4-24 & Table 4-13). In case of the Zabadani Municipality and the Damascus City Water Supply and Sewerage Authority (DAWSSA) the demand sites had to be subdivided in order to consider different well fields within a sub-catchment.

Table 4-13: Demand sites and respective groundwater supplies.

Demand Site	Population (Census 2004)	Water Use per Capita [l/d]	Water Use [Mm^3/y]	Groundwater Supply
BLOUDAN	3101	1661	1.88	GW_BLOUDAN, GW_CHEQIF
BOUQEIN	1866	763	0.52	GW_MADAYA
DAWSSA			19.98	GW_BARADA_SP, GW_ZABADANI_CENTRE
DAWSSA_BARADA				GW_BARADA_SP
EIN HOUR	1974	402	0.29	GW_CHEQIF
HOSH_BEJET	604	499	0.11	GW_RAWDA
MADAYA	9371	289	0.99	GW_MADAYA
RAWDA	4536	157	0.26	GW_RAWDA
ZABADANI	26285	403	3.87	GW_ZABADANI_W, GW_CHEQIF; GW_BLOUDAN
ZABADANI_AD				GW_ZABADANI_W
TOTAL	**47737**		**27.89**	

The agricultural demand (rain fed and irrigated agriculture) is calculated in WEAP for each land use class polygon for the respective crop types, climate and soil parameters.

4.4.4 Demand – Supply linkage

Based on the given data a maximum flow percentage of the current demand was assigned to consider the jointly utilized well fields and aquifers. As mentioned above for DAWSSA and Zabadani Municipality the Demand Sites in WEAP had to be split in order to assign different well fields inside a sub-catchment (Table 4-14).

Table 4-14: Demand – Supply linkage inside WEAP.

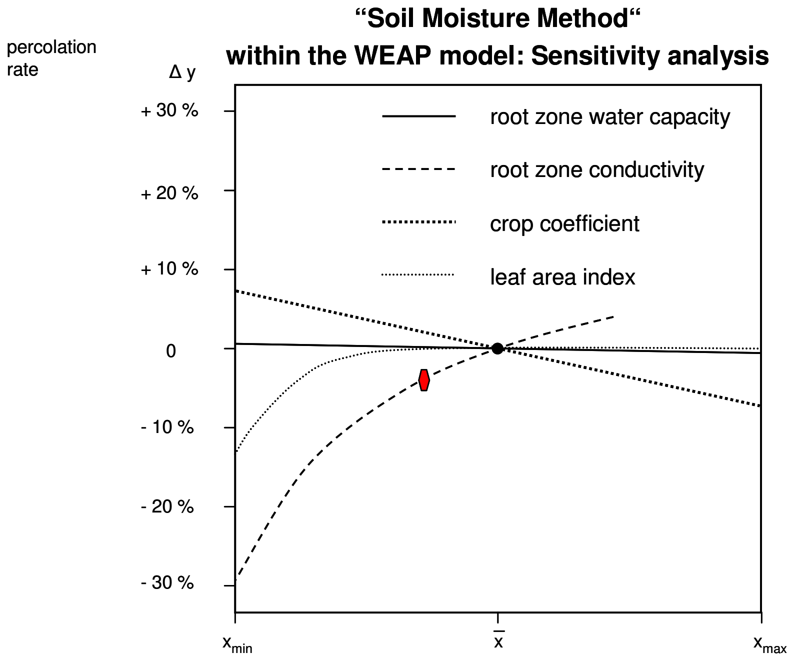
Municipality	Population (Census 2004)	Demand Site	Municipal Supply Percentage	Supply from Groundwater	Well field
BLOUDAN	3101	BLOUDAN	70.04	GW_CHEQIF	Cheqif
		BLOUDAN	29.96	GW_BLOUDAN	Bloudan
DAWSSA		DAWSSA	5.00	GW_ZABADANI_CENTRE	Zabadani
		DAWSSA	7.00	GW_BARADA_SP	Francis
		DAWSSA_BARADA	88.00	GW_BARADA_SP	Barada Spring
ZABADANI	26285	ZABADANI	28.30	GW_CHEQIF	Cheqif
		ZABADANI	12.26	GW_BLOUDAN	Zabadani E
		ZABADANI	13.21	GW_ZABADANI_W	Zabadani NW
		ZABADANI_AD	46.23	GW_ZABADANI_W	Aish al Dabaa
BOUQEIN	1866	BOUQEIN	100.00	GW_MADAYA	Madaya
EIN HOUR	1974	EIN HOUR	100.00	GW_CHEQIF	Ein Hour
HOSH_BEJET	604	HOSH_BEJET	100.00	GW_RAWDA	Hosh Bejet
MADAYA	9371	MADAYA	100.00	GW_MADAYA	Madaya
RAWDA	4536	RAWDA	100.00	GW_RAWDA	Rawda

4.4.5 WEAP – Algorithm

There is a choice among three WEAP tools to simulate catchment processes such as evapotranspiration, runoff, infiltration and irrigation demands. The first two methods, the Rainfall Runoff and Irrigation Demands Only versions of the FAO Crop Requirements approach, only use crop coefficients to calculate evapotranspiration in the catchment and neglect soil impacts. Since the 2005 version, WEAP includes a simulation model of the soil water balance, called the "Soil Moisture Method". Because it is the only approach to simulate infiltration processes and calculate site-specific groundwater recharge rates, the "Soil Moisture Method" was evaluated as the most appropriate WEAP tool for DSS applications in the Zabadani area. Although it is the most complex of the three methods and requires more extensive soil and climate parameterization, in terms of soil physics it is still a very simple, non-mechanistic model that abstracts from all relevant soil hydrological processes.

The one dimensional, 2-compartment (or "bucket") soil moisture accounting scheme is based on empirical functions that describe evapotranspiration, surface runoff, interflow and deep percolation for a watershed unit. In this project the percolation is transmitted directly to groundwater storage; that means the second bucket is ignored because of an existing link to a groundwater node and the soil water balance model is simplified to a one bucket-approach. Potential evapotranspiration (ET_{pot}) is based on PENMAN-MONTEITH reference crop potential evapotranspiration that is modified by a crop or plant specific coefficient kc. The actual evapotranspiration (ET_{act}) is determined by using an empirical term, containing crop-specific ET_{pot} and soil moisture (or the relative soil water storage respectively) as the only independent variable. When interflow is neglected, surface runoff is dependent only on soil moisture and the leaf area index of the land cover and percolation is dependent only on soil moisture and root zone conductivity. In comparison with mechanistic models like SWAP the WEAP approach is based on a limited range of input variables: two soil hydrological parameters such as topsoil water holding capacity and saturated hydraulic conductivity and two plant parameters as mentioned above. In general, the WEAP internal approach can be described as a simple capacity model and the water content is expressed in "percent field capacity". If both types of models are compared by the degree of process abstraction many differences can be found; mechanistic models use soil hydraulic functions and a numerical solution of the RICHARD‘S equation, while in WEAP soil water fluxes are driven only by the saturated hydraulic conductivity and not by potential gradients. The last issue has to be regarded as the most severe limitation of the WEAP specific model.

To understand WEAP’s functionality and to identify best-fitting parameters a sensitivity analysis was carried out. Four parameters were considered (root zone water capacity, root zone conductivity, crop coefficient, and leaf area index) and the relative change of the percolation rate is expressed in dependence on the variation of these parameters (Figure 4-26). For both soil physical parameters the entire range of values occurring in soils is considered (Figure 4-26): for the water capacity of the root zone the spectrum extends from 25 mm up to maximum values of 475 mm, for the hydraulic conductivity of the root zone the spectrum ranges from 1 cm/d up to maximum values of 650 cm/d and a logarithmic scale is used for the x-axis. The red mark in the diagram indicates the value (10 cm/d) that can be assumed for typical Fluvisols in the central part of the Zabadani Valley. Results concerning relative importance of parameters can be summarized as follows: a variation in the water holding capacity does not affect final results. When crop coefficient and leaf area index are varied the maximum change in groundwater recharge is about 15 %. When the root zone conductivity exceeds values of 100 cm/d the percolation rate is not calculated anymore. Below 5 cm/d the percolation rate decreases considerably.



root zone water capacity:	25 mm	225 mm	475 mm
root zone conductivity:	log(1 cm/d) = 0 clay	log(25 cm/d) = 1.4 sandy loam / loamy sand	log(650 cm/d) = 2.8 coarse sand
crop coefficient	0.05	0.5	1
leaf area index	1	5	10

Figure 4-26: Sensitivity analysis of the Soil Moisture Method

A more general evaluation of the "Soil Moisture Method" within the WEAP model leads to the following conclusions:

- The empirical term used to estimate actual evapotranspiration leads to realistic and plausible results.
- The amount of percolation is extremely dependent on the hydraulic conductivity of the root zone.
- "Water holding capacity" and "hydraulic conductivity" as they are used as input variables for the WEAP model do not correspond to "field capacity" (FC) and "saturated hydraulic conductivity" (K_{sat}) as they are defined within the scope of soil science; both physical values are used as WEAP-specific items.
- Beside these rules the most appropriate value for the water holding capacity of the root zone (FCWEAP) also depends on the length of the time step.
- Water flows are simulated by using a constant value of the saturated hydraulic conductivity instead of using a continuous function of the unsaturated hydraulic conductivity.
- Percolation takes place even if the soil water content falls below field capacity; this conflicts with basic fundamentals in soil physics.

- The occurrence of surface runoff is dependent on topsoil moisture and leaf area index, but not on the slope of the soil surface. As a consequence, even for typical Fluvisols with well calibrated soil physical parameters WEAP predicts surface runoff.

4.4.6 Input Data

4.4.6.1 Precipitation

The monthly average precipitation was calculated for each sub-catchment using the measurements of the Zabadani, Madaya, Bloudan and Serghaya stations (method explained in chapter 4.2.3).

Table 4-15: Precipitation input data.

monthly sub-catchment average precipitation [mm]	correction factor	10/04	11/04	12/04	01/05	02/05	03/05	04/05	05/05
C_BARADA_SP	1.1566	9	210	49	150	193	28	39	27
C_BLOUDAN	1.0021	9	214	50	153	196	28	40	27
C_CHEQIF	1.1467	9	212	50	151	195	28	40	27
C_EX_RECH_N	1.7687	14	321	75	229	295	42	60	40
C_EX_RECH_S	1.3920	11	254	59	181	233	33	48	32
C_MADAYA	0.9188	8	183	43	130	168	24	34	23
C_RAWDA	1.0845	8	197	46	141	181	26	37	25
C_SERGHAYA	1.2497	10	230	54	164	211	30	43	29
C_TEKIYE	0.8636	7	163	38	116	150	21	31	21
C_ZABADANI_CENTRE	0.9265	7	168	39	120	155	22	32	21
C_ZABADANI_W	1.2932	10	235	55	168	216	31	44	30

Sub-catchment precipitation = (average of Zabadani, Madaya, Bloudan, Serghaya stations) x correction factor

4.4.6.2 Temperature

As there are only 3 meteorological stations (Yabous, Barada Spring and Serghaya) with temperature records available, the average of the monthly max and min temperature was calculated. Based on the data of the RUSSIAN STUDY (1986 – Volume II Book 1, Fig. 3.1) a temperature/elevation gradient of 0.6°C/ 100 m was applied to calculate according to the relief the average temperatures for each catchment.

$$T_{avg\_sc} = T_{avg} + dT = T_{avg} + ((Z_{avg} - Z_{sc}) * G)$$

T_{avg_sc} :	monthly average temperature in the (sub-)catchment
T_{avg}:	monthly average of the 3 stations measurements
Z_{avg}:	average elevation of the 3 stations (1367m a.s.l.)
Z_{sc}:	mean elevation of the (sub-)catchment (calculated by the DEM – data)
G:	temperature/ elevation gradient (0.6°C/ 100 m)

Table 4-16: Temperature input data.

sub-catchment	Z_{SC} [m a. s.l.]	monthly sub-catchment average temperature [°C]												
		dT	10/04	11/04	12/04	01/05	02/05	03/05	04/05	05/05	06/05	07/05	08/05	09/05
average of the 3 climate stations	1367	0	14.58	8.81	8.09	4.93	2.95	8.33	11.80	15.83	19.95	23.56	23.66	19.49
C_BARADA_SP	1194	1.04	15.62	9.85	9.13	5.97	3.99	9.37	12.84	16.87	20.99	24.6	24.7	20.53
C_BLOUDAN	1448	-0.47	14.11	8.34	7.62	4.46	2.48	7.86	11.33	15.36	19.48	23.09	23.19	19.02
C_CHEQIF	1673	-1.82	12.76	6.99	6.27	3.11	1.13	6.51	9.98	14.01	18.13	21.74	21.84	17.67
C_EX_RECH_N	1683	-1.90	12.68	6.91	6.19	3.03	1.05	6.43	9.9	13.93	18.05	21.66	21.76	17.59
C_EX_RECH_S	1368	-0.02	14.56	8.79	8.07	4.91	2.93	8.31	11.78	15.81	19.93	23.54	23.64	19.47
C_MADAYA	1203	0.98	15.56	9.79	9.07	5.91	3.93	9.31	12.78	16.81	20.93	24.54	24.64	20.47
C_RAWDA	1211	0.93	15.51	9.74	9.02	5.86	3.88	9.26	12.73	16.76	20.88	24.49	24.59	20.42
C_SERGHAYA	1583	-1.30	13.28	7.51	6.79	3.63	1.65	7.03	10.5	14.53	18.65	22.26	22.36	18.19
C_TEKIYE	1149	1.32	15.90	10.13	9.41	6.25	4.27	9.65	13.12	17.15	21.27	24.88	24.98	20.81
C_ZABADANI_ CENTRE	1154	1.28	15.86	10.09	9.37	6.21	4.23	9.61	13.08	17.11	21.23	24.84	24.94	20.77
C_ZABADANI_W	1384	-0.10	14.48	8.71	7.99	4.83	2.85	8.23	11.7	15.73	19.85	23.46	23.56	19.39

4.4.6.3 Humidity and Wind speed

It is difficult to determine a clear pattern for the humidity and wind speed distribution through the measurements of 3 stations, therefore the monthly averages of these 3 stations have been applied to all sub-catchments.

Table 4-17: Average humidity and wind speed data for the Zabadani Basin.

month	10/04	11/04	12/04	1/05	2/05	3/05	4/05	5/05	6/05	7/05	8/05	9/05
average humidity [%]	52	66	60	71	76	55	49	47	40	35	35	46
average wind speed [m/s]	3	3	3	5.5	4	3	4.5	4	4	3.5	3	3

4.4.6.4 Land Use

Based on the soil survey of the Zabadani Basin, respective soil parameters have been calculated for each sub-catchments land use class and have been entered into the soil water models SWAP and CROPWAT for calibrating the respective parameters in WEAP. All soil and plant parameters inside WEAP are dependent on the time step and don’t correlate to field survey or literature values so that the respective values in WEAP represent only calibration parameters to give reasonable groundwater recharge and irrigation demand as an output (s. chapter 4.4.8.6 for calibration approach and final soil and plant parameters).

4.4.6.5 River cross section/ Flow-Stage-Width relationship

In order to have the MODFLOW river package working in the linkage with WEAP, the Flow-Stage-Width relationship has to be assigned for each river reach inside WEAP. As there are no detailed cross sections along the river available and the fluctuation of the river is not very high the section of the Tekije river gauge section was applied to all river reaches.

Table 4-18: Flow Stage Width relationship at Tekije river gauge.

Flow [m³/s]	Stage [m]	Width [m]
0.00	0.00	4.50
0.70	0.68	6.27
0.90	0.73	6.40
1.20	0.77	6.50
1.40	0.80	6.58
1.92	0.87	6.76
2.12	0.89	6.81
2.43	0.93	6.92
2.90	0.98	7.05
3.62	1.05	7.23
4.25	1.07	7.28
4.25	1.07	7.28
4.66	1.10	7.36
4.80	1.15	7.49
8.11	1.31	7.91
14.44	1.60	8.66

4.4.6.6 Extra Recharge

The groundwater inflow is simulated in the models by applying extra recharge to the polygons at the eastern and south-eastern margin. The volumes have been calibrated in Modflow. Inside WEAP the respective volume is assigned to the respective groundwater nodes (GW_EX_RECH_N and -_S) as “natural recharge”, which adds the volumes to the ones calculated for recharge by precipitation and irrigation return flow.

4.4.7 Linkage to MODFLOW model

In order to get the linkage between WEAP and Modflow working it is necessary to define the respective relations. Initially a polygon-shapefile (each polygon representing the respective MODFLOW cell) has to be created. Then the following attributes have to be assigned to each MODFLOW CELL according the WEAP and MODFLOW model designs:

- MODFLOW path number
- MODFLOW row number
- WEAP sub-catchment
- WEAP land use class
- WEAP groundwater nodes
- WEAP demand site(s) (to be supplied by respective well-cells)
- WEAP pumping wells cells (representing well fields and assigning pumping layer(s))
- WEAP River reaches (related to MF river-cells and MF-drain-cells)

4.4.8 Calibration

As already mentioned above groundwater is the main water resource of the Zabadani Basin. Groundwater recharge is the most important calibration parameter for both models (WEAP and MODFLOW), however it is also the most difficult parameter of the water balance to calculate or estimate, as there are no direct measurements available. Several approaches are described below and a synthesis is given at the end of the chapter.

4.4.8.1 Empiric Approach

The recharge coefficient is calculated as a grid representing the percentage of the sum of previously assigned weighted values of the soil water holding capacity, the geology, the land use and the slope. The calculation's result was then reclassified to values between 5 and 50% (range estimate). Monthly recharge values are derived by multiplying the monthly precipitation by the recharge coefficient.

$$\mathbf{RechCoef_{recl} = WHC + Geology + Land\ use + Slope + DGW}$$

RechCoef: *Recharge Coefficient - values from 5% (low) to 50% (high).*

WHC: *WaterHoldingCapacity - values from 1 (high) to 10 (low)*

Geology: *values assigned to geological units according to their permeability – from 1 (low) to 10 (high) where Tertiary=1, Quaternary=3, Cretaceous=6 and Jurassic=10*

Land use: *values of 1(undeveloped areas) or 2 (agricultural areas)*

Slope: *values of 1 (< 5%), 2 (5-15%) or 3 (> 15%)*

DGW: *Depth to groundwater table - values of 1 (>50m) or 2 (<50m)*

The urbanized areas of the villages of Zabadani, Bloudan, Madaya and Rawda were classified as "sealed surfaces" and therefore excluded from the calculation.

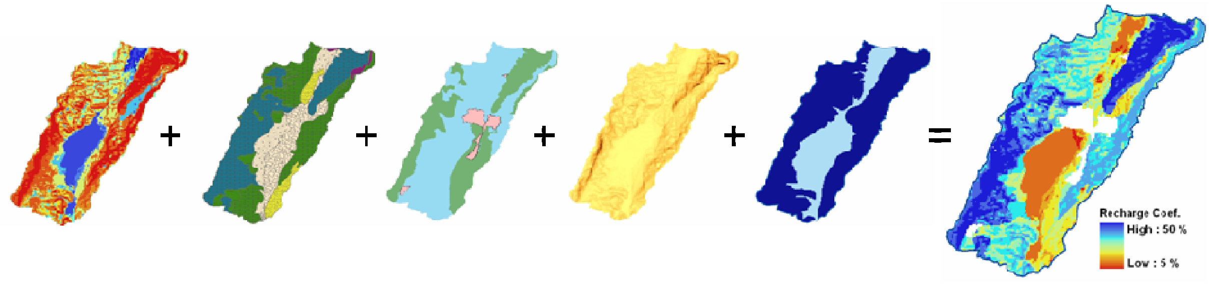


Figure 4-27: Recharge coefficient calculation by adding up weighted grids.

As single grid cells cannot be processed by the used modelling software, the project area was subdivided into polygons, representing similar land use-units (equivalent to irrigation units) and approximately similar recharge coefficients. An average recharge coefficient and an average monthly precipitation value were then calculated and assigned to each polygon.

Figure 4-28: Springs and respective catchments in the Antilebanon Mountains.

4.4.8.2 Spring Discharge Approach

In the karstified rock units of the Antilebanon Mountain Range major karstic springs appear in the study area or close to it (Figure 4-28). Anjar Springs (El Hakim, M., 2005) and Figeh Spring (Bazin, F., 1973, Lamoreaux, P.E., Hughes, T.H. & Memon, B.A., 1989, Sogreah, 1975) are quite well studied, however the outline and area of their subsurface catchments are still not very clear as there have been no tracer experiments applied and also isotope signatures are not giving a clear indicator. For these springs and in a first rough assessment of Barada Spring the groundwater recharge was assumed to be equal to the respective spring discharge and the infiltration coefficient is then simply calculated by dividing discharge by rainfall and area (Table 4-19, Figure 4-28).

Table 4-19: Infiltration coefficient derived from spring discharges.

Spring/ Spring Group Name	**Anjar**	**Barada**	**Figeh**
Karstic aquifer	Cenoman	Jurassic	Cenoman/ Touron
Average discharge [m³/s]	2.84	3.70	7.00
Average discharge [Mm³/y]	89.42	116.68	219.00
Recharge area [km²]	216	175	660
Yearly average rainfall [mm]	757	850	695
Yearly average rainfall [Mm³]	163.512	148.750	458.700
Infiltration Coefficient	0.55	0.78	0.48
Yearly GW-recharge [mm]	413.98	583.42	331.82
Yearly GW-recharge [Mm³]	89.42	116.68	219.00
Reference	s.above	estimation	s.above

4.4.8.3 Lysimeter Approach

BAZIN (1973) and SOGREAH (1975) report on lysimeter measurements in the villages Bloudan, Hureire and Ifre revealing infiltration coefficients of 60 – 70% of the precipitation. However no references about the lysimeter setup have been available for this study, so these results remain somehow vague.

4.4.8.4 Regional Studies

In the RUSSIAN STUDY (1986) the Barada and Awaj River basins have been divided into multiple hydrogeologic subbasins (Figure 4-28) and respective water balances were calculated. The delimitation of these basins as well as the water balance calculations are questionable, however the range of calculated infiltration coefficients is between 40 -70 % (Table 4-20).

Table 4-20: Recharge characteristics of the different hydrogeologic basins.

Source: RUSSIAN STUDY, 1986, location see Figure 4-28.

Subbasin	Area [km²]	Infiltration Coefficient [%]	Groundwater Runoff [l/s*km²]
A-I-1	214	70	25.8
A-I-2	280	63	18.8
A-I-3	732	57	13.8
A-I-6	39	42	2.04

The Jordanian Digital Water Master Plan (Jordan Ministry of Water and Irrigation) applied for the infiltration coefficient 5 – 25% with the maximum values in the Ajlun area in NW Jordan.

4.4.8.5 Soil Water Models (SWAP & CROPWAT)

Because of the specific model characteristics and limitations in WEAP’s s Soil Moisture Method (s. chapter 4.4.5), percolation rates were calculated additionally by running an external, more sophisticated soil water balance model. Results can be used to identify best-fitting parameters as well as to validate the WEAP model itself. Two specific models have been chosen as external models to simulate the soil water balance: SWAP (KROES & VAN DAM 2003) and CROPWAT (CLARKE et al. 1998).

CROPWAT is a decision support system developed by the Land and Water Development Division of FAO for planning and management of irrigation. CROPWAT is meant as a practical tool to carry out standard calculations for reference evapotranspiration, crop water requirements and crop irrigation requirements, and more specifically the design and management of irrigation schemes. It allows the development of recommendations for improved irrigation practices, the planning of irrigation schedules under varying water supply conditions and the assessment of production under rain fed conditions or deficit irrigation. Procedures for calculation of the crop water requirements and irrigation requirements are based on methodologies presented in FAO Irrigation and Drainage Papers No. 24 "Crop Water Requirements" and No. 33 "Yield Response to Water". The development of irrigation schedules and evaluation of rain fed and irrigation practices are based on a daily soil water balance using various options for water supply and irrigation management conditions. For sites with deep water tables without capillary rise to the root zone CROPWAT can serve as a simple but reliable and effective simulation model to determine actual evapotranspiration and groundwater recharge.

SWAP is a by far more sophisticated, mechanistic model that simulates vertical transport of water, solutes and heat in variably saturated, cultivated soils. The model has been developed by Alterra and Wageningen University, and is designed to simulate transport processes at field scale level and during whole growing seasons. The theoretical background and modelling concepts that were used for soil water flow, solute transport, heat flow, evapotranspiration, crop growth, multi-level drainage and interaction between field water balance and surface water management is given by KROES et al. (2003). Modelling soil water flow e.g. includes a numerical solution of the Richard‘s equation, a physical method to determine actual soil evaporation, calculation of actual plant transpiration under consideration of water stress and simulation of macropore flow in clay soils. When all required soil and plant parameters are available or can be estimated by expert knowledge, handbooks or pedotransfer functions with sufficient precision, a widespread and well established mechanistic model like SWAP is the best suited tool to determine evapotranspiration and percolation from the soil.

In the Upper Barada Catchment the CROPWAT model was applied to calculate actual evapotranspiration for the entire agricultural land. On areas belonging to the land use classes "irrigated terraces", "unirrigated terraces" and "unirrigated terraces Cretaceous" fruit trees are the dominant or even exclusive crop. Potential evapotranspiration was calculated by using meteorological data from Barada Spring station, while precipitation data were regionalized by spatial interpolation between existing measuring points. Because a process-based rainfall runoff model was not available, the relative proportion of surface runoff was constantly assumed as 11.8 % of gross precipitation. The resulting net precipitation acted as model input. Site-specific soil hydrological parameters were available from previously developed estimation tables, describing required parameters as a function of parent material and slope class. For running the CROPWAT model, the available water capacity referred to a pF interval from 2.5 to 4.2 had to be calculated from existing water capacity data. For areas classified as "forest" the same plant physiological parameters as for fruit trees were used in CROPWAT. Areas of the land use class "gardens villas farms" were modelled by posting vegetables as the typical crop.

The western and eastern mountain range (land use classes "Jurassic undeveloped", "Cretaceous undeveloped" and "Cretaceous Neogene undeveloped") can be characterized by very steep slopes, shallow soil cover and almost no vegetation. Under these conditions transpiration can be neglected and doesn’t need to be modelled, but evaporation from bare soil might occur. To have at least a rough estimate of the mean annual evaporation rate the SWAP model was applied. The only remaining land use class is named "densely built up". Here almost all surfaces are sealed and incoming rainfall is transmitted directly to surface runoff. No modelling was carried out and evapotranspiration and groundwater recharge were set to 0.

Default values of gross and net precipitation and surface runoff as well as model results of actual evapotranspiration and groundwater recharge for all sub-catchments and land use classes under natural conditions without irrigation are given in Table 4-21. These values describe "reality" and are used as a basis for further WEAP calibration.

The water balance was considered as:

precipitation = surface runoff + actual evapotranspiration + groundwater recharge

The actual evapotranspiration was calculated by CROPWAT; surface runoff occurs only in January and February accounting about 12% of the yearly precipitation. This fraction was calculated by the difference between the Barada River discharge, at the basin boundary and the Barada Spring discharge. The surface runoff was estimated to be evenly distributed in all subareas to be 12% of the yearly precipitation. Thus groundwater recharge could be calculated as the remaining fraction:

*groundwater recharge = precipitation – 0.12 * precipitation – actual evapotranspiration*

The irrigation demand was calculated also in CROPWAT applying the “no stress for crop” irrigation scheme. The applied irrigation water volume causes an increase in evapotranspiration and groundwater recharge respectively. Inside WEAP the calculated irrigation volumes have been calibrated by adjusting the upper and lower irrigation thresholds.

Table 4-21: Land use class input data and SWAP/CROPWAT results.

sub-catchment	land use class	area [ha]	precipitation brutto [mm/y]	surface runoff [mm/y]	precipitation netto [mm/y]	ET_{act} [mm/y]	GW-recharge [mm/y]
C_BARADA_SP	irrigated terraces	1373.5	639	75	563	273	290
C_BARADA_SP	Jurassic undeveloped	310.5	1002	118	884	67	817
C_BLOUDAN	Cretaceous Neogene undeveloped	87.6	594	70	524	108	416
C_BLOUDAN	densely built up	250.8	606	72	535		0
C_BLOUDAN	forest	91.6	642	76	566	196	370
C_BLOUDAN	irrigated terraces	15.9	589	69	519	302	217
C_CHEQIF	densely built up	11.9	648	76	571		0
C_CHEQIF	irrigated terraces	314.5	642	76	567	250	317
C_CHEQIF	Jurassic undeveloped	688.7	724	85	639	101	538
C_EX_RECH_N	Jurassic undeveloped	844.0	1089	129	961	125	836
C_EX_RECH_N	unirrigated terraces Cretaceous	91.6	972	115	857	256	601
C_EX_RECH_S	irrigated terraces	183.1	760	90	670	237	433
C_EX_RECH_S	Jurassic undeveloped	79.6	1062	125	936	106	830
C_MADAYA	densely built up	119.4	579	68	511		0
C_MADAYA	forest	11.9	589	69	519	173	346
C_MADAYA	villas farms gardens	183.1	545	64	481	94	387
C_RAWDA	densely built up	51.8	945	112	834		0
C_RAWDA	irrigated terraces	1624.3	619	73	546	237	309
C_RAWDA	Jurassic undeveloped	135.4	1055	125	931	67	864
C_SERGHAYA	irrigated terraces	1365.5	682	81	602	290	312
C_SERGHAYA	Jurassic undeveloped	951.5	819	97	722	110	612
C_SERGHAYA	unirrigated terraces Cretaceous	752.4	834	98	736	265	471
C_TEKIYE	villas farms gardens	449.9	536	63	473	102	371
C_TEKIYE	irrigated terraces	242.9	508	60	448	326	122
C_ZABADANI CENTRE	densely built up	242.9	594	70	524		0
C_ZABADANI CENTRE	villas farms gardens	143.3	586	69	517	136	381
C_ZABADANI CENTRE	irrigated terraces	1274.0	556	66	491	348	143
C_ZABADANI_W	densely built up	75.6	646	76	569		0
C_ZABADANI_W	irrigated terraces	139.3	679	80	599	258	341
C_ZABADANI_W	Jurassic undeveloped	796.2	882	104	778	134	644
C_ZABADANI_W	unirrigated terraces Cretaceous	1051.0	742	88	654	246	408

For all areas under irrigation (land use class "irrigated terraces") irrigation demand and management was modelled with CROPWAT. In the Upper Barada Catchment soil water storage is filled up during the rainy season until soil water contents are close to field capacity. This status is usually reached at the turn of the year or in mid January. As a consequence, groundwater recharge does not start earlier. At the beginning of the vegetation period soil water storage completely supplies the needs of plants. During the following weeks the soil water deficit is increasing; under natural conditions actual evapotranspiration reaches its maximum around the 10th of May. At this time irrigation has to start. In CROPWAT the irrigation schedule is defined by two criteria: application timing (lower threshold) and application depth (upper threshold). By choosing the lower threshold the user decides what degree of depletion is tolerable: irrigation starts when a specified % of the readily available moisture has been used up. When 100 % are filled in the crop never becomes stressed. By choosing the upper threshold the user decides what irrigation amount will be calculated to refill the soil moisture store to a specified % of the readily available moisture. When 100 % are filled in irrigation returns the soil to field capacity. In the Zabadani area "optimal" irrigation was selected, i.e. the irrigation amount is always equal to the soil moisture deficit and no yield reduction occurs. The soil moisture deficit returns to zero after the irrigation and no water is wasted. For fruit trees, table grapes etc. 100 % readily available moisture is equal to approximately 40 % total available moisture.

Table 4-22 contains model results of irrigation amounts, actual evapotranspiration and groundwater recharge for all irrigated areas. In case of optimal irrigation the actual evapotranspiration is constantly 671 mm over the vegetation period. Irrigation amount varies between 452 and 492 mm. These differences result mainly from differences in soil water holding capacities.

Table 4-22: CROPWAT results applying the „no stress to crop“ irrigation scheme.

irrigated area in sub-catchment	area [ha]	irrigation water volume [mm/y]	surface runoff [mm/y]	ET_{act} [mm/y]	GW-recharge [mm/y]
C_BARADA_SP	1373.5	491	86	675	443
C_BLOUDAN	15.9	484	63	697	339
C_CHEQIF	314.5	490	79	677	431
C_EX_RECH_S	183.1	483	100	673	566
C_RAWDA	1624.3	492	78	665	406
C_SERGHAYA	1365.5	467	89	670	468
C_TEKIYE	242.9	480	67	675	280
C_ZABADANI_CENTRE	1274.0	452	67	670	278
C_ZABADANI_W	139.3	467	90	680	496

4.4.8.6 Calibration and parameter fitting of the "Soil Moisture Method" within the WEAP model

As mentioned above, "water holding capacity" and "hydraulic conductivity" as they are used as input variables for the WEAP model do not correspond to "field capacity" (FC) and "saturated hydraulic conductivity" (k_{sat}) as they are defined within the scope of soil science; both physical values are used as WEAP-specific items. When typical values for root zone capacity and root zone conductivity are taken from existing thematic maps groundwater recharge from percolating water is overestimated while actual evapotranspiration is underestimated. As a consequence, parameter values as required for the WEAP model must not be derived from easily mapable soil characteristics by applying well established pedotransfer functions. As a general rule the following regularities can be formulated: FCWEAP has to be > FCSoil Science, k_{sat}WEAP has to be << k_{sat}Soil Science. In the same way plant coefficients cannot easily be taken from FAO guidelines or estimation tables. Fitting WEAP's internal parameters requires an extensive calibration procedure.

For all spatial units of the project area (n = 31) the WEAP output was calibrated against simulation results of actual evapotranspiration as obtained by the SWAP/CROPWAT model and presented in Table 4-21 and Table 4-22. All parameter settings are based on a constant proportion of surface runoff (11.8 % of gross precipitation) and site-specific predictions of evapotranspiration. A maximum deviation of 2 - 3 % from target values was aspirated. As part of the calibration procedure, the soil water balance was modelled by using separate climatic information for every land use class within every sub-catchment, while in WEAP every sub-catchment can only be described by a single data set of meteorological variables. Because of these circumstances the user is forced to express spatial variability in climate by a change in parameter settings. For that reason, almost every spatial unit is characterized by a unique setting of plant and soil parameters; even units of the same land use class differ in crop coefficient and leaf area index values.

WEAP output results for surface runoff, actual evapotranspiration and groundwater recharge under natural conditions with irrigation as well as parameter settings are given in Table 4-23.

Table 4-23: Calibrated WEAP-parameters (SWAP/CROPWAT)

sub-catchment	land use class	area ha	precip. 1000m³	Irrig. 1000m³	surface runoff 1000m³	ET_{act} 1000m³	GW-recharge 1000m³	lower thres-hold	upper thres-hold	Kc-values in WEAP (Min-Max-Oct)	FC [mm] in WEAP	kf [mm/m] in WEAP	LAI Jan.+Feb.in WEAP
C_BARADA_SP	irrigated terraces	1373.5	9683	6744	1175	9271	6088	35	59	0 - 0,8 - 0,35	750	86	2 * 9,9
C_BARADA_SP	Jurassic undeveloped	310.5	2189		255	201	1676			0.125	60	205	2 * 7,5
C_BLOUDAN	Cretaceous Neogene undeveloped	87.6	628		67	88	421			0.2	100	160	2 * 7
C_BLOUDAN	Cretaceous undeveloped	195.1	1399		162	211	1011			0.2	100	160	2 * 7
C_BLOUDAN	densely built up	242.8	1741				112			0.1	10	60	const. 0,1
C_BLOUDAN	forest	91.6	657		83	188	421			0 - 0,5 - 0,1	400	175	2 * 2,2
C_BLOUDAN	irrigated terraces	15.9	97	77	10	111	54	30	60	0 - 0,85 - 0,4	500	75	2 * 8
C_BLOUDAN	Jurassic undeveloped	143.3	1027		125	178	734			0.235	100	160	2 * 6
C_BLOUDAN	unirrigated terraces	557.4	3996		476	1287	2272			0 - 0,6 - 0,15	365	130	2 * 3,5
C_BLOUDAN	villas farms gardens	8.0	---		---	---	---			---	---	---	---
C_CHEQIF	Cretaceous undeveloped	27.9	199		26	36	143			0.285	75	195	2 * 3,5
C_CHEQIF	densely built up	11.9	85				4			0.1	10	60	const. 0,1
C_CHEQIF	irrigated terraces	314.5	2195	1541	248	2129	1354	25	59	0 - 0,9 - 0,45	450	100	2 * 6,2
C_CHEQIF	Jurassic undeveloped	545.4	3882		470	566	2846			0.185	100	160	2 * 6,6
C_CHEQIF	unirrigated terraces	59.7	425		49	142	218			0 - 0,6 - 0,15	420	130	2 * 3
C_EX_RECH_N	Jurassic undeveloped	1051.0	11305		1321	1308	8665			0.225	120	245	2 * 9,5
C_EX_RECH_N	unirrigated terraces Cretaceous	131.4	1413		164	334	898			0 - 0,7 - 0,25	400	200	2 * 5,5
C_EX_RECH_S	irrigated terraces	183.1	1558	885	184	1233	1037	30	60	0 - 0,825 - 0,375	700	98	const. 20
C_EX_RECH_S	Jurassic undeveloped	91.6	778		91	100	591			0.2	95	215	2 * 8,5
C_MADAYA	Cretaceous Neogene undeveloped	525.5	3221		384	564	2290			0.2	100	160	2 * 4,5
C_MADAYA	densely built up	119.4	732				49			0.1	10	60	const. 0,1
C_MADAYA	forest	11.9	73		8	18	36			0 - 0,5 - 0,1	400	180	2 * 2,2
C_MADAYA	unirrigated terraces	163.2	1000		119	348	530			0 - 0,6 - 0,15	365	130	2 * 3
C_MADAYA	villas farms gard.	183.1	1122		127	158	775			0 - 0,55 - 0,1	150	205	2 * 2,8

Table 4-23: Calibrated WEAP-parameters (SWAP/CROPWAT), cont.

sub-catchment	land use class	area ha	precip. 1000m^3	Irrig. 1000m^3	surface runoff 1000m^3	ET_{act} 1000m^3	GW-recharge 1000m^3	lower thres-hold	upper thres-hold	Kc-values in WEAP (Min-Max-Oct)	FC [mm] in WEAP	kf [mm/m] in WEAP	LAI Jan.+Feb.in WEAP
C_RAWDA	densely built up	51.8	342				23			0.1	10	60	const. 0,1
C_RAWDA	irrigated terraces	1624.3	10736	7991	1273	10800	6596	29	59	0 - 0,8 - 0,35	800	73.8	15 + 2 * 12
C_RAWDA	Jurassic undeveloped	135.4	895		101	86	669			0.125	60	190	2 * 7,5
C_SERGHAYA	Cretaceous undeveloped	99.5	767		99	132	578			0.24	105	185	2 * 5,25
C_SERGHAYA	irrigated terraces	1365.5	10419	6377	1219	9143	6388	23	50	0 - 0,975 - 0,5	800	121	2 * 3,85
C_SERGHAYA	Jurassic undeveloped	1007.2	7765		916	1116	5789			0.215	95	200	2 * 5
C_SERGHAYA	unirrigated terraces	191.1	1473		152	415	781			0 - 0,6 - 0,2	395	160	2 * 3,4
C_SERGHAYA	unirrigated terraces Cretaceous	820.1	6322		731	2106	3364			0 - 0,7 - 0,2	430	148	2 * 3,2
C_TEKIYE	Cretaceous Neogene undeveloped	684.7	3744		456	830	2482			0.23	100	140	2 * 4,9
C_TEKIYE	irrigated terraces	242.9	1280	1166	162	1640	681	25	50	0,2 - 0,9 - 0,4	350	70	2 * 7,5
C_TEKIYE	villas farms gardens	449.9	2460		285	451	1681			0 - 0,55 - 0,1	200	200	2 * 2,8
C_ZABADANI_CENTRE	densely built up	242.8	1369				90			0.1	10	60	const. 0,1
C_ZABADANI_CENTRE	irrigated terraces	1274.0	7185	5758	852	8540	3538	25	51	0,15 - 0,85 - 0,4	500	86.5	2 * 3,75
C_ZABADANI_CENTRE	unirrigated terraces Cretaceous	11.9	---		---	---	---			---	---	---	---
C_ZABADANI_CENTRE	villas farms gardens	143.3	808		96	192	553			0 - 0,75 - 0,3	200	200	2 * 3,3
C_ZABADANI_W	densely built up	75.6	596				30			0.1	10	60	const. 0,1
C_ZABADANI_W	irrigated terraces	139.3	1099	651	125	947	691	25	55	0 - 0,875 - 0,45	700	104	2 * 9,5
C_ZABADANI_W	Jurassic undeveloped	796.2	6281		734	1096	4495			0.285	75	196	2 * 8,5
C_ZABADANI_W	unirrigated terraces Cretaceous	1051.0	8292		991	2522	4760			0 - 0,6 - 0,2	400	160	2 * 4,25

Present parameter settings lead to plausible dimensions of evapotranspiration and groundwater recharge. Despite some dubious model characteristics present parameter settings allow scenario calculations in the case of increasing or decreasing annual precipitation (Figure 4-29).

The calibrated soil moisture model (by the soil water models SWAP & CROPWAT) results on groundwater recharge are also within the magnitude of the other groundwater recharge calculation/ estimation approaches results and are therefore validated even by a wider range of models/ estimations.

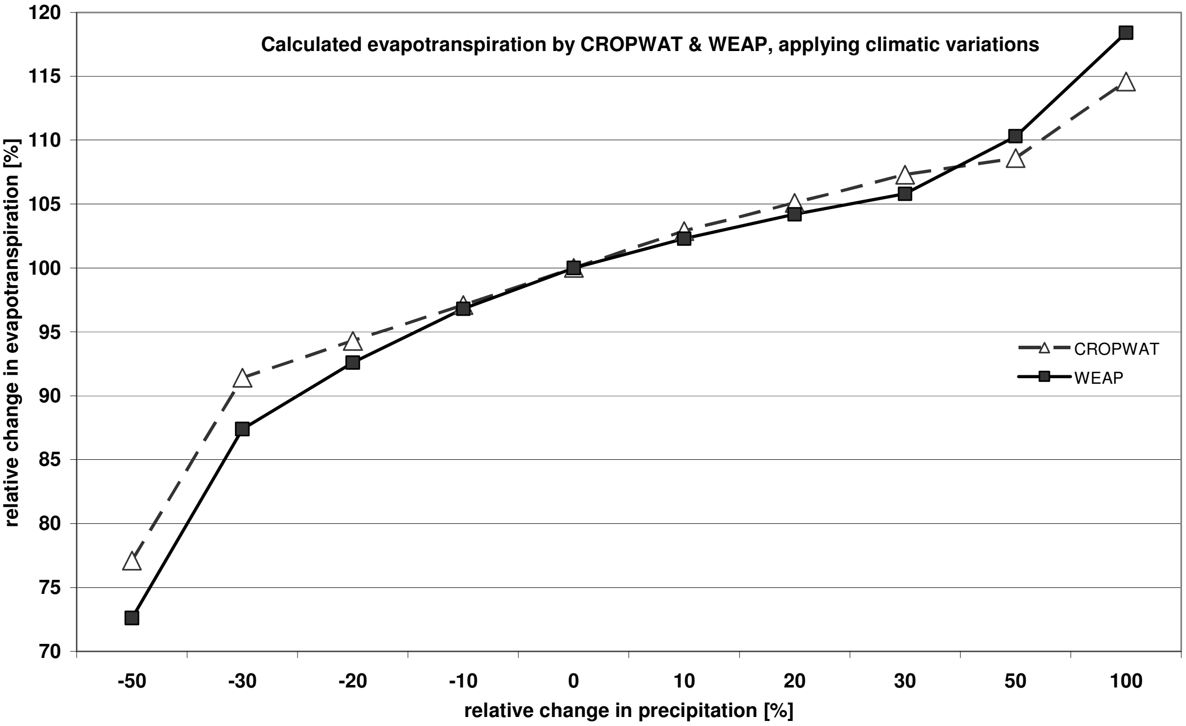
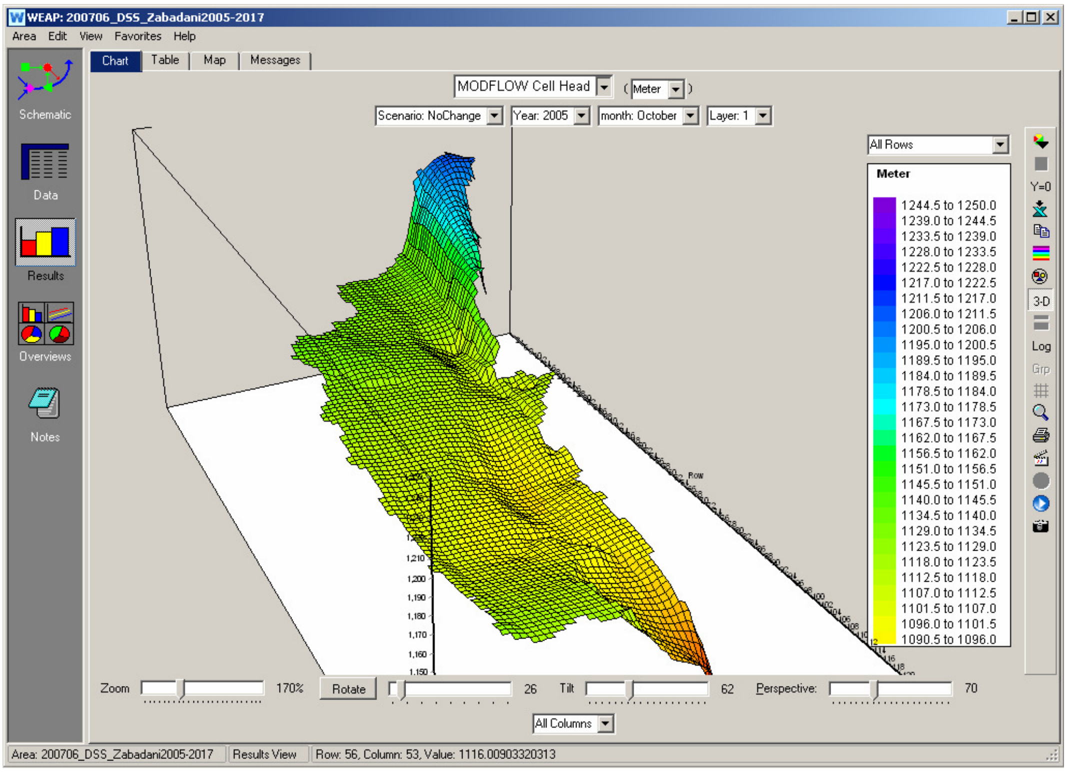


Figure 4-29: Calculated evapotranspiration WEAP versus CROPWAT.

4.4.9 Results

By the linked WEAP-MODFLOW models realistic soil-, groundwater balances and hydraulic heads for the reference year 2004/ 2005 could be calculated and the results can be visualized by WEAP in various scales from the total area down to the sub-catchment and its land use class levels (Figure 4-30, Figure 4-31 & Figure 4-32). For the Barada Spring the yearly discharge was computed correctly, however the monthly fluctuation due to the karstic nature and rapid and slow flow components couldn’t be matched exactly (Figure 4-21).



WEAP: 200706_DSS_Zabadani2005-2017

MODFLOW Cell Head (Meter)

Scenario: NoChange

Year: 2005

month: October

Layer: 1

Zoom 170%

Rotate 26

Tilt 62

Perspective: 70

Area: 200706_DSS_Zabadani2005-2017

Results View

Row: 56, Column: 53, Value: 1116.00903320313

Figure 4-30: 3D view of the computed groundwater surface.

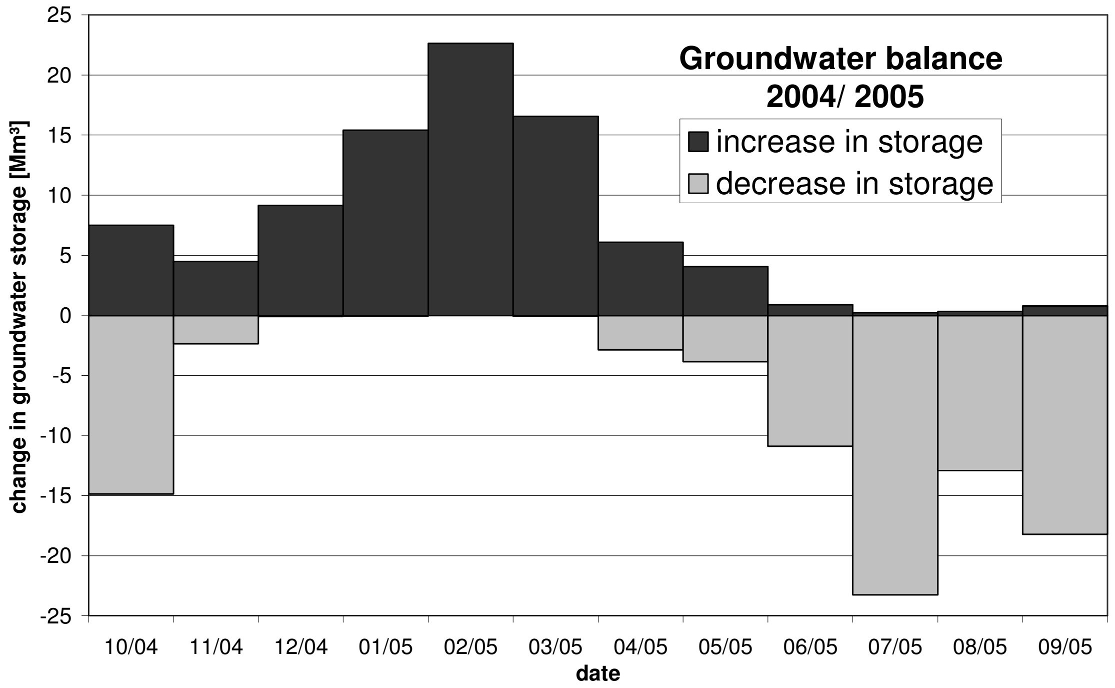


Figure 4-31: Computed general groundwater balance.

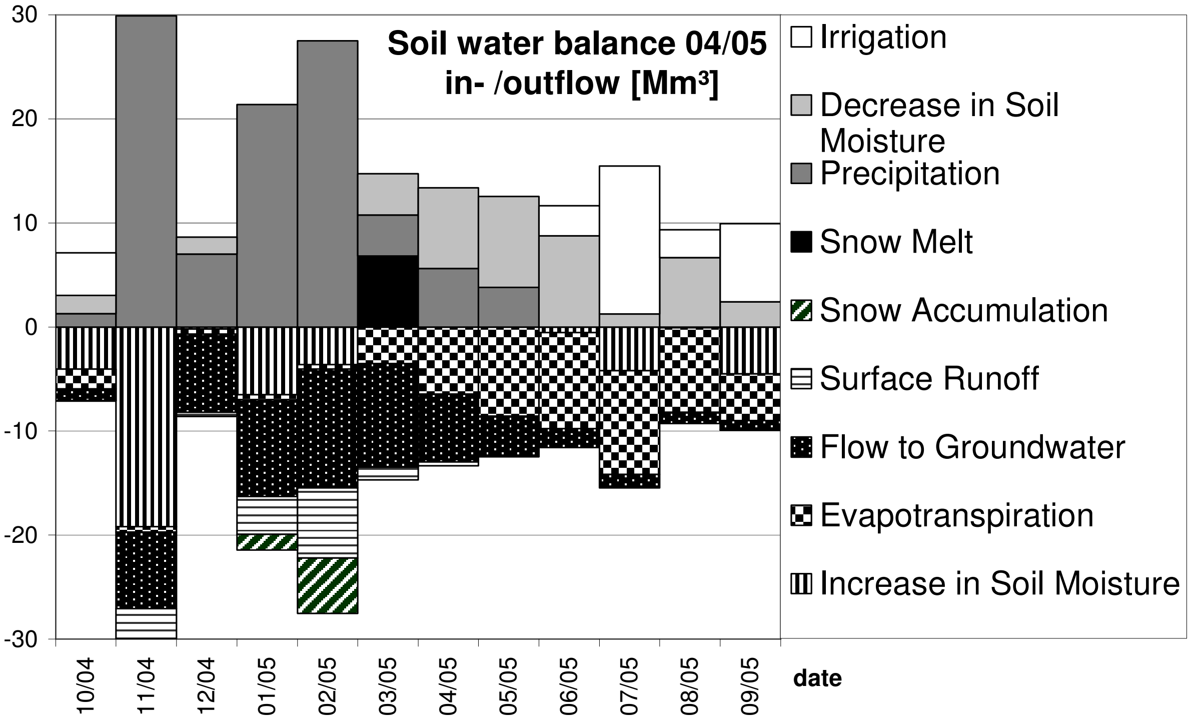


Figure 4-32: Computed detailed soil water balance.

4.4.10 Scenarios

Two sets of scenarios have been calculated by the DSS, a historic scenario (1997-2007) in order to check the calibration accuracy of the models and a planning scenario set (2005-2017) of three different climate/demand change scenarios.

Historic Scenario 1998-2007

In the past decade some extreme years have occurred, 1999 to 2001 have been three consecutive years in a row with less than 50% of the average precipitation, whereas 2003 has been a very wet year with 150% of the long-term average precipitation. The respective hydraulic heads and groundwater balances show clearly the impact of these extreme years compared to the average ones.

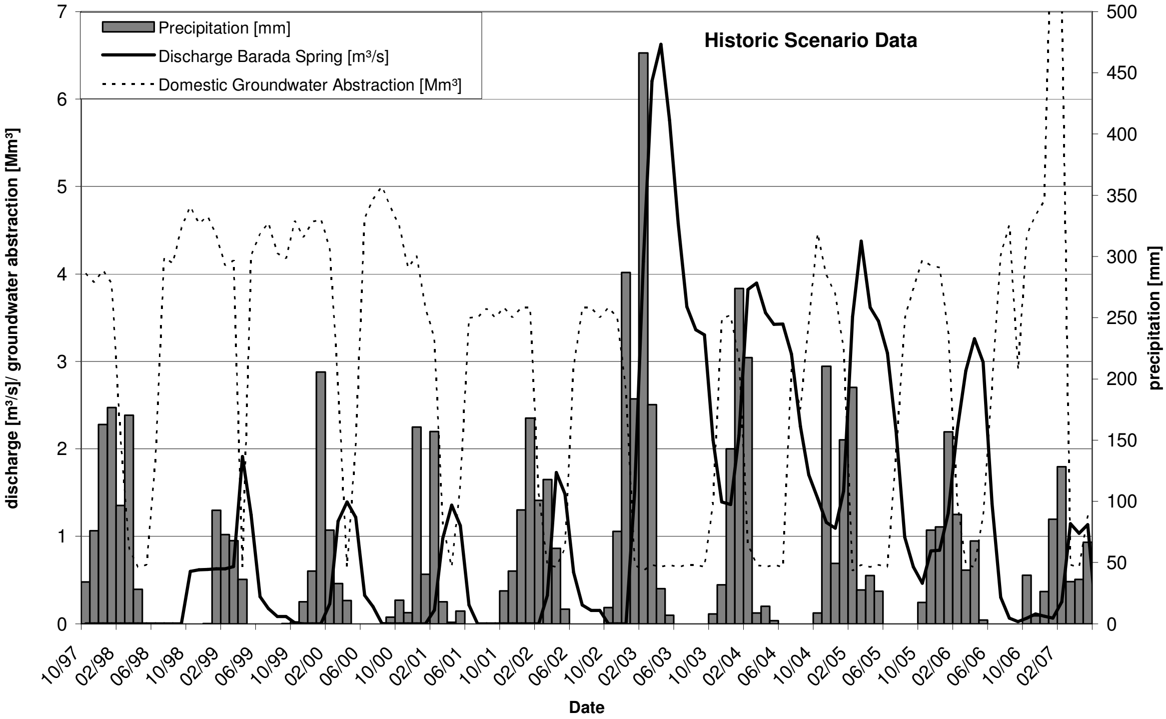


Figure 4-33: Precipitation, Barada Spring flow and domestic abstractions.

Planning Scenario Set 2005-2017

Scenario A: Demand changes (DRA 2X DAWSSA 3X AGR 0.7):

Jointly with the members of the Steering Committee of the Zabadani Basin DSS realistic scenarios for the coming 10 years (13 years from reference year) have been discussed. Each stakeholder contributed with his (institutional) estimates of the future water demand and supply:

DAWSSA:	increase in demand by 300%
DRA:	increase in demand by 200%
Agriculture:	change to drip irrigation, decrease in water demand by 30%

Scenario B: Climate change scenario (80 rain)

Long-term climate change impacts have been assessed by KUNSTMANN ET AL. (2007) by downscaling the global B2 climate scenario model of ECHAM4 to a resolution of 18 km by 18 km in the eastern Mediterranean/ Near East region. Preliminary calculation results (daily precipitation data) have been derived for two thirty year (1961-1990 and 2070-2099) time periods. The calculated results for the Zabadani Basin are shown in the figure below. The graph indicates a clear decrease in precipitation and by averaging the yearly precipitations in the two time periods, a decrease in precipitation of twenty percent can be calculated. This decrease of twenty percent was applied to the planning scenario 2005 -2017 in order to see on an even shorter time scale the impact of decreases in precipitation.

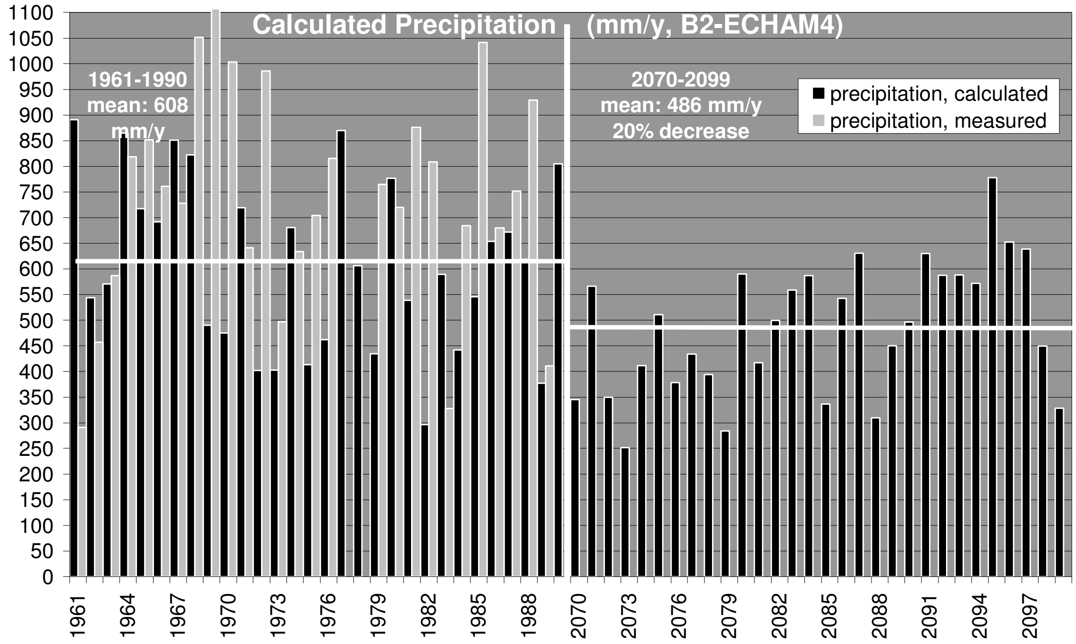


Figure 4-34: Calculated precipitation data for Zabadani Basin

(dataset from KUNSTMANN ET AL., 2007, applying B2 – ECHAM4 - model)

Scenario C: Drought cycle scenario (50 rain)

The historic precipitation measurements (Figure 4-35, only the Damascus station has a continuous long-term precipitation record) show that there is roughly every five to thirteen years a "drought" year with less than half of the mean annual rainfall. From 1999 to 2001 there had been three "drought" years in a row, causing severe impacts on the domestic and irrigation water supply. Therefore an additional planning scenario was created by reducing the average precipitation of the year 2004/ 2005 to 50% and calculating the impacts of consecutive drought years.

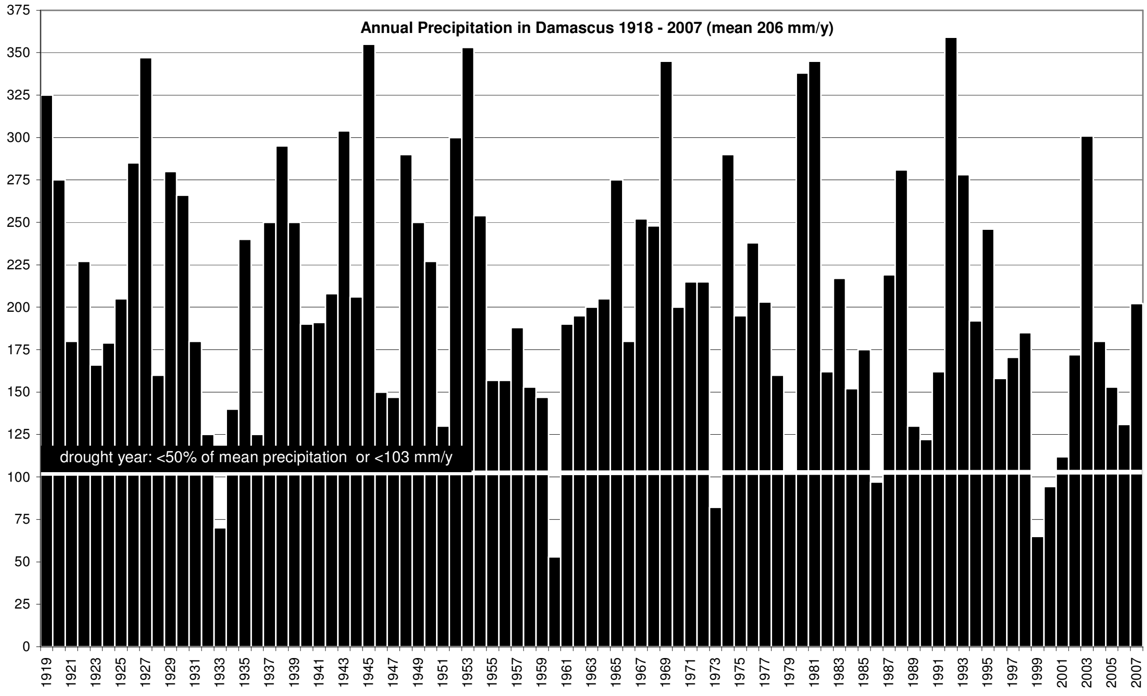


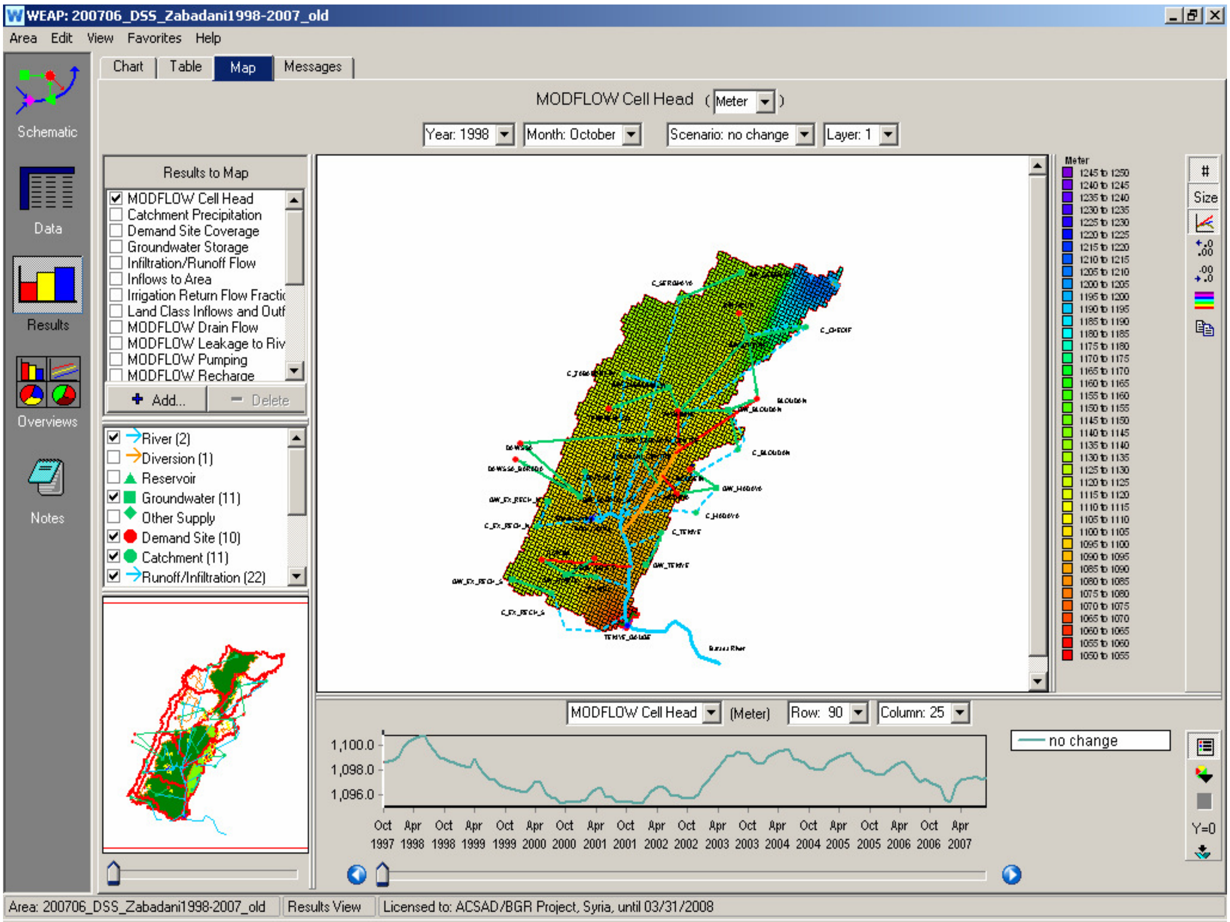
Figure 4-35: Annual Precipitation in Damascus from 1918 to 2007.

Scenario D: closed basin (no GW inflow)

In this scenario the groundwater inflow (extra recharge) from outside the surface water basin is stopped from the hydrological year 2006 onward. As the newly drilled and since 22 August 2007 operating DAWSSA - well field in Jdeidet Yabous (3km off the SW corner of the basin) may reduce or even stop the groundwater inflow into the Zabadani Basin, a possible realistic scenario and it's impact is presented in the respective results below.

4.4.11 Scenario Results

The historic scenario result for the hydraulic head (Figure 4-36) shows the decline of the groundwater level during the dry years (1999 – 2001), but also the full recovery during the very wet year of 2003. Unfortunately there are very few monitoring wells with a continuous record for that time in order to validate the water level fluctuations. The computed discharge of Barada Spring (Figure 4-37) matches like in the reference year fairly good for the yearly sum, however the monthly fluctuations couldn't be matched exactly. Figure 4-38 and Figure 4-39 show the groundwater and soil water balances respectively for the Zabadani Basin. Based on these historic balances the hydraulic system of the Zabadani Basin can be well understood in dry and wet year conditions (changes in groundwater recharge, groundwater storage and irrigation demand for example).


WEAP: 200706_DSS_Zabadani1998-2007_old

MODFLOW Cell Head (Meter)

Year: 1998 | Month: October | Scenario: no change | Layer: 1

Results to Map

☑ MODFLOW Cell Head
☐ Catchment Precipitation
☐ Demand Site Coverage
☐ Groundwater Storage
☐ Infiltration/Runoff Flow
☐ Inflows to Area
☐ Irrigation Return Flow Fractic
☐ Land Class Inflows and Outf
☐ MODFLOW Drain Flow
☐ MODFLOW Leakage to Riv
☐ MODFLOW Pumping
☐ MODFLOW Recharge

☑ River (2)
☐ Diversion (1)
☐ Reservoir
☑ Groundwater (11)
☐ Other Supply
☑ Demand Site (10)
☑ Catchment (11)
☑ Runoff/Infiltration (22)

MODFLOW Cell Head (Meter) | Row: 90 | Column: 25

Area: 200706_DSS_Zabadani1998-2007_old | Results View | Licensed to: ACSAD/BGR Project, Syria, until 03/31/2008

Figure 4-36: Computed heads for the historic scenario 1998 – 2007.

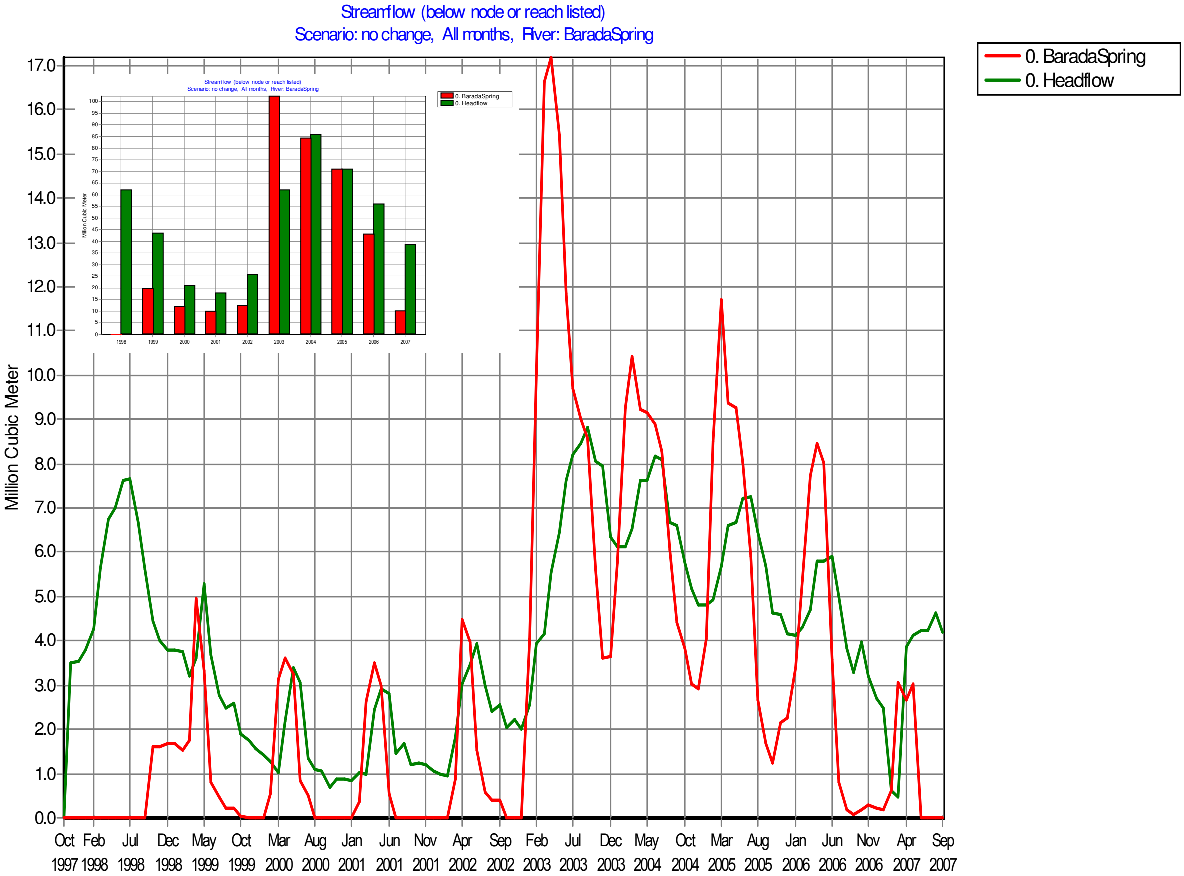
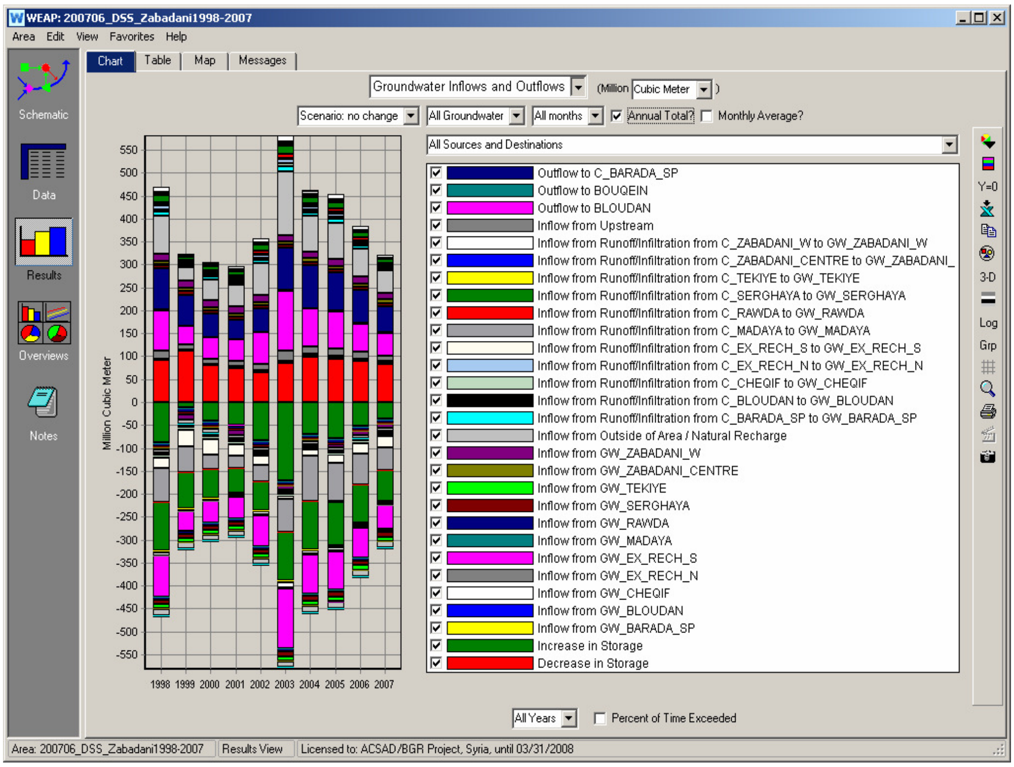


Figure 4-37: Measured versus computed discharge of Barada Spring. (monthly/yearly – measured - computed)



Groundwater Inflows and Outflows (Million Cubic Meter)

Scenario: no change | All Groundwater | All months | ☑ Annual Total? | ☐ Monthly Average?

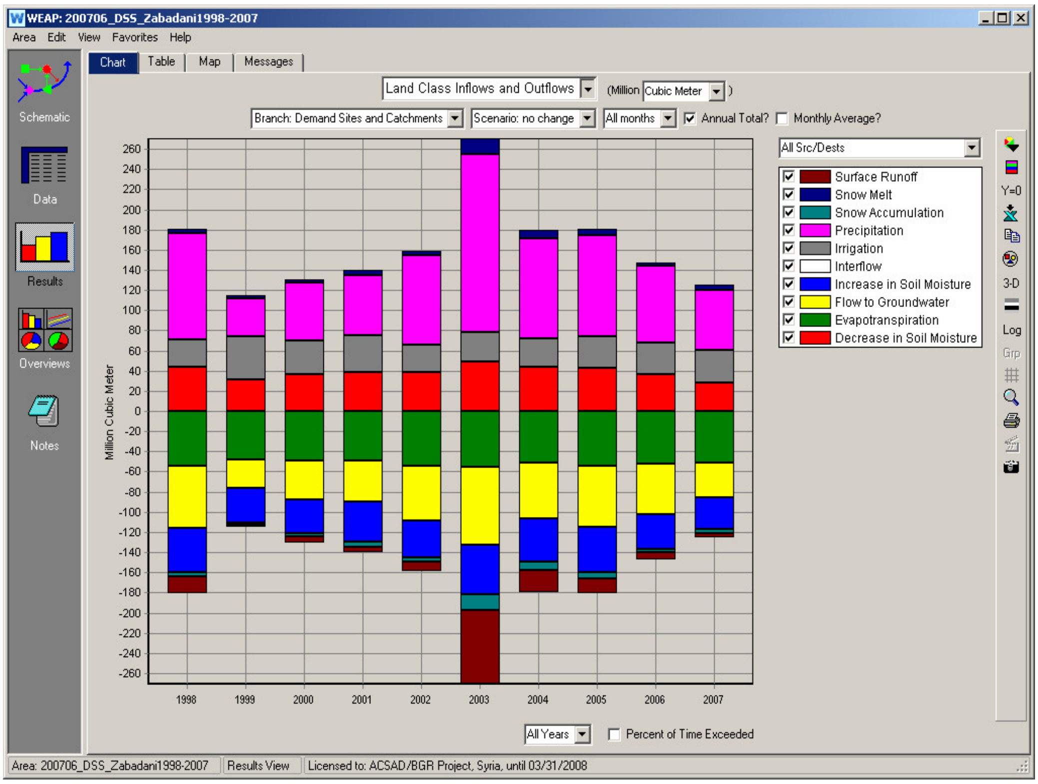
All Sources and Destinations

- ☑ Outflow to C_BARADA_SP
- ☑ Outflow to BOUQEIN
- ☑ Outflow to BLOUDAN
- ☑ Inflow from Upstream
- ☑ Inflow from Runoff/Infiltration from C_ZABADANI_W to GW_ZABADANI_W
- ☑ Inflow from Runoff/Infiltration from C_ZABADANI_CENTRE to GW_ZABADANI_
- ☑ Inflow from Runoff/Infiltration from C_TEKIYE to GW_TEKIYE
- ☑ Inflow from Runoff/Infiltration from C_SERGHAYA to GW_SERGHAYA
- ☑ Inflow from Runoff/Infiltration from C_RAWDA to GW_RAWDA
- ☑ Inflow from Runoff/Infiltration from C_MADAYA to GW_MADAYA
- ☑ Inflow from Runoff/Infiltration from C_EX_RECH_S to GW_EX_RECH_S
- ☑ Inflow from Runoff/Infiltration from C_EX_RECH_N to GW_EX_RECH_N
- ☑ Inflow from Runoff/Infiltration from C_CHEQIF to GW_CHEQIF
- ☑ Inflow from Runoff/Infiltration from C_BLOUDAN to GW_BLOUDAN
- ☑ Inflow from Runoff/Infiltration from C_BARADA_SP to GW_BARADA_SP
- ☑ Inflow from Outside of Area / Natural Recharge
- ☑ Inflow from GW_ZABADANI_W
- ☑ Inflow from GW_ZABADANI_CENTRE
- ☑ Inflow from GW_TEKIYE
- ☑ Inflow from GW_SERGHAYA
- ☑ Inflow from GW_RAWDA
- ☑ Inflow from GW_MADAYA
- ☑ Inflow from GW_EX_RECH_S
- ☑ Inflow from GW_EX_RECH_N
- ☑ Inflow from GW_CHEQIF
- ☑ Inflow from GW_BLOUDAN
- ☑ Inflow from GW_BARADA_SP
- ☑ Increase in Storage
- ☑ Decrease in Storage

All Years | ☐ Percent of Time Exceeded

Area: 200706_DSS_Zabadani1998-2007 | Results View | Licensed to: ACSAD/BGR Project, Syria, until 03/31/2008

Figure 4-38: Detailed computed groundwater balance 1998 – 2007.



Land Class Inflows and Outflows (Million Cubic Meter)

Branch: Demand Sites and Catchments | Scenario: no change | All months | ☑ Annual Total? | ☐ Monthly Average?

All Src/Dests

- ☑ Surface Runoff
- ☑ Snow Melt
- ☑ Snow Accumulation
- ☑ Precipitation
- ☑ Irrigation
- ☑ Interflow
- ☑ Increase in Soil Moisture
- ☑ Flow to Groundwater
- ☑ Evapotranspiration
- ☑ Decrease in Soil Moisture

All Years | ☐ Percent of Time Exceeded

Area: 200706_DSS_Zabadani1998-2007 | Results View | Licensed to: ACSAD/BGR Project, Syria, until 03/31/2008

Figure 4-39: Detailed computed soil water balance 1998 – 2007.

For the four planning scenarios 2005-2017 the following figures indicate the respective impacts. Figure 4-40 shows the hydraulic head fluctuations, with the most severe drawdown occurring in scenario D, followed by C and, depending on the proximity to a well field, the scenarios A and B. A similar ranking of the decline of the discharge of Barada Spring is presented in Figure 4-41 causing almost a total cease in scenarios C and D. Looking at the overall aquifer storage, Figure 4-42 gives the computed results putting the scenario C as the most severe one. Figure 4-43 shows the detailed groundwater balances with the respective fractions and the most severe decline in the overall balance for scenario C and D.

Depending on the required information/ target planning area constraint these and additional inputs can be aggregated together by the user in the desired way. For water resources planning the crucial question is how large and how many years a negative groundwater balance (increase in storage – decrease in storage) is allowed and what are the limits.

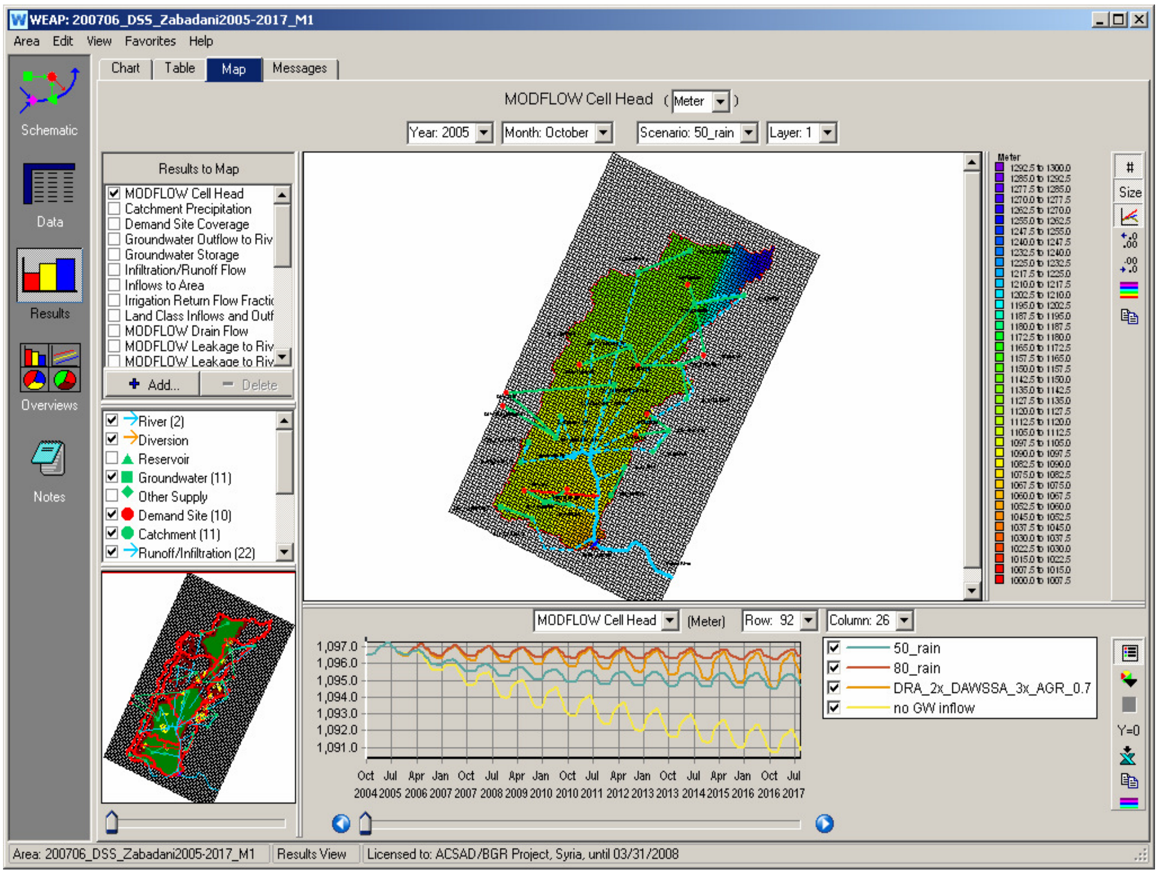


Figure 4-40: Computed groundwater levels for 2005 – 2017.

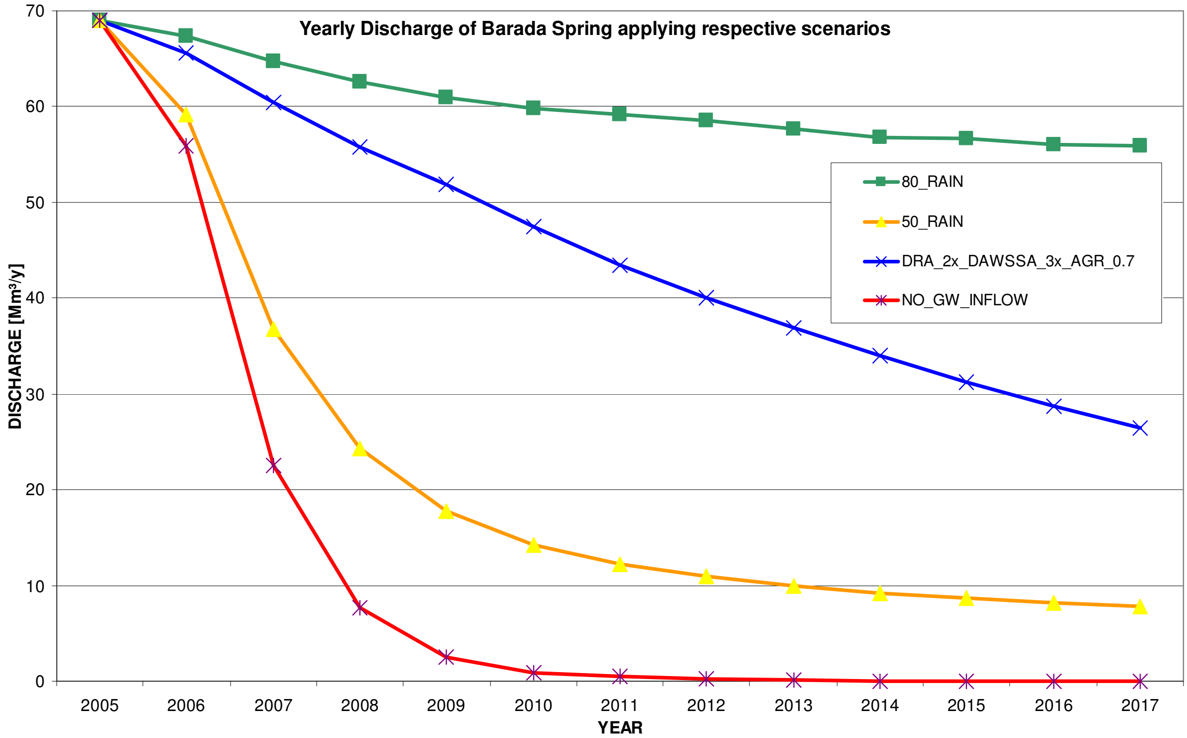
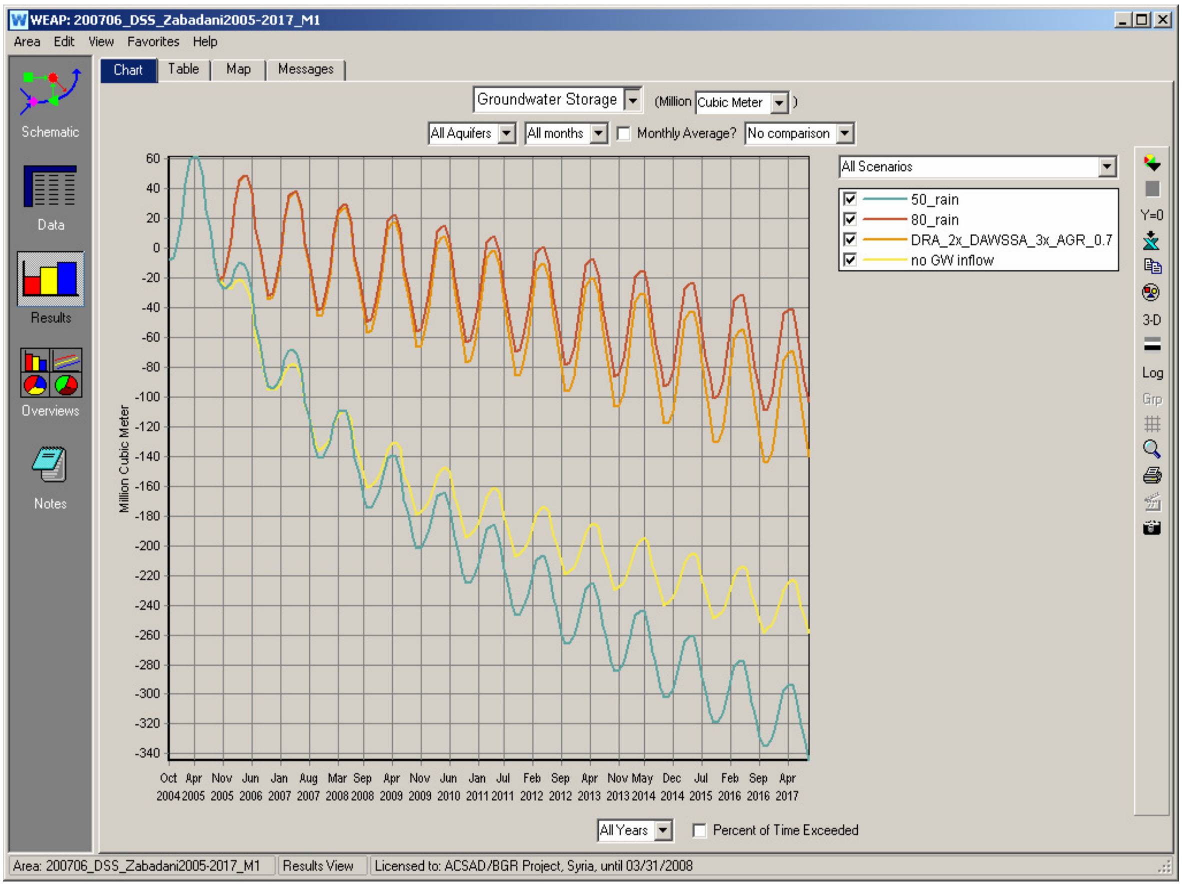


Figure 4-41: Computed yearly discharge of Barada Spring for 2005 – 2017.



WEAP: 200706_DSS_Zabadani2005-2017_M1

Groundwater Storage (Million Cubic Meter)

All Aquifers | All months | ☐ Monthly Average? | No comparison

All Scenarios

☑ 50_rain
☑ 80_rain
☑ DRA_2x_DAWSSA_3x_AGR_0.7
☑ no GW inflow

All Years | ☐ Percent of Time Exceeded

Area: 200706_DSS_Zabadani2005-2017_M1 | Results View | Licensed to: ACSAD/BGR Project, Syria, until 03/31/2008

Figure 4-42: Computed groundwater storage for 2005 – 2017.

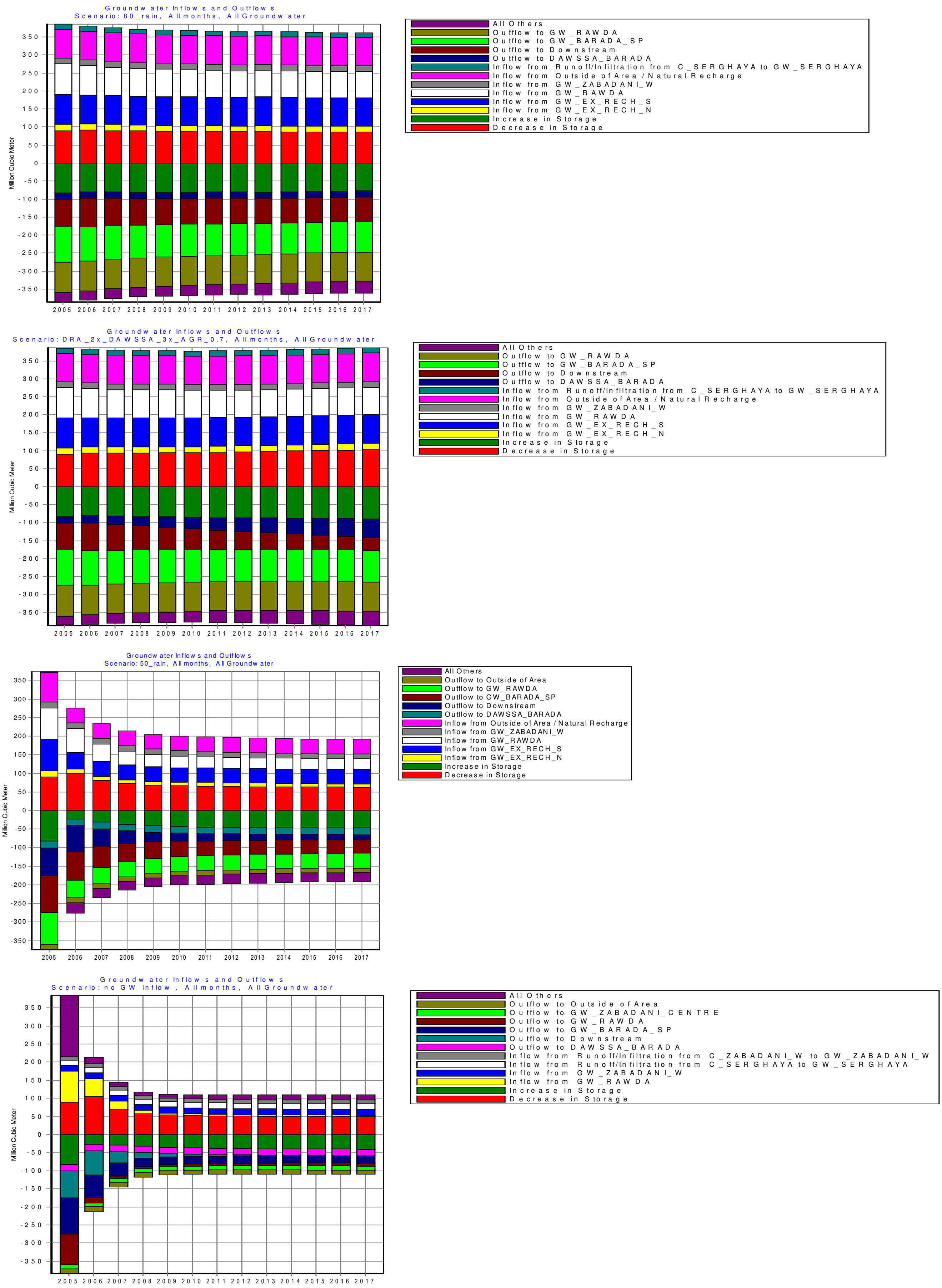


Figure 4-43: Computed groundwater balances for scenarios A, B, C and D.

4.4.12 DSS – Impact and Application in Institutional Planning

In the Zabadani Basin the DSS – pilot study raised for the first time critical questions, which started a first discussion process:

- There is significant groundwater inflow from the south (ca. 70 Mm^3/y) into the Zabadani Basin to feed mainly the Barada Spring.
- What is the exact groundwater catchment area of Barada Spring as the outline of the RUSSIAN STUDY (1986) is obviously wrong, because the Anjar spring catchment was neglected?
- How can be the groundwater resources of a basin managed if the exact limits are unknown?
- The Jdeited Yabous well field is operating (DAWSSA) since August 2007 – up to now it is unknown if the pumping will influence the discharge of Barada Spring and the groundwater flow directions and volumes.

Between 2.9.2007 and 6.9.2007 a first DSS training course was given to staff from DAWSSA, GDBAB, WRIC and Orontes basin directorate, ministry of irrigation in Jordan and the Saudi geological survey in order to practically demonstrate and train the capabilities of a DSS-system.

On 23.9.2007 a DSS-presentation was given at the Water Resources Directorate, Damascus (former GDBAB) under the patronage of General Director of the Water Resources Commission of the Syrian Ministry of Irrigation and respective participants from the ministry institutions. The institutions agreed to nominate in each relevant institution two skilled staff members to be trained on the job to apply and implement the DSS-system.

By November 2007 this on the job training process started, parallel joint efforts have to be undertaken to refine the DSS by collecting additional (field-)data and sharing them among the respective institutions.

5 PILOT AREA II: BERRECHID BASIN, MOROCCO

In the abstract and the introduction the target of the ACSAD – BGR cooperation project was already mentioned: the application of a DSS in two pilot areas in two ACSAD-member countries.

In Morocco the Hydraulic Agency of Bouregreg and Chaouia (L'Agence du Bassin Hydraulique de Bouregreg et de la Chaouia, ABHBC) in Benslimane and the respective ministry have chosen the Berrechid Basin as a pilot area for the project. Mr. Kacem el Hajji and Mr. Mohammed Dechich from the ABHBC have been assigned as cooperation partners and thanks to their effort a DSS could be established there and documented in the following sections.

In contrary to the Zabadani Basin, Syria a calibrated MODFLOW groundwater flow model was already existing as a basis and all relevant input and model data have been used also as DSS input and calibration data.

5.1 Background

The Berrechid Basin is located just south of Casablanca, Morocco between the Atlantic Ocean and the Phosphate Plateau (Figure 5-2). The total area is about 1500 km². Geomorphologically it is a flat basin with elevations of 140 m a.s.l. in the north and about 350 m a.s.l. at the southern margin at the Settat Plateau. The topographic gradient doesn't exceed 0.2 % except at the southern margin where it can increase to 0.8%.

It is a tectonic basin with subsidence and sedimentation since the Triassic.

Due to the basin's fertile soil and great groundwater potential, the agricultural development and also the irrigated areas increased significantly during the past years, growing mainly vegetables, fodder crops and fruit trees. Overexploitation of the aquifer caused a regional groundwater drawdown of about ten meters in the centre of the basin, dry wells and reduced productivity of the wells in the area.

5.2 Hydrogeology and Hydrology

5.2.1 Hydrogeology

As mentioned above the Berrechid Basin is a tectonic basin with subsidence since the Triassic.

The main (normal) faults along its margin are:

- The fault passing by Médiouna, witch creates a tectonic boundary between the primary bedrock formations and those post-Triassic, with a NNE-SSW direction.

- The fault with NNW-SSE direction passing by Médiouna witch was detected by the structural interpretation of the stratigraphic section of drillings.

- The fault with SW-NE direction passing by El Gara. This fault obviously represents the SE limit of the Berrechid Basin.

In Pliocene, minor faults induced a moderate subsidence of the basin. A short transgression of the sea with detritical limestone deposits occurred in this period.

Beside the bedrock of Silurian and Devonian age also sediments of the Permo-Trias, Infracenomanian, Cenomanian and Pliocene-Quaternary are cropping out in the area (Figure 5-1 to Figure 5-5). From base to top these are:

Bedrock (Silurian-Devonian)
The bedrock in the area consists of schists intercalated by layers of sandstone and quarzites. The main outcrops are along the SE and NW margins of the basin.

Permo-Trias
The Permo - Triassic sediments are represented in the Berrechid Basin by red clays intercalated by minor basalts and evaporates. The base is formed by a conglomerate layer with variable thicknesses (some centimetres to ten meters).

Infracenomanien
The Infra-Cenomaninan sediments consist of detritical red clays followed by layers of white to yellow marls and limestones. The total thickness of this unit is about 40 m.

Cenomanien
Yellow marls and limestones with greenish marl intercalations reaching thicknesses of 120 m.

Plio-Quaternary
Clays, sands, sandstones and sandy limestones and minor conglomerates (max. 10 m thickness) at the base reaching a total thickness of 10–40 m. Along paleochannels the thickness can be even larger.

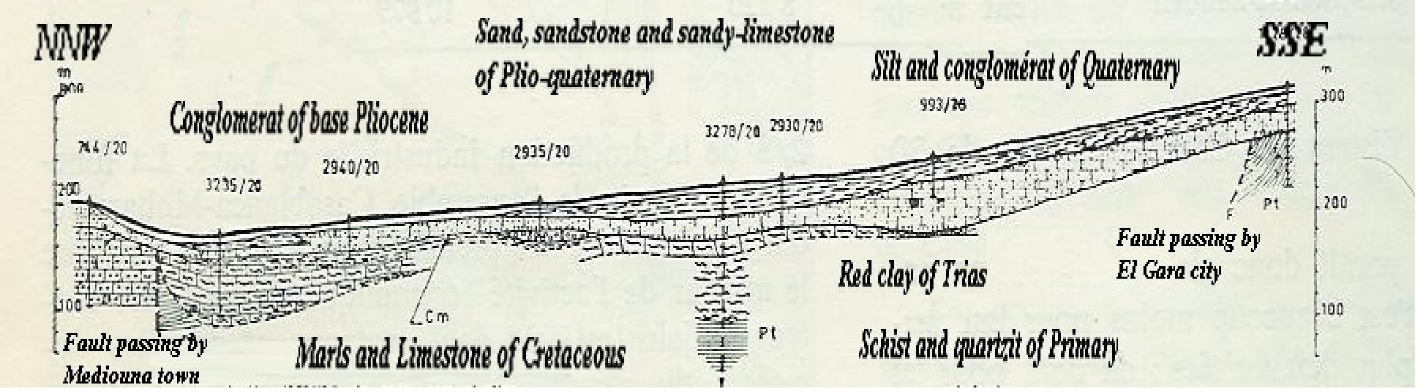


Figure 5-1: Geological cross section of the Berrechid Basin (ABHBC, 2005).

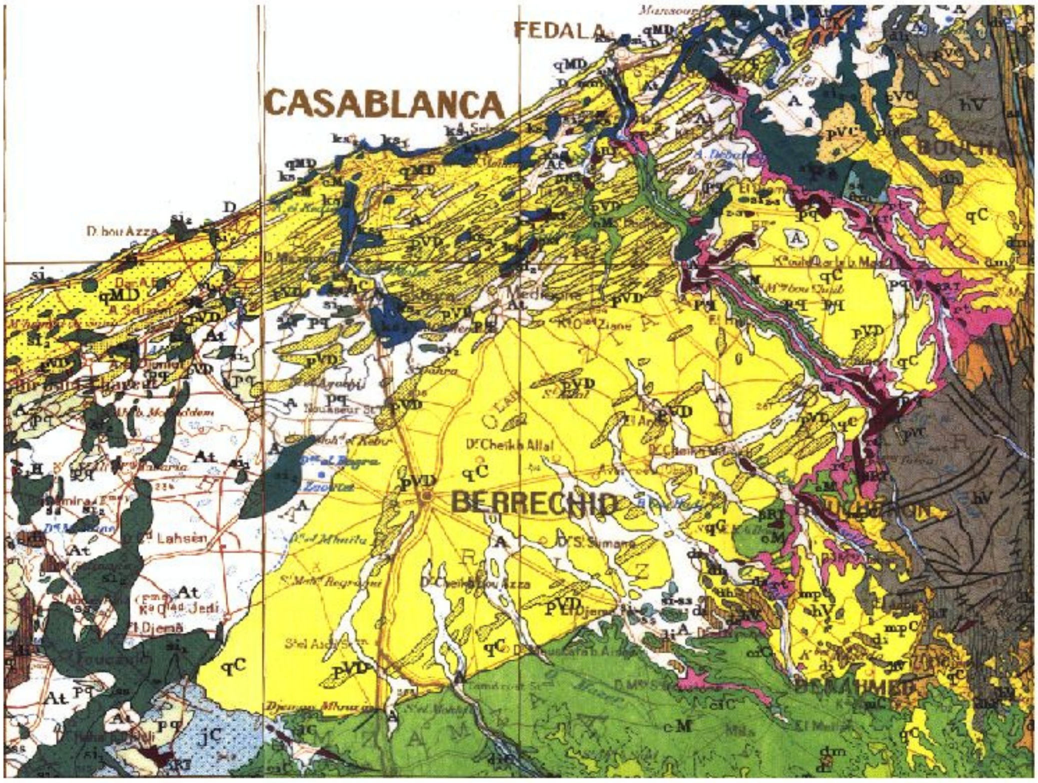


Figure 5-2: Geological map of the Berrechid Basin (ABHBC, 2005).

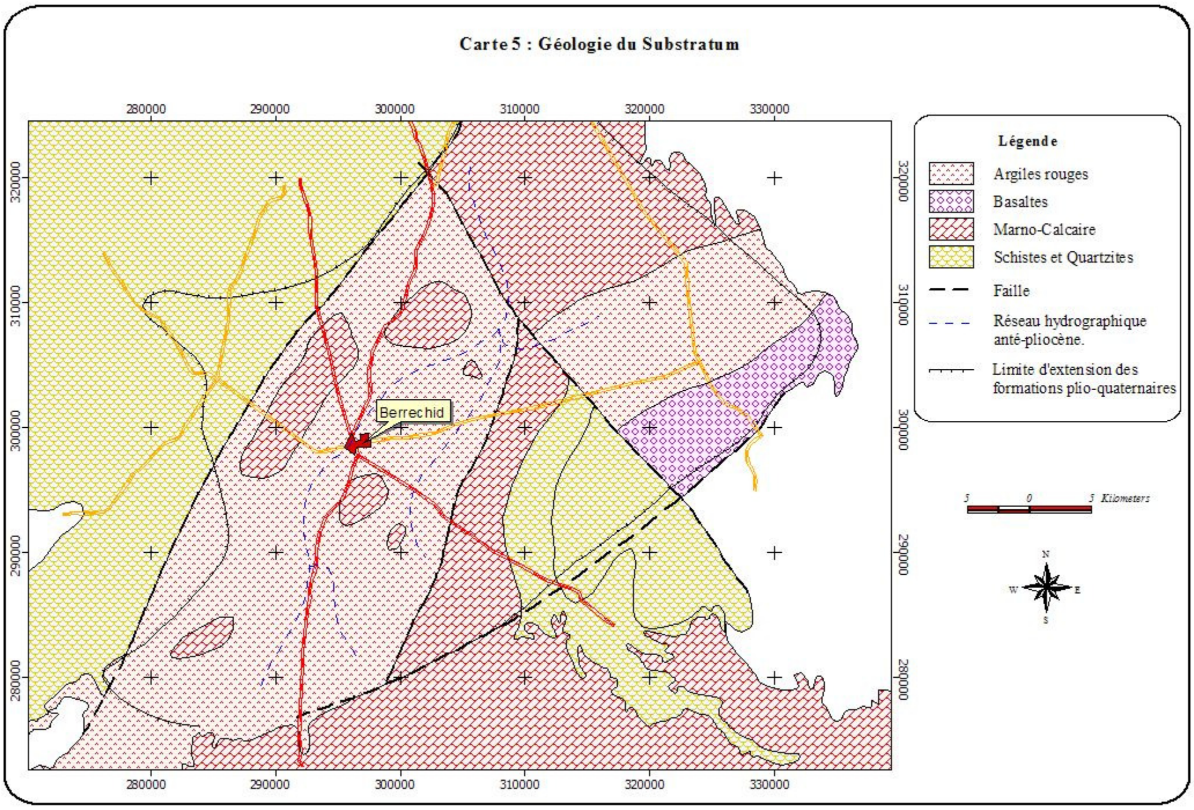


Figure 5-3: Geological map of the basement of the Berrechid Basin (ABHBC, 2005).

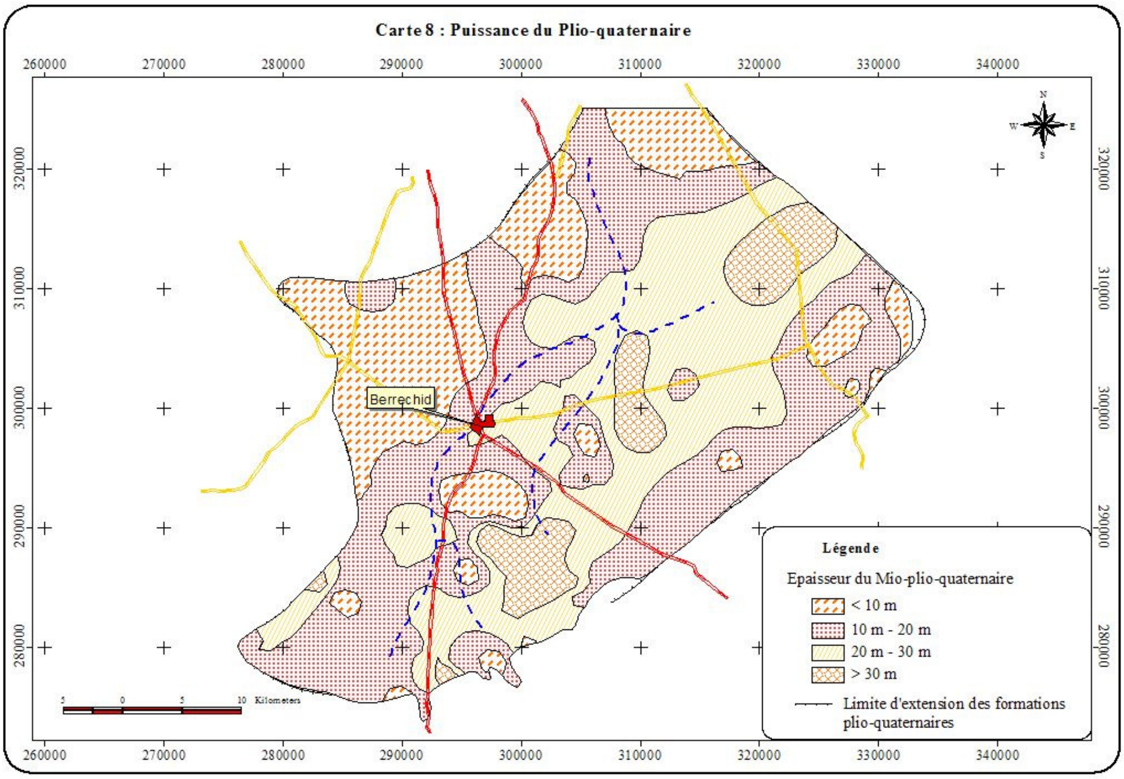
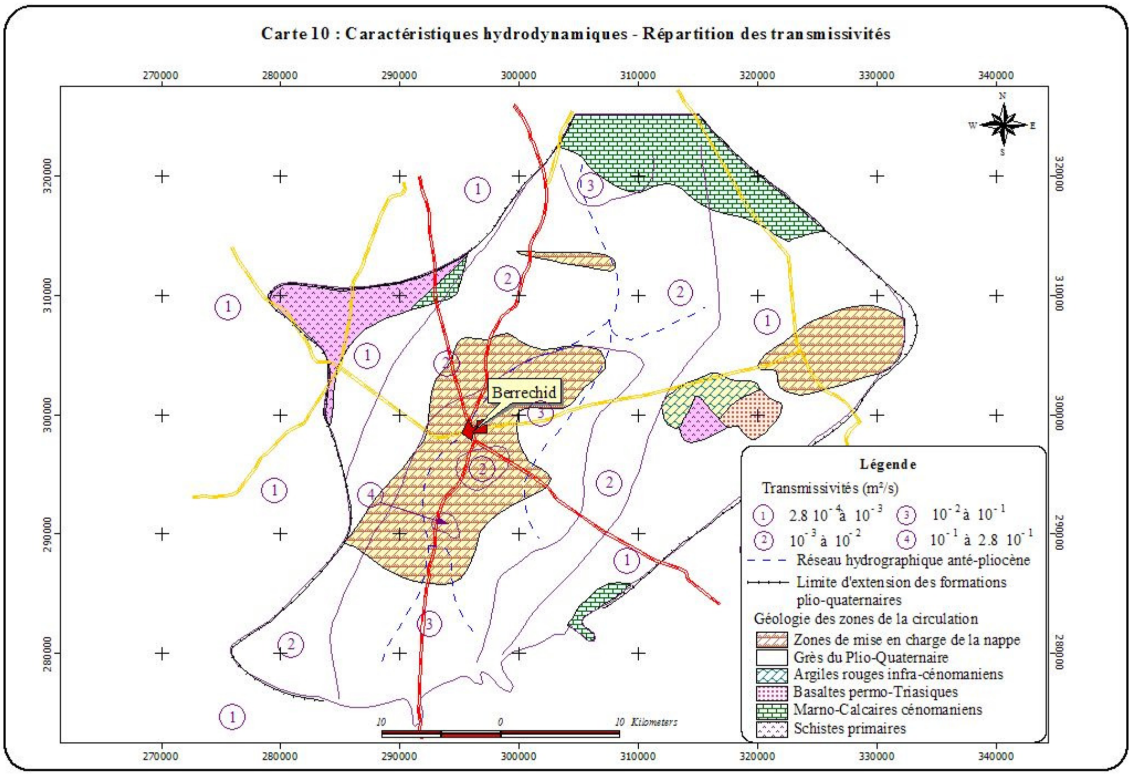


Figure 5-4: Thickness of the Pliocene-Quaternary sediments (ABHBC, 2005).



(areas in brown are covered by thick layers of silt/ clay leading there to confined aquifer conditions and the lack of groundwater recharge from precipitation; ABHBC, 2005)

Figure 5-5: Hydrogeological map of the Berrechid aquifer (ABHBC, 2005).

The main regional aquifer of the Berrechid Basins is formed by the Pliocene sands, sandstones and sandy limestones reaching a total thickness of 5 – 40 m. However, locally other aquifers exist (Figure 5-4 & Figure 5-5), which are:

- Weathered and fissured bedrock
- Sandy sediments of Permo-Triassic and the Infra-Cenomanian;
- Marls and limestones of Cenomanian;
- Conglomerates of the Quaternary age.

The bottom of the aquifer, depending on the location (Figure 5-3), consist of:

- Marls and limestone of the Cenomanian ;
- Red clays of the Cenomanien ;
- Triassic basalts: distributed in a limited zone of 110 km² to the NE part of El Gara city ;
- Primary quartzite schist: The schist forms the substratum of the principal aquifer in the SW and NW part of the basin, under a thin Plio-Quaternary cover less than 10 m.

The lateral boundaries of the Berrechid Basin aquifer are:

- The phosphate plateau in the South formed by marls and limestones of the cenomanian, representing another aquifer which is connected to the Berrechid aquifer giving groundwater inflow to the Berrechid Basin ;
- The valley of the El Mellah River with its clay formation. This is non permeable boundary with only few local springs as a groundwater outflow there;
- Marls and limestones in the North, which represent an outflow area via Hassar river;
- Bedrock outcrops of impermeable shists form a no flow boundary along the W and NW margin of the basin.

The aquifer is mainly unconfined, only in the centre area of Berrechid city thick silts and clay layers causing confined conditions (Figure 5-1 & Figure 5-5). Depending on the aquifer thickness transmissivities range between $2.8*10^{-4}$ and $2.8*10^{-1}$ m²/s.

The recharge of the Berrechid aquifer is coming from:

- direct infiltration of rain;
- infiltration of the seasonal wadi streams (Tamedrost, Mazer, El Himmer and Boumoussa), which partially infiltrate and evaporate in the Berrechid Basin.
- lateral groundwater inflow from the Settat plateau aquifer.
- Minor return flow from irrigation and waste water

The outflow from the Berrechid aquifer is through lateral groundwater outflow towards Chaouia Plain and the pumping for irrigation and drinking water.

The groundwater flow direction in the Berrechid Basin is S to NW (Figure 5-6). In some areas, the overexploitation had caused a disturbance to this natural flow direction.

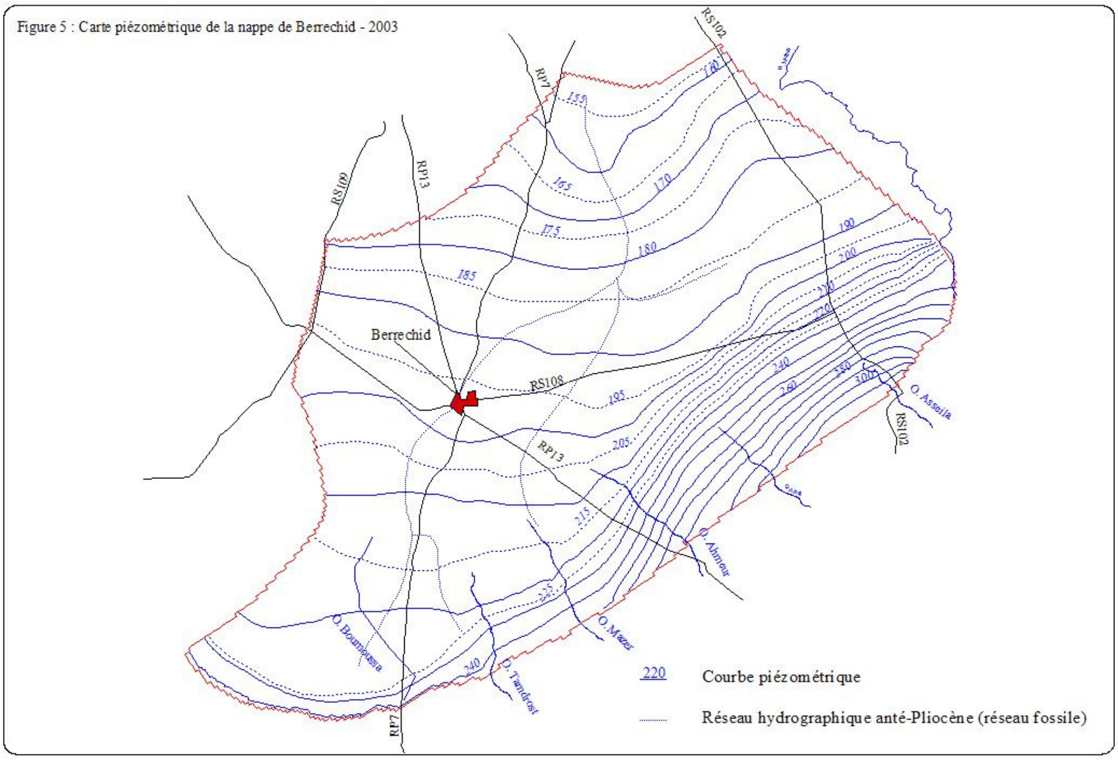


Figure 5-6: Groundwater contours in the year 2003 (ABHBC, 2005).

5.2.2 Hydrology

The Berrechid Basin is an end basin of several wadis (Figure 5-6 and Table 5-1) draining the Phosphate Plateau, whose seasonal runoff flow partially evaporates and the remainder infiltrates into the aquifer. The largest wadis are: El Himmer, Mazer, Tamdrost and Boumoussa.

Table 5-1: Main wadis discharging into the Berrechid Basin.

Wadi	Catchment area [km²]	Specific flow [l/s/km²]	Annual average flow [Mm³]
Tamdrost	630	0.1	9
Ahmer	173	0.34	3
Mazer	183	0.39	3
Boumoussa	166	0.38	2

5.2.3 Climate

The climate in the Berrechid Basin is semi arid to arid, with some influence of the Atlantic Ocean (air humidity gradient according to the distance from the coast, common formation of fog in winter). It is characterized by a wet winter and a dry and hot summer.

The annual distribution of rainfall in the Berrechid Basin is characterized by two seasons:

- Rainy season from October to April
- Dry season from May to September

The annual average rainfall is about 325 mm having its peak month in December. Table 5-2 gives the monthly average rainfall, calculated by data of seven climatological stations located in or close to the Berrechid Basin:

Table 5-2: Average monthly and yearly precipitation (mm) in the Berrechid Basin.

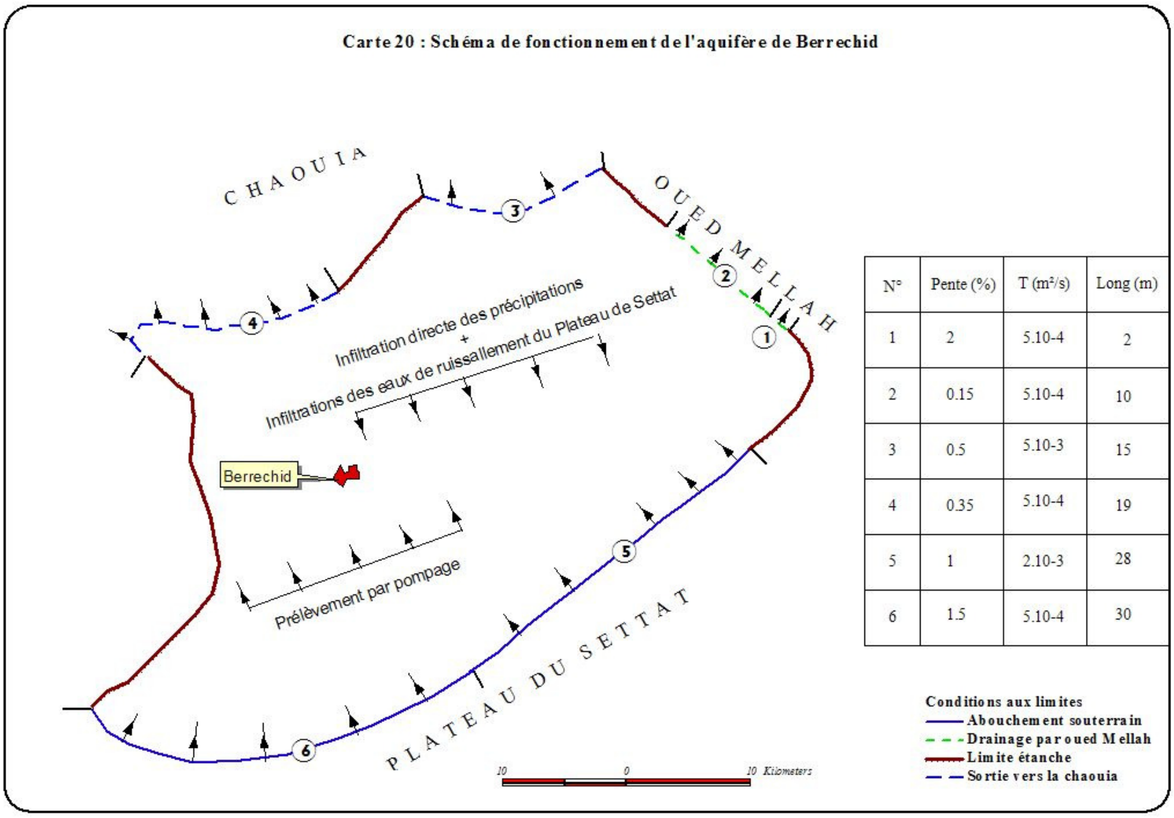
Station/ Month	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Total**
NOUACEUR	3.9	24.5	30.4	52.8	44.1	39.8	32.5	29.9	10.6	2.0	0.4	0.8	271.7
S. AHMED BEN ALI	2.9	21.5	31.7	63.6	51.2	46.4	36.0	33.6	8.1	0.9	0.1	0.5	296.4
EL MERS	4.8	24.5	45.1	58.5	54.1	46.7	38.3	32.4	13.1	2.9	2.3	0.2	322.6
TAMDROUST	4.4	21.6	36.5	55.2	48.6	42.1	33.1	32.1	9.3	1.1	0.5	0.3	284.6
SETTAT	5.4	25.0	37.0	63.4	54.4	47.6	37.8	32.5	12.7	2.4	0.6	0.3	319.0
EL GARA	7.4	31.1	49.4	70.0	56.6	50.3	43.6	38.8	16.5	4.0	2.4	2.4	372.4
BANAHMED	7.1	27.6	52.9	56.9	56.1	44.7	45.6	39.9	16.6	4.6	2.3	3.4	357.7
MEAN	**5.3**	**25.2**	**42.1**	**61.3**	**53.5**	**46.3**	**39.1**	**34.9**	**12.7**	**2.7**	**1.4**	**1.2**	**325.5**

The mean air temperatures range from 10℃ in winter to 34℃ in summer with a yearly average of about 20℃.

5.2.4 Basin Boundary

As mentioned already above the Berrechid Basin is a geomorphologic and a tectonic basin, therefore the hydrogelogical basin boundaries are either faults or outcrops of impermeable or low permeable layers. The respective lateral boundaries are (Figure 5-7, see respective **boundary section numbers**):

- In the south the Settat Plateau: normal fault, groundwater inflow from the Cenomanien aquifer of the Settat Plateau (specified head boundary, **5** and **6**)
- In the east wadi Melah: outcrop of the impermeable Triassic clays giving the origin of local springs (no flow boundary or specified head boundary – groundwater outflow in the area of springs/ drainage, **1** and **2**).
- In the north and northeast: groundwater outflow through the marls and limestones towards Chaouia basin (specified head boundary, **3** and **4**).
- In the west and the remaining areas: outcrop of impermeable bedrock (no flow boundary).



N°	Pente (%)	T (m²/s)	Long (m)
1	2	5.10-4	2
2	0.15	5.10-4	10
3	0.5	5.10-3	15
4	0.35	5.10-4	19
5	1	2.10-3	28
6	1.5	5.10-4	30

(Pente = hydraulic gradient, T = Transmissivity, Long = boundary length in kilometres, ABHBC, 2005)

Figure 5-7: Modelled boundary conditions of the Berrechid Basin.

5.3 Groundwater Flow Model (MODFLOW)

The Hydraulic Agency of Bouregreg and Chaouia (L'Agence du Bassin Hydraulique de Bouregreg et de la Chaouia) has contracted the consulting engineering office ANZAR CONSEIL to undertake a study on modelling the Berrechid aquifer in four missions :

- Synthesis of existing studies and update on hydrogeological data for the Berrechid aquifer.
- Establishing a mathematical groundwater flow model as a water resources management tool for the Berrechid aquifer.
- Establishing and evaluating a hydrodispersive model and proposing best water resources management scenarios for the Berrechid aquifer.
- Delivering a report of conclusions and recommendations

For all 4 (sub-)missions detailed reports are available and are referred here to as ABHBC (2005). In the following sections only some contents are summarized.

5.3.1 Conceptual Model

Based on all available hydrogeological and hydrological information a conceptual model was developed as shown in Figure 5-7. The respective boundary and recharge conditions have been already described in the chapters above. The whole aquifer was considered as unconfined even there are some local areas with confined conditions.

The hydrological year 1979/1980 was considered as a reference year of average precipitation and with a balanced groundwater balance (Table 5-3) assuming steady state conditions.

Table 5-3: Groundwater balance of the Berrechid Basin for 1979/1980.

Berrechid Basin groundwater balance for 1979/80			
Inflows (MCM)		**Outflows (MCM)**	
Infiltration from precipitation	14.01	Pumping outflow (domestic and irrigation)	36.58
Infiltration from wadi flow	7.19	Chaouia outflow	7.31
Lateral groundwater inflow (Settat Plateau)	24.53	Mellah river drainage	2.17
Total : 46 MCM		**Total : 46 MCM**	

5.3.2 Input Data

The detailed input data aggregation and regionalisation is described in the respective model reports (ABHBC, 2005), however the main inputs will be summarized here in order to understand the modelling constraints as they are also calibration target for the WEAP model later on. Figure 5-7 shows the general operation scheme of the Berrechid aquifer:

- Infiltration of 100% of the effective rain in the areas with low thickness of a silty/ clayey cover.
- Infiltration of part of the runoff of the wadis, draining the Settat plateau.
- Underground inflow along the Phosphates plateau border;
- Withdrawal for drinking water and irrigation supply.
- Local drainage through the Malleh River.
- Discharge towards the Chaouia Plain, through bedrock formations.

5.3.2.1 Groundwater recharge from precipitation

Due to the low relief and missing natural surface water drainage networks the surface runoff was neglected. For the calculation of the actual evapotranspiration the formula of TURC was adjusted to the local climate (ABHBC, 2005) and then applied. Subtracting the results from the three measured precipitation stations and averaging them leads to the effective precipitation or groundwater recharge from precipitation (Table 5-4).

As 280 km^2 of the Berrechid Basin aquifer area is covered by a non-permeable muddy cover (Figure 5-5), the contribution of the effective precipitation has been taken into account only to the remainder area of 1220 km² giving an average annual groundwater recharge from precipitation of about 15 Mm³. The assigned values to the MODFLOW cells with a permeable cover are shown in Table 5-5.

Table 5-4: Calculated effective precipitation.

Year	**Station’s effective precipitation [mm/y]**			
	Nouaceur	**El Mers**	**Tamdroust**	**Average**
	A	B	C	(A+((B+C)/2))/2
1972	0			
1973	61			
1974	0	0	0	0.0
1975	6.7	25.5	2	10.2
1976	27.6	30.8	10.5	24.1
1977	31.5	43.7	50.6	39.3
1978	44.7	40.5	35.2	41.3
1979	2	33.1	9	11.5
1980	0	8.2	0	2.1
1981	0	0	0	0.0
1982	0	0	0	0.0
1983	2.7	11.5	0	4.2
1984	0.2	4.4	12.2	4.3
1985	7.1	9.6	37.2	15.3
1986	0	0	0	0.0
1987	18	4.3	15.4	13.9
1988	6.2	13.1	4	7.4
1989	6.2	13.8	1.3	6.9
1990	9.6	11.5	0	7.7
1991	3.8	0	0	1.9
1992	0	0	0	0.0
1993	19.5	39.9	12.1	22.8
1994	0	0	0	0.0
1995	94.8	50.2	52.3	73.0
1996	89.3	75.3	65.8	79.9
1997	1.5	29.4	13.4	11.5
1998	0	0	0	0.0
1999	0	7.8	0	2.0
2000	0.7	7.9	1.7	2.8
2001	0.2	12.4	8.3	5.3
Mean	**14.4**	**16.9**	**11.8**	**14.4**

5.3.2.2 Groundwater recharge from wadi runoff infiltration

As there is a lack of continuous river gauge records the data of the Ben Ahmed climate station was used to calculate by the same TURC formula a regional average of the effective precipitation of the wadi catchments draining into the Berrechid Basin. The result of 32 mm/y was then used to calculate the total surface runoff in these catchments: 32 mm/y * 1220 km^2 = 39 Mm^3/y.

Additional assumptions are:

- 20% of the calculated surface runoff will reach the Berrechid Basin;
- 80% of the flow reaching the Berrechid Basin is infiltrating there.

Thus about 8 Mm^3 of wadi runoff will reach the Berrechid Basin, of which then about 6.5 Mm^3 will infiltrate to the groundwater. The assigned values to the respective MODFLOW .rech-file are shown in Table 5-5.

5.3.2.3 Lateral groundwater in- and outflows

The lateral groundwater in- and outflow volumes are calibrations constraints depending on the assigned permeability and head values.

5.3.2.4 Domestic and irrigation water abstraction

The total groundwater abstractions for domestic and irrigation use are shown in Table 5-7.

Irrigation groundwater abstraction has been entered as negative recharge to the MODFLOW model differentiating 4 different irrigation schemes (MF1-4) in 4 spatial zones (Figure 5-8 & Table 5-5).

Figure 5-8: Irrigation zones in the Berrechid Basin.

Table 5-5: Modflow cell values for the .rech-file.

(net value of abstractions for irrigation, recharge from wadi runoff and recharge from rain [10^{-10}m/s]).

YEAR	Irrigation zones (neg. recharge)				Recharge from rivers				Recharge from rain
	MF1	MF2	MF3	MF4	Ahmer	Tamdrost	Boumoussa	Mazer	
79/80	-16.90	-16.90	-16.90	0.00	39.50	165.00	31.30	43.70	3.64
80/81	-18.09	-18.09	-17.69	0.00	0.32	1.36	0.26	0.36	0.67
81/82	-18.70	-18.70	-17.80	-17.65	8.07	33.72	6.39	8.92	0.01
82/83	-19.39	-19.39	-18.10	-18.10	1.50	6.27	1.18	1.66	0.00
83/84	-20.09	-20.09	-18.30	-18.30	18.95	79.19	14.99	20.94	1.33
84/85	-20.79	-20.79	-18.50	-18.50	28.59	119.56	22.62	31.58	1.34
85/86	-21.49	-21.49	-18.70	-18.70	43.34	181.32	34.27	47.92	4.77
86/87	-23.28	-23.28	-19.79	-19.79	22.63	94.67	17.98	25.06	0.05
87/88	-25.18	-25.18	-20.79	-20.79	35.46	147.40	27.99	39.14	4.35
88/89	-27.07	-27.07	-21.79	-21.79	68.94	288.05	54.53	76.09	2.35
89/90	-28.97	-28.97	-22.69	-22.69	32.81	137.12	25.90	36.16	2.16
90/91	-30.87	-30.87	-23.59	-23.59	41.77	174.45	33.09	46.15	2.41
91/92	-32.87	-32.87	-24.29	-24.29	13.99	58.62	11.11	15.53	0.63
92/93	-33.79	-33.79	-24.30	-24.30	0.22	0.94	0.18	0.25	0.01
93/94	-34.69	-34.69	-24.20	-24.20	41.51	173.11	32.85	45.83	7.05
94/95	-35.59	-35.59	-24.00	-24.00	0.69	2.89	0.55	0.77	0.12
95/96	-36.49	-0.59	-23.80	-23.80	67.77	282.28	53.60	74.85	22.62
96/97	-37.38	0.00	-23.60	-23.60	134.71	562.61	106.97	148.58	25.16
97/98	-38.28	0.00	-21.15	-21.15	11.94	49.83	9.46	13.18	4.02
98/99	-39.18	-38.45	-18.55	-18.55	23.04	96.20	18.19	25.41	0.07
99/00	-40.18	-40.18	-15.95	-15.95	3.70	15.50	2.93	4.09	0.61
00/01	-41.08	-41.08	-15.90	-13.45	26.48	110.83	20.99	29.33	0.85
01/02	-41.98	-41.98	-15.90	-11.05	2.48	10.36	1.97	2.74	1.64
02/03	-42.98	-0.92	-15.90	-11.00	67.43	280.89	53.34	74.48	22.53
03/04	-43.98	-43.04	-15.90	-11.00	29.58	123.66	23.40	32.67	1.81

The domestic abstractions and irrigation abstractions for pivot irrigation areas have been assigned to the MODFLOW .wel-file (Table 5-6).

Table 5-6: Assigned well abstractions in Mm³ for in the MODFLOW .wel-file.

WELL_NAME	Pivot1_Well5	1950/27-1951/27	3061/27	2024/27	1199/27	Pivot1_Well1	Pivot1_Well2	Pivot1_Well3	Pivot1_Well4	3011/28	876/28	2155/28	2149/28	1431/28
WEAP groundwater node	GW_Sud	GW_Boumoussa	GW_Boumoussa	GW_Sud	GW_Sud	GW_Imp	GW_Imp	GW_Imp	GW_Imp	GW_Central	GW_Imp	GW_SudEst	GW_Ahmer	GW_Central
WEAP demand site	PIVOT_1_5	SETTAT	SETTAT_3061	SETTAT	SETTAT_1199	PIVOT1_N	PIVOT1_N	PIVOT1_S	PIVOT1_S	BERRECHID	BERRECHID	EL GARA	EL GARA	EL GARA
Groundwater use	irrigation	domestic	domestic	domestic	domestic	irrigation	irrigation	irrigation	irrigation	domestic	domestic	domestic	domestic	domestic
1980	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1981	0.000	0.367	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.568	0.000	0.000	0.000
1982	0.000	0.735	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.063	0.000	0.000	0.002
1983	0.000	0.986	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.113	0.000	0.000	0.249
1984	0.000	0.996	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.889	0.000	0.000	0.306
1985	0.000	0.748	0.000	0.654	0.000	0.000	0.000	0.000	0.000	0.000	0.793	0.000	0.000	0.299
1986	0.000	0.814	0.000	1.295	0.000	0.000	0.000	0.000	0.000	0.000	0.758	0.000	0.000	0.387
1987	0.000	0.934	0.000	1.567	0.000	0.000	0.000	0.000	0.000	0.000	0.718	0.000	0.000	0.533
1988	0.470	1.036	0.000	1.830	0.000	0.627	0.627	0.627	0.627	0.000	0.720	0.000	0.000	0.634
1989	0.473	1.083	0.000	1.931	0.285	0.631	0.631	0.631	0.631	0.028	0.720	0.000	0.000	0.695
1990	0.473	0.860	0.000	1.877	1.276	0.631	0.631	0.631	0.631	0.310	0.647	0.000	0.127	0.732
1991	0.473	0.922	0.000	2.185	1.562	0.631	0.631	0.631	0.631	0.620	0.541	0.012	0.326	0.713
1992	0.473	1.029	0.315	1.815	1.792	0.631	0.631	0.631	0.631	0.637	0.583	0.079	0.389	0.713
1993	0.005	0.988	0.725	0.936	1.656	0.305	0.305	0.631	0.631	0.568	0.604	0.117	0.330	0.724
1994	0.000	0.897	0.816	0.521	1.261	0.315	0.315	0.631	0.631	0.513	0.423	0.143	0.312	0.717
1995	0.000	0.632	0.549	0.401	0.841	0.315	0.315	0.631	0.631	0.433	0.115	0.149	0.284	0.660
1996	0.000	0.527	0.319	0.398	0.581	0.152	0.152	0.631	0.631	0.413	0.000	0.119	0.251	0.297
1997	0.000	0.346	0.204	0.346	0.329	0.158	0.158	0.631	0.631	0.209	0.000	0.123	0.182	0.378
1998	0.000	0.321	0.064	0.239	0.219	0.158	0.158	0.631	0.631	0.034	0.122	0.147	0.212	0.420
1999	0.000	0.346	0.042	0.147	0.186	0.158	0.158	0.631	0.631	0.010	0.065	0.140	0.234	0.339
2000	0.000	0.404	0.032	0.089	0.109	0.158	0.158	0.631	0.631	0.007	0.000	0.141	0.183	0.177
2001	0.000	0.295	0.100	0.030	0.028	0.003	0.003	0.321	0.321	0.001	0.449	0.113	0.153	0.054
2002	0.000	0.167	0.120	0.002	0.001	0.000	0.000	0.315	0.315	0.000	0.568	0.109	0.161	0.022
2003	0.000	0.050	0.056	0.000	0.000	0.000	0.000	0.315	0.315	0.000	0.522	0.106	0.166	0.012
2004	0.000	0.001	0.029	0.000	0.000	0.000	0.000	0.315	0.315	0.000	0.533	0.100	0.164	0.010

Table 5-7: Direct recharge to and abstraction from the Berrechid aquifer 80–02.

Year	Rain infiltration (MCM)	River infiltration (MCM)	Irrigation abstraction (MCM)	Domestic abstraction (MCM)
79/80	14.1	6.59	34.8	1.78
80/81	2.5	0	37.4	1.41
81/82	0	1.36	40	2
82/83	0	0.24	41.5	2.52
83/84	5.2	3.19	43	2.02
84/85	5.2	4.79	44.5	2.74
85/86	18.6	7.26	46	3.52
86/87	0	3.74	50.02	3.87
87/88	17	5.93	54.1	4.4
88/89	9	11.57	58.18	4.92
89/90	8.4	5.38	62.27	6.3
90/91	9.3	6.99	66.35	7.18
91/92	2.3	2.28	70.5	7.44
92/93	0	0	69.4	6.23
93/94	27.7	7.04	68.3	5.27
94/95	0	0	67.2	3.43
95/96	89.1	11.48	66.1	2.63
96/97	97.5	22.7	65	1.84
97/98	13.9	1.59	72	1.74
98/99	0	3.89	79.5	1.39
99/00	2.4	0.55	87	1.01
00/01	3.3	4.51	94.5	1.34
01/02	6.4	0.32	102	1.05

Source: ABHCH, 2005

5.3.3 Numeric Model

The Berrechid Basin numerical model grid consists of 164 rows, 266 columns, and 1 unconfined layer, i.e. 44 156 cells (24 401 active cells), with 250 m grid length and width respectively. The Groundwater Modelling System GMS 3.1 (www.ems-i.com/GMS/gms.html) was used as pre-processor of Modflow2000. The model was first calibrated in steady state for the reference year 1979/ 1980, and then the parameters have been used as starting values for the transient model and further refined. The model time step is yearly.

5.3.4 Results

Steady state model

The analysis of the evolution of hydraulic heads indicates that the aquifer was well balanced in the year 1979/1980, which makes the data set suitable for steady state calibration.

The steady state calibration was done by comparing the water heads simulated by the model with the real heads measured in the observation wells.

The calibration targets have been the following criteria:

- Calculating the same general shape of the reference piezometric heads;
- Assigning permeability values near of the permeability measured in pumping tests;
- Calculating a reliable water balance with no flooded or dry cells.
- In the calibration procedure, some incoherencies let to the adjustment of some bottom elevations and the permeability values.

It is important to notice that the reference piezometric map was elaborated with the measurements of only some twenty observation wells, and that this well density is not representative of the total 1500 km² of the aquifer. Thus, the model could not match the reference piezometry in some local areas.

But in general, the calibration was satisfying and the gap between the simulated and the measured heads didn't exceed 0.5% in the observation wells, as shown in the table below.

Table 5-8: Measured versus calculated heads for the reference year 1979/ 1980

Observation well	Measured head (m)	Simulated head (m)	Error (m)	Relative error
907/27	227.2	227.6	-0.4	0.2%
3235/20	165.0	164.2	0.8	0.5%
2947/20	172.3	172.1	0.2	0.1%
2775/20	282.3	283.0	-0.7	0.3%
2771/20	178.4	177.7	0.7	0.4%
2380/20	261.7	262.7	-1.0	0.4%
725/20	194.7	194.8	-0.1	0.1%
653/28	224.5	224.8	-0.3	0.1%
154/28	219.0	219.7	-0.7	0.3%
1771/27	224.5	225.4	-0.9	0.4%
1431/28	211.2	211.2	0.0	0.0%
1430/28	237.9	237.6	0.4	0.2%
1775/27	224.5	225.5	-0.9	0.4%
909/27	228.0	227.3	0.7	0.3%
795/27	223.0	222.7	0.3	0.1%
660/27	222.0	222.3	-0.3	0.1%
102/27	220.4	219.7	0.7	0.3%
3234/20	165.0	164.2	0.9	0.5%
2881/20	173.2	172.2	1.0	0.5%
2090/20	204.3	204.6	-0.4	0.2%
1676/20	165.0	165.3	-0.3	0.2%
937/20	189.9	189.9	0.0	0.0%
565/19	200.0	199.4	0.6	0.3%

The calculated groundwater balance for the reference year is already presented in Table 5-3.

Transient model

The transient model calibration was realised for the 1980-2004 period, applying the permeability values of the steady state calibration, with some minor modifications.

Only six values of storage coefficient from pumping tests were available over all the aquifer, therefore assigning values for this parameter to the model cells took into consideration the specific lithologies and the confined/ unconfined zones of the aquifer.

The calibration procedure tested the model reactions to different storage coefficient values, for the confined and unconfined areas, and compared the calculated heads to the measured ones. In addition to the procedure above, an adjustment of some terms of the water balance was necessary to match the simulated and the observed heads.

By the transient model calibration, the permeability distribution has been adjusted more accurately compared to the results of the steady state calibration. The final values are as follows:

- Mean value : $6*10^{-4}$ m/s ;
- Median value : $3*10^{-4}$ m/s ;
- Minimum value : $5*10^{-6}$ m/s ;
- Maximum value : 0.01 m/s.

The comparison between measured and modelled permeabilities shows that the modelled values are matching in an average range of 35% of the measured ones (Table 5-9).

By the calibrated steady state and transient state model a fairly accurate groundwater balance could be calculated for the years 1980-2004 (Table 5-10) and by updating respective input data these water balances can be updated further on indicating the degree of overexploitation of the Berrechid aquifer.

Table 5-9: Measured versus modelled permeabilities for the transient model.

Well	**X**	**Y**	**K_measured [m/s]**	**K_model [m/s]**	**K_mesured/ K_model**
875/20	296100	305700	0.000250	0.00040	0.6
911/20	297000	306800	0.000256	0.00040	0.6
1358/20	308300	312100	0.000313	0.00020	1.6
1359/20	307800	312100	0.000272	0.00020	1.4
1578/20	311000	318800	0.002120	0.00100	2.1
1662/20	305300	318400	0.001250	0.00092	1.4
2895/20	306600	318950	0.001714	0.00085	2.0
2922/20	308275	316775	0.001214	0.00100	1.2
2926/20	299750	301550	0.001679	0.00150	1.1
2930/20	308400	302650	0.001307	0.00045	2.9
2932/20	304500	310800	0.000397	0.00040	1.0
2934/20	300000	299500	0.001279	0.00090	1.4
2935/20	307800	309700	0.000385	0.00035	1.1
2936/20	311800	314600	0.000850	0.00020	4.3
2940/20	305850	315000	0.000261	0.00020	1.3
2941/20	299700	304250	0.000176	0.00050	0.4
2943/20	295100	299350	0.000864	0.00050	1.7
3698/20	304100	310175	0.000635	0.00050	1.3
3699/20	318700	307800	0.000032	0.00005	0.6
461/27	292800	279050	0.002537	0.00328	0.8
670/27	292300	278950	0.004714	0.00500	0.9
1186/27	293620	290400	0.003900	0.00300	1.3
1199/27	290250	284900	0.005350	0.00100	5.4
1771/27	284465	283445	0.000390	0.00175	0.2
1950/27	292550	278950	0.004800	0.00427	1.1
874/28	299200	295700	0.000410	0.00075	0.5
971/28	296000	284000	0.002230	0.00200	1.1
972/28	294500	297150	0.002577	0.00100	2.6
989/28	295750	295030	0.000650	0.00075	0.9
991/28	301300	295900	0.001048	0.00150	0.7
1006/28	306950	297750	0.000310	0.00071	0.4
1008/28	305700	293400	0.000892	0.00062	1.4
1009/28	301300	290650	0.001400	0.00150	0.9
1024/28	296325	288150	0.000910	0.00300	0.3
1267/28	295000	289900	0.015300	0.01000	1.5
1268/28	295000	291000	0.014000	0.01000	1.4
1270/28	295300	291000	0.008272	0.01000	0.8
1271/28	295005	291000	0.007800	0.01000	0.8
1272/28	294400	289750	0.003650	0.00300	1.2
1278/28	295000	291000	0.018733	0.01000	1.9
1431/28	302200	295200	0.003191	0.00150	2.1
3011/28	301100	295575	0.001100	0.00150	0.7

Source: ABHCH, 2005

Table 5-10: Calculated groundwater balances for the years 1979-2004.

Year	**INFLOWS [Mm^3]**				**OUTFLOWS [Mm^3]**				**Water balance**
	Lateral GW-inflow	Rain infiltration	River infiltration	Total	Lateral GW-outflow	Irrigation pumping	Drinking water pumping	Total	
1980	24	14	7	**46**	-10	-37	0	**-47**	**0**
1981	27	3	0	**29**	-10	-39	-1	**-49**	**-20**
1982	27	0	1	**29**	-9	-42	-2	**-53**	**-25**
1983	28	0	0	**28**	-9	-44	-2	**-55**	**-27**
1984	28	5	3	**37**	-9	-45	-2	**-56**	**-20**
1985	28	5	5	**38**	-9	-47	-2	**-58**	**-19**
1986	27	19	8	**54**	-9	-48	-3	**-61**	**-7**
1987	28	0	4	**33**	-9	-52	-4	**-64**	**-31**
1988	28	17	6	**52**	-9	-56	-7	**-72**	**-20**
1989	27	9	13	**49**	-9	-60	-8	**-76**	**-27**
1990	28	9	6	**43**	-9	-64	-9	**-81**	**-38**
1991	29	10	8	**46**	-8	-67	-10	**-86**	**-40**
1992	30	3	3	**36**	-8	-71	-10	**-90**	**-54**
1993	32	0	0	**32**	-7	-73	-9	**-89**	**-57**
1994	30	28	8	**66**	-8	-75	-7	**-90**	**-24**
1995	33	0	0	**33**	-7	-76	-6	**-89**	**-56**
1996	26	90	12	**129**	-10	-73	-4	**-88**	**41**
1997	23	100	25	**148**	-13	-75	-4	**-91**	**56**
1998	28	16	2	**47**	-10	-75	-3	**-89**	**-42**
1999	31	0	4	**35**	-9	-81	-3	**-92**	**-57**
2000	32	2	1	**35**	-8	-81	-3	**-92**	**-56**
2001	32	3	5	**41**	-7	-83	-2	**-91**	**-51**
2002	34	7	0	**40**	-6	-84	-2	**-92**	**-51**
2003	28	90	12	**130**	-9	-81	-2	**-91**	**39**
2004	32	7	1	**45**	-7	-88	-1	**-96**	**-51**

5.4 WEAP Model

The MODFLOW model of the Berrechid Basin and its input parameter calculations or estimations have been also used as basis to enter and aggregate respective data into a WEAP model in order to maintain spatial and data integrity (recharge patterns from rainfall/ wadi runoff, irrigated areas, effective precipitation calculation, etc.). Some additions have been made according to actual and future land use and water use changes.

As in MODFLOW the year 1979/1980 was used as a reference year and yearly time step was set in WEAP.

5.4.1 Sub-catchments

The target of delimitating of sub-catchments in the Berrechid Basin was to define reasonable planning units, which are consistent to the MODFLOW river recharge zones and otherwise follow if possible municipal boundaries as main base data are available on the municipality level (crop, irrigation, domestic water use data, etc.).

A total of eleven sub-catchments have been delimited (Figure 5-9, Figure 5-11 and Table 5-11):

- Five “big” sub-catchments, subdividing the Berrechid Basin into representative planning units.
- Four units representing the wadi runoff infiltration areas of the four principle wadis similar to MODFLOW.
- Currently waste water treatment plants are constructed for the Settat and Berrechid cities, therefore additional sub-catchments have been created to model future reuse options of treated waste water for irrigation.

Table 5-11: WEAP-sub-catchments and their classification constraints.

Sub-catchment	Area [ha]	Catchment classification
C_Ahmer	1031	Wadi runoff catchment
C_Boumoussa	1225	Wadi runoff catchment
C_Central	27744	Planning unit
C_EU_Berrechid	550	Waste water reuse area
C_EU_Settat	469	Waste water reuse area
C_Imp	20288	Planning unit
C_Mazer	894	Wadi runoff catchment
C_NordOuest	25081	Planning unit
C_Sud	18231	Planning unit
C_SudEst	55838	Planning unit
C_Tamdrost	706	Wadi runoff catchment

The respective catchment and groundwater nodes and rivers have been assigned to the WEAP schematic model. The main rivers drain directly into the groundwater of the respective “river-sub-catchments” - this has been entered in the WEAP-schematic by linking the river end nodes directly to the respective groundwater nodes (Figure 5-11).

Figure 5-9: Sub-catchments assigned in WEAP

5.4.2 Land Use Classes

A total number of 27 land use classes have been assigned in WEAP (Table 5-12, Figure 5-10 and Figure 5-11) taking into consideration initial assignments of the MODFLOW model and/ or current or future land use changes and intersecting respective attributes:

- Irrigation zone of the MODFLOW model (Figure 5-8)
- Pivot irrigation zones of the MODFLOW model (Pivot1, Pivot2)
- New irrigation zone in the south (irrigue sud permeable pas en MF)
- Permeability zone of the MODFLOW model (impermeable or permeable)
- Current urban areas and urban/ industrial development areas (urban)

Table 5-12: Land use classes of the Berrechid Basin

Land use class	Area [ha]
irrigue MF1 impermeable	163
irrigue MF1 impermeable Pivot1_N	631
irrigue MF1 impermeable Pivot1_S	475
irrigue MF1 impermeable Pivot2	50
irrigue MF1 impermeable urban Berrechid_CENTRAL	44
irrigue MF1 impermeable urban Berrechid_NW	1194
irrigue MF1 impermeable urban Berrechid_SE	50
irrigue MF1 impermeable_CENTRAL	3263
irrigue MF1 impermeable_NE	2519
irrigue MF1 impermeable_S	4294
irrigue MF1 impermeable_SE	1569
irrigue MF1 permeable	39569
irrigue MF1 Pivot2 permeable	1031
irrigue MF2 impermeable urban Berrechid_NW	100
irrigue MF2 impermeable_CENRAL	1894
irrigue MF2 impermeable_NW	1731
irrigue MF2 permeable	200
irrigue MF3 impermeable	2050
irrigue MF3 impermeable urban Berrechid	319
irrigue MF3 permeable	7363
irrigue MF4 permeable	3969
irrigue sud permeable pas en MF	9675
non irrigue impermeable	5750
non irrigue permeable	57619
urban Mediouna permeable	313
urban Nouacer Aeroport permeable	3044
urban zone industrial Rdadna permeable	3181

By intersecting these land use classes with the sub-catchments a total of 48 sub-catchment-land use classes have been defined.

Figure 5-10: Land use map of the Berrechid Basin.

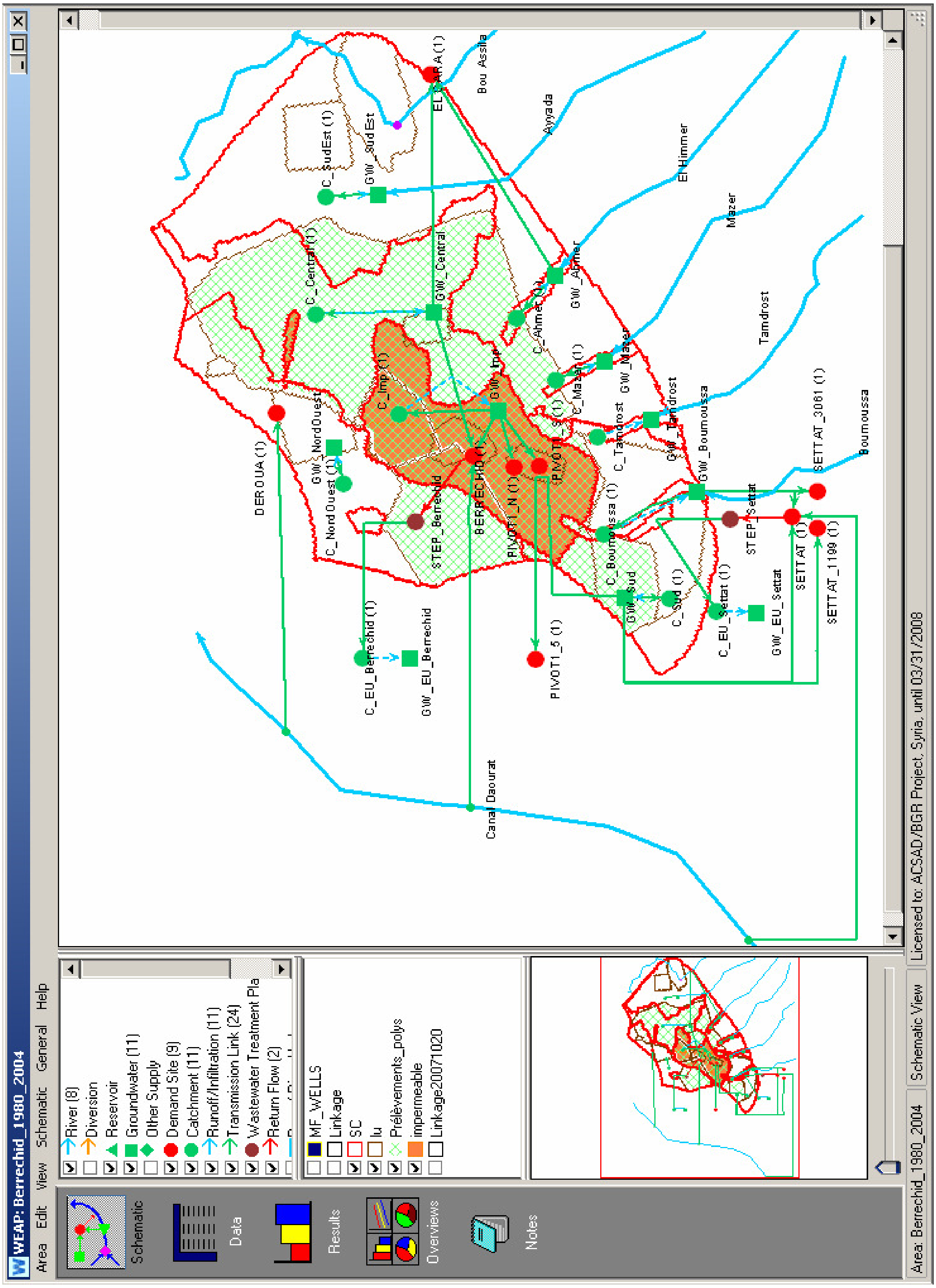


Figure 5-11: WEAP-schematic of the Berrechid Basin model.

5.4.3 Demand Sites

In general the irrigation demand is calculated for each land use class inside WEAP using the FAO Crop requirement algorithm. Three pivot irrigation demand sites have been defined as they have a water use record available (Pivot1_N, Pivot1_S and Pivot1_5) and in addition the domestic demand sites, the cities of Berrechid, Deroua, El Gara and Settat (subdivided into Settat, Settat_1199 and Settat_3061).

Table 5-13: Demand sites and respective water use rates in the Berrechid Basin.

DEMAND SITES AND ANNUAL WATER USE RATES [Mm^3/y]									
YEAR	DOMESTIC DEMAND						PIVOT IRRIGATION DEMAND		
	BERRECHID	DEROUA	EL GARA	SETTAT	SETTAT_1199	SETTAT_3061	PIVOT1_5	PIVOT1_N	PIVOT1_S
1980	0.00	0.04	0.00	2.14	0.00	0.00	0.00	0.00	0.00
1981	0.57	0.04	0.00	1.93	0.00	0.00	0.00	0.00	0.00
1982	1.06	0.05	0.00	1.74	0.00	0.00	0.00	0.00	0.00
1983	1.11	0.05	0.25	1.67	0.00	0.00	0.00	0.00	0.00
1984	0.89	0.05	0.31	1.86	0.00	0.00	0.00	0.00	0.00
1985	0.79	0.05	0.30	1.67	0.00	0.00	0.00	0.00	0.00
1986	0.76	0.05	0.39	1.19	0.00	0.00	0.00	0.00	0.00
1987	0.75	0.05	0.53	1.05	0.00	0.00	0.00	0.00	0.00
1988	0.83	0.06	0.63	0.95	0.00	0.00	0.00	1.25	2.51
1989	0.92	0.06	0.70	0.80	0.28	0.00	0.47	1.26	2.52
1990	1.03	0.06	0.86	0.40	1.28	0.00	0.47	1.26	2.52
1991	1.18	0.07	1.05	0.07	1.56	0.00	0.47	1.26	2.52
1992	1.34	0.08	1.18	0.14	1.79	0.32	0.47	1.26	2.52
1993	1.56	0.08	1.17	1.17	1.66	0.72	0.47	1.26	1.87
1994	1.81	0.10	1.17	2.39	1.26	0.82	0.01	1.26	1.89
1995	2.10	0.11	1.09	3.91	0.84	0.55	0.00	1.26	1.89
1996	2.39	0.13	0.67	4.27	0.58	0.32	0.00	1.26	1.57
1997	2.53	0.16	0.68	4.49	0.33	0.20	0.00	1.26	1.58
1998	2.49	0.12	0.78	5.03	0.22	0.06	0.00	1.26	1.58
1999	2.55	0.18	0.71	5.26	0.19	0.04	0.00	1.26	1.58
2000	2.74	0.24	0.50	5.56	0.11	0.03	0.00	1.26	1.58
2001	3.03	0.29	0.32	6.08	0.03	0.10	0.00	0.63	0.65
2002	3.18	0.34	0.29	6.37	0.00	0.12	0.00	0.63	0.63
2003	3.34	0.40	0.28	6.68	0.00	0.06	0.00	0.63	0.63
2004	3.51	0.47	0.27	6.88	0.00	0.03	0.00	0.63	0.63

5.4.4 Demand – Supply linkage

The nine demand sites are supplied by one or more supply sources (Table 5-14). Based on the given data the fractions of supply sources are assigned as respective maximum flow volumes and supply preferences. The demand sites SETTAT and PIVOT1 had to be further subdivided as they have more than one well(field) within one aquifer.

Table 5-14: Demand-supply linkage.

demand site	supply from	well name	supply preference
SETTAT	GW_Sud	2024/27	1
	GW_Boumoussa	1950/27 & 1951/27	1
	Canal Daourat		2
SETTAT_1199	GW_Sud	1199/27	1
SETTAT_3061	GW_Boumoussa	3061/27	1
BERRECHID	GW_Imp	876/28	1
	GW_Central	3011/28	1
	Canal Daourat		2
DEROUA	Canal Daourat		1
EL GARA	GW_SudEst	2155/28	1
	GW_Central	1431/28	1
	GW_Ahmer	2149/28	1
PIVOT1_N	GW_Imp	Pivot1_wells1-2	1
PIVOT1_S	GW_Imp	Pivot1_wells3-4	1
PIVOT1_5	GW_Sud	Pivot1_Well5	1

5.4.5 WEAP – Algorithm

The input data and the conceptual model of the MODFLOW model have been the input and calibrations constraints for the WEAP – Model:

- No surface runoff in the basin itself (precipitation is either infiltrating or evapotranspirating
- In the central area impermeable sediments prevent groundwater recharge
- No soil and detailed climate data have been available

Based on these constraints the FAO rainfall runoff model has been used in building the WEAP-model:

- “**Irrigation demands only (FAO) method**” for the central impermeable area (sub-catchment C_Imp), neglecting any groundwater recharge or surface runoff processes.
- “**Rainfall runoff (FAO) method**” for all the remaining area

The FAO crop requirements are calculated assuming a demand site with simplified hydrological and agro-hydrological processes such as precipitation, evapo-transpiration, and crop growth emphasizing irrigated and rainfall agriculture. Obviously non-agricultural crops can be included as well. The following equations were used to implement this approach where subscripts LC is land cover, HU is hydro-unit, I is irrigated, and NI is non-irrigated:

$$PrecipAvailableForET_{LC} = Precip_{HU} * Area_{LC} * 10^{-5} * PrecipEffective_{LC}$$

$$ETpotential_{LC} = ETreference_{HU} * Kc_{LC} * Area_{LC} * 10^{-5}$$

$PrecipShortfall_{LC,I} = \mathrm{Max}\ (0, ETpotential_{LC,I} - PrecipAvailableForET_{LC,I})$

$SupplyRequirement_{LC,I} = (1 / IrrFrac_{LC,I}) * PrecipShortfall_{LC,I}$

$SupplyRequirement_{HU} = \sum_{LC,I} SupplyRequirement_{LC,I}$

The above four equations are used to determine the additional amount of water (above the available precipitation) needed to supply the evapotranspiration demand of the land cover (and total hydro unit) while taking into account irrigation efficiencies.

Based on the system of priorities, the following quantities can be calculated:

$Supply_{HU}$ = Calculated by WEAP allocation algorithm

$Supply_{LC,I} = Supply_{HU} * (SupplyRequirement_{LC,I} / SupplyRequirement_{HU})$

$ETActual_{LC,NI} = \mathrm{Min}\ (ETpotential_{LC,NI}, PrecipAvailableForET_{LC,NI})$

$ETActual_{LC,I} = \mathrm{Min}\ (ETpotential_{LC,I}, PrecipAvailableForET_{LC,I})$

$+ IrrFrac_{LC,I} * Supply_{LC,I}$

$EF_{LC} = ETActual_{LC} / ETpotential_{LC}$

As a result, the actual yield can be calculated with the following equation:

$ActualYield_{LC} = PotentialYield_{LC} * \mathrm{Max}\ (0, (1 - YieldResponseFactor_{LC}$

$* (1 - EF_{LC})))$

Runoff to both groundwater and surface water can be calculated with the following equations:

$Runoff_{LC} = \mathrm{Max}\ (0, PrecipAvailableForET_{LC} - ETpotential_{LC})$

$+ (Precip_{LC} * (1 - PrecipEffective_{LC}))$

$+ (1 - IrrFrac_{LC,I}) * Supply_{LC,I}$

$RunoffToGW_{HU} = \sum_{LC} (Runoff_{LC} * RunoffToGWFraction_{LC})$

$RunoffToSurfaceWater_{HU} = \sum_{LC} (Runoff_{LC} * (1 - RunoffToGWFraction_{LC}))$

Units and definitions for all variables above are:

Area [HA] - Area of land cover
Precip [MM] - Precipitation
PrecipEffective [%] - Percentage of precipitation that can be used for

evapotranspiration
PrecipAvailableForET [MCM] - Precipitation available for evapotranspiration
Kc [-] - FAO crop coefficient
ETreference [MM] - Reference crop evapotranspiration
ETpotential [MCM] - Potential crop evapotranspiration
PrecipShortfall [MCM] - Evapotranspiration deficit if only precipitation is considered
IrrFrac [%] - Percentage of supplied water available for ET (i.e. irrigation efficiency)
SupplyRequirement [MCM] - Crop irrigation requirement
Supply [MCM] - Amount supplied to irrigation (calculated by WEAP allocation)
EF [-] - Fraction of potential evapotranspiration satisfied
YieldResponseFactor [-] - Factor that defines how the yield changes when the ETactual is less than the ETpotential.
PotentialYield [KG/HA] - The maximum potential yield given optimal supplies of water
ActualYield [KG/HA] - The actual yield given the available evapotranspiration
Runoff [MCM] - Runoff from a land cover
RunoffToGW [MCM] - Runoff to groundwater supplies
RunoffToSurfaceWater [MCM] - Runoff to surface water supplies

As mentioned above the FAO-method it is a simplified model and has the weakness that irrigation demand is dependent on groundwater recharge based on 2 main parameters (ETref & Kc) ignoring any soil specific processes (s. WEAP User Guide). In chapter 5.4.8 this dilemma is discussed regarding the calibration limitations.

5.4.6 Input Data

Precipitation: Due to the low relief of the Berrechid Basin the precipitation records have been averaged like in the MODFLOW input (yearly average = (A+((B+C)/2))/2, A: Nuaceur, B: El Mers and C: Tamdroust Station records) and assigned evenly to the whole area.

Table 5-15: Yearly precipitation in the Berrechid Basin

Year	Precipitation [mm]
1980	317
1981	198
1982	215
1983	221
1984	271
1985	281
1986	340
1987	190
1988	340
1989	305
1990	300
1991	304
1992	244
1993	158
1994	376
1995	175
1996	526
1997	544
1998	317
1999	198
2000	228
2001	272
2002	287
2003	389
2004	174

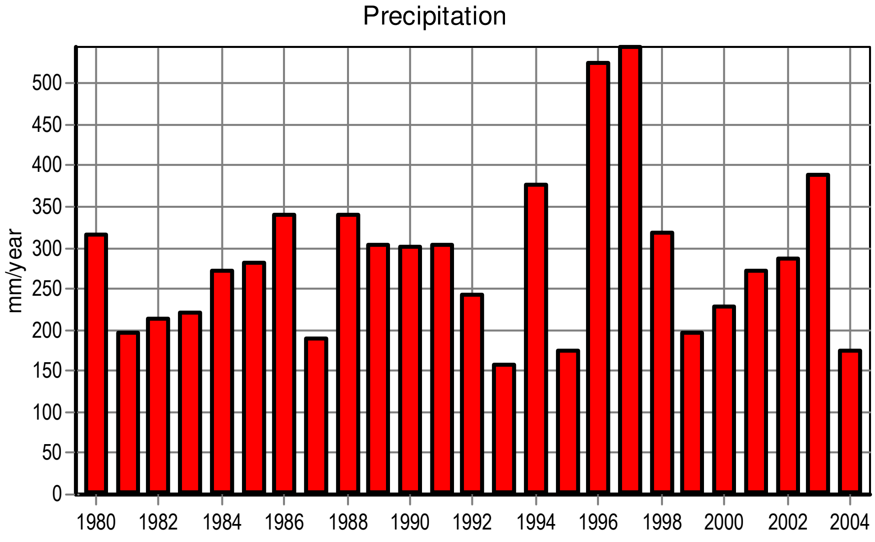


Figure 5-12: Yearly precipitation in the Berrechid Basin.

ET_{ref}: The crop reference evapotranspiration was assigned evenly to 1200 mm/y having the crop coefficient Kc left as the only calibration parameter on the land use class level to calibrate groundwater recharge and irrigation demand respectively.

The Kc-assignment will be presented in chapter 5.4.8.

5.4.7 Linkage to MODFLOW model

In order to get the linkage between WEAP and Modflow working it is necessary to define the respective relations. Initially a polygon-shapefile (each polygon representing the respective MODFLOW cell) has to be created. Then the following attributes have to be assigned to each MODFLOW CELL according the WEAP and MODFLOW model designs:

- MODFLOW path number
- MODFLOW row number
- WEAP sub-catchment
- WEAP land use class
- WEAP groundwater nodes
- WEAP demand site(s) (to be supplied by respective well-cells)
- WEAP pumping wells cells (representing well fields and assigning pumping layer(s))

5.4.8 Calibration

The calibration constraint was to match the inputs and outputs of the stand alone MODFLOW model for the historic scenario 1980-2004. As introduced in chapter 5.4.5 the FAO rainfall runoff method relates only on 2 calibration parameters (ET_{ref} and Kc) to adjust irrigation demand and groundwater recharge respectively. As ET_{ref} is assigned at the sub-catchment level it was kept constant at 1200 mm/year and the Kc value was calibrated in order to match the irrigation demand. For the unirrigated areas Kc was calibrated to match groundwater recharge (s. Table 5-16 & Table 5-17).

In Figure 5-13 the calibration results are presented as difference between the groundwater recharge input in MODFLOW and the one calculated in WEAP. The figure shows that in the wet years groundwater recharge is underestimated in WEAP for the 14 permeable and irrigated land use classes. To solve this issue a function could be entered in WEAP like:

If yearly precipitation > 325 mm add additional groundwater recharge of xx Mm^3

This was not applied as this would be just a manual workaround to have the same results in MODFLOW and in WEAP. The initial MODFLOW recharge estimation has been very rough so that the only reasonable solution is to refine the time steps of the models to at least a monthly scale and to consider also soil and climate characteristics (soil moisture method).

Table 5-16: Calibration constraint for respective land use classes.

ID	Sub-catchment-land use class	Calibration constraint
1	C_Ahmer | irrigue MF1 permeable	IRRIGATION DEMAND
2	C_Ahmer | non irrigue permeable	GW-RECHARGE
3	C_Boumoussa | irrigue MF1 impermeable	IRRIGATION DEMAND
4	C_Boumoussa | irrigue MF1 permeable	IRRIGATION DEMAND
5	C_Boumoussa | irrigue MF4 permeable	IRRIGATION DEMAND
6	C_Boumoussa | irrigue sud permeable - pas en MF	GW-RECHARGE
7	C_Central | irrigue MF1 permeable	IRRIGATION DEMAND
8	C_Central | irrigue MF1 Pivot2 permeable	IRRIGATION DEMAND
9	C_Central | irrigue MF2 permeable	IRRIGATION DEMAND
10	C_Central | non irrigue permeable	GW-RECHARGE
11	C_Central | urban Nouacer Aeroport permeable	GW-RECHARGE
12	C_EU_Berrechid | non irrigue permeable	GW-RECHARGE
13	C_EU_Settat | irrigue sud permeable - pas en MF	GW-RECHARGE
14	C_Imp | irrigue MF1 impermeable Pivot1_N	IRRIGATION DEMAND
15	C_Imp | irrigue MF1 impermeable Pivot1_S	IRRIGATION DEMAND
16	C_Imp | irrigue MF1 impermeable Pivot2	IRRIGATION DEMAND
17	C_Imp | irrigue MF1 impermeable urban Berrechid_CENTRAL	IRRIGATION DEMAND
18	C_Imp | irrigue MF1 impermeable urban Berrechid_NW	IRRIGATION DEMAND
19	C_Imp | irrigue MF1 impermeable urban Berrechid_SE	IRRIGATION DEMAND
20	C_Imp | irrigue MF1 impermeable_CENTRAL	IRRIGATION DEMAND
21	C_Imp | irrigue MF1 impermeable_NE	IRRIGATION DEMAND
22	C_Imp | irrigue MF1 impermeable_S	IRRIGATION DEMAND
23	C_Imp | irrigue MF1 impermeable_SE	IRRIGATION DEMAND
24	C_Imp | irrigue MF2 impermeable urban Berrechid_NW	IRRIGATION DEMAND
25	C_Imp | irrigue MF2 impermeable_CENRAL	IRRIGATION DEMAND
26	C_Imp | irrigue MF2 impermeable_NW	IRRIGATION DEMAND
27	C_Imp | irrigue MF3 impermeable	IRRIGATION DEMAND
28	C_Imp | irrigue MF3 impermeable urban Berrechid	IRRIGATION DEMAND
29	C_Imp | non irrigue impermeable	IRRIGATION DEMAND
30	C_Mazer | irrigue MF1 permeable	IRRIGATION DEMAND
31	C_Mazer | non irrigue permeable	GW-RECHARGE
32	C_NordOuest | irrigue MF1 permeable	IRRIGATION DEMAND
33	C_NordOuest | irrigue MF2 permeable	IRRIGATION DEMAND
34	C_NordOuest | irrigue MF3 permeable	IRRIGATION DEMAND
35	C_NordOuest | non irrigue permeable	GW-RECHARGE
36	C_NordOuest | urban Mediouna permeable	GW-RECHARGE
37	C_NordOuest | urban Nouacer Aeroport permeable	GW-RECHARGE
38	C_Sud | irrigue MF1 permeable	IRRIGATION DEMAND
39	C_Sud | irrigue MF3 permeable	IRRIGATION DEMAND
40	C_Sud | irrigue MF4 permeable	IRRIGATION DEMAND
41	C_Sud | irrigue sud permeable - pas en MF	GW-RECHARGE
42	C_Sud | non irrigue permeable	GW-RECHARGE
43	C_SudEst | irrigue MF1 permeable	IRRIGATION DEMAND
44	C_SudEst | non irrigue impermeable	GW-RECHARGE
45	C_SudEst | non irrigue permeable	GW-RECHARGE
46	C_SudEst | urban zone industrial Rdadna permeable	GW-RECHARGE
47	C_Tamdrost | irrigue sud permeable - pas en MF	GW-RECHARGE
48	C_Tamdrost | non irrigue permeable	GW-RECHARGE

Table 5-17: Assigned Kc-values for respective land use classes.

YEAR		80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04
KC value in respective LAND USE CLASS ID	1	0.28	0.19	0.20	0.12	0.25	0.26	0.31	0.19	0.31	0.29	0.29	0.29	0.25	0.18	0.35	0.19	0.46	0.47	0.31	0.22	0.24	0.28	0.29	0.35	0.20
	2	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	3	0.15	0.11	0.11	0.12	0.14	0.14	0.17	0.11	0.17	0.16	0.16	0.17	0.14	0.11	0.20	0.12	0.27	0.28	0.18	0.13	0.15	0.17	0.17	0.22	0.13
	4	0.28	0.19	0.20	0.12	0.25	0.26	0.31	0.19	0.31	0.29	0.29	0.29	0.25	0.18	0.35	0.19	0.46	0.47	0.31	0.22	0.24	0.28	0.29	0.35	0.20
	5	0.26	0.16	0.20	0.12	0.25	0.26	0.30	0.18	0.30	0.28	0.28	0.28	0.23	0.16	0.34	0.18	0.44	0.45	0.29	0.19	0.21	0.24	0.25	0.31	0.16
	6	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	7	0.28	0.19	0.20	0.12	0.25	0.26	0.31	0.19	0.31	0.29	0.29	0.29	0.25	0.18	0.35	0.19	0.46	0.47	0.31	0.22	0.24	0.28	0.29	0.35	0.20
	8	0.28	0.19	0.20	0.12	0.25	0.26	0.31	0.19	0.31	0.29	0.29	0.29	0.25	0.18	0.35	0.19	0.46	0.47	0.31	0.22	0.24	0.28	0.29	0.35	0.20
	9	0.28	0.19	0.20	0.12	0.25	0.26	0.31	0.19	0.31	0.29	0.29	0.29	0.25	0.18	0.35	0.19	0.41	0.42	0.26	0.22	0.24	0.28	0.29	0.30	0.20
	10	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	11	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	12	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	13	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	14	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.53	0.55	0.36	0.27	0.30	0.33	0.35	0.44	0.26
	15	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.53	0.55	0.36	0.27	0.30	0.33	0.35	0.44	0.26
	16	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.53	0.55	0.36	0.27	0.30	0.33	0.35	0.44	0.26
	17	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.53	0.55	0.36	0.27	0.30	0.33	0.35	0.44	0.26
	18	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.53	0.55	0.36	0.27	0.30	0.33	0.35	0.44	0.26
	19	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.53	0.55	0.36	0.27	0.30	0.33	0.35	0.44	0.26
	20	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.53	0.55	0.36	0.27	0.30	0.33	0.35	0.44	0.26
	21	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.53	0.55	0.36	0.27	0.30	0.33	0.35	0.44	0.26
	22	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.53	0.55	0.36	0.27	0.30	0.33	0.35	0.44	0.26
	23	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.53	0.55	0.36	0.27	0.30	0.33	0.35	0.44	0.26
	24	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.44	0.45	0.26	0.27	0.30	0.33	0.35	0.33	0.26
	25	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.44	0.45	0.26	0.27	0.30	0.33	0.35	0.33	0.26
	26	0.31	0.21	0.23	0.24	0.28	0.29	0.34	0.22	0.35	0.33	0.33	0.33	0.29	0.22	0.40	0.24	0.44	0.45	0.26	0.27	0.30	0.33	0.35	0.33	0.26
	27	0.31	0.21	0.23	0.23	0.27	0.28	0.33	0.21	0.34	0.31	0.31	0.32	0.27	0.20	0.38	0.21	0.50	0.52	0.32	0.21	0.23	0.27	0.28	0.37	0.19
	28	0.31	0.21	0.23	0.23	0.27	0.28	0.33	0.21	0.34	0.31	0.31	0.32	0.27	0.20	0.38	0.21	0.50	0.52	0.32	0.21	0.23	0.27	0.28	0.37	0.19
	29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	30	0.28	0.19	0.20	0.12	0.25	0.26	0.31	0.19	0.31	0.29	0.29	0.29	0.25	0.18	0.35	0.19	0.46	0.47	0.31	0.22	0.24	0.28	0.29	0.35	0.20
	31	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	32	0.28	0.19	0.20	0.12	0.25	0.26	0.31	0.19	0.31	0.29	0.29	0.29	0.25	0.18	0.35	0.19	0.46	0.47	0.31	0.22	0.24	0.28	0.29	0.35	0.20
	33	0.28	0.19	0.20	0.12	0.25	0.26	0.31	0.19	0.31	0.29	0.29	0.29	0.25	0.18	0.35	0.19	0.41	0.42	0.26	0.22	0.24	0.28	0.29	0.30	0.20
	34	0.28	0.19	0.20	0.12	0.25	0.26	0.30	0.18	0.30	0.28	0.28	0.28	0.23	0.16	0.34	0.18	0.44	0.45	0.29	0.19	0.21	0.25	0.26	0.32	0.16
	35	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	36	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	37	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	38	0.28	0.19	0.20	0.12	0.25	0.26	0.31	0.19	0.31	0.29	0.29	0.29	0.25	0.18	0.35	0.19	0.46	0.47	0.31	0.22	0.24	0.28	0.29	0.35	0.20
	39	0.28	0.19	0.20	0.12	0.25	0.26	0.30	0.18	0.30	0.28	0.28	0.28	0.23	0.16	0.34	0.18	0.44	0.45	0.29	0.19	0.21	0.25	0.26	0.32	0.16
	40	0.26	0.16	0.20	0.12	0.25	0.26	0.30	0.18	0.30	0.28	0.28	0.28	0.23	0.16	0.34	0.18	0.44	0.45	0.29	0.19	0.21	0.24	0.25	0.31	0.16
	41	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	42	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	43	0.28	0.19	0.20	0.12	0.25	0.26	0.31	0.19	0.31	0.29	0.29	0.29	0.25	0.18	0.35	0.19	0.46	0.47	0.31	0.22	0.24	0.28	0.29	0.35	0.20
	44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	45	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	46	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	47	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14
	48	0.25	0.16	0.18	0.00	0.22	0.23	0.27	0.16	0.27	0.25	0.24	0.25	0.20	0.13	0.30	0.15	0.38	0.39	0.25	0.16	0.19	0.22	0.24	0.26	0.14

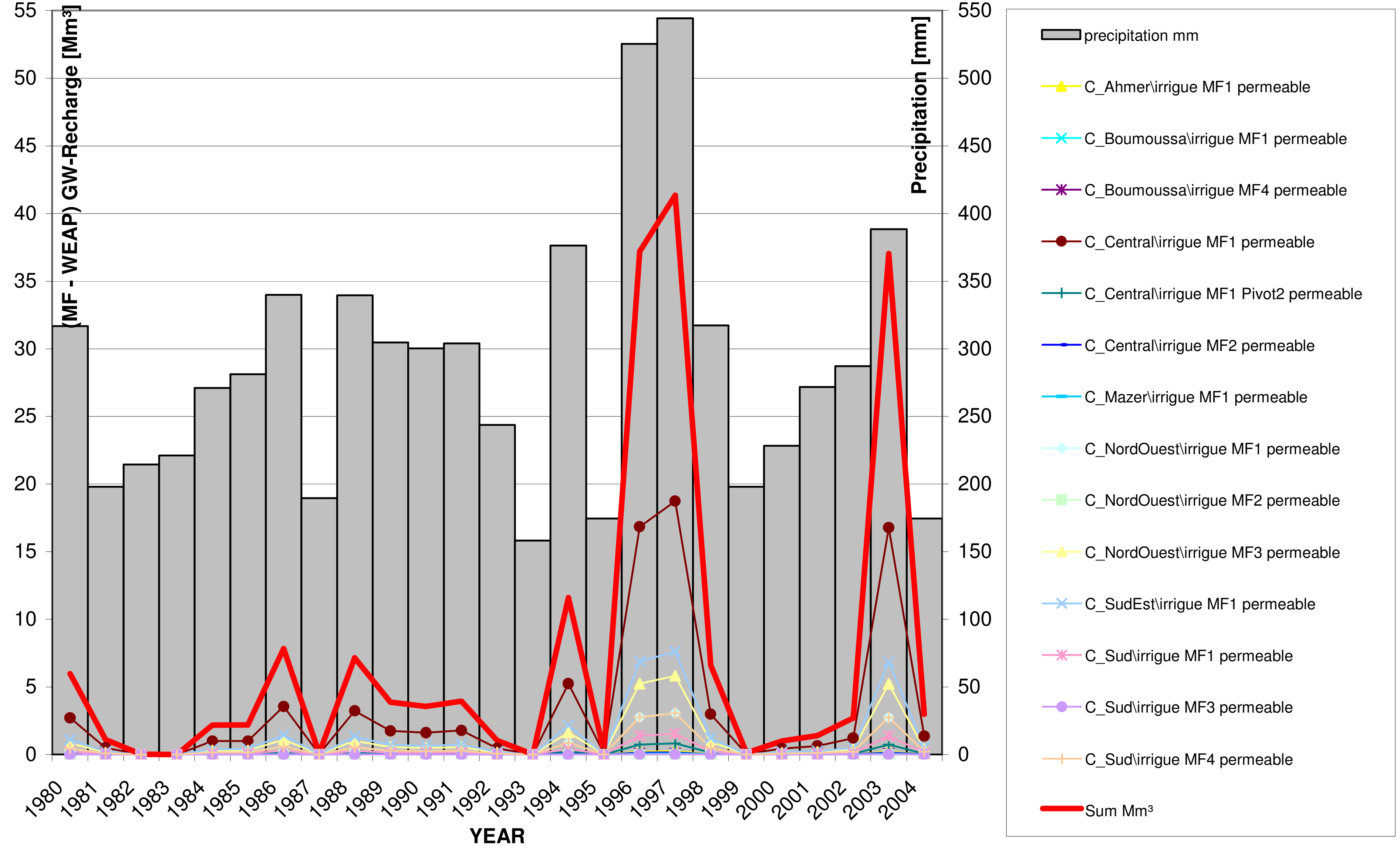


Figure 5-13: Groundwater recharge calibration in relation to precipitation.

5.4.9 Results

The reference scenario 1980 – 2004 modelled correctly the increases in domestic and irrigation demands. Irrigation (here all demand sites starting with C_) is the largest fraction of the water uses (Figure 5-14).

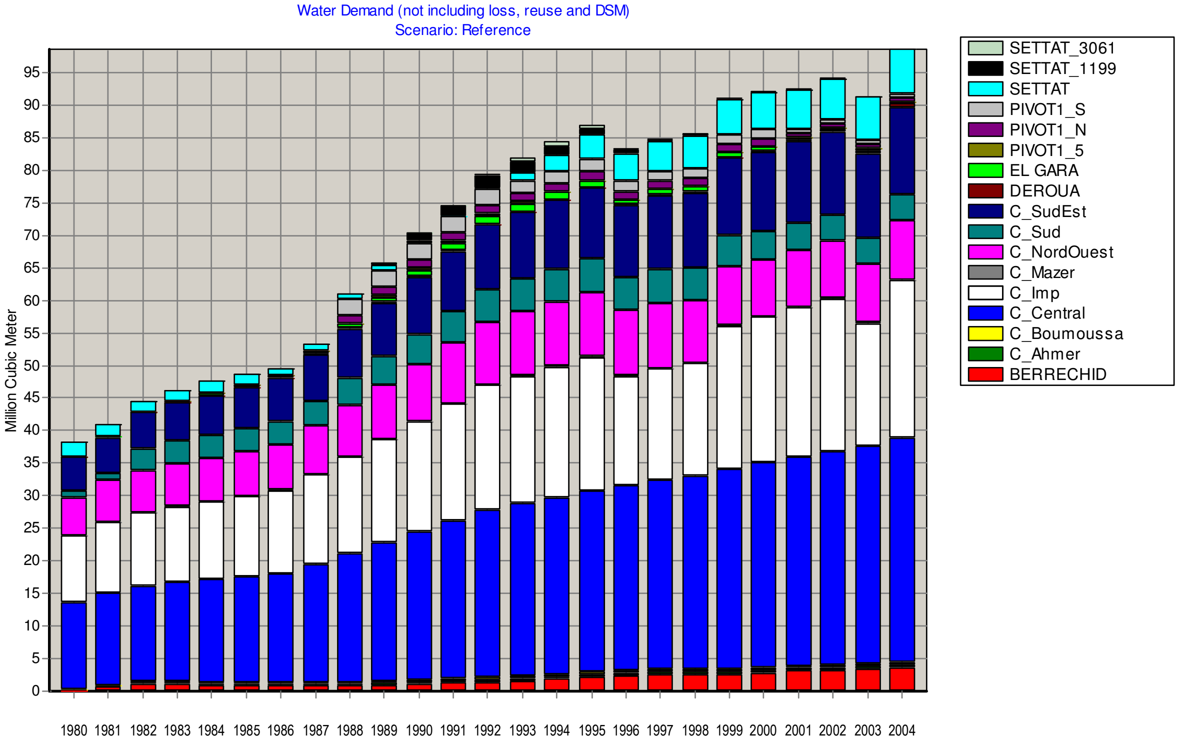
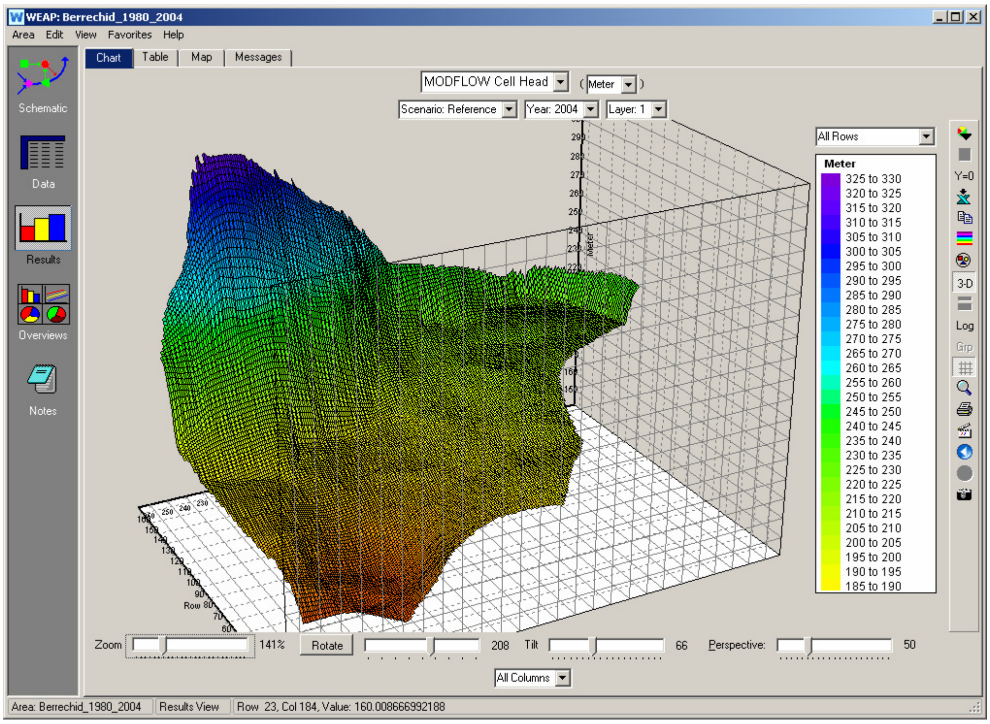


Figure 5-14: Increasing domestic and irrigation demands in the Berrechid Basin.

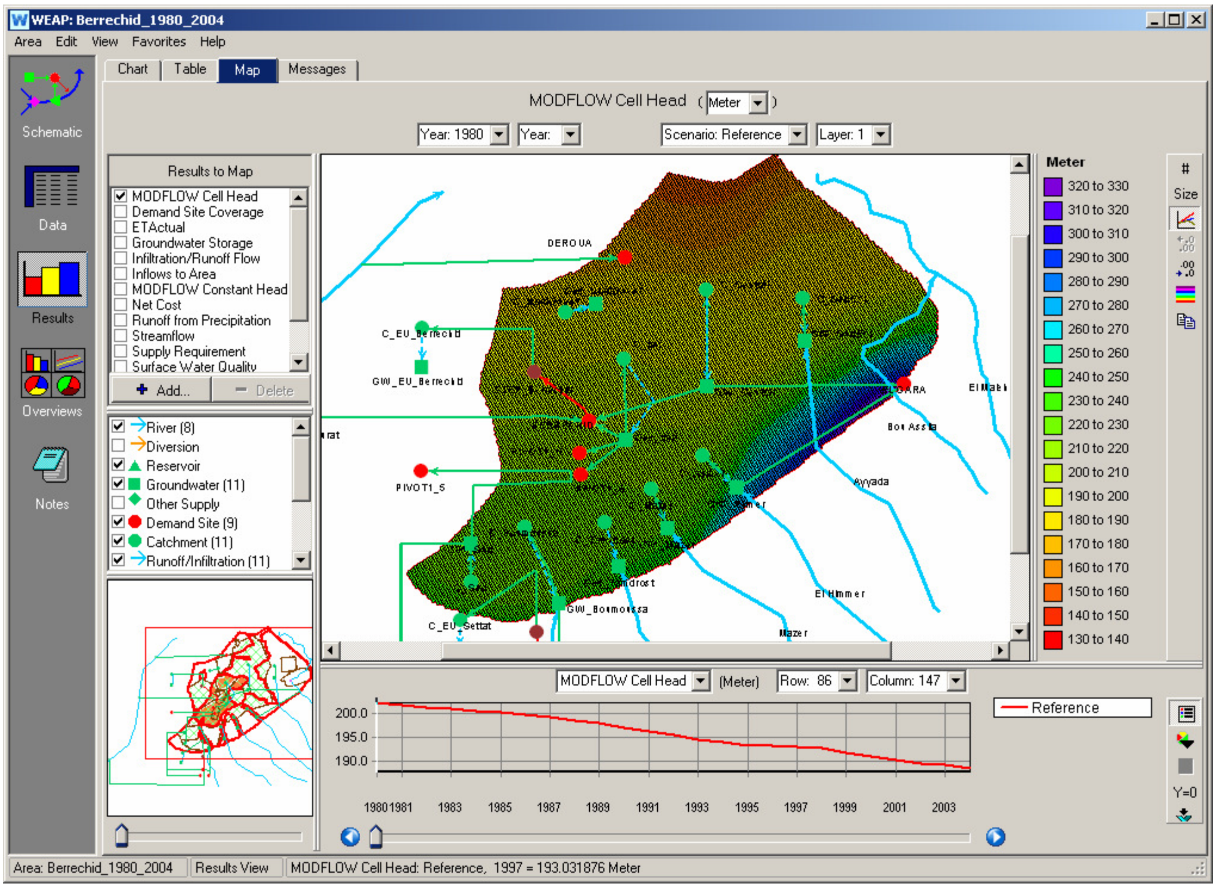


MODFLOW Cell Head (Meter)

Scenario: Reference Year: 2004 Layer: 1

Area: Berrechid_1980_2004 Results View Row 23, Col 184, Value: 160.008666992188

Figure 5-15: 3D-view of the hydraulic head in the Berrechid Basin.



WEAP: Berrechid_1980_2004

Area Edit View Favorites Help

Chart | Table | Map | Messages

MODFLOW Cell Head (Meter)

Year: 1980 | Year: | Scenario: Reference | Layer: 1

Results to Map

- ☑ MODFLOW Cell Head
- ☐ Demand Site Coverage
- ☐ ETActual
- ☐ Groundwater Storage
- ☐ Infiltration/Runoff Flow
- ☐ Inflows to Area
- ☐ MODFLOW Constant Head
- ☐ Net Cost
- ☐ Runoff from Precipitation
- ☐ Streamflow
- ☐ Supply Requirement
- ☐ Surface Water Quality

- ☑ River (8)
- ☐ Diversion
- ☑ Reservoir
- ☑ Groundwater (11)
- ☐ Other Supply
- ☑ Demand Site (9)
- ☑ Catchment (11)
- ☑ Runoff/Infiltration (11)

MODFLOW Cell Head (Meter) | Row: 86 | Column: 147

Area: Berrechid_1980_2004 | Results View | MODFLOW Cell Head: Reference, 1997 = 193.031876 Meter

Figure 5-16: Hydraulic head decline between 1980 and 2004.

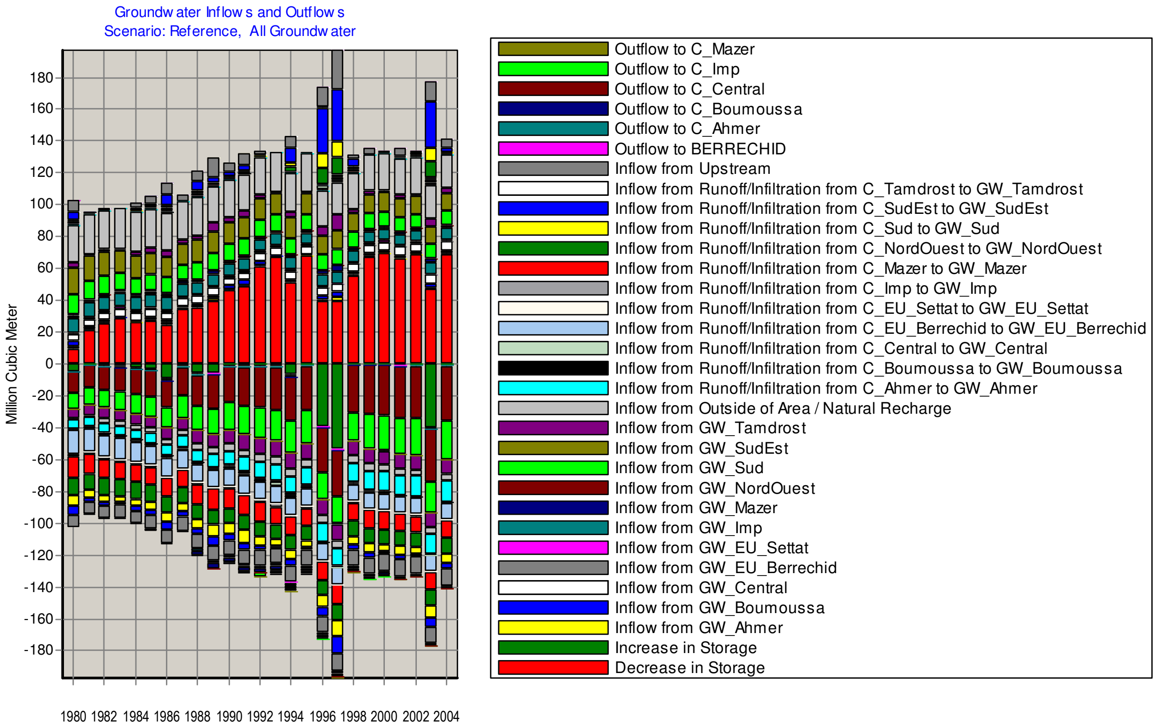


Figure 5-17: Detailed groundwater balance for the reference scenario 1980-2004.

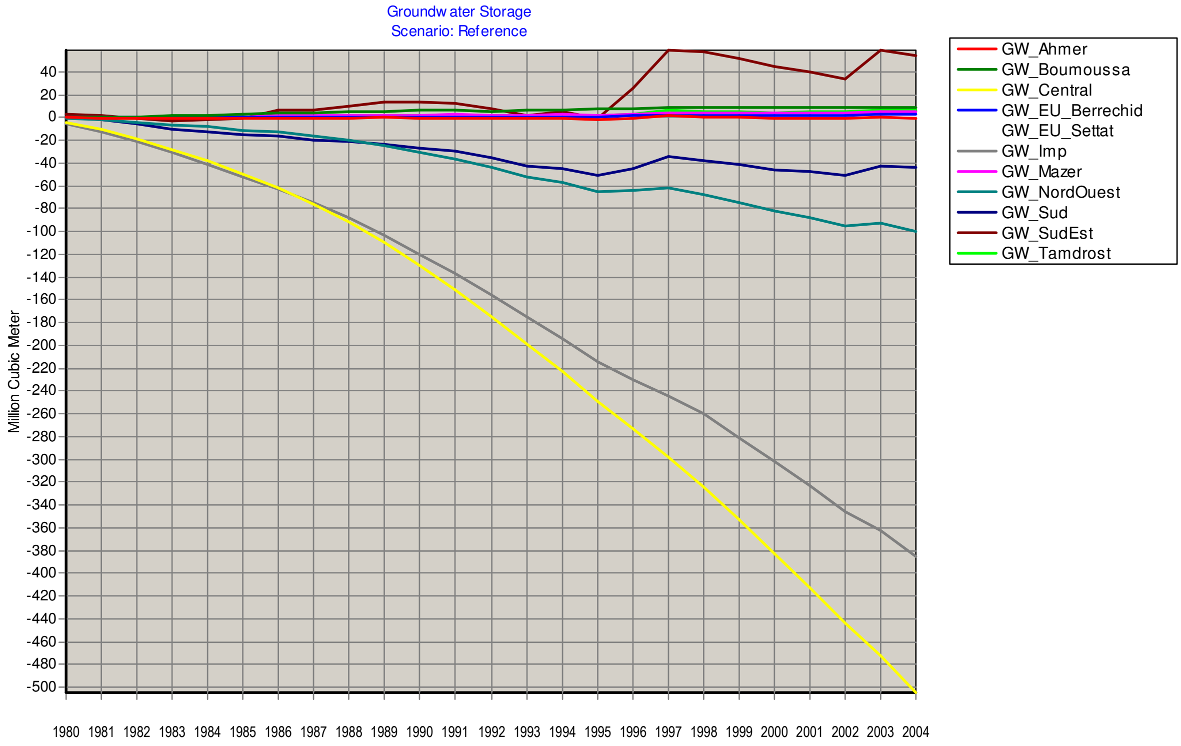


Figure 5-18: Groundwater storage in the WEAP-sub-catchments.

The increased demands have been satisfied by increased groundwater abstractions leading to a severe decrease in groundwater storage and declining water levels. Figure 5-17 shows that the main inflow or water resource fraction (positive) is coming from a decrease in storage (red), whereas a significant increase in storage occurred only in the wet years of 1996, 1997 and 2007 (dark green). Only along the south-eastern margin (GW_SudEst) of the basin storage is slightly increasing through time, whereas all the other areas show a decline in head and storage (Figure 5-15, Figure 5-16 and Figure 5-18).

5.4.10 Scenarios

A planning scenario 2005 – 2025 will be developed incorporating all the expected water use changes. As major development planning projects haven't been finalized, input data are still pending. The WEAP schematic however was designed already to modify according to future constraints:

- Increase in domestic water demand
- Start of operation of wastewater treatment plants in Settat and Berrechid
- Reuse of treated wastewater for the irrigation of the sub-catchments C_EU_Berrechid and C_EU_Settat
- Land use changes: satellite image interpretation studies showed already that there are newly irrigated areas added (land use class "irrigue sud permeable pas en MF) and previously irrigated areas are now non-irrigated (MF zone 1).

Through urbanisation previously agricultural land is now urbanised (land use class “irrigue MF… impermeable urban Berrechid…”. Similar land use changes and new water demands have to be assigned to the land use classes “urban Mediouna, urban Nouacer and urban zone industrial Rdadna permeable”.

- Flood control dams are now constructed for the major wadis coming from the south. Respective water management scenarios for the stored flood water have to be defined (artificial recharge, direct irrigation use,…).

- Measures to reduce the irrigation abstraction.

As a preliminary planning scenario set following constraints have been applied:

for all scenarios an increase in domestic abstractions:

- Berrechid: 5.5% ;
- Settat : 3% ;
- Deroua: 17% till 2010 then 3%

A) irrigation increase by 2.4% yearly

B) no change in irrigation (keeping the current status)

C) decrease of irrigation abstractions by 0.7% yearly

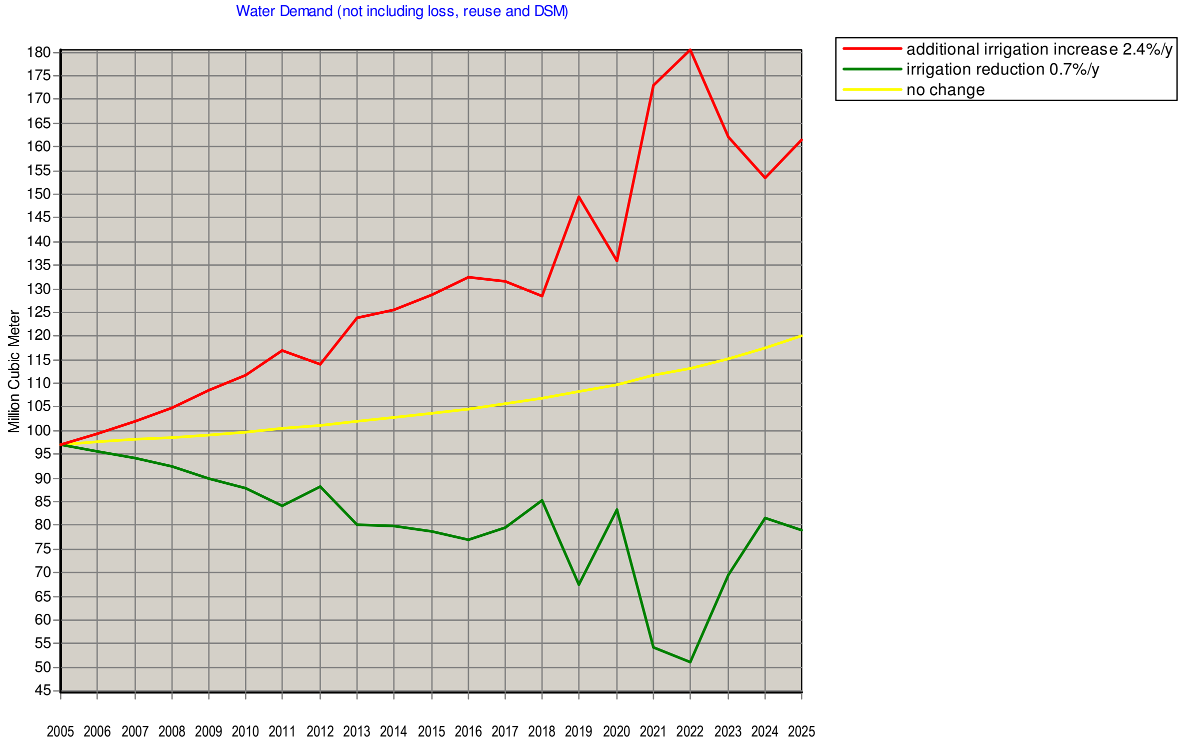
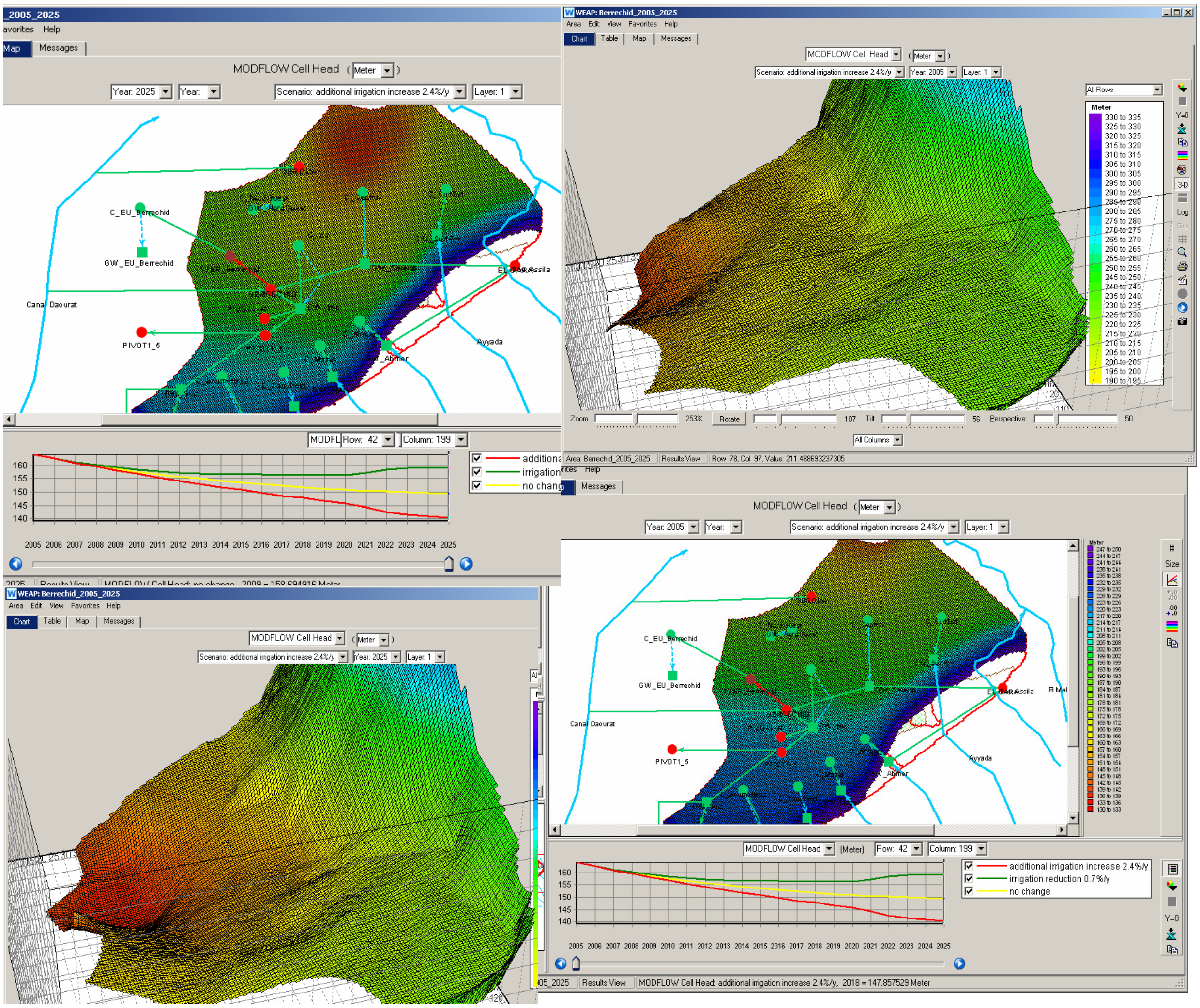


Figure 5-19: Water demand for the 3 planning scenarios A, B and C.

5.4.11 Scenario Results

The results of the preliminary planning scenario set show the impact of the respective constraints to hydraulic head and the water balance (Figure 5-20 & Figure 5-21). ABHBC (2005) calculated the total groundwater storage of the Berrechid Basin in 1980 to 1.6 billion m³. During the historic scenario 1980 - 2004 already 900 million m³ have been taken from the initial groundwater storage leaving only 700 million m³ available. Therefore the total reserve would be depleted by 2008. In Figure 5-20 the respective declines of the hydraulic heads are shown indicating a regional drawdown of about 25m in the worst scenario. These results give only a first impression of impacts on different measures. As stated above all other constraints have to be entered into the DSS in order to refine the scenarios and the respective results.

Additionally the models should be refined to a monthly time step to give more realistic results of the respective water balances and inside WEAP the soil moisture method algorithm should be applied to model the impact of the soil attributes on the water balances.



Area: Berrechid_2005_2025 | Results View | Row 78, Col 97, Value: 211.488693237305

Results View | MODFLOW Cell Head: additional irrigation increase 2.4%/y, 2018 = 147.857529 Meter

Figure 5-20: Hydraulic heads in the respective scenarios (2025 left; 2005 right)

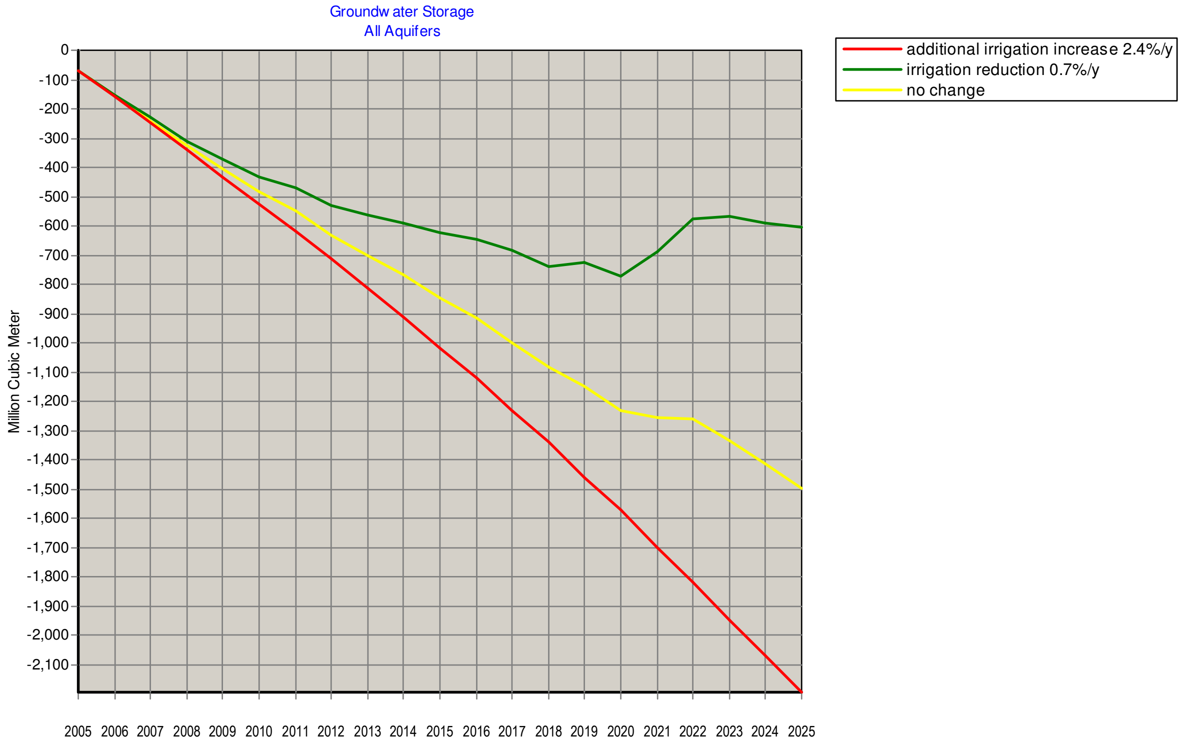


Figure 5-21: Groundwater storage for the 3 planning scenarios A, B and C.

5.4.12 DSS – Impact and Application in Institutional Planning

The DSS-results of the historic 1980-2004 and future 2005-2025 scenarios showed the current status of groundwater overuse and possible action plans for the future. The DSS can be a valuable planning tool to understand the current situation and to decide on the best planning scenario for the future to manage the groundwater resource in a sustainable way.

The DSS was introduced and applied by the ABHBC as a pilot study to test and evaluate the capabilities of it as a water management tool. With a yearly time step and the rough yearly input parameters or estimations (calibrated to match the MODFLOW inputs) the general trends could be modelled and respective results visualized. However to apply the DSS as dynamic model for current and future planning with detailed information on the MODFLOW cell/ land use class level, the time step and the input parameters have to be refined.

The ministry and also the other basin agencies have been showing large interest on the DSS-tool and in two national training workshops in February and April 2008 this tool has been introduced to additional basin agencies. There is also a large interest to use a common national method/ tool (which could be the WEAP/MODFLOW-DSS) to calculate water balances on a basin level, which will be then integrated into a national water master plan. Therefore DSS will soon prove its strengths and capabilities on basin and on national levels.

6 CONCLUSIONS AND RECOMMENDATIONS

Within the framework of a technical cooperation project a Decision Support System (DSS) for water management as a user-friendly, inexpensive, efficient and easily shareable tool has been developed incorporating MODFLOW and WEAP as modelling components.

The user can manipulate inputs and evaluate and compare results of various current as well as future scenarios in the target area, such as:

- Human activities (population growth, urbanization, domestic demands)
- Agriculture activities (land use, crop types, irrigation practices)
- Climate impacts (climate change models, regional climate cycles)
- Network characteristics (transmission link losses and limits, well field characteristics, well depths)
- Additional resources (artificial recharge, waste water reuse)

The results are visualized as graphs, maps and tables (hydraulic heads, water balances, etc.) and support the decision making process among the relevant stakeholders and decision makers.

The DSS has been successfully tested in the Zabadani Basin, Syria and the Berrechid Basin, Morocco. For historic and future scenarios realistic results (hydraulic heads, surface and groundwater balance, etc.) on MODFLOW cell, land use class, sub-catchment or catchment scale could be calculated and visualized in graphs, maps and tables.

The application in Berrechid Basin, Morocco however showed that a yearly time step is too rough for water management planning as all the seasonal effects are neglected. Therefore a monthly time step is a good trade off between detailed information and effective calculation times.

Through the project several helper tools (Google Earth image extractor, MODFLOW to Shape) have been developed and are further improved. Also a detailed Tutorial and respective sample models have been developed and will be further improved. The most recent versions are freely downloadable from www.acsad-bgr.org.

In the next project phase (08/2008 – 07/2011) the DSS will be further:

- disseminated in the Arab region (training workshops, regional workshops, on the job trainings, networking, etc.)

- technically improved (incorporation of CropWat, MODPATH and optimization options).

- applied focusing on socioeconomic aspects (case study, Damascus Water Supply and Sewerage Authority).

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