ALL_WATER_gw

Software for

Groundwater Resources Management Optimization
(GWRMO)

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CASE STUDY APPLICATION

ZEUSS KOUTINE AQUIFER
TUNISIA

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1. Introduction

The studied aquifer “Zeuss Koutine” is located in the Eastern South of Tunisia (Fig. 1).

Figure 1. Location of the study area and the Zeus Koutine aquifer.

In Eastern South of Tunisia, groundwater is the mainly resource used for drinking water to supply the cities of Medenine, Jerba, Zarzis, Benguerdene and a part of Tataouine city. The supplied population in the study area is about 500 000 in 2004, according to the last official report of the National Institute of Statistics (INS, 2004). In addition, the cities of Jerba and Zarzis represent one of the most important touristic regions of Tunisia. They represent 21 % of the national capacity (Chapoutot, 2008). The touristic capacity of Jerba is about 49 150 beds in 2009 (www.wikipedia.com). The touristic capacity of Zarzis is estimated to 16 000 in the same year. The agricultural activity still based on not irrigated olive trees. Starting from 1990, irrigated areas are created around wells drilled in the Zeuss Koutine aquifer. The total irrigated surface is estimated to 530 ha in 2010. The expected higher evolution of the population in the region and the important socio-economic development, especially the tourism, will apply a large pressure on the Zeuss Koutine groundwater in the future. The sea water intrusion constitutes other problem facing the managers of the water resources in the studied region.

Decision makers and managers of the Zeuss Koutine aquifer are persuaded by the need to protect the only natural resource of water in the region. Two main tasks have been started to improve the water storage in the aquifer and to reduce the water abstraction. The first one is a set of soil and water harvesting works done between 1980 and 1990 to improve rainwater infiltration in the river basins of the aquifer. Next photos are examples of soil and water conservation management performed in the region from the top of the mountains (1), in the river basin (2 and 3), to develop rainfall agriculture under very hard conditions, and in the river (4 and 5) to increase the water infiltration in case of floods:

(1)

(2)

(3)

(4)

(5)

Photos 1, 2, 3, 4, 5. Example of soil and water conservation managements realised in the Zeuss Koutine watershed.

The second task is the build of two desalinization plants in Zarzis and Jerba cities, in 1999 and 2000 respectively, to supply them by drinking water.

The strategic importance of the Zeuss Koutine aquifer has encouraged the development of research and development activities to preserve the resource by improving its management.

Most of the previous works leads to the development of annual MODFLOW models. The last one is developed by INAT (Hadded, 2008). Based on this model, the collaboration between INAT, BGR, ACSAD and GTZ, by training and technical workshops, permitted the development of a yearly management model for the Zeuss Koutine aquifer, using the WEAP software. It is now improved to a monthly model for the period from 1982 to 2015. The precious contribution of the regional administrations of Agriculture and the Drinking Water Utility of Medenine governorate has been fundamental to understand and to model the water resources and the hydraulic system as close as possible to the reality.

In parallel, the optimization tool ***ALL_WATER_gw*** has been designed to communicate with WEAP and MODFLOW to collect the data of the hydraulic system and the demand sites (Nouiri, 2011). ***ALL_WATER_gw*** considers four objectives in the problem formulation: i) the demand satisfaction, ii) the minimization of the maximal drawdown in aquifer water table, iii) the minimization of the unit cost of water supply, over a planning period and iv) the quality (salinity) satisfaction. Wells maximal pumping rate and drawdown as well as pipe transfer capacities are also taken in consideration in the proposed problem formulation, as hydraulic constraints. The user guide provides more details about the problem formulation and the functionalities of the software.

The present report describes the development of the Zeuss Koutine WEAP-MODFLOW DSS and the use of the ***ALL_WATER_gw*** software to optimize its management between 2010 and 2015. In section 2 it is presented monthly time series (1997-2010) of the water pumped from the Zeuss Koutine aquifer and supplied to the main cities. It is also described the hydraulic system used to supply drinking water. In addition, a history of the groundwater management is presented in this section. Section 3 is brief presentation of the MODFLOW model. The section 4 is reserved for the WEAP-MODFLOW DSS presentation. In the section 5 the main steps of the application of ***ALL_WATER_gw*** for the Zeuss Koutine case study and the optimization results are presented.

2. Case study presentation

2.1. Zeuss Koutine water supply between 1997 and 2010

The water supplied by the National Drinking Water Utility (NDWU) to the main cities is measured using flow meters. Last years, a real time telemetry system has been installed in the hydraulic network. It allows the real time collection of all measured parameters in the central office at Medenine. The NDWU data are presented as monthly reports. Next figure details the monthly water supplied to the cities of Medenine, Benguerdene, Zarzis (representing the complex Jerba-Zarzis). The rural agglomerations and industries are grouped and called in the next “Other”.

The average yearly water supply for the period 1997-2010 is about 13 Millions m^3. Jerba-Zarzis and Medenine cities require averages about 41 % and 36 % of the total water supplied, respectively. Benguerdene and Other have been supplied by a yearly average about 17 % and 6 %, respectively.

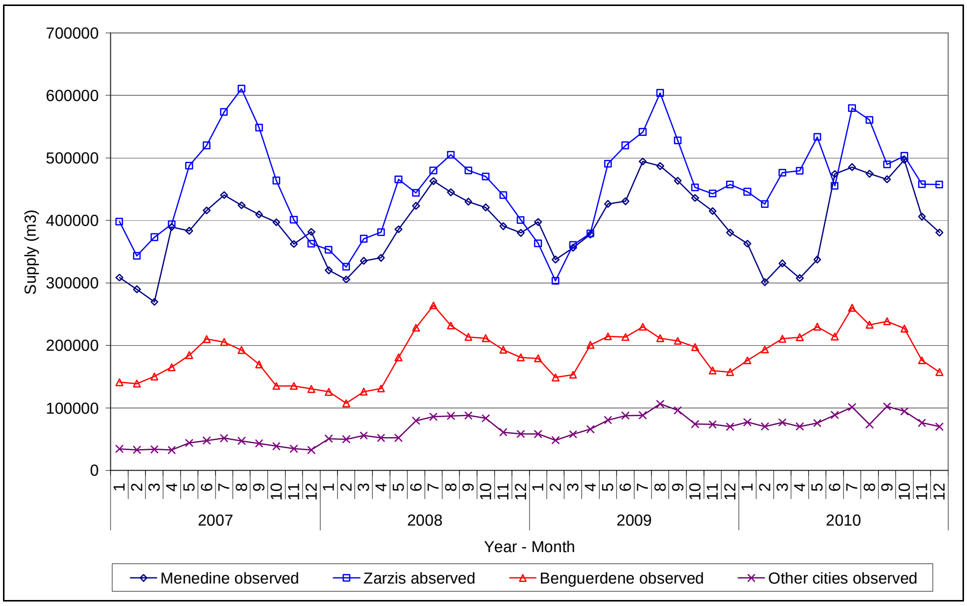


Figure 2. Monthly water supply observed in the cities Medenine, Jerba-Zarzis, Benguerdene and Other between 1997 and 2010.

The graph above shows that while Medenine, Benguerdene and Othe are characterized by a regular monthly variation of water supply, Jerba-Zarzis city presents a particular one. The amplitude between the lowest and the highest values are important. This can be explained by the high and the non regular touristic activity in the summer in addition to the climatic effect on domestic water use.

Next figure shows the modulation of the average monthly water supply to the main cities:

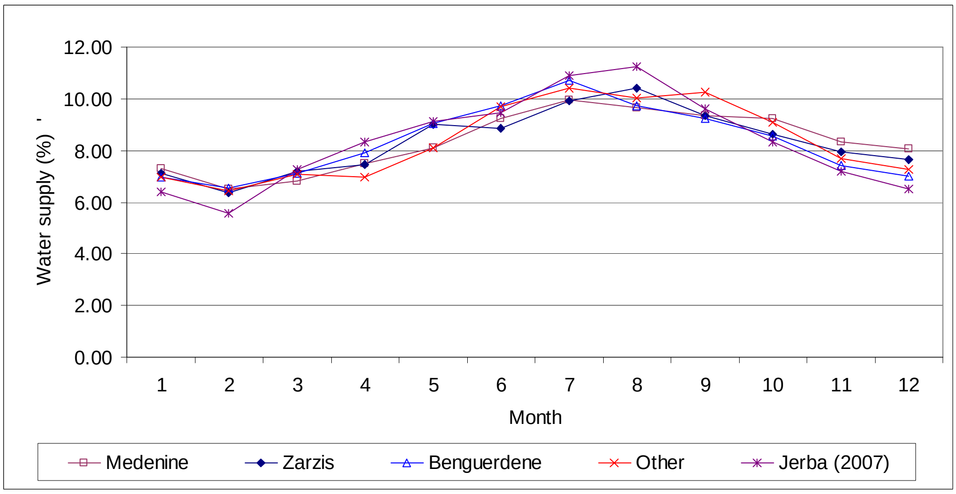


Figure 3. Modulation of the average monthly water supply to the main cities using the Zeuss Koutine groundwater.

The graph above demonstrates that the average monthly modulation of the water supply to the main cities using the Zeuss Koutine groundwater is almost the same. The peak month of supply is July for the domestic cities Medenine, Benguerdene and Other. August is the peak month for Jerba and Zarzis, characterized by high touristic activities. These particular modulations will be used in WEAP to define the monthly water demand variation.

2.2. General description of the hydraulic network:

To reach the end user, water is pumped from wells of the Zeuss Koutine aquifer. Drinking water is pumped first in small tanks if there is a local need (photo 6).

Photo 6. Typical water production schematic: Well and elevated tank.

After satisfying the near houses, water is pumped using booster stations (Photo 7) to the most important tank in the region: Tajra. The storage capacity of Tajra tank is 7500 m^3. (5000 m^3 + 2500 m^3). Its elevation is 149 m.

Photo 7. Pumping booster station.

Photo 8. Example of drinking water tank.

From the main tank of Tejra, water is supplied to the cities of Medenine, Tataouine, Jarzis, Jerba and Benguerdene. Seen the spatial variability of the water salinity, the manager use the 2500 m^3 tank to collect water of good quality (salinity less than 2 g/l), which is the case for the wells Ksar Chrif. This water is usually reserved to supply Medenine, Other and part of Tataouine cities by gravity. To satisfy the quantity and the quality requirement of the previous cited cities, the Tejra 2500 m^3 tank is supplied by water pumped from the "Bir Mgarine" aquifer. This aquifer is characterized by good water quality (less than 1.5 g/l).

The salty water, pumped from all the other wells, is collected in the 5000 m^3 tank. 40 km of pipes are used to connect the most distant wells (Hir Fredj 1 and 2) to the Tajra tank. This water supplies Jerba, Zarzis and part of Benguerdene by gravity. The hydraulic network from Tejra tank to the supplied cities is subject of the pressure reduction in the "Lassifer" site, at the elevation of 102 m. At the same site, water is collected which comes from the "Lassifer" and "Hessi Abdelmelek 1" wells. Last years, pumping booster stations are used in the supply network to increase the flow to face the increase of the water demand.

For irrigation, water is usually pumped and collected in small elevated tank, as presented in photo 6. Those users (farmers) can be supplied by gravity.

To overcome the water quantity and salinity problems, in Jerba, Zarzis and Benguerdene cities, other water resources are used in each of the concerned cities. Indeed, Benguerdene is also supplied from the "Maouna" groundwater. In Zarzis, a desalinization plant is built in 1999. This station produces 15 000 m^3 per day with a salinity of 0.5 g/l. The treatment process requires 1.2 KWh/m^3 of energy. The same solution has been adopted in Jerba. In 2000 identical desalinization plants have been built and an extension is performed in 2008 with a capacity of 5 000 m^3. In addition, it is used the "Mareth" well, located in the North of Zeuss Koutine aquifer to supply Lassifer site and then the cities of Jerba, Zarzis and Benguerdene. The contribution of this well is estimated by the manager to be less than 5 %. It will not be considered in the present study.

The next figure presents the hydraulic system used for groundwater management in the studied region.

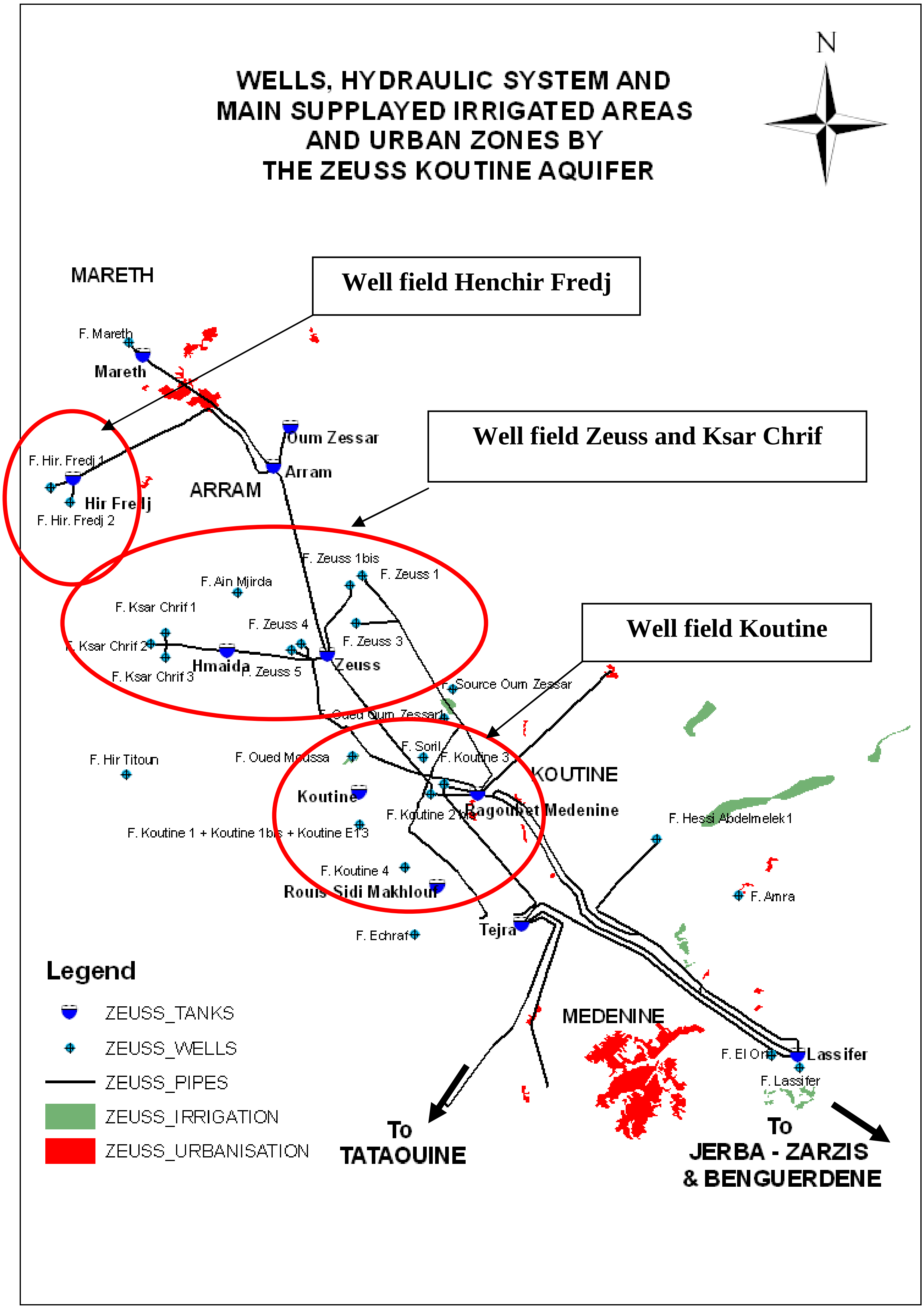


Figure 4. Hydraulic system to supply cities by drinking water from Zeuss Koutine aquifer.

2.3. Analyses of the historic management of water abstraction

2.3.1 Groundwater abstraction

The collected data of the abstractions in the period 2006 – 2009 demonstrate that the aquifer Zeuss Koutine supplied the region by an average daily volume of 53 000 m^3/day. The minimal and the maximal observed values, in the same period, are 32 000 and 67 500 m^3/day respectively. The next figure presents the pumping activities of the most important wells (drinking water) used to manage the Zeuss Koutine aquifer from 2006 to 2009.

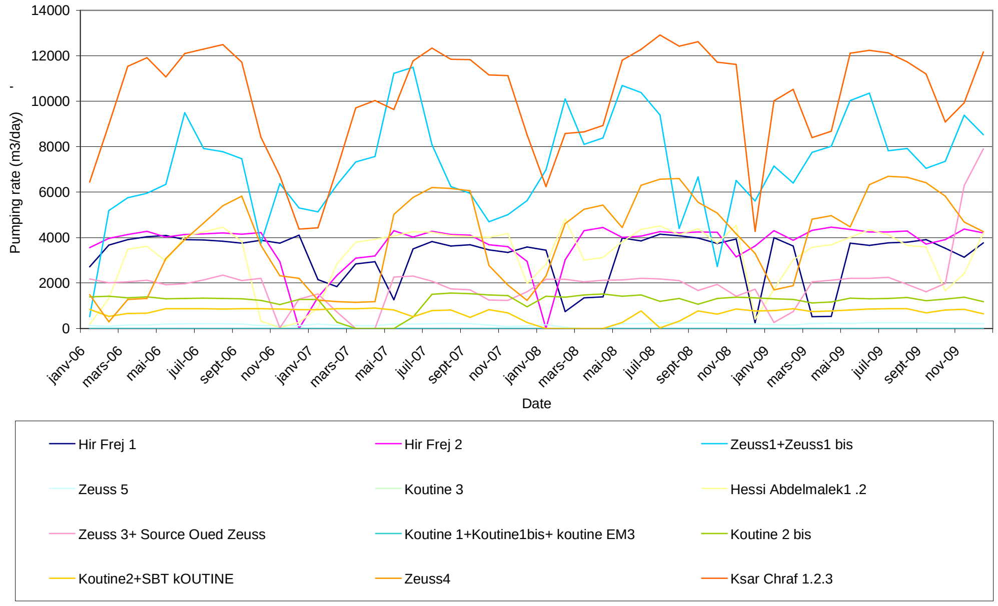


Figure 5. Pumping activities of the most important wells in the Zeuss Koutine aquifer.

From the figure 4 and the previous graph it is possible to identify three main well fields used to supply the region by drinking water:

- The well field “ZEUSS” is formed by the wells: Zeuss 1, Zeuss 1bis, Zeuss 3, 4, 5 and Ksar Cherif 1, 2 and 3. This well field has been characterized by an average daily abstraction of 5900 m^3/day during the period 2006 – 2009. The minimal and the maximal daily abstractions, during the same period are 16 416 and 25 910 m^3/day respectively. The ZEUSS well field has contributed by an average of 31 % in the total abstraction (drinking and irrigation) from the aquifer.
- The well field “KOUTINE” is formed by the wells Koutine 1, 1bis, 2, 3, 4 and 5. The average, the minimal and the maximal daily abstractions from this field are 1868, 815 and 2359 m^3/day respectively, during the same period. The KOUTINE well field has contributed by an average of 4 % in the total abstraction from the studied aquifer.
- The well field “HIR_FREJ” is formed by the two wells: Hir Fredj 1 and 2. The average, the minimal and the maximal daily abstractions from this field are 6935, 3438 and 8399 m^3/day respectively, during the same period. This well field has contributed by an average of 13 % in the total abstraction from the studied aquifer.

The next figure shows the monthly modulation of the abstractions for the previous defined well fields during the period 2006 – 2009. It is possible to underline that in addition to its higher contribution in the demand satisfaction, the ZEUSS well field is characterized by an increase of its use. The two other defined well fields seem to have regular use along the analysis period.

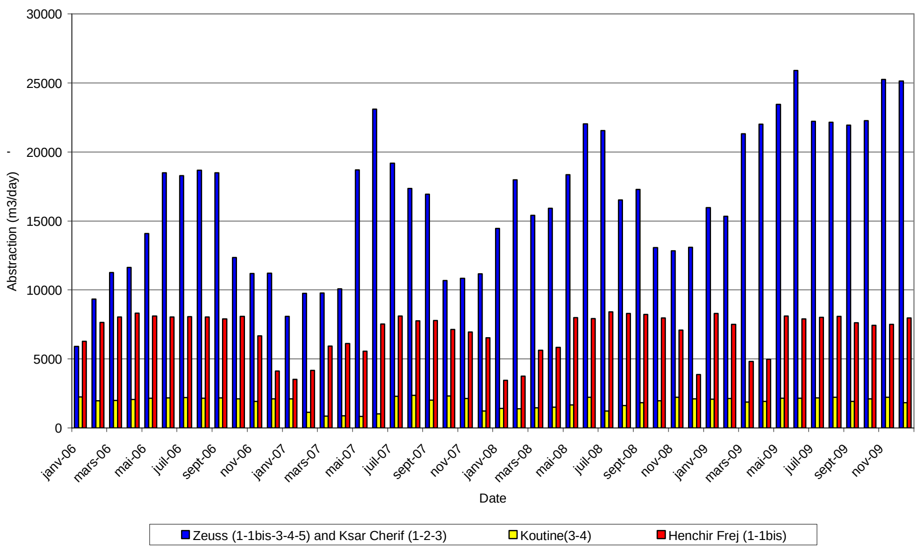


Figure 6. Pumping activities of the three wells fields of the Zeuss Koutine aquifer.

Thus, it is possible to conclude that the well fields “ZEUSS” and “HIR_FREJ” are important. They contribute by an average of 44 % of the water demand. Their use has to be controlled to avoid important drawdown impact.

2.3.2 Energy consumption

One of the most important problems to manage in the study area is the energy consumption. As explained before, a large part of the used water has to be pumped at least two times to reach the storage tanks before its supply to the end users. This paragraph summarizes the energy consumed in the different components of the hydraulic system: wells, pumping booster stations and desalinization plants. Next graph presents the average consumption of energy for wells in the Zeuss Koutine aquifer:

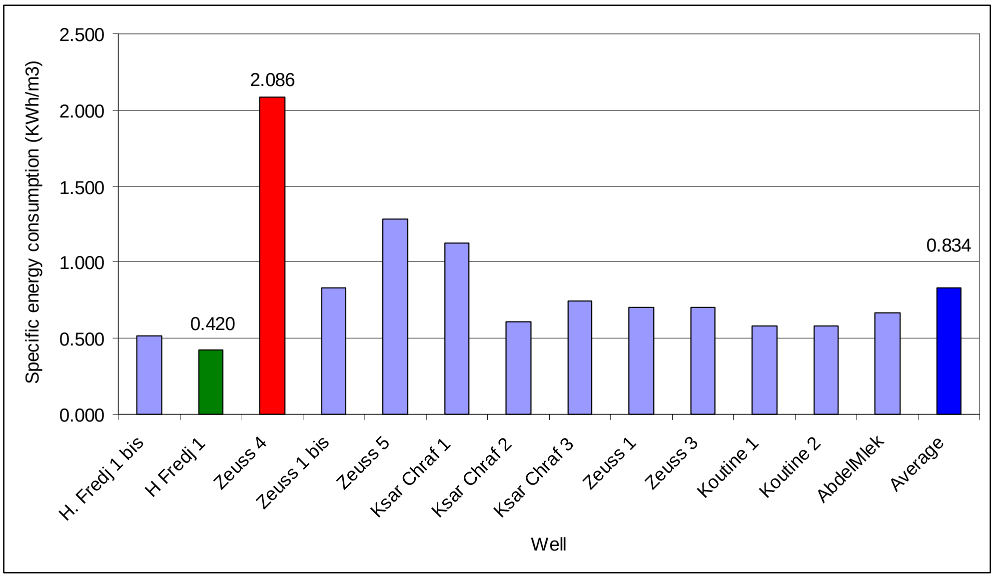


Figure 7. Average energy consumption by well in the Zeuss Koutine aquifer.

For the whole Zeuss Koutine aquifer, the average energy consumption is estimated to 0.834 KWh/m^3. The well “Zeuss 4” is the biggest consumer of energy. The well “Hir Fredj” is characterized by the lowest specific energy consumption.

The “Maouna” aquifer supplying Benguerdene city is managed through four wells. Next figure summarize their average specific energy consumption:

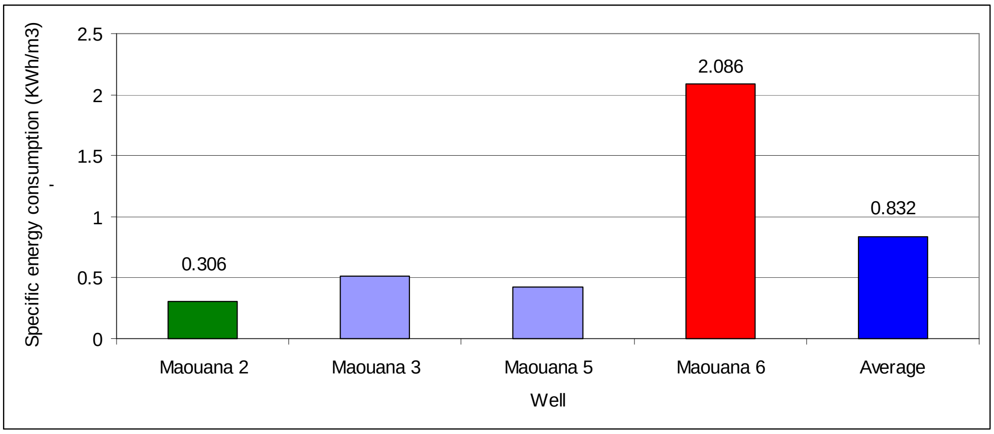


Figure 8. Average energy consumption by well in the Maouna aquifer.

While the average specific consumption of energy is almost the same as for the “Zeuss Koutine” aquifer (0.832 KWh/m^3), three wells pumping in the “Maouna” aquifer are characterized by low energy consumption. The lowest value is 0.306 KWh/m^3. Only “Maouna 6” well presents abnormal value.

The average specific consumption of energy of the “Bir Mgarine” aquifer, supplying Medenine city, is estimated to 0.538 KWh/m^3. The maximal value (0.967 KWh/m^3) still acceptable if compared to the other aquifers average values. The detail by well is presented in the next graph:

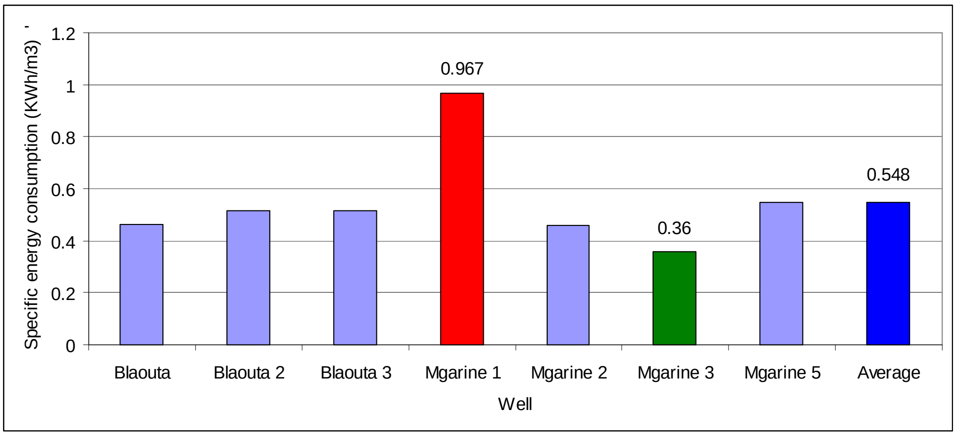


Figure 9. Average energy consumption by well in the Bir Mgarine aquifer.

The two non conventional water sources in the region (desalinization plants) consume an average of 1.2 KWh to desalinize one m^3 of water. The projected sea water desalinization plant in Jerba will consume an average of 2.5 KWh/m^3.

In addition to the energy consumed to abstract water from the aquifers, booster stations are used to transfer water from the production sites to the end users locations. Next graph summarize the average specific energy consumed by booster stations:

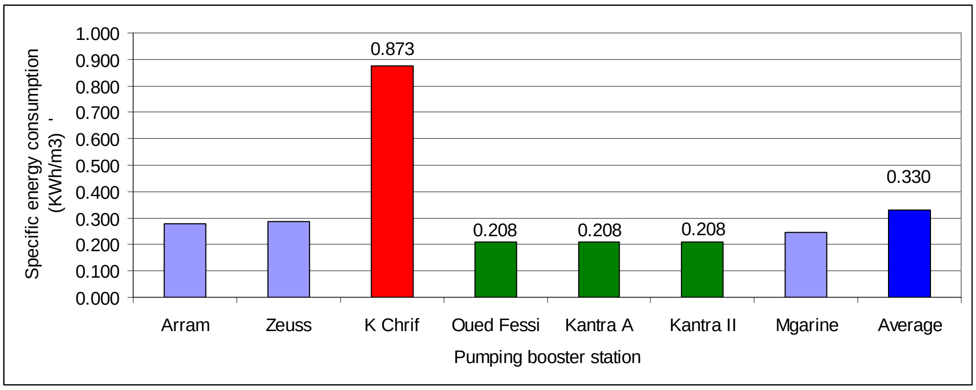


Figure 10. Average energy consumption by pumping booster stations.

Most of the pumping booster stations consume less than the average value of 0.330 KWh/m^3. Only the booster station “Ksar Chrif”, supplying Medenine city, presents higher energy consumption.

2.4. Conceptual model of the hydraulic system in the Eastern South of Tunisia

In order to elaborate the WEAP model of the hydraulic system in the Eastern South of Tunisia, it is proposed the next simple schematic:

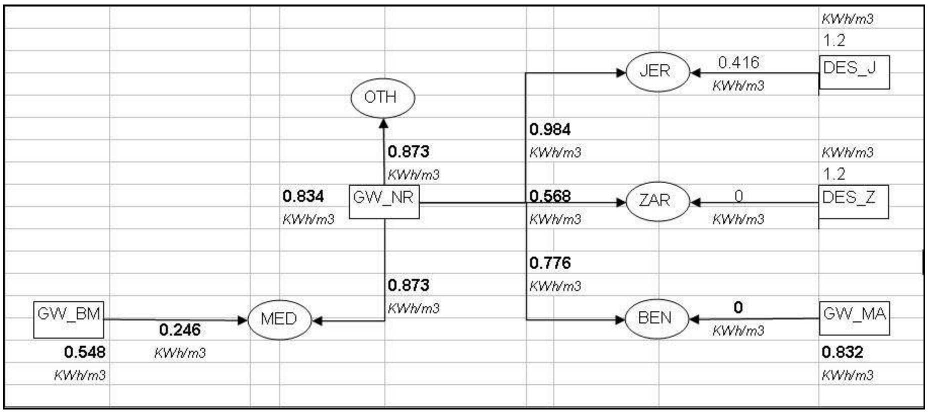


Figure 11. Simplified schematic of the hydraulic system of the Eastern South of Tunisia.

Where:

MED: Medenine city,
OTH: Other cities,
JER : Jerba city,
ZAR: Zarzis city,
BEN: Benguerdene city,

GW_BM: Groundwater Bir Mgarine
GW_NR: Groundwater natural Recharge,
GW_M: Groundwater Maouna,
DES_J: Desalinization plant of Jerba,
DES_Z: Desalinization plants of Zarzis,

In the future, the NDWU managers have the plan to install a sea water desalinization plant in Jerba, called in the next: “Sea_Water_Desalinization”. The projected station will supply Jerba and Zarzis cities. In addition, it is planned the installation of a desalinization plant in Benguerdene, called in next “Desalinization_Benguerdene”. Thus, the update of the schematic of figure 11 by the future water projects leads to the next points:

- Jerba city will be supplied by four sources: Zeuss Koutine, two salty desalinization plants and the sea desalinization plants,
- Zarzis city will be supplied by three sources: Zeuss Koutine, the salty and the sea desalinization plants,

- Benguerdene will be supplied by three sources: Zeuss Koutine, Maouna and the salty desalinization plant.
- Medenine still supplied by the two sources as shown in the figure 11.

The maximum volume flow of the linkage between demand sites and the water sources are restricted by the pipe and the booster station. Next table summarizes the linkage "Demand sites" – "Water sources":

Table 1. Maximum flows of the linkages "Demand sites" – "Water sources"

Water source	**Demand site**	**Restriction by the pipe**		**Restriction by booster station**	**Maximum Flow (m^3/s)**
		Pipe diameter (mm)	**Maximum flow (m^3/s) (v=1.5 m/s)**	**Maximum flow (m^3/s)**	
Zeuss Koutine	Medenine	800	0.754	0.42	0.420
Bir Mgarine	Medenine	*Fixed flow*			0.050
Zeuss Koutine	Benguerdene	300	0.294	0.06	0.060
Maouna	Benguerdene	300	0.106		0.106
Desalinization_Benguerdene	Benguerdene	*Desalinization plant capacity*			0.023
Zeuss Koutine	Zarzis	800	0.754		0.754
Desalinization_Zarzis	Zarzis	*Desalinization plant capacity*			0.174
Sea_Water_Desalinization	Zarzis	*Desalinization plant capacity*			0.579
Zeuss Koutine	Jerba	600	0.424		0.424
Desalinization_Jerba	Jerba	*Desalinization plant capacity*			0.174
Desalinization_Jerba_2	Jerba	*Desalinization plant capacity*			0.058
Sea_Water_Desalinization	Jerba	*Desalinization plant capacity*			0.579
Zeuss Koutine	Other	*Not limited*			1.000
Zeuss Koutine	Tataouine	*Fixed flow*			0.060

3. MODFLOW model for the Zeuss Koutine aquifer

3.1 Introduction

The Zeuss Koutine aquifer is the main water resource of the cities of Medenine, Jerba, Zarzis, Benguerdene and Tataouine, in the Southeast of Tunisia. Seen its strategic importance for the region, many technical and scientific studies have been done to understand the behaviour of this hydraulic system and its interaction with the climate conditions and the Human managements.

This presentation of the MODFLOW model of "Zeuss Koutine" aquifer is based on the work done by Hadded (2008) and improved in the framework of the collaboration between INAT, BGR, GIZ, ACSAD and the regional administration of agriculture of Medenine gouvernorate.

This section describes first the study area and the physical model. In second step, the hydro geological model is presented.

3.2 Study area and physical model descriptions

3.2.1 Location, hydrology, rivers network and geology

The "Zeuss Koutine" aquifer is located in Easter South of Tunisia (Figure 1). It belongs to the coastal plain of the Jeffara and located approximately between the latitudes 33°20' N and 33°

40' N and the longitudes 10° 10' E and 10°30' E. The area of the aquifer is estimated to 1305 Km^2, shared by four main river basins: “Oued Zigzaou”, “Oued Zeuss”, “Oued Oum Zessar”, and “Oued Sidi Makhlouf”.

The studied region is characterized by an arid climate. The annual average rainfall does not exceed 200 mm, with height spatial and temporal variability. The average temperature varies between a minimum of 12.5°C, in January, and 30.4°C, in August. The region is also subject to East/North East and South winds, cold and humid in winter and hot and dry in summer. The average monthly values of evaporation measured in Medenine climatic station varies between 98.6 mm, in January, and 234.2 mm, in July (Essid, 2005). So, theses climatic conditions lead to negative water balance around the year, even for the wet season.

Five rivers drain the surface rainwater from the upper zones (Dahar) to the sea or to Sebkhas. From the North to the South, next are the existing rivers: “Oued Zigzaou”, “Oued Zeuss”, “Oued Koutine-Oum Zessar”, “Oued Sidi Makhlouf” and “Oued Morra” (Figure 12). Next table summarize the principal river basins proprieties (IRA-IRD, 2003):

Table 2. Principal proprieties of the river basins of the Zeuss Koutine aquifer.

Parameter	Oued Zeuss	Oued Oum Zesser	Oued Zigzaou	Oued Morra	Oued Sidi Makhlouh
Area (Km^2)	200	387	261	209	134
Average slope (m/Km)	10.30	9.38	14.8	13.31	3.25

The volume of surface water runoff (V in m^3) in a river basin is estimated using the next empirical formulas (Fersi, 1997):

$$V = 16.39 \times P \times (I)^{1/2} \times S \qquad (1)$$

Where “P” is the rainfall (mm), “I” is the average slope of the river basin (m/Km) and “S” is the area of the river basin (Km^2).

For a yearly average rainfall of 180 mm, the total volume of surface runoff on the Zeuss Koutine river basins is estimated to 10.23 Millions m^3.

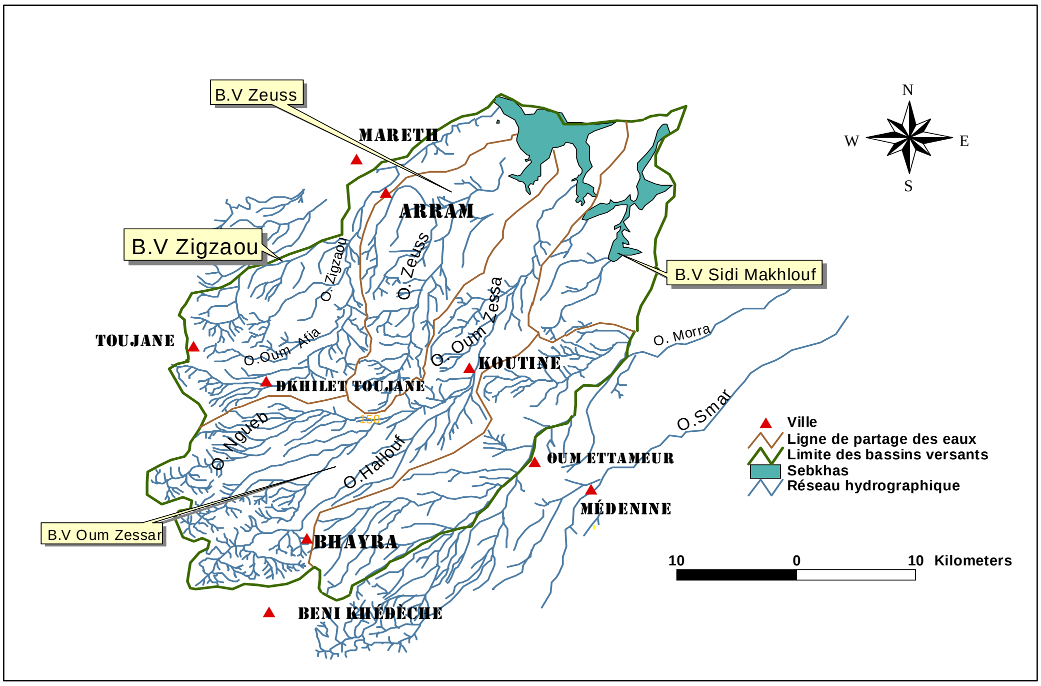


Figure 12. River basins of the Zeuss Koutine aquifer.

The geological formations are of alternating continental and marine origin. The oldest submerging layers are represented by a marine superior Permian, and the most recent ones are of the recent Quaternary. Between these two formations appear strata of different age which are generally declining in northward direction. Next figure present the geological map of the Zeuss Koutine aquifer:

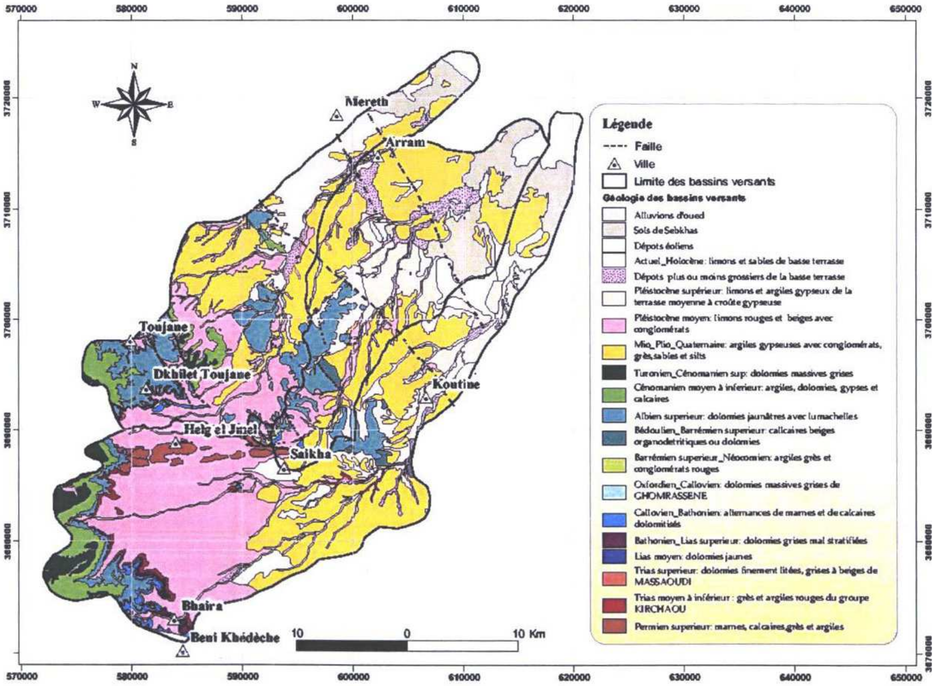


Figure 13. Geological map of the Zeuss Koutine aquifer (Essid, 2005).

The Eastern South of Tunisia is characterized by three tectonic units: the Permien Monoclinal of Djebel Tebaga, the Dhar Monoclinal and the Jeffara plain. Eight faults are visible in this tectonic. Most of them have North-West/South-East orientation, as shown by the red line in the next figure.

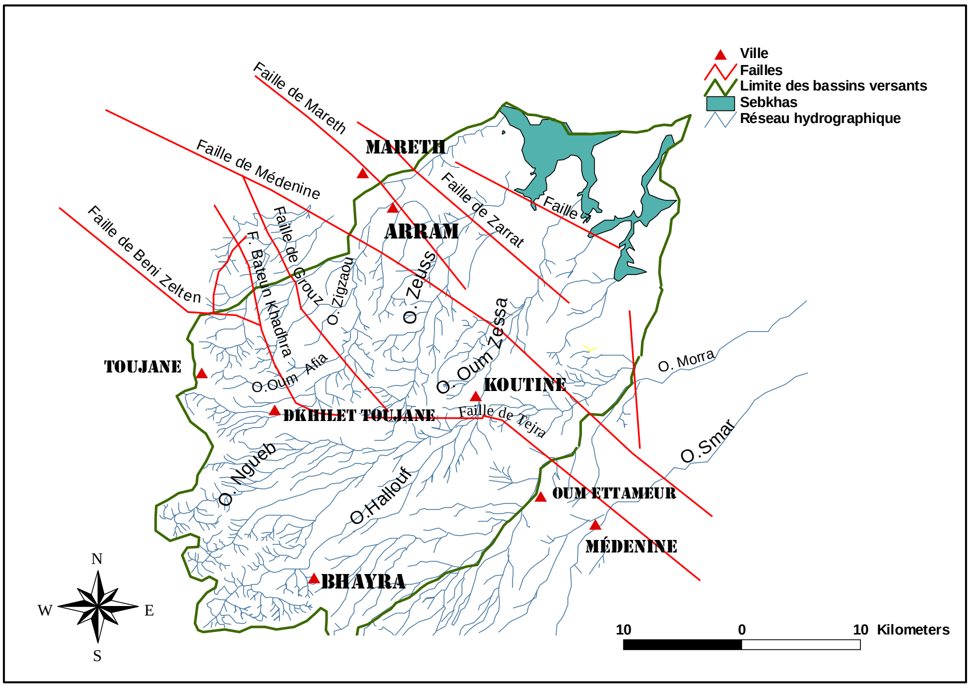


Figure 14. Faults in the Zeuss Koutine river basins (Hadded, 2008).

3.2.2 Hydrogeology

The Zeuss Koutine aquifer is bounded on the North by the aquifer Gabes South, on the Northwest by Jebels Matmata, on the South by the sandstone aquifer in the Triassic and on East by adjacent watersheds. It includes all the layers flowing in the Jurassic carbonate formations of the Albo-Aptian, Turonian and lower Senonian and constitutes a hydrogeological multilayer unit where the relays are possible either through faults or by vertical drainage.

The Zeuss Koutine aquifer consists of four carbonate formations that arise from the oldest to the most recent as follows: “Jurassic”, “Albo-Aptien”, “Turonien”, “Inferior Senonien”.

The Jurassic aquifer is a set of dolomite and limestone. It is fed by rainwater infiltration and the water discharge from the aquifer of sandstone of the lower Triassic in the Southern region on the front Koutine-Tejera-Medenine. The general flow of the Jurassic aquifer is done from the South-West to North-East along the main axis Chrarif Ksar-Zeuss. The Albo-Aptian aquifer is encountered locally. It receives much of its food by infiltration of rainwater. The flow is from South to North. The Turonian is captured mainly at Oued Zeuss by Zeuss 1 bis well. This aquifer is influenced by food from the deep Jurassic in the West. The two lower Senonian limestone units are the main aquifers captured in the collapsed part of the Jeffara at Oued Zeuss. These limestones constitute good aquifers. Next figure shows the boundaries of the Zeuss Koutine aquifer (Hadded, 2008):

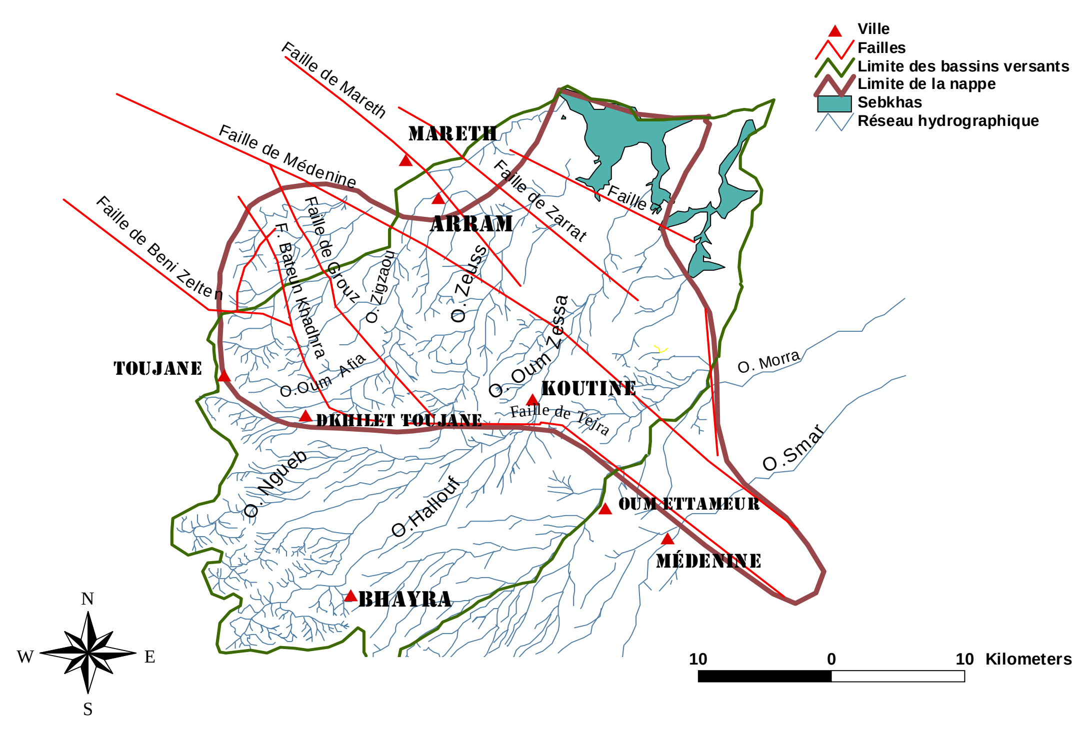


Figure 15. Boundaries of the Zeuss Koutine aquifer (Hadded, 2008).

3.3 Hydro geological model

The Jurassic limestone layer is in contact with other bands across the network of faults that characterizes the region. This allowed considering groundwater of Zeuss Koutine as a single unconfined aquifer. The elevation of the top is considered to be represented by the natural topography of the land and the bottom depth varies between 170 and 680 m. It increases while moving toward the Northeast, especially after the collapse of Medenine flaw (Hadded, 2008).

MODFLOW 2000 (Harbaugh, 2005) is used to build the hydrodynamic model of the Zeuss Koutine aquifer. The model domain covers an area of approximately 783 km^2. It enrolled in a matrix of 57 columns and 48 rows. There is 2736 square mesh and regular with one kilometre aside of which 783 were active. The model consists of a single aquifer.

The following figure shows the structure of the model developed and precise the locations of the used wells. The green cells represent the constant head limit of the Trias aquifer. The gray cells represent the drain condition by Oum Zassar Sebkha.

Two recharge conditions are considered. The first is the direct recharge of rainwater with a rate of 2.42 % (Pallas et al, 2005). The second condition is the infiltration to the groundwater of runoff in rivers. The infiltration rates in rivers are considered variables over time. Indeed, the agricultural regional administration in the governorate of Medenine has lunched on the beginning of 1980 a soil and water harvesting program in the Zeuss Koutine river basins (photos 4 and 5). After each 500 m, it is build a barrier capable to maintain hundreds of m^3 of water. Managers, very satisfied by the result of their effort, say “*for most of the rains, there is no floods in rivers, water reach the sea and the sebkha only for very strong rains*”. The lower rivers slopes have also valuated contribution on this result.

The model is calibrated in steady state (year 1982) and in transient regime, for the period 1983 to 2009.

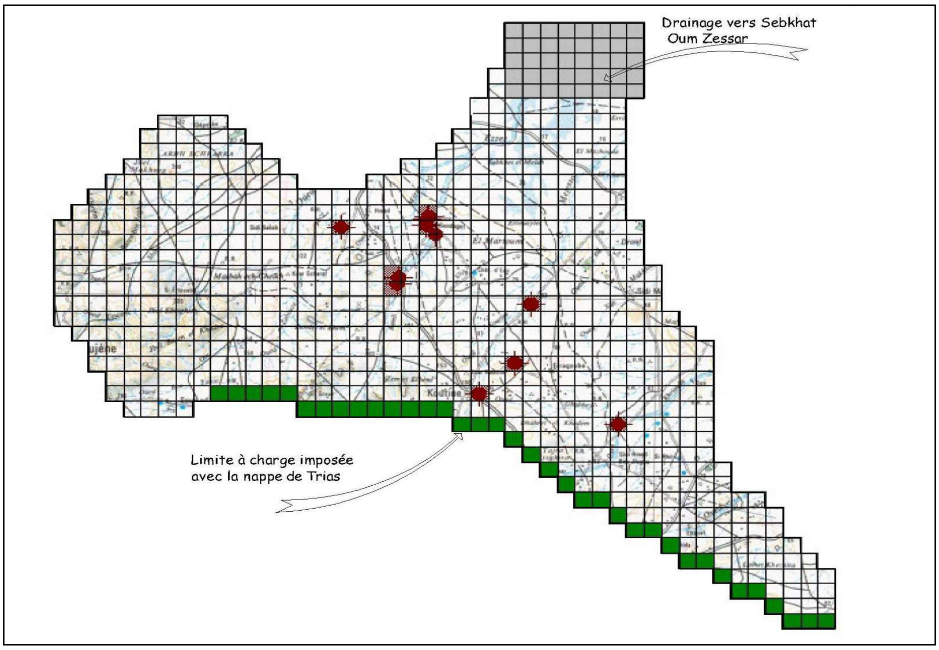


Figure 16. Structure of the model of Zeuss Koutine aquifer (Hadded, 2008).

4. WEAP-MODFLOW Decision Support System (DSS)

In order to model the real hydraulic system used to manage the Zeuss Koutine aquifer and the neighbour water sources, it is chosen to build a DSS based on the monthly MODFLOW model. Next paragraphs detail the WEAP schematic, the input data and the reference scenario results.

4.1 WEAP schematic

The conceptual model presented in figure 11 and the future water projects are considered to build the WEAP schematic as shown in the next figure:

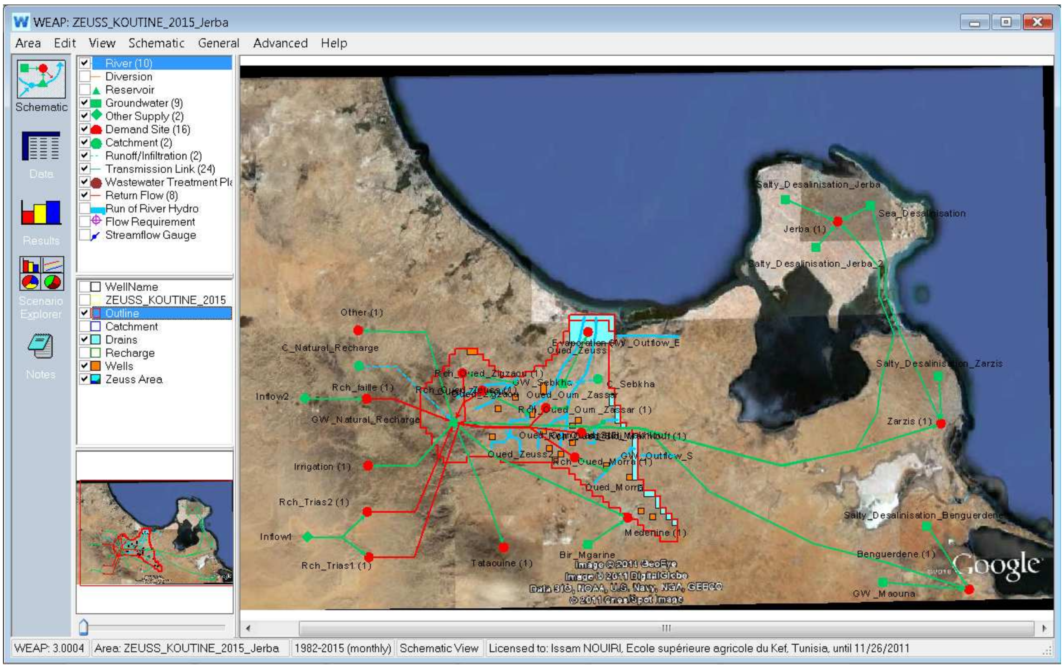


Figure 17. WEAP schematic of the Zeuss Koutine study area.

The proposed WEAP schematic contains sixteen demand site nodes. In addition to the six domestic and touristic demand sites (Medenine, Tataouine, Jerba, Zarzis, Benguerdene, Other), WEAP demand site nodes are used to represent the irrigation demand (Irrigation), the recharge to Zeuss Koutine from the Trias aquifer (Rch_Trias1 and Rch_Trias2) and from the Gabes aquifer (Rch_faille). Two “Other supply” nodes (Inflow 1 and Inflow 2) are used to generate this recharge. Demand site nodes are also used to model the evaporation from the aquifer (Evaporation) and the recharge in the rivers (Rch_Oued_Zigzaou, Rch_Oued_Zeuss, Rch_Oued_Oum_Zassar, Rch_Oued_Sidi_Makhlouf and Rch_Oued_Morra).

The groundwater sources and the desalinization plants are represented in the present WEAP schematic by groundwater nodes. Zeuss Koutine aquifer is represented by two groundwater nodes. The first is called “GW_Natural_Recharge”, subject of natural recharge due to the rain. The second groundwater node, called “GW_Sebkha”, is used to model the evaporation process. The desalinization plant of Jerba is represented by two groundwater nodes to model separately the principal plant and the mobile unit. Thus, the schematic enclose nine groundwater nodes.

Twenty-four transmission links are used to supply the demand site nodes by the nine groundwater nodes. To simulate the recharge, eight return flow links between demand site and the natural recharge groundwater node are used.

4.2 Input data

4.2.1 Rain, headflow and infiltration

The basic data used to model the natural recharge by infiltration is the monthly rain, in each of the watershed of the Zeuss Koutine aquifer, measured by the four meteorological stations in the region: Mareth, Toujene Dkhila, Koutine and Allamet Machlouch (Figure 18).

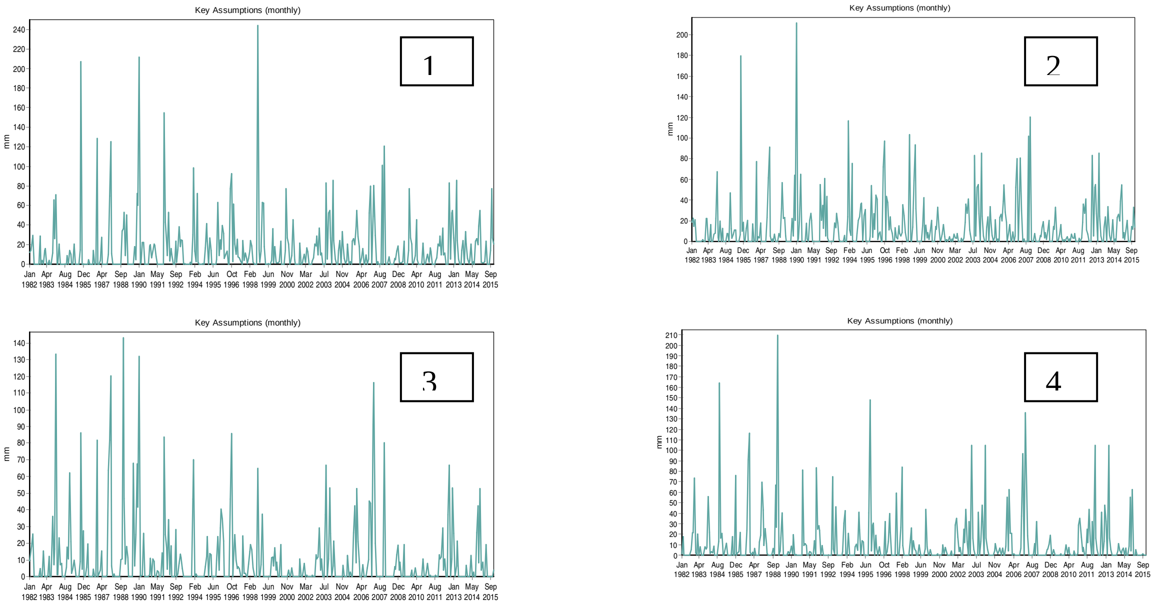


Figure 18. Monthly rains measured in the stations Mareth$^{(1)}$, Toujene Dkhila$^{(2)}$, Koutine$^{(3)}$ and Allamet Machlouch$^{(4)}$.

For the future period (2011-2015), it is reproduced the last five years. To read these data in the WEAP schematic, the “ReadFromFile” WEAP function is used. Data are saved in a “csv” file under the WEAP Area folder. These data are used to compute the head flow in each of the rivers, using the empirical formula in equation 1 (Figure 19):

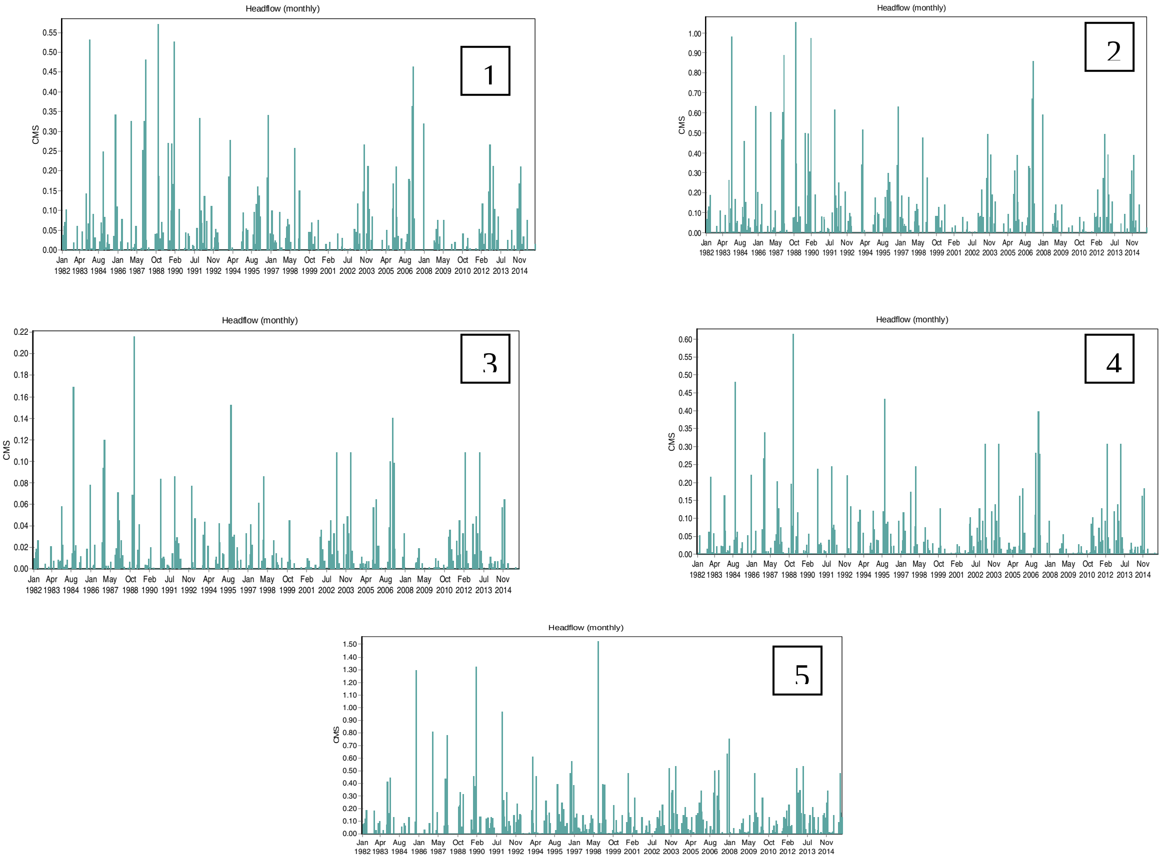


Figure 19. Monthly head flows computed in the rivers Oued Zeuss $^{(1)}$, Oued Oum Zassar $^{(2)}$, Oued Sidi Makhlouf $^{(3)}$, Oued Morra $^{(4)}$ and Oued Zigzaou$^{(5)}$.

The river head flows, computed using equation 1, are used to determine the recharge in the Zeuss Koutine aquifer applying variable recharge rates. It is considered a recharge rate of 50% for all the rivers in the starting year (1982). It takes a progressive value between 1983 and 1990 and a constant (90%) value starting from 1990. The WEAP expression builder is used to consider this temporal variability of the recharge after the current account year, as presented in next equation:

Recharge Rate = If(year<=1990, LinForecast(1985,60, 1990,90),90) (2)

Next figures represent the monthly recharge amounts to GW_Natural_Recharge:

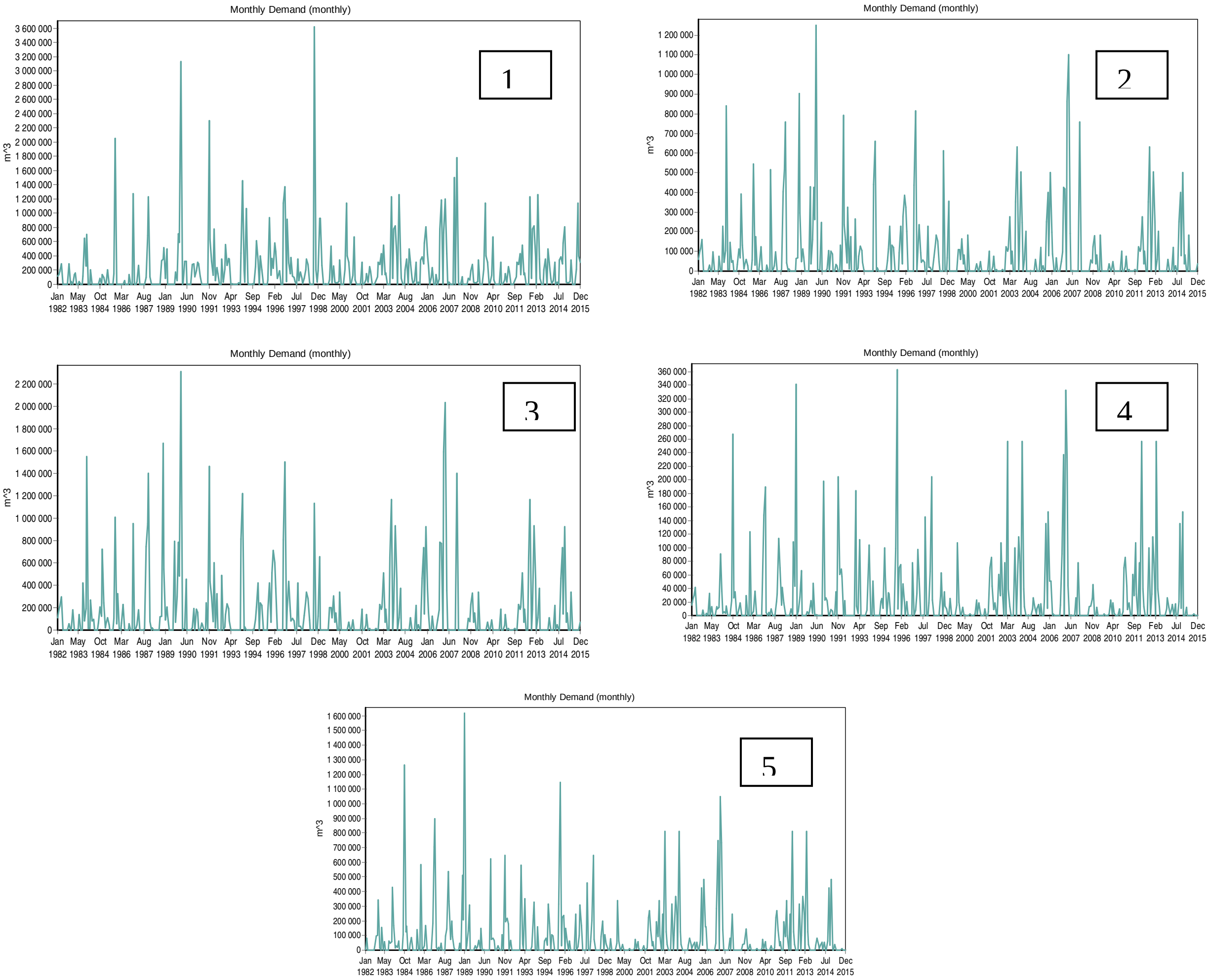


Figure 20. Monthly infiltration computed in the rivers Oued Zeuss (1), Oued Oum Zassar (2), Oued Sidi Makhlouf (3), Oued Morra (4) and Oued Zigzaou(5).

These infiltration amounts constitute the monthly water demands for the demand site nodes used to model the recharge in the rivers as detailed in section (4.1). Their consumption is equal 0 %. All the demand will be returned to the aquifer through the return flow links.

4.2.2 Demand site nodes and water demand

Two methods are used to compute the water demand. The first uses the annual activity level, the annual water use rate and the monthly variation. This is used for Medenine, Jerba, Zarzis and Benguerdene cities, the Evaporation and Irrigation nodes. The second method is to introduce a monthly demand. It is applied for Other and Tataouine cities and the demand site nodes used to model the recharge.

For the domestic and touristic demand site nodes, the official population statistics of 1984, 1994 and 2004 are the observed data of the Annual Activities Levels. Linear forecasting is used to define the populations at each time step of the model. Next figures present the domestic and the touristic annual activity levels of Medenine, Jerba, Zarzis and Benguerdene:

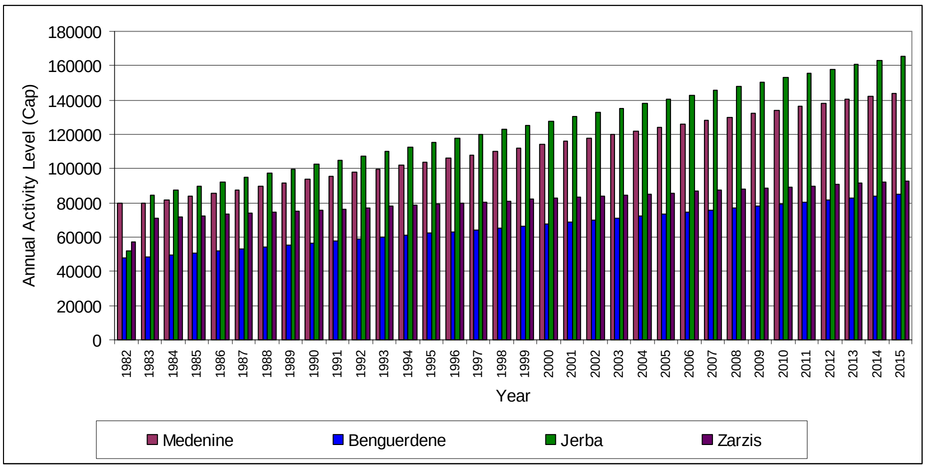


Figure 21. Annual Activity Levels of Medenine, Benguerdene, Jerba and Zarzis cities.

For Jerba and Zarzis cities, the Annual Activity Levels are computed as the sum of the domestic and the touristic values. Different Annual Water Use Rates are used to compute their water demand, as presented in the next figure:

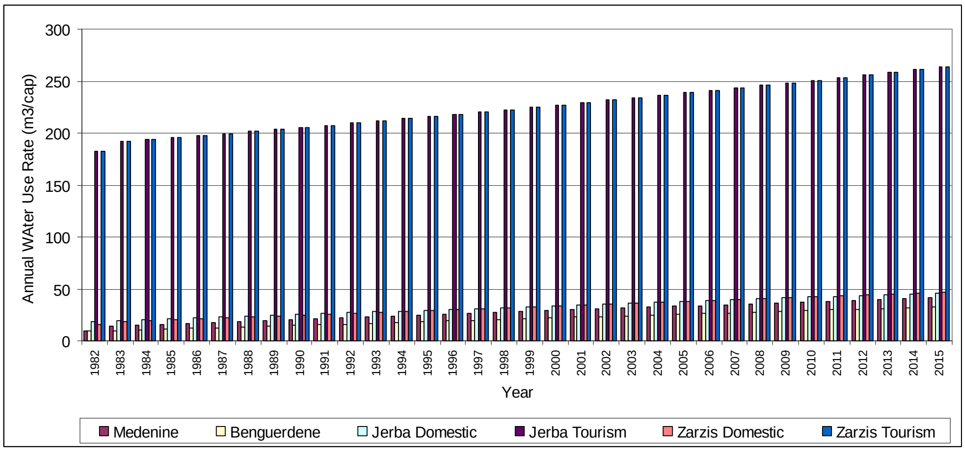


Figure 22. Annual Water Use Rate of Medenine, Benguerdene, Jerba and Zarzis cities.

To compute the monthly water demand of this set of demand site nodes, their average monthly variation presented in figure 3 is used.

The Monthly Demand of Tataouine is defined by a constant flow (60 l/s) leaving the Tejra tank. For Other, it is not possible to define an “Annual Activity Level” and nor an “Annual Water Use Rate”. Indeed, this demand site node represents the small agglomerations, the few industries, and ungrouped consumers supplied directly from the main pipes. The drinking water utility of Medenine governorate grouped their demand in the monthly report under the name “Other demands”. To keep the same aggregation done by the water resource manager, it is considered for this demand site the monthly demand measured between 1997 and 2010. To compute water demand for all time steps of the study period, it is used a linear forecasting. The result is presented in next figure:

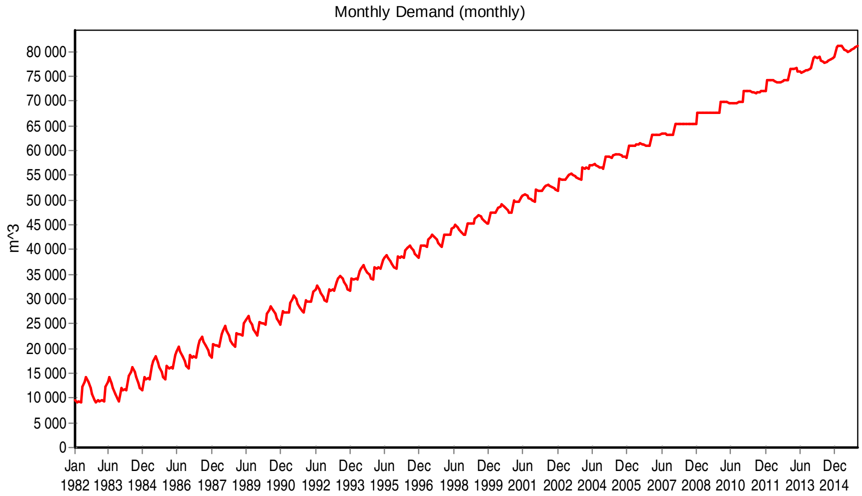


Figure 23. Monthly demand of Other cities.

The maximal allowed concentration of salinity in inflow to domestic and touristic demand sites is taken equal 1.5 g/l. For irrigation, 2 g/l is allowed. The computed monthly demands of the demand sites used to model the recharge to the groundwater are presented in next graph:

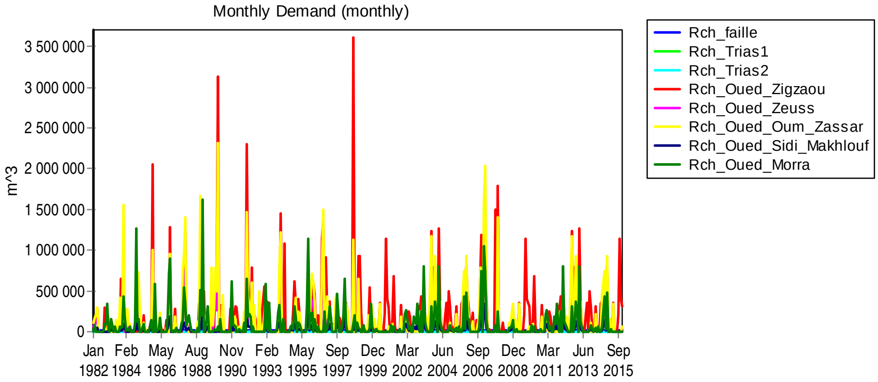


Figure 24. Monthly demand of demand site nodes used to model the recharge.

In the present WEAP model, the same Demand priority characterizes the demand site nodes. Seen the MODFLOW model is designed with one layer, the “Pump layer” WEAP variable for each of the demand sites supplied from Zeuss Koutine aquifer is equal 1.

4.2.3 Groundwater nodes

The nine groundwater nodes used to model the water resources in the studied area are characterized in WEAP by the variables: Startup Year, Storage Capacity, Initial Capacity, Maximun Withdrawal, Natural Recharge, Salinity Concentration and the Variable Operating Cost. Next table present the Startup years of the groundwater nodes representing the desalinization plants:

Table 3. Startup years of the desalinization plants.

Desalinization plants	Startup year
Desalinization_Zarzis	1999
Desalinization_Jerba	2000
Desalinization_Jerba_2	2008
Desalinization_Benguerdene	2013
Sea_Water_Desalinszation	2013

The storage capacities of the groundwater nodes representing the desalinization plants are lived to the default value (0) and a file named “AllowNegativeGW.yes” is created and copied to the Zeuss Koutine area folder. This allows getting negative groundwater storage. Next graph presents the groundwater nodes storage capacities:

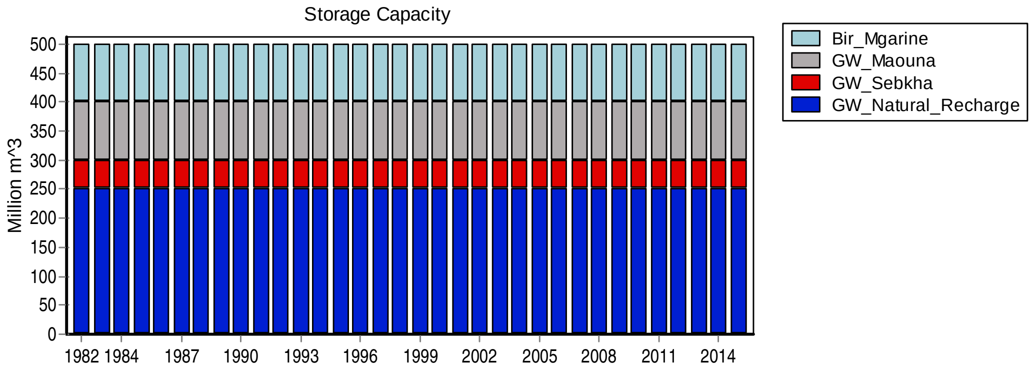


Figure 25. Storage capacities of the groundwater nodes.

For groundwater nodes other than the desalinization plants, it is considered that the initial storage is equal to the storage capacity for each of the groundwater nodes.

The maximum withdrawal for real aquifers (Zeus Koutine, Bir Mgarine and Maouna) is considered to be not limited. For groundwater nodes representing the desalinization plants, the maximum monthly abstraction is equal to the plant capacity, as presented in next graph:

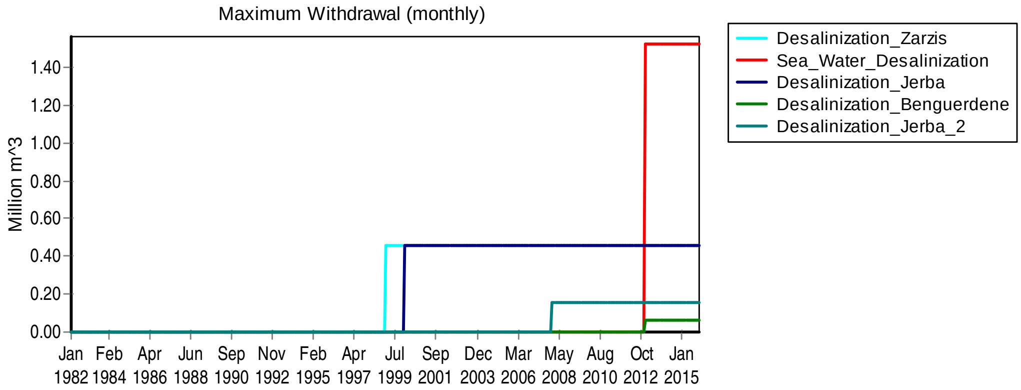


Figure 26. Maximum Withdrawal of the desalinization plants.

For the present WEAP model, only the GW_Natural_Recharge, representing part of the Zeuss Koutine aquifer is subject of natural recharge. Next figure presents the monthly values of the natural recharge due to rain:

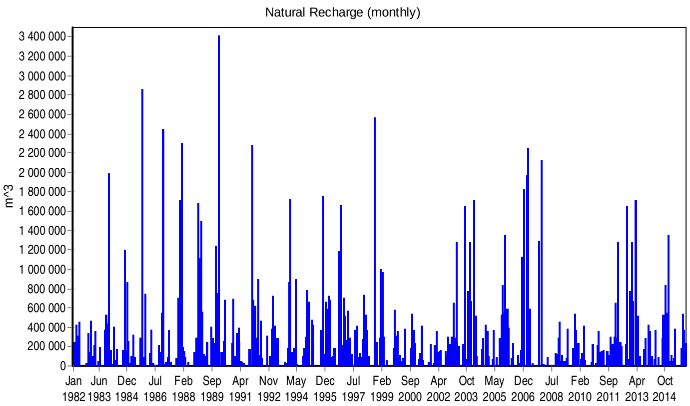
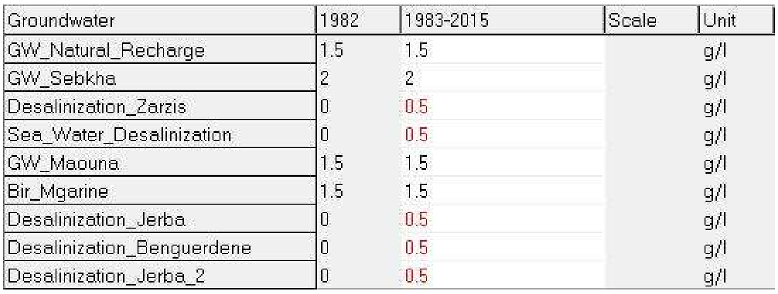


Figure 27. Natural recharge for the groundwater node GW_Natural_Recharge

The salinity concentrations of the groundwater nodes are detailed in the next table:

Table 4. Salinity concentrations of the groundwater nodes.



Groundwater	1982	1983-2015	Scale	Unit
GW_Natural_Recharge	1.5	1.5		g/l
GW_Sebkha	2	2		g/l
Desalinization_Zarzis	0	0.5		g/l
Sea_Water_Desalinization	0	0.5		g/l
GW_Maouna	1.5	1.5		g/l
Bir_Mgarine	1.5	1.5		g/l
Desalinization_Jerba	0	0.5		g/l
Desalinization_Benguerdene	0	0.5		g/l
Desalinization_Jerba_2	0	0.5		g/l

Seen the variability of the energy pricing over time, it is chosen to consider that the specific consumption of energy (detailed in section 2.3) is the variable operating costs of each of the groundwater nodes. This approach allows also comparison between study areas in different country, using different pricing approaches and different and monetary units. Next graph summarizes the values of this variable for all groundwater nodes:

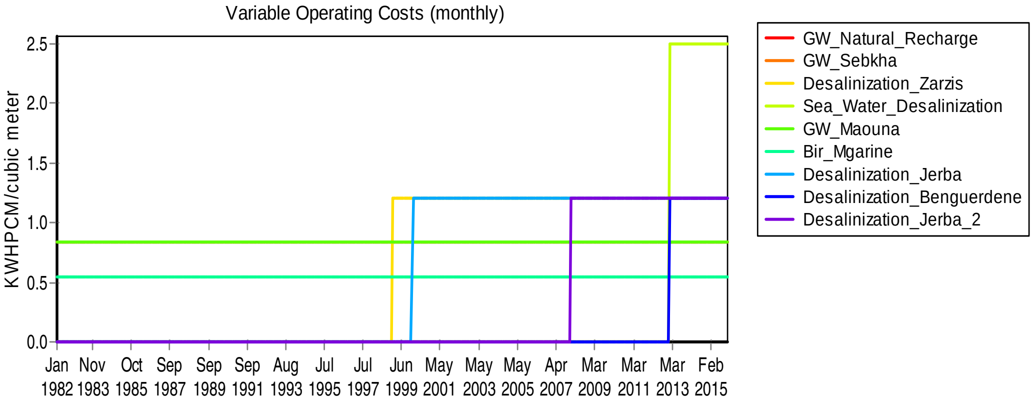


Figure 28. Variable operating cost of the groundwater nodes.

4.2.4 Transmission links

The transmission links between groundwater sources and demand site nodes are characterized essentially by their “Maximum Flow Volume”, “Loss from System” and by the “Variable Operating Costs” variables. The maximum flow volumes are given in table 1. It is assumed in this study that the loss from the supply network is equal 10 % of flow passing the pipes. The variable operating costs are given in the figure 11.

4.2.5 Linkage WEAP - MODFLOW

The linkage between the WEAP schematic and the MODFLOW model is performed using the linkage shape file. This step allows the link of the MODFLOW model cells to the WEAP components in the schematic. Next figure summarizes the linkage of domestic, touristic and agriculture demand sites nodes to the well cells of the MODFLOW model, recognized by their rows and columns:

Table 5. Linkage between domestic and irrigation demand site nodes and well cells of the MODFLOW model.

MF_RC	DEMAND1	DEMAND2	Demand3
09-15	Jerba	Zarzis	Other
09-16	Jerba	Zarzis	Other
15-28	Jerba	Zarzis	Other
16-28	Jerba	Zarzis	Other
17-23	Irrigation		
19-20	Medenine	Tataouine	Other
19-26	Jerba	Benguerdene	Other
20-26	Jerba	Zarzis	Other
21-34	Irrigation		
22-33	Irrigation		
23-28	Irrigation		
24-19	Jerba	Benguerdene	Other
24-31	Other		
26-29	Other		
27-31	Jerba	Zarzis	Other
28-30	Zarzis	Benguerdene	Other
29-39	Jerba	Zarzis	Other
31-43	Irrigation		
37-45	Other		
38-47	Jerba	Zarzis	Other

4.3 Results of the reference scenario

The main simulation results of the reference scenario using the presented WEAP-MODFLOW DSS are presented in next paragraphs.

4.3.1 Water demand

Next graph summarize the monthly water demand computed for the domestic and touristic demand site nodes:

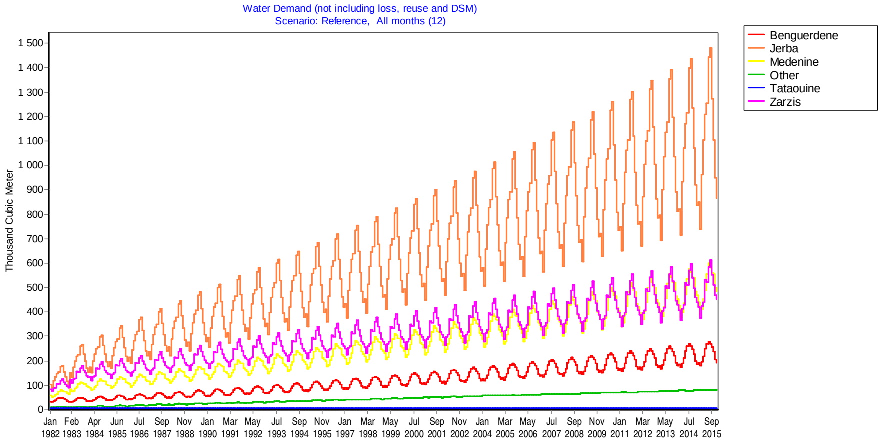


Figure 29. Monthly water demand for domestic and touristic demand sites nodes.

The figure above demonstrates that Jerba is the most important city in term of water demand. Medenine and Zarzis are characterized by equivalent demands. Benguerdene city presents lower water demand. With the reference scenario, all the water demands are covered 100 %.

In order to validate the water demand computed by WEAP, it is used observed data of the water supplied to Medenine, Zarzis and Benguerdene in the period 2007 – 2010. Next figures present the observed and the computed water demand for each of the demand sites:

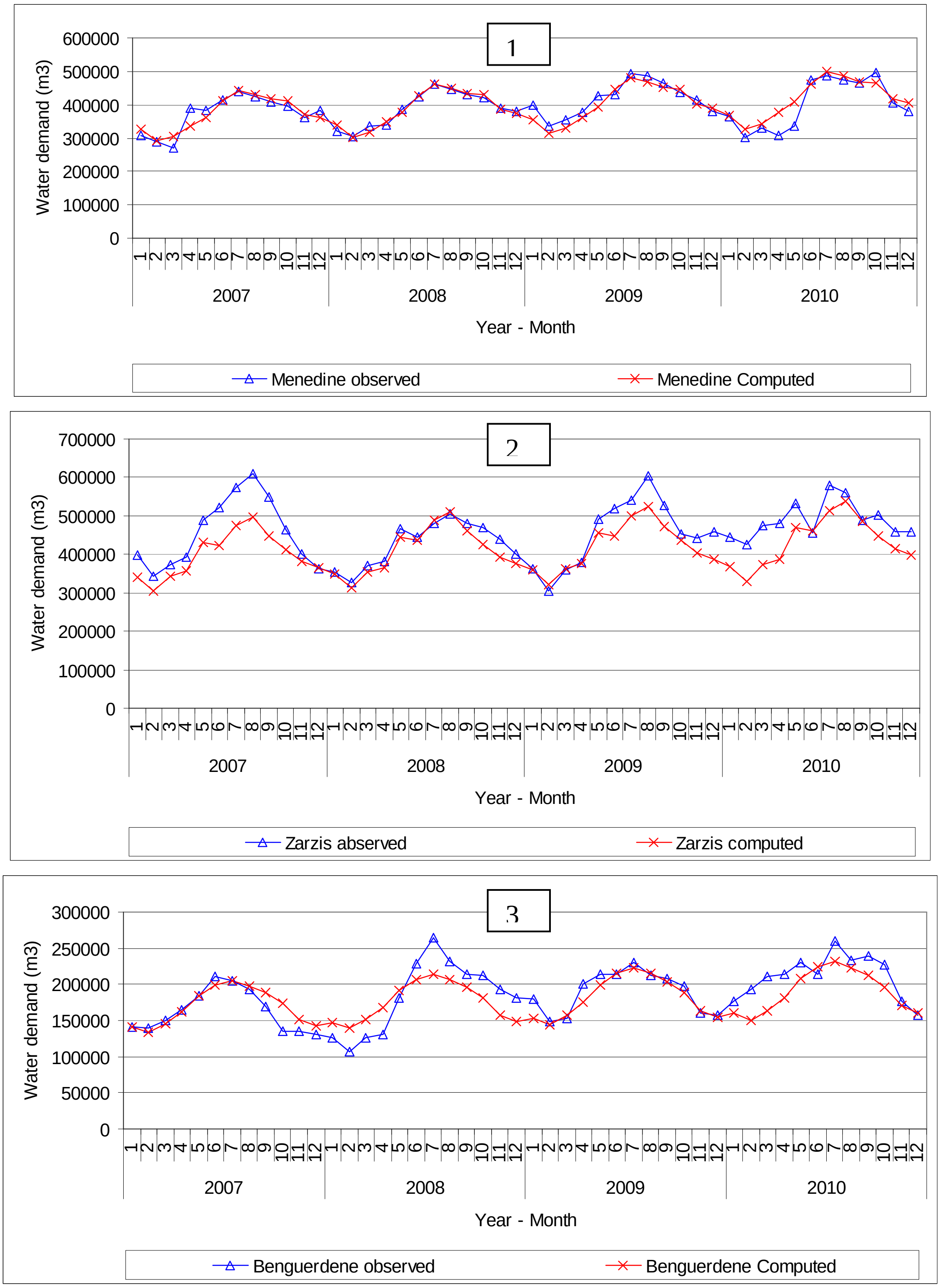


Figure 30. Monthly water demands observed and computed for Medenine (1), Zarzis (2) and Berguerdene (3).

4.3.2 Transmission links flow

To satisfy the water demand, WEAP has computed the transmission links flows presented in the following graphs. Next figure present the supply to Medenine:

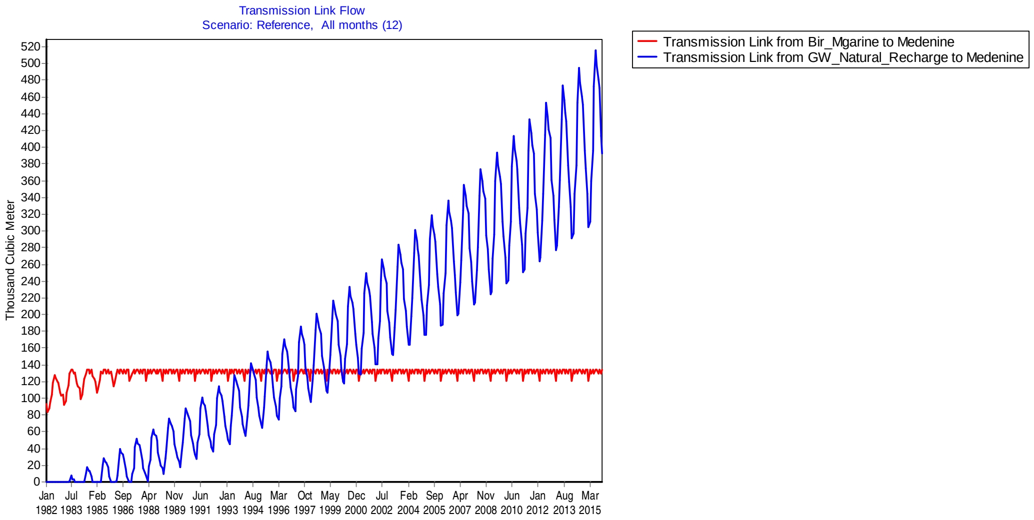


Figure 31. Monthly transmission link flows to Medenine.

The city of Medenine is supplied first by Bir Mgarine, because of the lower cost, and secondly by GW_Natural_Recharge groundwater. Seen the flow limitation from the first aquifer, the water demand increase generates an increase of the use of Zeuss Koutine aquifer.

Jerba is supplied by four transmission links. Their flows are presented in next figure.

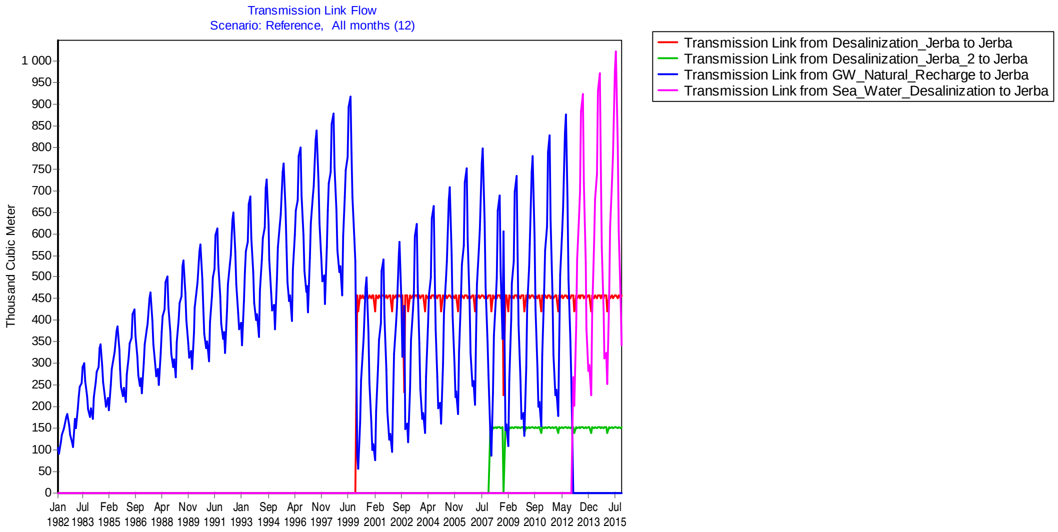


Figure 32. Monthly transmission links flows to Jerba.

Up to 2000, there is only Zeuss Koutine aquifer that supplies the city. In 2000, the desalinization plant of Jerba is used. This event is accompanied by a strong reduction of the volume used from Zeuss Koutine. The same behaviour is noted when the second salty water desalinization plant is started (2008). When the sea water desalinization plant will be started, it will be capable to supply the city. There is no need to supply water from the Zeuss Koutine.

For Zarzis city, transmission link flows are presented in the next figure:

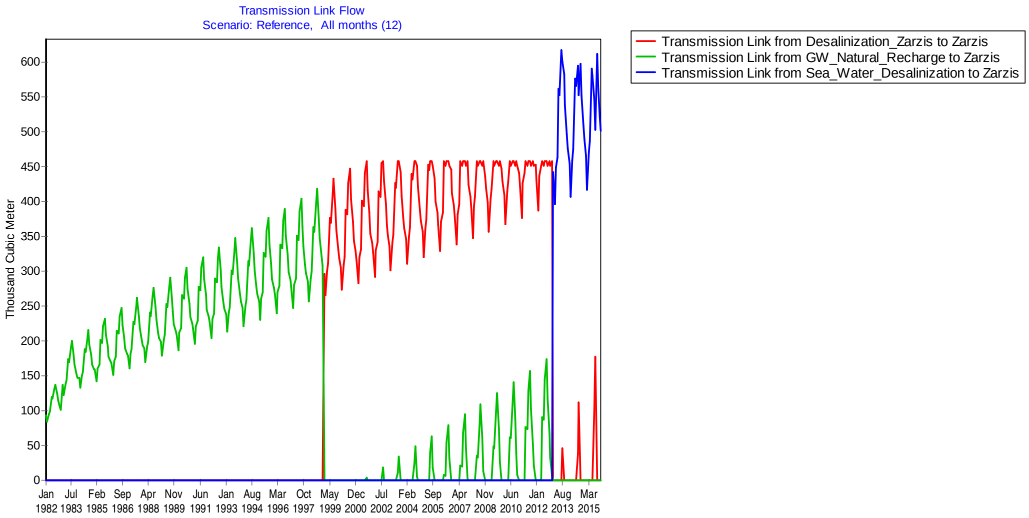


Figure 33. Monthly transmission link flows to Zarzis.

The figure above shows that when the desalinization plant of Zarzis is started (1999) and is sufficient to cover the water demand, the Zeuss Koutine is not used. In 2002, the desalinization reaches its maximal capacity and there is the need to use groundwater of Zeuss Koutine. The start up of the sea water desalinization plant (2013) eliminates the use of groundwater. The salty desalinized water is then used only in the peak water demand periods.

Transmission links flows to Benguerdene are characterized by flows presented in next figure:

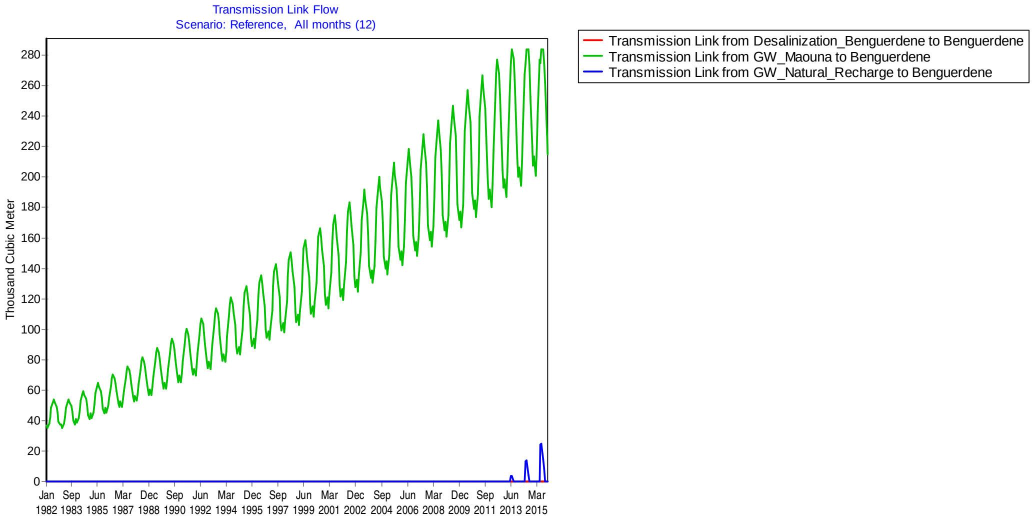


Figure 34. Monthly transmission links flows to Benguerdene.

It is clear that WEAP uses the lower cost water source: GW_Maouna instead of the Zeuss Koutine and the desalinization plant. At the end of the study period, the Zeuss Koutine groundwater is used just in the peak water demand months. There is no need for the desalinization up to 2015.

4.3.3 Groundwater cell head

The initial cells heads of Zeuss Koutine aquifer are presented in next figure:

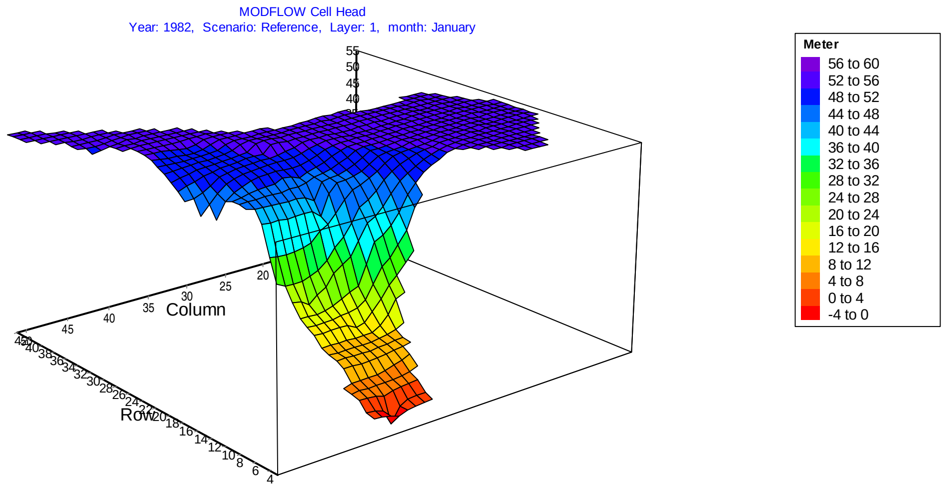


Figure 35. Initial Cells heads of Zeuss Koutine aquifer (1982).

The cells heads of the aquifer on 2010 are presented in next figure:

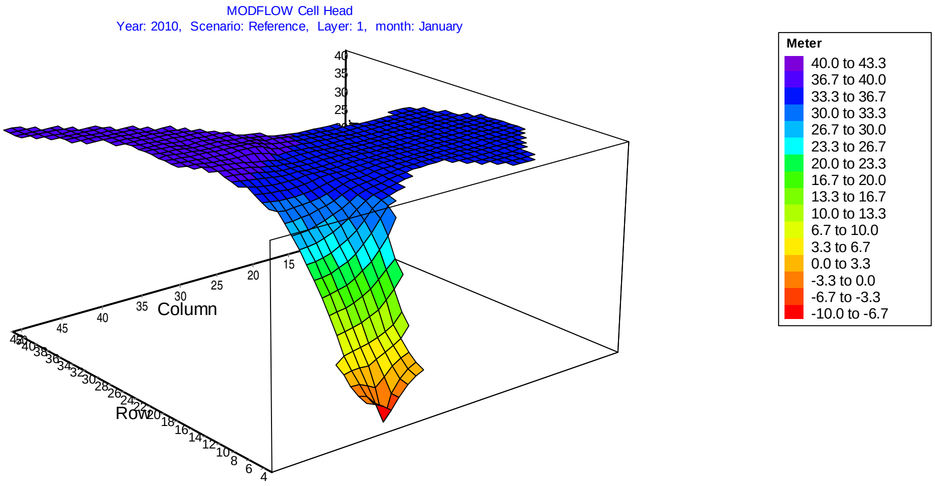


Figure 36. Cells heads of Zeuss Koutine aquifer on 2010.

On 2015, the cells heads are shown in next figure:

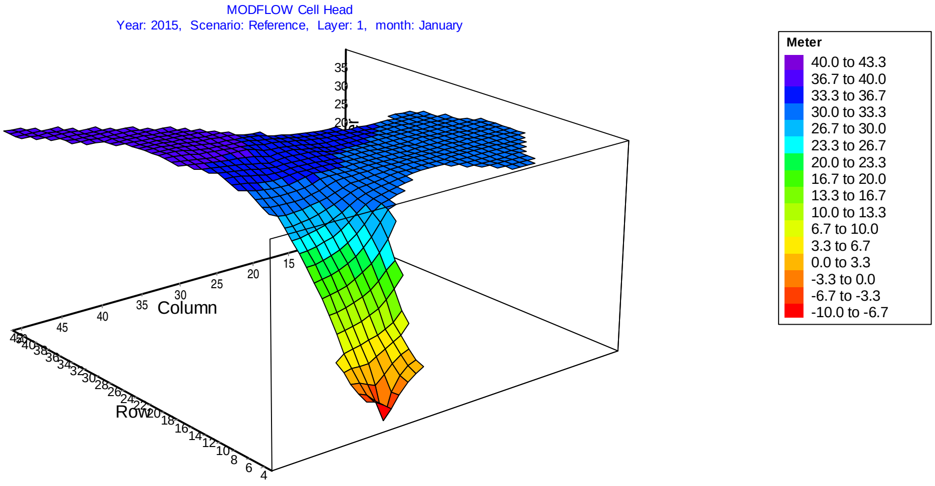


Figure 37. Cells heads of Zeuss Koutine aquifer on 2015.

The comparison of the computed cells heads with the observed values is done for the three piezometers of the Zeuss Koutine aquifer. Next figure summarizes the results for “Glib Ettine”, “Koutine 2” and “Ghabbey”:

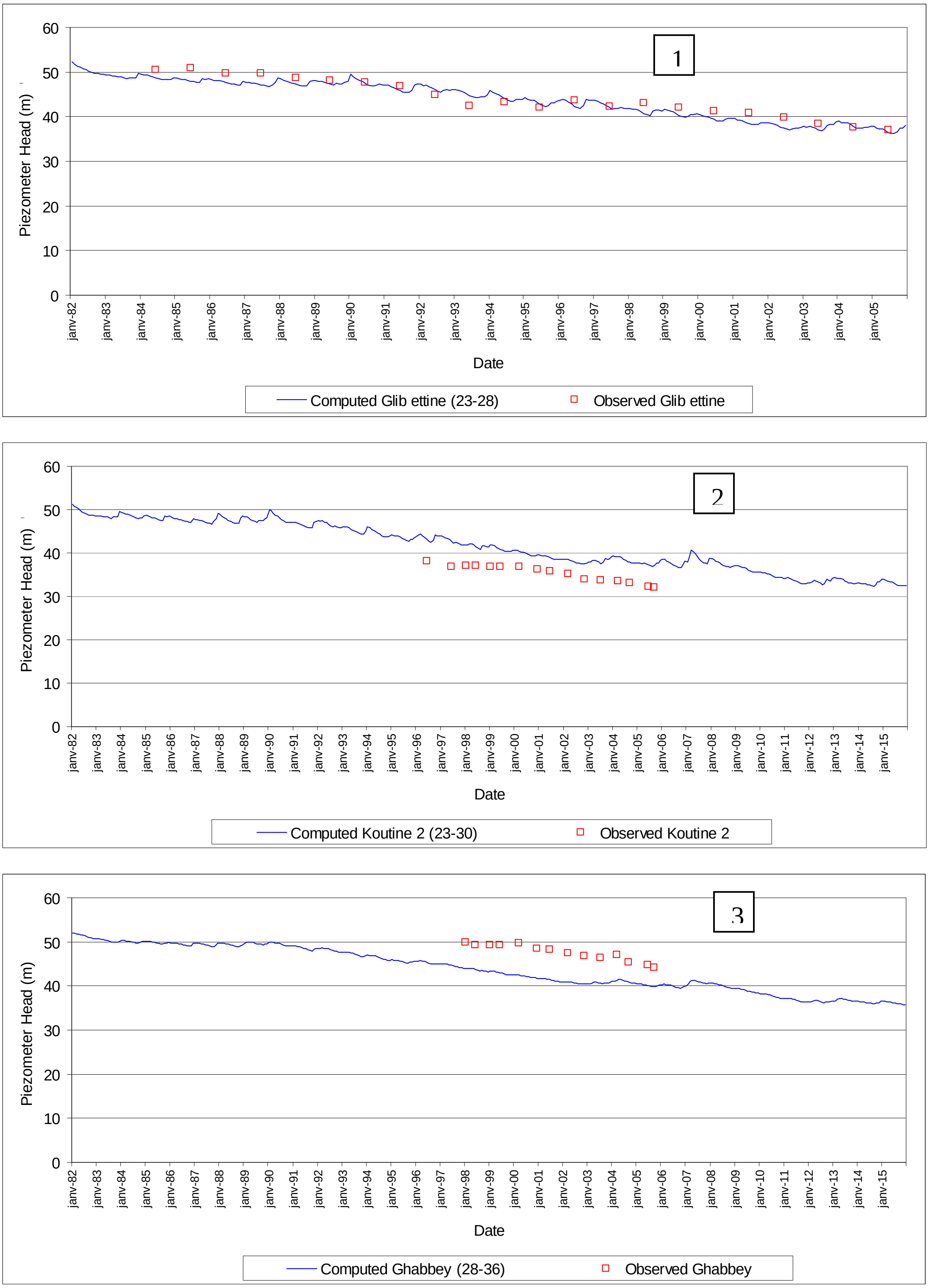


Figure 38. Observed and computed cell heads for piezometer “Glib Ettine” (1), “Koutine 2” (2) and “Ghabbey” (3) by the “Reference” scenario.

The computed cell heads for “Glib Ettine” piezometer are very close to those observed. The absolute maximal difference is equal to 3 m and represents 6 % of the observed value. For the Koutine 2 piezometer, the maximal absolute difference is evaluated to 6 m. It represents 16 % of the observed value. The maximal difference between computed and observed cell head in the piezometer Ghabbey is estimated to 7 m and represents 15 % of the observed value.

4.3.4 Average water cost

The groundwater management proposed by WEAP to satisfy the water demands is characterized by the average cost of one cubic meter of water. Next figure presents the monthly average cost of water:

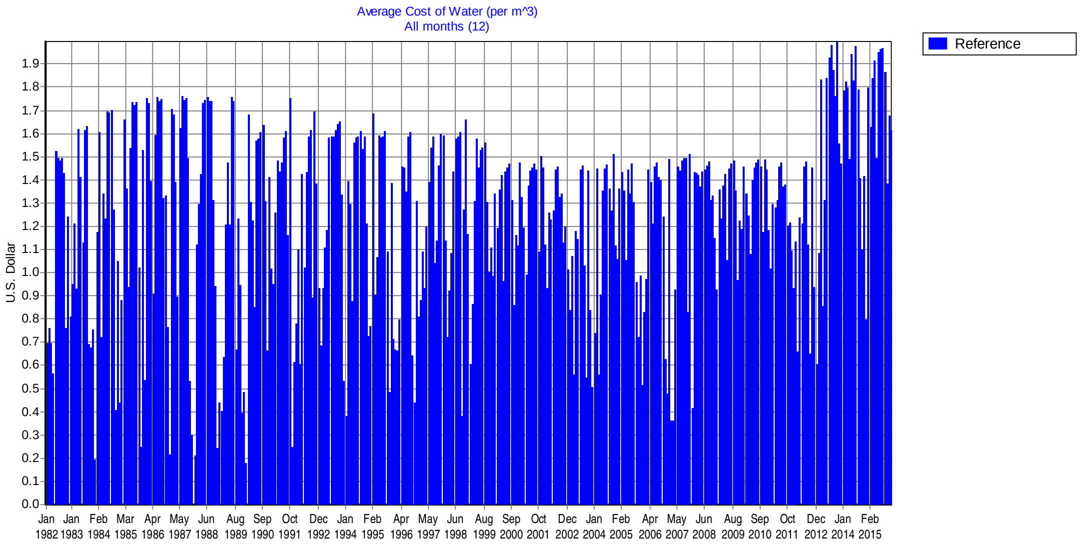


Figure 39. Monthly average cost of water per m^3 computed by the “Reference” scenario.

Last graph shows three periods of average water cost. In the first one, between 1982 and 1999, the average cost of water is about 1.60 KWh/m^3. The second period is defined between years 1999 and 2012 with an average water cost of 1.45 KWh/m^3. The last period is characterized by an average cost of 1.95 KWh/m^3. It is defined between 2013 and 2015.

The average water cost periods are defined by the water sources used. Indeed, in the first one the Zeuss Koutine is the main water source. It requires at least two pumping steps to supply the demand site nodes. The second period corresponds to the start-up year of the desalinization plants of Jerba and Zarzis. The last period, with the highest average water cost, is defined by the use of the sea water desalinization plant.

4.4 Conclusion

The WEAP-MODFLOW DSS is build. Input data are taken from official statistics reports, drinking water utility reports and from network maps. Field trips in the study area have also a valued income in the quality of the presented results.

Obtained results demonstrate that the WEAP-MODFLOW DSS of the Zeuss Koutine aquifer is capable to reproduce the real behaviour of the natural system. Water demands in the main cities are calibrated for four years. The impact of the real water management on the Zeuss Koutine aquifer is reproduced by the developed DSS with acceptable confidence. Indeed, the heads computed in the piezometers cells are close to the observed values. The maximal difference is evaluated to 16 % of the observed value. The DSS data will be used to optimize the groundwater management of Zeuss Koutine aquifer with ***ALL_WATER_gw***.

5. Optimization of the Zeuss Koutine groundwater management.

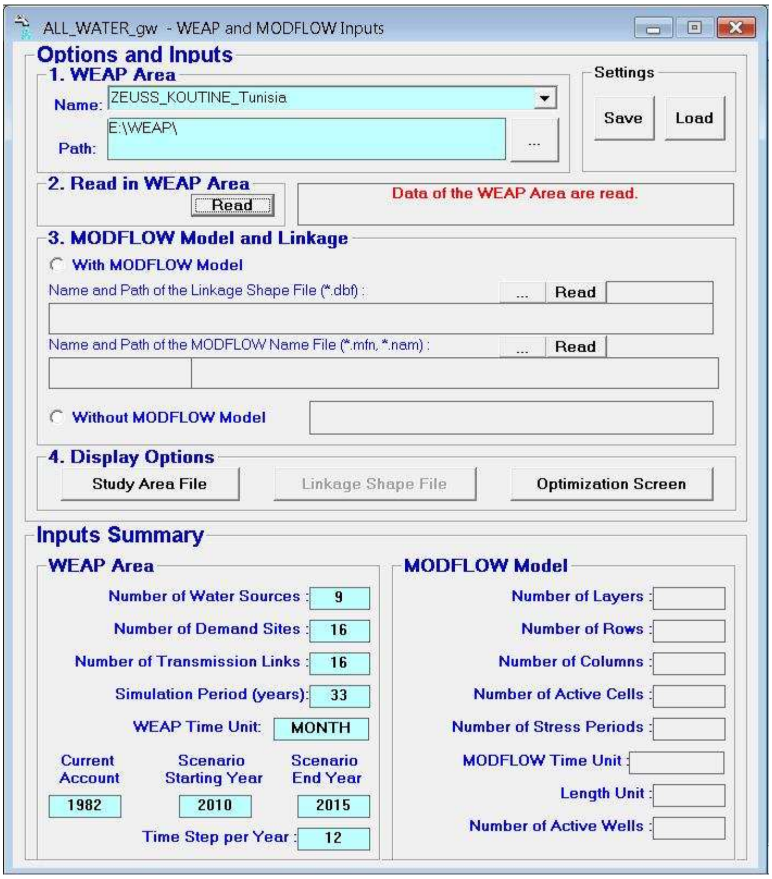
5.1 Introduction

This section presents the use of the ***ALL_WATER_gw*** software to optimize groundwater management of the Zeuss Koutine aquifer between 2010 and 2015. The developed WEAP-MODFLOW DSS, called in next “ZEUSS_KOUTINE_Tunisia”, is used to model interactions between surface and groundwater and the demands. Three main steps are detailed. The first is the read of the input data from the WEAP Area, the linkage shape file and the MODFLOW model. The second step shows how to choose objectives and constraints, the parameters of the Genetic Algorithm and the convergence criteria’s. The last step is the run of the software and the use of results on the WEAP-MODFLOW DSS framework.

5.2 Read of the input data from the WEAP Area project

5.2.1 Read in the WAEP Area

After starting ***ALL_WATER_gw*** and choosing the WEAP Area to work with, the starting year of the optimization (2010) is specified. The software browse the WEAP Area branches and read in the variables values of the demand site nodes, the groundwater nodes and the transmission links. Output files are created and the summary of the WEAP Area is displayed in the user interface. Next figure presents the ***ALL_WATER_gw*** user interface after reading the “Zeuss_Koutine_Tunisia” WEAP Area:



Name: ZEUSS_KOUTINE_Tunisia

Path: E:\WEAP\

Data of the WEAP Area are read.

Number of Water Sources : 9

Number of Demand Sites : 16

Number of Transmission Links : 16

Simulation Period (years): 33

WEAP Time Unit: MONTH

Current Account	Scenario Starting Year	Scenario End Year
1982	2010	2015

Time Step per Year : 12

Figure 40. User interface of ***ALL_WATER_gw*** after reading the “Zeuss_Koutine_Tunisia” WEAP Area.

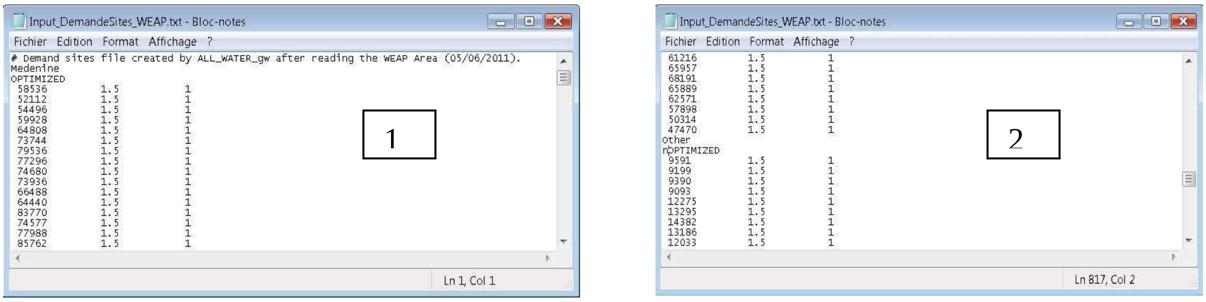
As displayed in the user interface, there are 9 groundwater sources, 16 demand sites and 16 transmission links in the WEAP Area. In parallel, a message box asks to edit the created demand site text file.

This step is performed to choose the demand sites that require optimization of their supply. To ensure this, the "ChoiceD" parameter (see user manual) is kept equal "OPTIMIZED" for the demand sites considered by the optimization. For each of the remaining demand sites, the "ChoiceD" parameter is changed to "nOPTIMIZED".

For the studied WEAP Area, there are a sets of demand sites nodes does not need optimization: demand sites nodes used to model the recharge (Rch_faille, Rch_Trias1, Rch_Trias2, Rch_Oued_Zigzaou, Rch_Oued_Zeuss, Rch_Oued_Oum_Zassar, Rch_Oued_Sidi_Makhlouf, Rch_Oued_Morra).

In addition, the analysis of the observed water consumption in 2010, it is concluded that the consumptions of Jerba, Zarzis, Medenine, and Benguerdene cities represent about 50 %, 21 %, 20 % and 9 %, respectively.

For Benguerdene city, Zeuss Koutine is used as complement of Maouna aquifer due to the higher cost of the first. Seen the lower consumption percentage of Benguerdene city from Zeuss Koutine and the existence of lower cost and better water quality resource, only the demand sites Medenine, Jerba and Zarzis will be considered in the optimization without MODFLOW model.

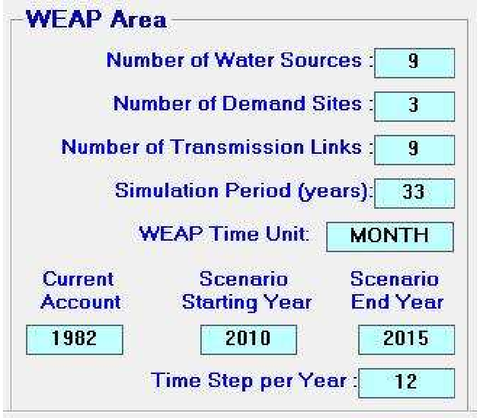


```
# Demand sites file created by ALL_WATER_gw after reading the WEAP Area (05/06/2011).
Medenine
OPTIMIZED
 58536        1.5         1
 52112        1.5         1
 54496        1.5         1
 59928        1.5         1
 64808        1.5         1
 73744        1.5         1
 79536        1.5         1
 77296        1.5         1
 74680        1.5         1
 73936        1.5         1
 66488        1.5         1
 64440        1.5         1
 83770        1.5         1
 74577        1.5         1
 77988        1.5         1
 85762        1.5         1
```

```
 61216        1.5         1
 65957        1.5         1
 68191        1.5         1
 65889        1.5         1
 62571        1.5         1
 57898        1.5         1
 50314        1.5         1
 47470        1.5         1
other
nOPTIMIZED
 9591         1.5         1
 9199         1.5         1
 9390         1.5         1
 9093         1.5         1
 12275        1.5         1
 13295        1.5         1
 14382        1.5         1
 13186        1.5         1
 12033        1.5         1
```

Figure 41. Choose of the demand site nodes to be optimized (1) Medenine or not (2) Other.

To perform the next step, it is activated the option box "With MODFLOW model" in the section 3 of the user interface. The numbers of groundwater nodes (9), demand sites (3) and transmission links (9) to be considered in the next steps are updated and displayed in the "Inputs Summary" section of the user interface, as shown in the next figure:


WEAP Area

Number of Water Sources : 9

Number of Demand Sites : 3

Number of Transmission Links : 9

Simulation Period (years): 33

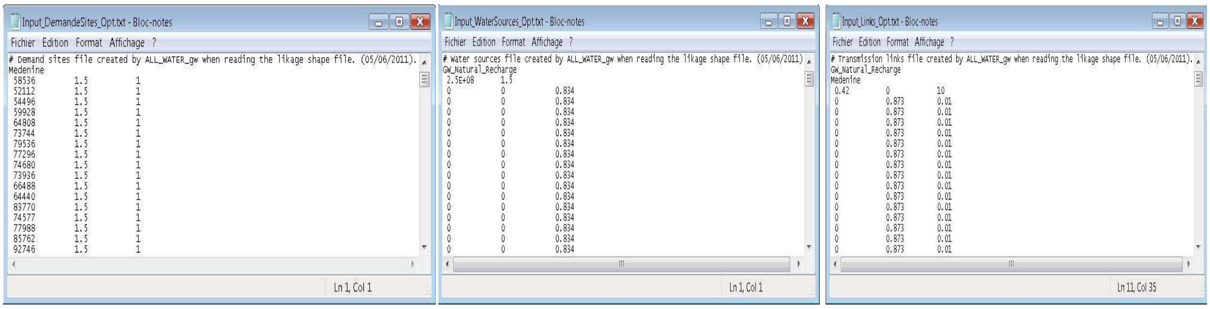
WEAP Time Unit: MONTH

Current Account	Scenario Starting Year	Scenario End Year
1982	2010	2015

Time Step per Year : 12

Figure 42. Update of the number of groundwater node, demand sites and transmission links.

The ***ALL_WATER_gw*** updates in parallel the files for demand sites and groundwater nodes and for the transmission links, as presented in next figure:



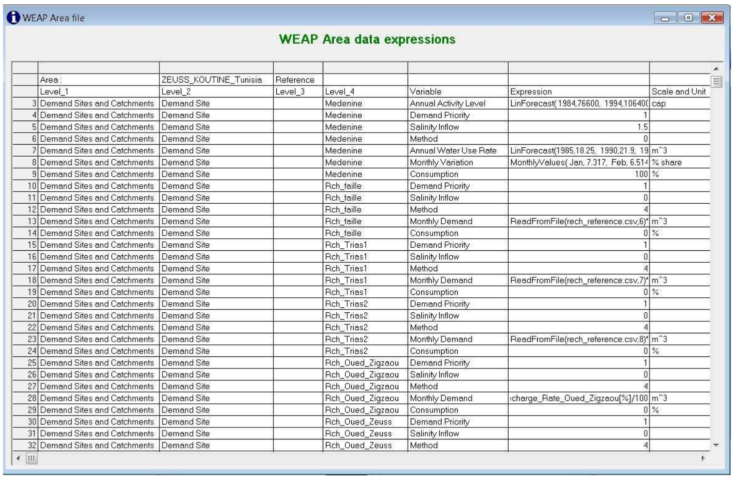
```
# Demand sites file created by ALL_WATER_gw when reading the likage shape file. (05/06/2011).
Medenine
 58536         1.5           1
 52112         1.5           1
 54496         1.5           1
 59928         1.5           1
 64808         1.5           1
 73744         1.5           1
 79536         1.5           1
 77296         1.5           1
 74680         1.5           1
 73936         1.5           1
 66488         1.5           1
 64440         1.5           1
 83770         1.5           1
 74577         1.5           1
 77988         1.5           1
 85762         1.5           1
 92746         1.5           1
```

```
# Water sources file created by ALL_WATER_gw when reading the likage shape file. (05/06/2011)
GW_Natural_Recharge
 2.5E+08       1.5
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
 0             0             0.834
```

```
# Transmission links file created by ALL_WATER_gw when reading the likage shape file. (05/06/2011).
GW_Natural_Recharge
Medenine
 0.42          0             10
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
 0             0.873         0.01
```

Figure 43. Updated files for demand sites, groundwater nodes and transmission links.

The data expression of the WEAP Area can be displayed in the user interface to be verified by user. Next figure is a screen shoot of a part of the data expression file, saved in the OPTIMIZATION folder:

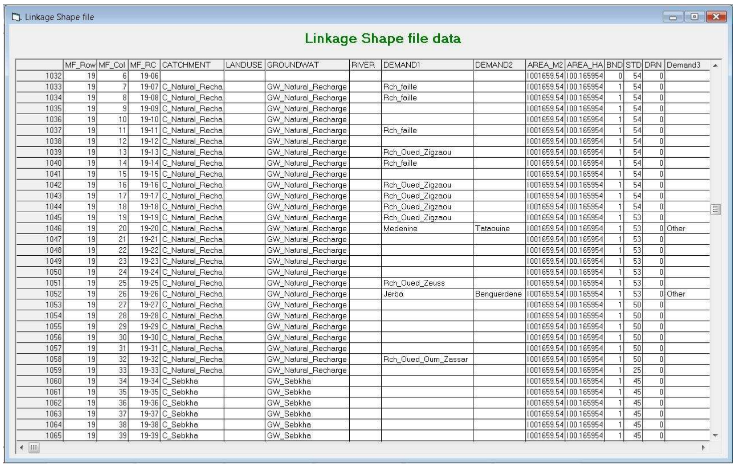


	Area :	ZEUSS_KOUTINE_Tunisia	Reference				
	Level_1	Level_2	Level_3	Level_4	Variable	Expression	Scale and Unit
3	Demand Sites and Catchments	Demand Site		Medenine	Annual Activity Level	LinForecast(1984,76600, 1994,10640(	cap
4	Demand Sites and Catchments	Demand Site		Medenine	Demand Priority	1	
5	Demand Sites and Catchments	Demand Site		Medenine	Salinity Inflow	1.5	
6	Demand Sites and Catchments	Demand Site		Medenine	Method	0	
7	Demand Sites and Catchments	Demand Site		Medenine	Annual Water Use Rate	LinForecast(1985,18.25, 1990,21.9, 19	m^3
8	Demand Sites and Catchments	Demand Site		Medenine	Monthly Variation	MonthlyValues(Jan, 7.317, Feb, 6.51	% share
9	Demand Sites and Catchments	Demand Site		Medenine	Consumption	100	%
10	Demand Sites and Catchments	Demand Site		Rch_faille	Demand Priority	1	
11	Demand Sites and Catchments	Demand Site		Rch_faille	Salinity Inflow	0	
12	Demand Sites and Catchments	Demand Site		Rch_faille	Method	4	
13	Demand Sites and Catchments	Demand Site		Rch_faille	Monthly Demand	ReadFromFile(rech_reference.csv,6)*	m^3
14	Demand Sites and Catchments	Demand Site		Rch_faille	Consumption	0	%
15	Demand Sites and Catchments	Demand Site		Rch_Trias1	Demand Priority	1	
16	Demand Sites and Catchments	Demand Site		Rch_Trias1	Salinity Inflow	0	
17	Demand Sites and Catchments	Demand Site		Rch_Trias1	Method	4	
18	Demand Sites and Catchments	Demand Site		Rch_Trias1	Monthly Demand	ReadFromFile(rech_reference.csv,7)*	m^3
19	Demand Sites and Catchments	Demand Site		Rch_Trias1	Consumption	0	%
20	Demand Sites and Catchments	Demand Site		Rch_Trias2	Demand Priority	1	
21	Demand Sites and Catchments	Demand Site		Rch_Trias2	Salinity Inflow	0	
22	Demand Sites and Catchments	Demand Site		Rch_Trias2	Method	4	
23	Demand Sites and Catchments	Demand Site		Rch_Trias2	Monthly Demand	ReadFromFile(rech_reference.csv,8)*	m^3
24	Demand Sites and Catchments	Demand Site		Rch_Trias2	Consumption	0	%
25	Demand Sites and Catchments	Demand Site		Rch_Oued_Zigzaou	Demand Priority	1	
26	Demand Sites and Catchments	Demand Site		Rch_Oued_Zigzaou	Salinity Inflow	0	
27	Demand Sites and Catchments	Demand Site		Rch_Oued_Zigzaou	Method	4	
28	Demand Sites and Catchments	Demand Site		Rch_Oued_Zigzaou	Monthly Demand	charge_Rate_Oued_Zigzaou[%]/100	m^3
29	Demand Sites and Catchments	Demand Site		Rch_Oued_Zigzaou	Consumption	0	%
30	Demand Sites and Catchments	Demand Site		Rch_Oued_Zeuss	Demand Priority	1	
31	Demand Sites and Catchments	Demand Site		Rch_Oued_Zeuss	Salinity Inflow	0	
32	Demand Sites and Catchments	Demand Site		Rch_Oued_Zeuss	Method	4	

Figure 44. Screen shoot of data expression of the Area Zeuss_Koutine_Tunisia.

5.2.2 Read of the Linkage Shape File

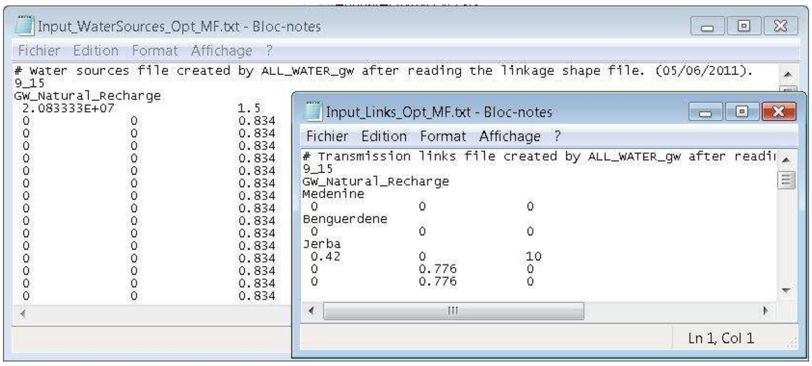
The Linkage Shape File is read after selecting the file, using the browse option, and by a click on the "Read" button. When this step is achieved, it is possible to display the linkage shape file to check for the details. Next figure presents a screen shoot of the Linkage Shape File of the "Zeuss_Koutine_Tunisia" WEAP Area:



	MF_Row	MF_Col	MF_RC	CATCHMENT	LANDUSE	GROUNDWAT	RIVER	DEMAND1	DEMAND2	AREA_M2	AREA_HA	BND	STD	DRN	Demand3
1032	19	6	19-06							1001659.54	100.165954	0	54	0	
1033	19	7	19-07	C_Natural_Recha		GW_Natural_Recharge		Rch_faille		1001659.54	100.165954	1	54	0	
1034	19	8	19-08	C_Natural_Recha		GW_Natural_Recharge		Rch_faille		1001659.54	100.165954	1	54	0	
1035	19	9	19-09	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	54	0	
1036	19	10	19-10	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	54	0	
1037	19	11	19-11	C_Natural_Recha		GW_Natural_Recharge		Rch_faille		1001659.54	100.165954	1	54	0	
1038	19	12	19-12	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	54	0	
1039	19	13	19-13	C_Natural_Recha		GW_Natural_Recharge		Rch_Oued_Zigzaou		1001659.54	100.165954	1	54	0	
1040	19	14	19-14	C_Natural_Recha		GW_Natural_Recharge		Rch_faille		1001659.54	100.165954	1	54	0	
1041	19	15	19-15	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	54	0	
1042	19	16	19-16	C_Natural_Recha		GW_Natural_Recharge		Rch_Oued_Zigzaou		1001659.54	100.165954	1	54	0	
1043	19	17	19-17	C_Natural_Recha		GW_Natural_Recharge		Rch_Oued_Zigzaou		1001659.54	100.165954	1	54	0	
1044	19	18	19-18	C_Natural_Recha		GW_Natural_Recharge		Rch_Oued_Zigzaou		1001659.54	100.165954	1	54	0	
1045	19	19	19-19	C_Natural_Recha		GW_Natural_Recharge		Rch_Oued_Zigzaou		1001659.54	100.165954	1	53	0	
1046	19	20	19-20	C_Natural_Recha		GW_Natural_Recharge		Medenine	Tataouine	1001659.54	100.165954	1	53	0	Other
1047	19	21	19-21	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	53	0	
1048	19	22	19-22	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	53	0	
1049	19	23	19-23	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	53	0	
1050	19	24	19-24	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	53	0	
1051	19	25	19-25	C_Natural_Recha		GW_Natural_Recharge		Rch_Oued_Zeuss		1001659.54	100.165954	1	53	0	
1052	19	26	19-26	C_Natural_Recha		GW_Natural_Recharge		Jerba	Benguerdene	1001659.54	100.165954	1	53	0	Other
1053	19	27	19-27	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	50	0	
1054	19	28	19-28	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	50	0	
1055	19	29	19-29	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	50	0	
1056	19	30	19-30	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	50	0	
1057	19	31	19-31	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	50	0	
1058	19	32	19-32	C_Natural_Recha		GW_Natural_Recharge		Rch_Oued_Oum_Zassar		1001659.54	100.165954	1	50	0	
1059	19	33	19-33	C_Natural_Recha		GW_Natural_Recharge				1001659.54	100.165954	1	25	0	
1060	19	34	19-34	C_Sebkha		GW_Sebkha				1001659.54	100.165954	1	45	0	
1061	19	35	19-35	C_Sebkha		GW_Sebkha				1001659.54	100.165954	1	45	0	
1062	19	36	19-36	C_Sebkha		GW_Sebkha				1001659.54	100.165954	1	45	0	
1063	19	37	19-37	C_Sebkha		GW_Sebkha				1001659.54	100.165954	1	45	0	
1064	19	38	19-38	C_Sebkha		GW_Sebkha				1001659.54	100.165954	1	45	0	
1065	19	39	19-39	C_Sebkha		GW_Sebkha				1001659.54	100.165954	1	45	0	

Figure 45. Screen shoot of the Linkage Shape File of the Area "Zeuss_Koutine_Tunisia".

After reading the connectivity between wells and the demand site nodes, ***ALL_WATER_gw*** created new water sources and transmission links text files as presented in the next figure:



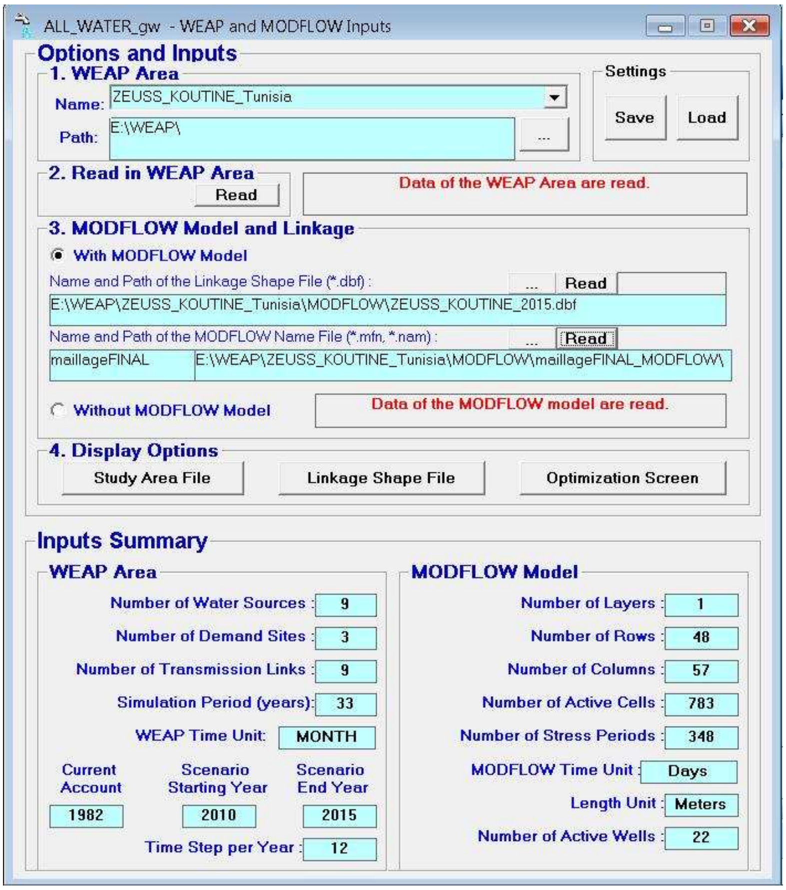
```
# Water sources file created by ALL_WATER_gw after reading the linkage shape file. (05/06/2011).
9_15
GW_Natural_Recharge
 2.083333E+07                       1.5
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
 0              0                   0.834
```

```
# Transmission links file created by ALL_WATER_gw after readi
9_15
GW_Natural_Recharge
Medenine
 0              0              0
Benguerdene
 0              0              0
Jerba
 0.42           0              10
 0              0.776          0
 0              0.776          0
```

Figure 46. Sources and transmission links text files after reading the Linkage Shape File.

5.2.3 Read of the MODFLOW model

As for the Linkage Shape File, it is selected the MODFLOW name file existing in the MODFLOW folder, using the browse option. The click on the “Read” button allows the read of the MODFLOW files. A summary of the MODFLOW model is displayed in the “Inputs Summary” of the user interface, as presented in next figure:



Name: ZEUSS_KOUTINE_Tunisia

Path: E:\WEAP\

Data of the WEAP Area are read.

● With MODFLOW Model

Name and Path of the Linkage Shape File (*.dbf) :

E:\WEAP\ZEUSS_KOUTINE_Tunisia\MODFLOW\ZEUSS_KOUTINE_2015.dbf

Name and Path of the MODFLOW Name File (*.mfn, *.nam) :

maillageFINAL E:\WEAP\ZEUSS_KOUTINE_Tunisia\MODFLOW\maillageFINAL_MODFLOW\

○ Without MODFLOW Model

Data of the MODFLOW model are read.

Number of Water Sources : 9

Number of Demand Sites : 3

Number of Transmission Links : 9

Simulation Period (years): 33

WEAP Time Unit: MONTH

Current Account: 1982

Scenario Starting Year: 2010

Scenario End Year: 2015

Time Step per Year : 12

Number of Layers : 1

Number of Rows : 48

Number of Columns : 57

Number of Active Cells : 783

Number of Stress Periods : 348

MODFLOW Time Unit : Days

Length Unit : Meters

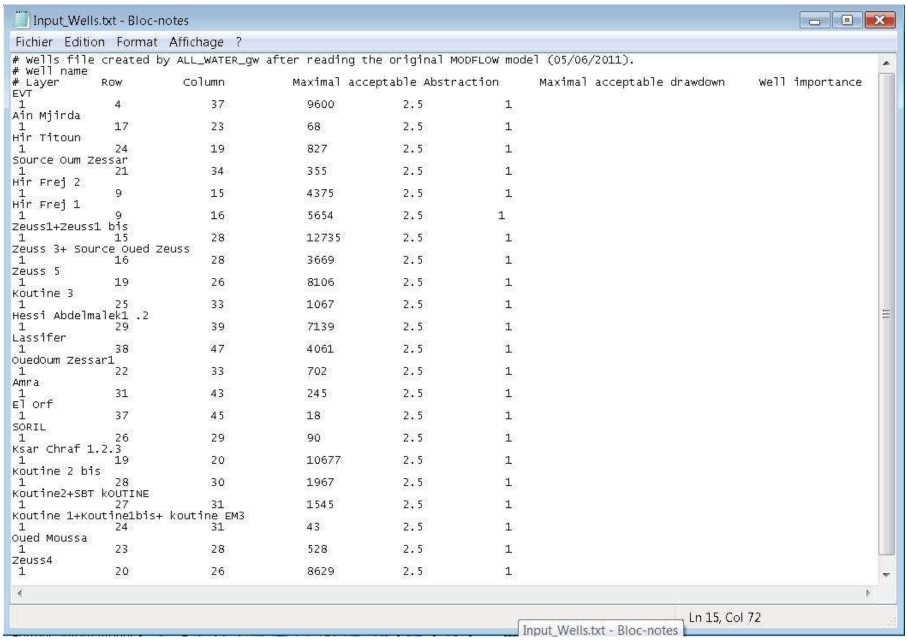
Number of Active Wells : 22

Figure 47. User interface of ***ALL_WATER_gw*** after reading the MODFLOW model.

The summary shows that the MODFLOW model is formed by 1 layer, 48 rows and 57 columns. It contains 783 active cells and 22 active wells.

To prepare the optimization step, an ***ALL_WATER_gw*** well file is automatically created to consider the constraints “Well Maximal Abstraction” and the “Drawdown Impact”.

The first constraint used is the “Maximal Acceptable Abstraction”. It is considered equal to the maximal abstraction observed in the history of each well, read from the MODFLOW well file. The second constraint is the “Maximal Acceptable Drawdown”. Seen that from 1965 to 2010, the average drawdown observed in the main piezometer of the aquifer (Glib Ettine) is about 0.5 m per year (Yahiaoui, 2011), it is chosen a maximal acceptable drawdown for the period 2010 – 2015 equal 2.5 m, for all the wells cells. In the present study, it is considered that all the wells have the same importance. Next figure shows this file after editing:



```
# wells file created by ALL_WATER_gw after reading the original MODFLOW model (05/06/2011).
# well name
# Layer      Row         Column          Maximal acceptable Abstraction      Maximal acceptable drawdown     Well importance
EVT
 1           4           37              9600        2.5           1
Ain Mjirda
 1           17          23              68          2.5           1
Hir Titoun
 1           24          19              827         2.5           1
Source Oum Zessar
 1           21          34              355         2.5           1
Hir Frej 2
 1           9           15              4375        2.5           1
Hir Frej 1
 1           9           16              5654        2.5          1
Zeuss1+Zeuss1 bis
 1           15          28              12735       2.5           1
Zeuss 3+ Source Oued Zeuss
 1           16          28              3669        2.5           1
Zeuss 5
 1           19          26              8106        2.5           1
Koutine 3
 1           25          33              1067        2.5           1
Hessi Abdelmalek1 .2
 1           29          39              7139        2.5           1
Lassifer
 1           38          47              4061        2.5           1
OuedOum Zessar1
 1           22          33              702         2.5           1
Amra
 1           31          43              245         2.5           1
El orf
 1           37          45              18          2.5           1
SORIL
 1           26          29              90          2.5           1
Ksar Chraf 1.2.3
 1           19          20              10677       2.5           1
Koutine 2 bis
 1           28          30              1967        2.5           1
Koutine2+SBT kOUTINE
 1           27          31              1545        2.5           1
Koutine 1+Koutine1bis+ koutine EM3
 1           24          31              43          2.5           1
Oued Moussa
 1           23          28              528         2.5           1
Zeuss4
 1           20          26              8629        2.5           1
```

Figure 48. ***ALL_WATER_gw*** well file after editing.

The required data from the WEAP-MODFLOW framework are loaded by ***ALL_WATER_gw***. The optimization step is started by a click on the button “Optimization Screen”.

5.3 Groundwater Management Optimization

The decision variables are the monthly “Maximum Flow Percent of Demand” of the 9 Transmission Links supplying the demand sites “Medenine”, “Jerba” and “Zarzis”. It means that ***ALL_WATER_gw*** have to identify the best values of 648 variables: abstractions of 72 months (6 years) for the 9 transmission links.

To ensure good results for the management optimization, it is performed first the management optimization without the MODFLOW model. This step allows an easy identification of the best parameters of the optimization. In second step, the management optimization with the MODFLOW model is done, considering the results and using the parameters identified in the first step.

For the present study, it is used a personal computer with 64-bit operating system, 2 processors cores (i3) and a total amount of system memory of 4.00 GB RAM.

5.3.1 Objectives and Constraints

The first task on the optimization step is to choose the objectives and the constraints to be considered by the optimization process. Because the WEAP Area contains a MODFLOW model, as specified in the data inputs step, ***ALL_WATER_gw*** proposed to perform the optimization considering all the objectives (Demand Satisfaction, Drawdown Minimization, Cost Reduction and Quality Satisfaction) and all the constraints (Link Maximal Capacity, Drawdown Impact and Well Maximal Abstraction) offered by the software. For the “Zeuss_Koutine_Tunisia” Area, all the objectives and the constraints are considered. In the first optimization step, the “Drawdown Minimisation” objective and the associated constraints are deactivated.

5.3.2 Genetic Algorithm Parameters

One of the hard tasks of the optimization is the definition of the Genetic Algorithm parameters. The best way is always to start with lower values of the “Maximal Number of Iterations” and the “Population size”. If the algorithm does not converge, it is needed to increase their values. The default values can be used as a starting point.

As explained in the user manual, the execution time is a function of the “Maximal Number of Iterations” and the “Population size”. The presence of a MODFLOW model reduces the computation speed and execution time is highly increased.

The first execution tests of ***ALL_WATER_gw***, without MODFLOW model, leads to the use of the next parameters values:

- Maximal Number of Iterations = 10 000,
- Population size = 30,
- Mutation Probability = 10 %,
- Percentage of Elitism = 50 %,
- Archive Set Size = 100.

With MODFLOW model, it is used next values:

- Maximal Number of Iterations = 1500,
- Population size = 30,
- Mutation Probability = 4 %,
- Percentage of Elitism = 50 %,
- Archive Set Size = 100.

5.3.3 Objectives Weights

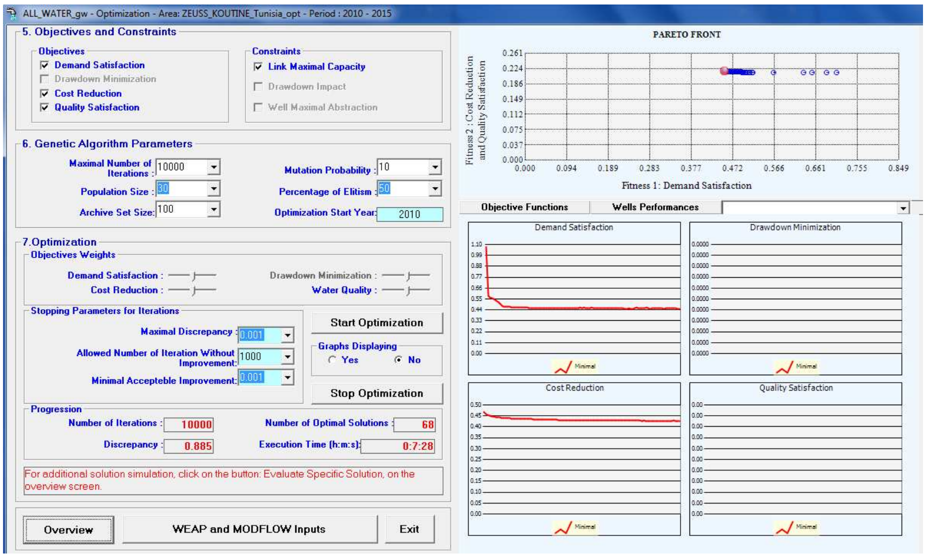
The specificity of the study area and the supplied cities leads to consider the same importance of the four objectives (50 %). Indeed, for drinking water, it is not allowed to have water shortage. Seen the strategic importance of Zeuss Koutine aquifer for the Eastern South of Tunisia, the minimization of the drawdown have the same importance. As detailed before, the specific cost of the water supplied from Zeuss Koutine is important. In addition, the desalinization of salty groundwater and the sea water consume much energy and are characterized by height costs. The managers are usually anxious about the management cost reduction while supplying water with acceptable quality. Thus, it is considered the same weights (50 %) for the “Cost Reduction” and the “Quality Satisfaction” (50 %) objectives.

5.3.4 Stopping parameters for iterations

To control the accuracy of the results, it is chosen a “Maximal Discrepancy” of 0.001. To prevent stagnation of the research, it is chosen a “Minimal Acceptable Improvement” of the “Discrepancy” equal to 0.001 and an “Allowed Number of Iteration Without Improvement” of 1000. Theses three parameters allow ***ALL_WATER_gw*** to stop the computation process before reaching the maximal number of iterations.

5.4 Optimization results without MODFLOW model

After 7 minutes and 28 seconds of execution time, without graphs displaying, it is identified 68 optimal solutions. The lowest “Discrepancy” is equal 0.885. Next figure is a screen shoot of the ***ALL_WATER_gw*** optimization user interface:



ALL_WATER_gw - Optimization - Area: ZEUSS_KOUTINE_Tunisia_opt - Period : 2010 - 2015

5. Objectives and Constraints

Objectives

☑ Demand Satisfaction
☐ Drawdown Minimization
☑ Cost Reduction
☑ Quality Satisfaction

Constraints

☑ Link Maximal Capacity
☐ Drawdown Impact
☐ Well Maximal Abstraction

6. Genetic Algorithm Parameters

Maximal Number of Iterations : 10000
Population Size : 30
Archive Set Size: 100
Mutation Probability : 10
Percentage of Elitism : 50
Optimization Start Year: 2010

7.Optimization

Objectives Weights

Stopping Parameters for Iterations

Maximal Discrepancy : 0.001
Allowed Number of Iteration Without Improvement: 1000
Minimal Accepteble Improvement: 0.001

Graphs Displaying ○ Yes ● No

Progression

Number of Iterations : 10000
Discrepancy : 0.885
Number of Optimal Solutions : 68
Execution Time (h:m:s): 0:7:28

For additional solution simulation, click on the button: Evaluate Specific Solution, on the overview screen.

Figure 49. Screen shoot of the ***ALL_WATER_gw*** optimization user interface without MODFLOW model.

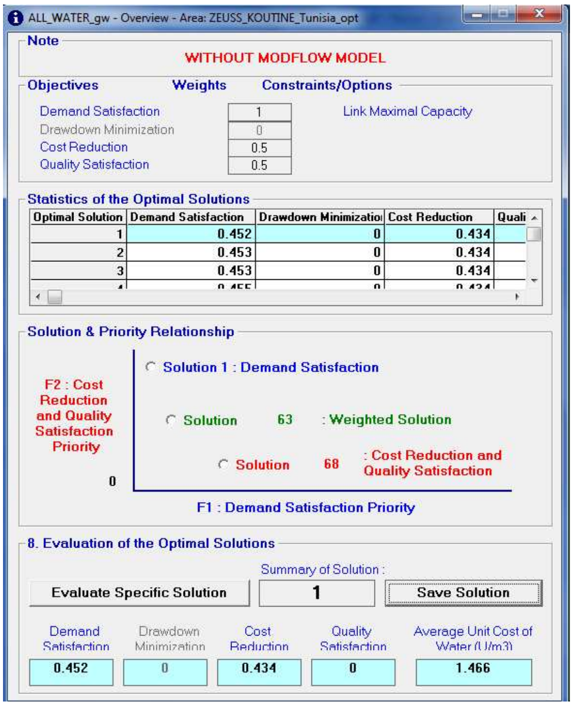
The identified optimal solutions form a PARETO front representing the relationship between the two fitness functions: the Demand Satisfaction and the Cost Reduction, in this case study. Theses optimal solutions disposition demonstrate that they have almost the same unit cost of water. The analysis of the objectives functions evolutions over iteration demonstrate that the quality requirements are satisfied in all the considered demand sites. The “Demand Satisfaction” objective function presents exponential tendency characterized by two phases:

- First phase: between 1 and 1000 iterations where the reduction rate of the objective function is the higher. At the end of this phase, the most important reductions of the objectives functions are done.
- Second phase: iteration great than 1000 where the reduction rate of the objective function become small and small. For great number of iterations, the reduction rate is almost zero. It is considered that the Genetic Algorithm converged to the optimal solutions.

For the “Cost Reduction” objective function, the reduction rate seems to be linear during the iteration process. As for the “Demand Satisfaction” objective function, there is no visible reduction for great number of iterations.

The last remarks lead to the conclusion that for time computing and solution accuracy efficiency, it is not necessary to perform great number of iterations. It will be sufficient for this example to perform 1000 iterations to get acceptable results.

Solution 1, characterized by the best demand satisfaction, is chosen to evaluate and to be compared with the WEAP “Reference” scenario. The overview user interface is used to simulate this solution, as shown in figure 50.



ALL_WATER_gw - Overview - Area: ZEUSS_KOUTINE_Tunisia_opt

Note

WITHOUT MODFLOW MODEL

Objectives	Weights	Constraints/Options
Demand Satisfaction	1	Link Maximal Capacity
Drawdown Minimization	0	
Cost Reduction	0.5	
Quality Satisfaction	0.5	

Statistics of the Optimal Solutions

Optimal Solution	Demand Satisfaction	Drawdown Minimizatio	Cost Reduction	Quali
1	0.452	0	0.434	
2	0.453	0	0.434	
3	0.453	0	0.434	

Solution & Priority Relationship

8. Evaluation of the Optimal Solutions

Summary of Solution :

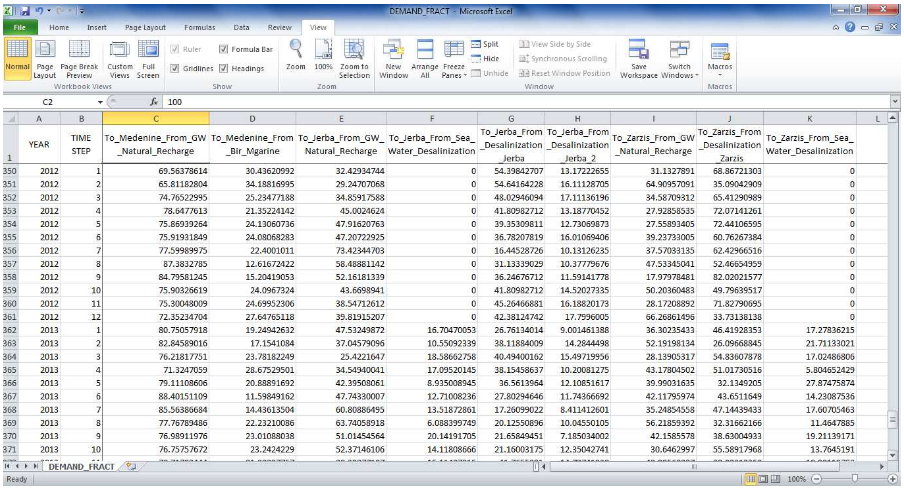
1

Demand Satisfaction	Drawdown Minimization	Cost Reduction	Quality Satisfaction	Average Unit Cost of Water (U/m3)
0.452	0	0.434	0	1.466

Figure 50. Evaluation of the optimal solutions 1.

For the chosen solution, the average unit cost of water is estimated to 1.466 KWh/m^3.

To simulate an optimal solution in WEAP, to be compared with existing scenarios, it is required to read the “Maximal Flow Percentage of Demand” from the “DEMAND_FRACT.csv” file produced by ***ALL_WATER_gw***. Next figure is an overview of this file:



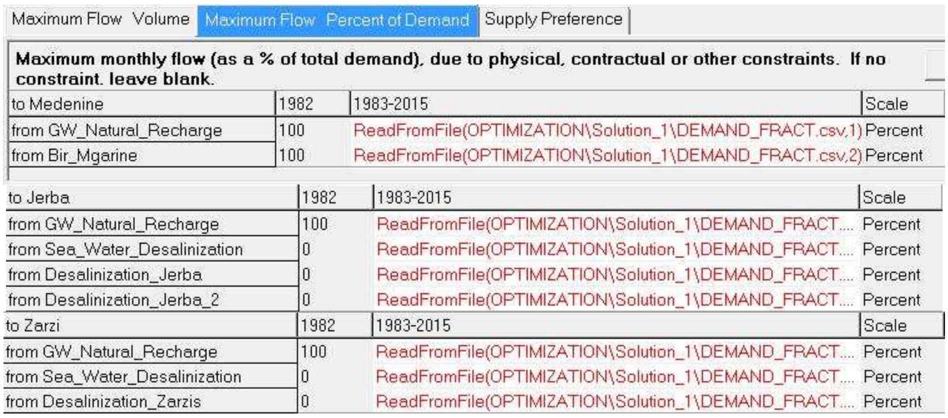
DEMAND_FRACT - Microsoft Excel

C2 100

	A	B	C	D	E	F	G	H	I	J	K
1	YEAR	TIME STEP	To_Medenine_From_GW_Natural_Recharge	To_Medenine_From_Bir_Mgarine	To_Jerba_From_GW_Natural_Recharge	To_Jerba_From_Sea_Water_Desalinization	To_Jerba_From_Desalinization_Jerba	To_Jerba_From_Desalinization_Jerba_2	To_Zarzis_From_GW_Natural_Recharge	To_Zarzis_From_Desalinization_Zarzis	To_Zarzis_From_Sea_Water_Desalinization
350	2012	1	69.56378614	30.43620992	32.42934744	0	54.39842707	13.17222655	31.1327891	68.86721303	0
351	2012	2	65.81182804	34.18816995	29.24707068	0	54.64164228	16.11128705	64.90957091	35.09042909	0
352	2012	3	74.76522995	25.23477188	34.85917588	0	48.02946094	17.11136196	34.58709312	65.41290989	0
353	2012	4	78.6477613	21.35224142	45.0024624	0	41.80982712	13.18770452	27.92858535	72.07141261	0
354	2012	5	75.86939264	24.13060736	47.91620763	0	39.35309811	12.73069873	27.55893405	72.44106595	0
355	2012	6	75.91931849	24.08068283	47.20722925	0	36.78207819	16.01069406	39.23733005	60.76267384	0
356	2012	7	77.59989975	22.4001011	73.42344703	0	16.44528726	10.13126235	37.57033135	62.42966516	0
357	2012	8	87.3832785	12.61672422	58.48881142	0	31.13339029	10.37779676	47.53345041	52.46654959	0
358	2012	9	84.79581245	15.20419053	52.16181339	0	36.24676712	11.59141778	17.97978481	82.02021577	0
359	2012	10	75.90326619	24.0967324	43.6698941	0	41.80982712	14.52027335	50.20360483	49.79639517	0
360	2012	11	75.30048009	24.69952306	38.54712612	0	45.26466881	16.18820173	28.17208892	71.82790695	0
361	2012	12	72.35234704	27.64765118	39.81915207	0	42.38124742	17.7996005	66.26861496	33.73138138	0
362	2013	1	80.75057918	19.24942632	47.53249872	16.70470053	26.76134014	9.001461388	36.30235433	46.41928353	17.27836215
363	2013	2	82.84589016	17.1541084	37.04579096	10.55092339	38.11884009	14.2844498	52.19198134	26.09668845	21.71133021
364	2013	3	76.21817751	23.78182249	25.4221647	18.58662758	40.49400162	15.49719956	28.13905317	54.83607878	17.02486806
365	2013	4	71.3247059	28.67529501	34.54940041	17.09520145	38.15458637	10.20081275	43.17804502	51.01730516	5.804652429
366	2013	5	79.11108606	20.88891692	42.39508061	8.935008945	36.5613964	12.10851617	39.99031635	32.1349205	27.87475874
367	2013	6	88.40151109	11.59849162	47.74330007	12.71008236	27.80294646	11.74366692	42.11795974	43.6511649	14.23087536
368	2013	7	85.56386684	14.43613504	60.80886495	13.51872861	17.26099022	8.411412601	35.24854558	47.14439433	17.60705463
369	2013	8	77.76789486	22.23210086	63.74058918	6.088399749	20.12550896	10.04550105	56.21859392	32.31662166	11.4647885
370	2013	9	76.98911976	23.01088038	51.01454564	20.14191705	21.65849451	7.185034002	42.1585578	38.63004933	19.21139171
371	2013	10	76.75757672	23.2424229	52.37146106	14.11808666	21.16003175	12.35042741	30.6462997	55.58917968	13.7645191

Figure 51. Overview of the “DEMAND_FRACT.csv” file produced by ***ALL_WATER_gw***.

This is done using the “ReadFromFile” WEAP function. Next figure shows the equations edited by the “Expression builder” of WEAP and displayed in the variable “Maximum Flow Percent of Demand”:



Maximum monthly flow (as a % of total demand), due to physical, contractual or other constraints. If no constraint, leave blank.

to Medenine	1982	1983-2015	Scale
from GW_Natural_Recharge	100	ReadFromFile(OPTIMIZATION\Solution_1\DEMAND_FRACT.csv,1)	Percent
from Bir_Mgarine	100	ReadFromFile(OPTIMIZATION\Solution_1\DEMAND_FRACT.csv,2)	Percent

to Jerba	1982	1983-2015	Scale
from GW_Natural_Recharge	100	ReadFromFile(OPTIMIZATION\Solution_1\DEMAND_FRACT....	Percent
from Sea_Water_Desalinization	0	ReadFromFile(OPTIMIZATION\Solution_1\DEMAND_FRACT....	Percent
from Desalinization_Jerba	0	ReadFromFile(OPTIMIZATION\Solution_1\DEMAND_FRACT....	Percent
from Desalinization_Jerba_2	0	ReadFromFile(OPTIMIZATION\Solution_1\DEMAND_FRACT....	Percent

to Zarzi	1982	1983-2015	Scale
from GW_Natural_Recharge	100	ReadFromFile(OPTIMIZATION\Solution_1\DEMAND_FRACT....	Percent
from Sea_Water_Desalinization	0	ReadFromFile(OPTIMIZATION\Solution_1\DEMAND_FRACT....	Percent
from Desalinization_Zarzis	0	ReadFromFile(OPTIMIZATION\Solution_1\DEMAND_FRACT....	Percent

Figure 52. Equations to read the “Maximum Flow Percent of Demand” from the csv file produced by ***ALL_WATER_gw***.

The WEAP Area results are updated by a click of the results view. In addition to the results presented in section reserved to the build of the DSS, it is presented next comparative results about the “Demand Satisfaction”, the “Transmission Links Flows”, the “Cells Head” and the “Average Cost of Water”.

The first verification of the optimisation results is the “Demand Site Coverage” (% of requirement met). Next figure show that the simulated optimal solution ensures the satisfaction of almost 100 % of the demands:

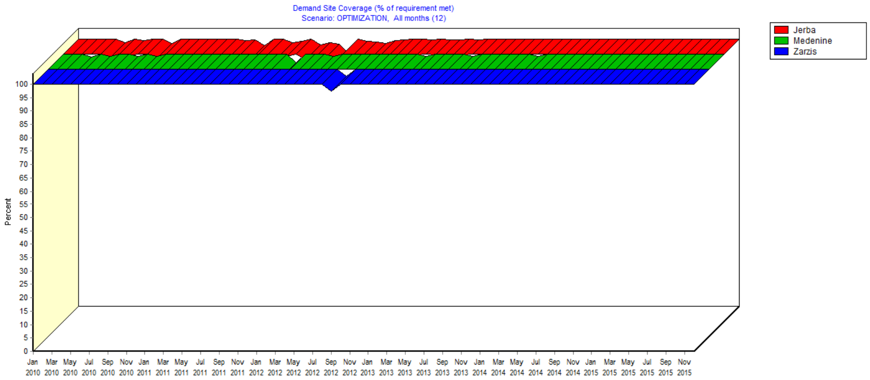


Figure 53. Demand Site Coverage of the simulated optimal solution without MODFLOW model on 2010-2015.

The demand satisfaction is ensured by the water supply presented in the next figures. The first one represents the supply to Medenine city.

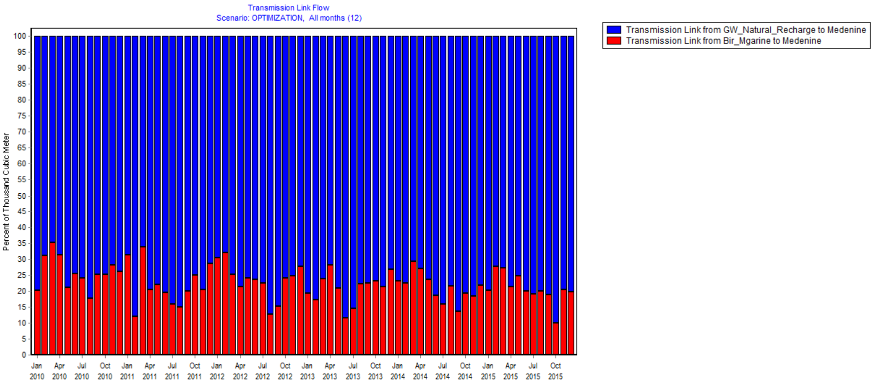


Figure 54. Optimized flows of transmission Links supplying Medenine without MODFLOW model on the period 2010-2015.

It is clear that the “Zeuss Koutine” aquifer (GW_Natural_Recharge) is the main source. This is the result of the pipe limitation coming from the “Bir Mgarine” aquifer. The same supply scheme is observed in the “Reference” scenario. Next figures present the optimal flows of the transmission links supplying Jerba and Zarzis cities:

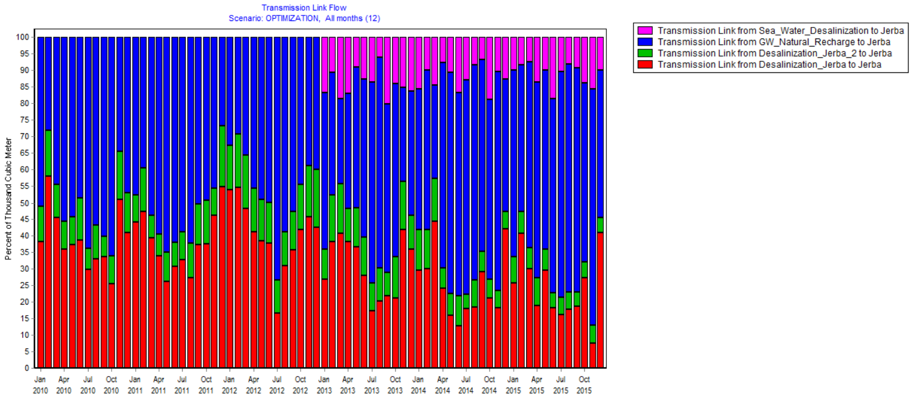


Figure 55. Optimized flows of transmission Links supplying Jerba without MODFLOW model on the period 2010-2015.

To supply Jerba, the optimal solution uses the four water sources. Because of the “Cost Reduction” objective, the “Sea_Water_Desalinization” plant is used as a complement and not as main source, starting from 2013. The “GW_Natural_Recharge” still the most used water source. The “Reference” scenario does not use this water source starting from 2013 (see section 4.3.2). The desalinization plant “Desalinization_Jerba” have to be used largely, up to 50 % in some months, between 2010 and 2013. After this date, its contribution has to be reduced especially in peak demand months. The “Desalinization_Jerba_2” plant can contributes with very small percentage to satisfy the demand of Jerba city.

The optimal water supply of Zarzis city (Figure 56) can be obtained by the use of the three available sources. The “Desalinization_Zarzis” plant and the “Zeuss Koutine” aquifer have to be the most used. Even when the “Sea_Water_Desalinization” plant will be started, its average contribution is about 20 % and does not exceed 30 %.

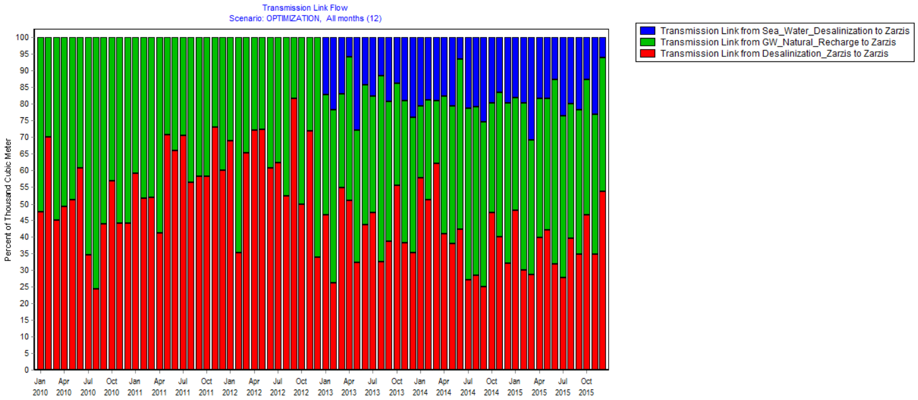


Figure 56. Optimized flows of transmission Links supplying Zarzis without MODFLOW model on the period 2010-2015.

In order to compare the temporal modulation of the piezometers cells heads of the “Reference” and “OPTIMIZATION” scenarios, it is presented the three graphs in figure 58. It is clearly shown that the largely use of the “Sea_Water_Desalinization” plant in the “Reference” scenario lead to the stabilization of the piezometres cells heads of the “Zeuss Koutine” aquifer. For the “OPTIMIZATION” scenario, the cells heads continue their decrease. This result is expected. It is considered only the “Demand Satisfaction” and the “Cost Reduction” objectives in the present run of ***ALL_WATER_gw***. It is also expected to get lower average cost of the water with the “OPTIMIZATION” scenario. Next figure is a comparison of the “Average Cost of Water” between the two scenarios:

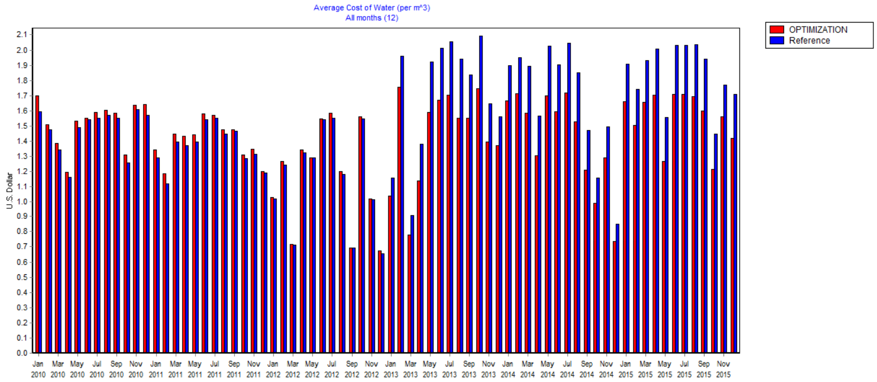
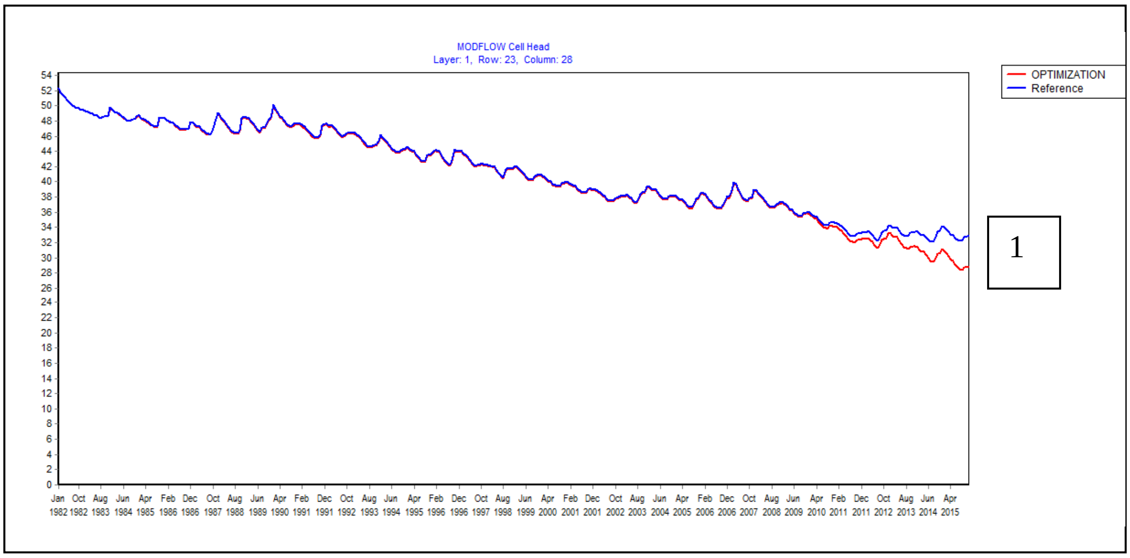
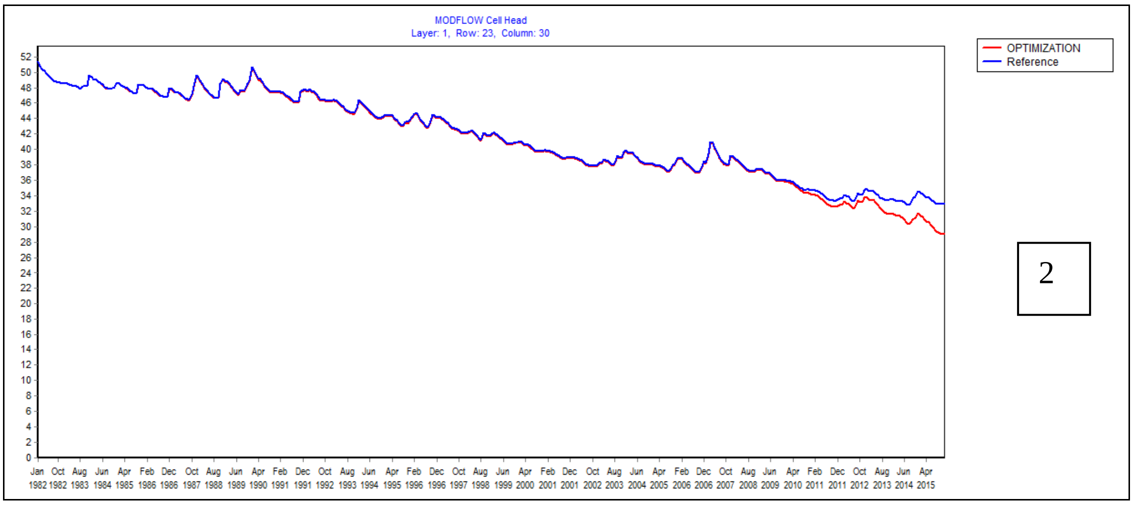


Figure 57. Optimized and Reference “Average Cost of Water” (KWh per m3) with MODFLOW model on the period 2010-2015.

The “Average Cost of Water” is lower with the “OPTIMIZATION” scenario. The difference is observed for almost all the time steps. Starting from 2013, there is a large cost difference between the two scenarios. It is possible to underline that the optimization can reduce the average cost of water by 19 % after 2013 but a greater drawdown will be observed.





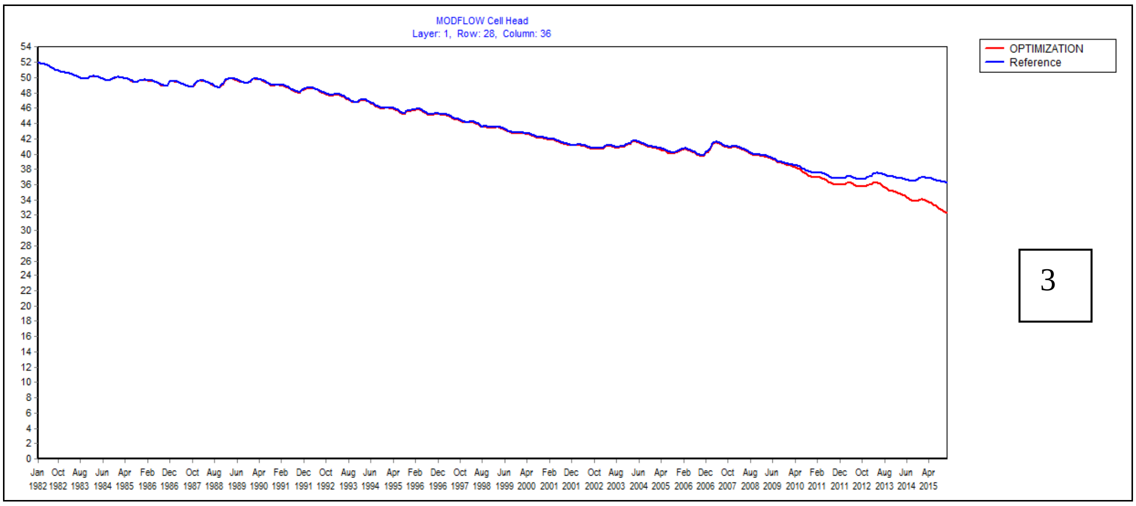
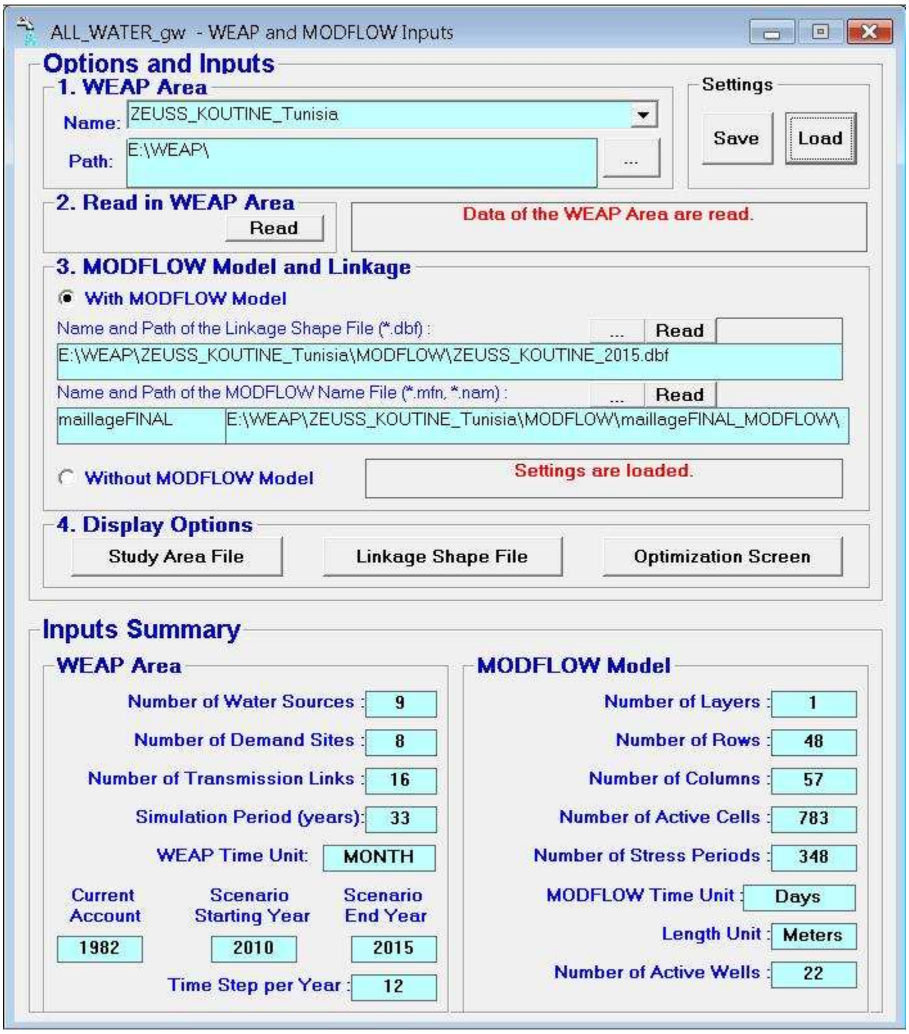


Figure 58. Optimized and Reference cells heads of the piezometers Glib Ettine (1), Koutine (2) and Ghabbey (3) without MODFLOW model.

5.5 Optimization results with MODFLOW model

To identify optimal solution considering the fourth objectives functions and the associated constraints, it is necessary to maintain all the demand site nodes that have a supply from the “Zeuss Koutine” aquifer. Thus, it is required to change the “ChoiceID” parameter of the demand sites nodes used to represent the drainage to the studied aquifer. Next figure show the ***ALL_WATER_gw*** user interface after reading the WEAP Area and editing the demand site file, the linkage shape file and the MODFLOW model.



Name: ZEUSS_KOUTINE_Tunisia

Path: E:\WEAP\

Data of the WEAP Area are read.

● With MODFLOW Model

Name and Path of the Linkage Shape File (*.dbf) : E:\WEAP\ZEUSS_KOUTINE_Tunisia\MODFLOW\ZEUSS_KOUTINE_2015.dbf

Name and Path of the MODFLOW Name File (*.mfn, *.nam) : maillageFINAL E:\WEAP\ZEUSS_KOUTINE_Tunisia\MODFLOW\maillageFINAL_MODFLOW\

○ Without MODFLOW Model

Settings are loaded.

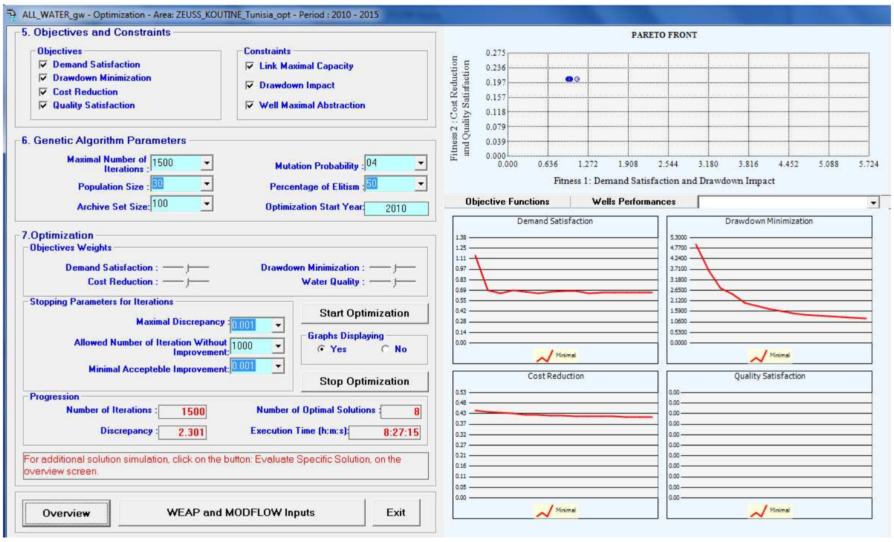
Number of Water Sources : 9
Number of Demand Sites : 8
Number of Transmission Links : 16
Simulation Period (years): 33
WEAP Time Unit: MONTH
Current Account: 1982
Scenario Starting Year: 2010
Scenario End Year: 2015
Time Step per Year : 12

Number of Layers : 1
Number of Rows : 48
Number of Columns : 57
Number of Active Cells : 783
Number of Stress Periods : 348
MODFLOW Time Unit : Days
Length Unit : Meters
Number of Active Wells : 22

Figure 59. User interface of ALL_WATER_gw after reading inputs for optimization with MODFLOW model.

As shown in the previous screen shoot, the optimization problem is formed by 8 demand site nodes supplied by 16 transmission links on 72 months: 1152 decision variables (“Flow Percentage of Demand”). Except the “Maximal Number of Iteration” and the “Mutation Probability” considered equal 1500 and 4, respectively, in this step, the same Genetic Algorithm Parameters and Stopping Parameters of Iterations are used.

After 8 hours, 27 minutes and 15 seconds of execution time, with graphs displaying, it is identified 8 optimal solutions. 45 000 solutions have been evaluated, each with a run of the MODFLOW model. The lowest “Discrepancy” is equal 2.301. Next figure is a screen shoot of the ***ALL_WATER_gw*** optimization user interface:



ALL_WATER_gw - Optimization - Area: ZEUSS_KOUTINE_Tunisia_opt - Period : 2010 - 2015

5. Objectives and Constraints

Objectives
- ☑ Demand Satisfaction
- ☑ Drawdown Minimization
- ☑ Cost Reduction
- ☑ Quality Satisfaction

Constraints
- ☑ Link Maximal Capacity
- ☑ Drawdown Impact
- ☑ Well Maximal Abstraction

6. Genetic Algorithm Parameters

Maximal Number of Iterations : 1500
Mutation Probability : 04
Population Size : 30
Percentage of Elitism : 50
Archive Set Size: 100
Optimization Start Year: 2010

7.Optimization

Objectives Weights

Stopping Parameters for Iterations

Maximal Discrepancy : 0.001
Allowed Number of Iteration Without Improvement: 1000
Minimal Accepteble Improvement: 0.001

Graphs Displaying: ● Yes ○ No

Progression

Number of Iterations : 1500
Number of Optimal Solutions : 8
Discrepancy : 2.301
Execution Time (h:m:s): 8:27:15

For additional solution simulation, click on the button: Evaluate Specific Solution, on the overview screen.

Figure 60. Screen shoot of the ALL_WATER_gw optimization user interface with MODFLOW model.

The identified optimal solutions form a compacted PARETO front representing the relationship between the Demand Satisfaction and the Drawdown Minimization, from one side, and the Cost Reduction and the Quality Satisfaction from the other side. The optimal solutions are characterized by almost the same values of the fitness functions.

The analysis of the objective functions evolution over iteration demonstrates that the three objectives functions displayed show a parallel decrease. The Demand Satisfaction objective function has a same behaviour as in the run without MODFLOW model. There is an important objective function reduction in the first 200 iterations and an asymptotic tendency after that. The Drawdown Minimisation objective function shows a continue reduction up to the last iterations. The Cost Reduction objective function showed also a comparative behaviour as in the previous ***ALL_WATER_gw*** run. There is a small and continue reduction over iteration up to the end of the run. The water quality is not a problem for the present case study. Its objective function is usually equal to 0. All the demand sites get water with the required quality.

As for the first run, the optimal solution that gives the priority to the Demand Satisfaction and the Drawdown Minimization is chosen to be simulated in WEAP and its performances are compared to the “Reference” scenario. The “Demand Sites Coverage” obtained by the simulated optimal solutions for the 8 demand site nodes are presented in the next figure:

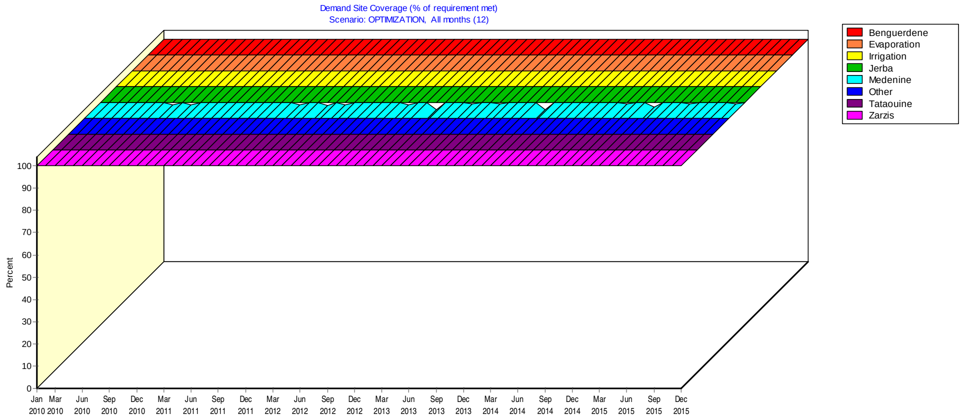


Figure 61. Demand Site Coverage of the simulated optimal solution with MODFLOW model for the period 2010-2015.

The last graph shows that the water demands are satisfied in all the time steps of the optimization period. Next figures explain the water delivered to the demand sites with more than one transmission link. It is the cases of Medenine, Jerba, Zarzis and Benguerdene. For the demand site nodes supplied by one transmission link, the coverage is always 100 %.

The optimal supply scheme of Medenine city is detailed in the next figure:

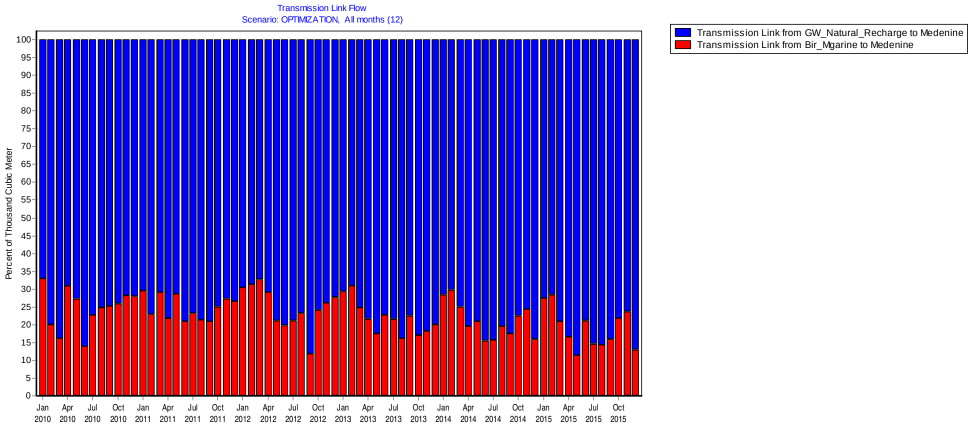


Figure 62. Optimized flows of transmission Links supplying Medenine with MODFLOW model on the period 2010-2015.

Seen the physical limitation of the “Bir Mgarine” transmission link, Medenine city has to be supplied mostly from the “Zeuss Koutine” aquifer. Its contribution is usually more than 70 %. The same option is also need when supplying Benguerdene city. Indeed, “Maouna” aquifer has to be used at almost 100 %, as shown in next figure:

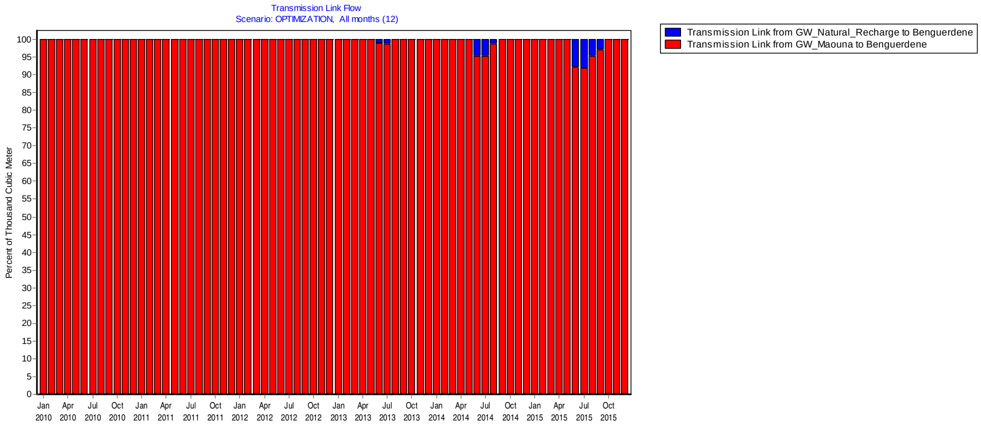


Figure 63. Optimized flows of transmission Links supplying Benguerdene with MODFLOW model on the period 2010-2015.

The optimal solution simulated by WEAP recommends supplying Jerba from “Zeuss Koutine” (45 – 65 %) and “Desalinization_Jerba” plant (55 – 35 %) until 2013. Starting from this date, the “Sea_Water_Desalinization” and “Desalinization_Jerba_2” plants need to be used. The observed result in the next figure is a considerable reduction of the abstraction from the “Zeuss Koutine” aquifer.

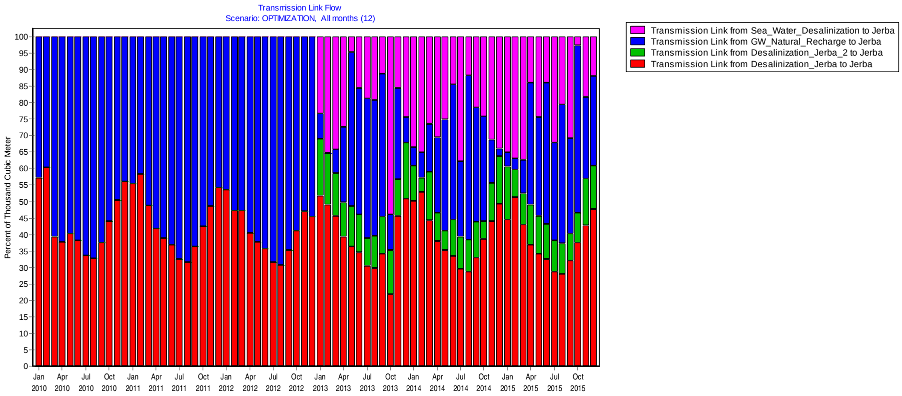


Figure 64. Optimized flows of transmission Links supplying Jerba with MODFLOW model on the period 2010-2015.

To reduce the abstraction from the “Zeuss Koutine” aquifer, the simulated optimal solution proposes to use the “Zeuss Koutine” aquifer only in the peak water demand with a contribution less than 25 % of the monthly demand. The “Desalinization_Zarzis” plant has to be the mostly used until 2013. After, the “Sea_Water_Desalinization” plant becomes the main water source for Zarzis and the abstraction from “Zeuss Koutine” is more reduced. The next figure presents the contribution of each of the water sources to supply Zarzis city.

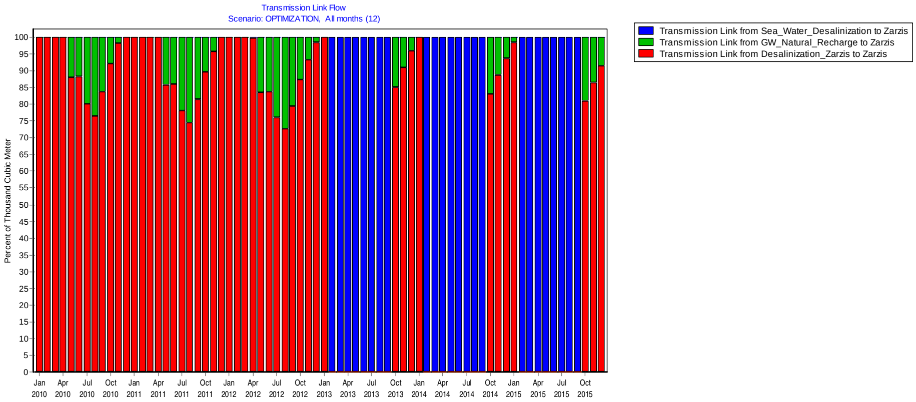


Figure 65. Optimized flows of transmission Links supplying Zarzis with MODFLOW model on the period 2010-2015.

The optimal groundwater management ensures a least “Average Cost of Water” than that characterizing the “Reference” scenario. Next figure detail this WEAP variable:

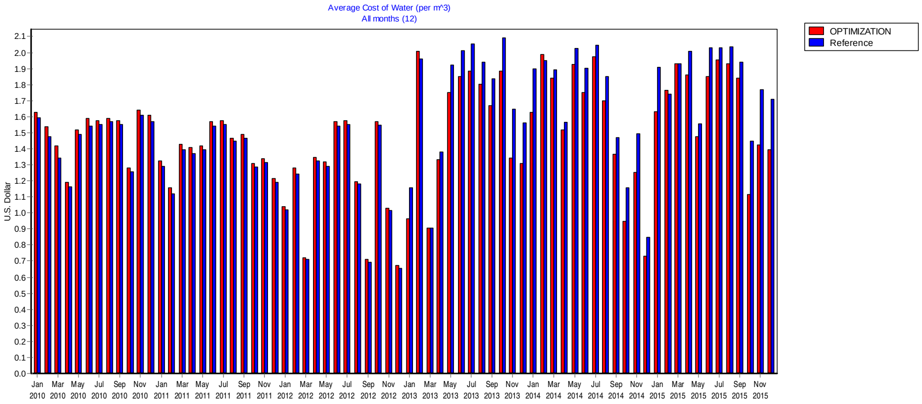


Figure 66. Optimized and Reference “Average Cost of Water” (KWh per m^3) with MODFLOW model on the period 2010-2015.

The monthly relative difference of the average cost of water is presented in the next figure:

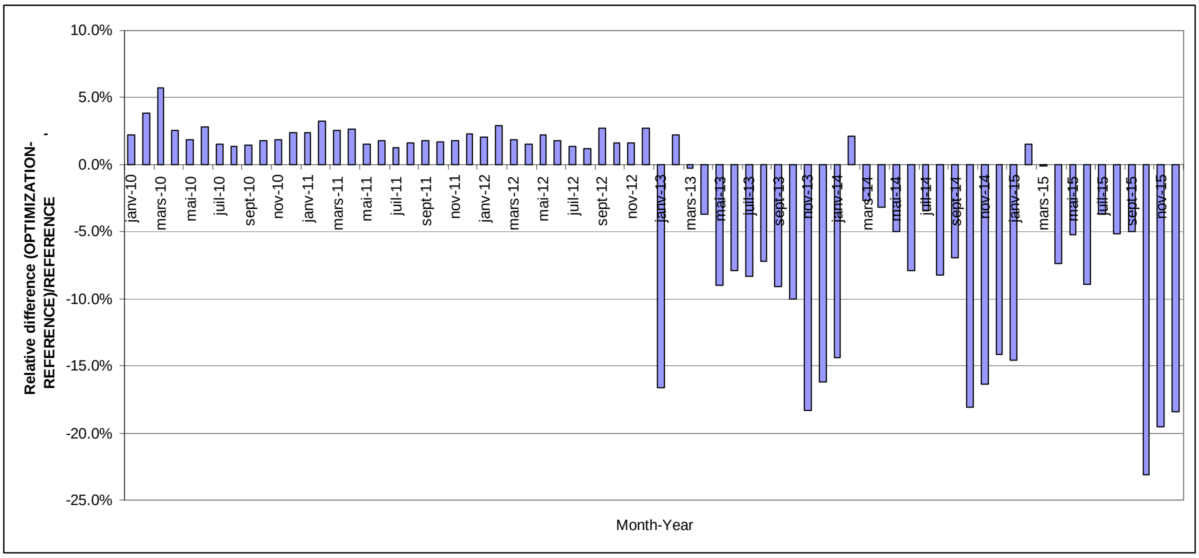


Figure 67. Monthly relative difference of the "Average Water Cost" on the period 2010-2015.

Two phases characterize the relative difference between the optimized and the Reference "Average Cost of Water". In the first one (2010 – 2012), the "OPTIMIZATION" scenario ensures higher costs (+2.1 %) with an average of 1.358 KWh/m^3. When the "Sea_Water_Desalinization" plant will be build (2013), the optimal groundwater management ensures lower average cost, of about 1.597 KWh/m^3. The relative cost reduction is estimated to - 8.3 %.

The optimal groundwater management of the "Zeuss Koutine" aquifer and the other water sources lead to a particular cell heads. Next figure detail the cell heads modulations over time for the main piezometers used to control the "Zeuss Koutine" aquifer.

The three graphs show that the cell heads generated by the simulation of the optimal groundwater abstraction are close to those obtained when the "Reference" scenario is applied. Indeed, the maximal observed difference between the optimized and the reference cell heads is estimated to 2 m, in the piezometer Glib Ettine (Row 23 - Column 28). It represents 5.8 % of the reference cell head. For the piezometers Koutine and Ghabbey, the maximal difference between the optimal and the reference cell heads are 1.9 and 1.7 m, respectively.

In comparison of the optimal cell heads obtained without the "Drawdown Minimization" objective function, it is underlined that considering all the objectives allow the identification of optimal solution that satisfy the demand and the quality requirements and reduce the cost and the continues drawdown.

When considering the "Drawdown Minimization" objective function the optimal solution identifies a groundwater management that reduces in parallel the cost while reducing the continue drawdown. The cost reduction is less than that obtained by the optimization without the MODFLOW model (19 %). It is possible to consider that ***ALL_WATER_gw*** identified a compromise between all the objectives.

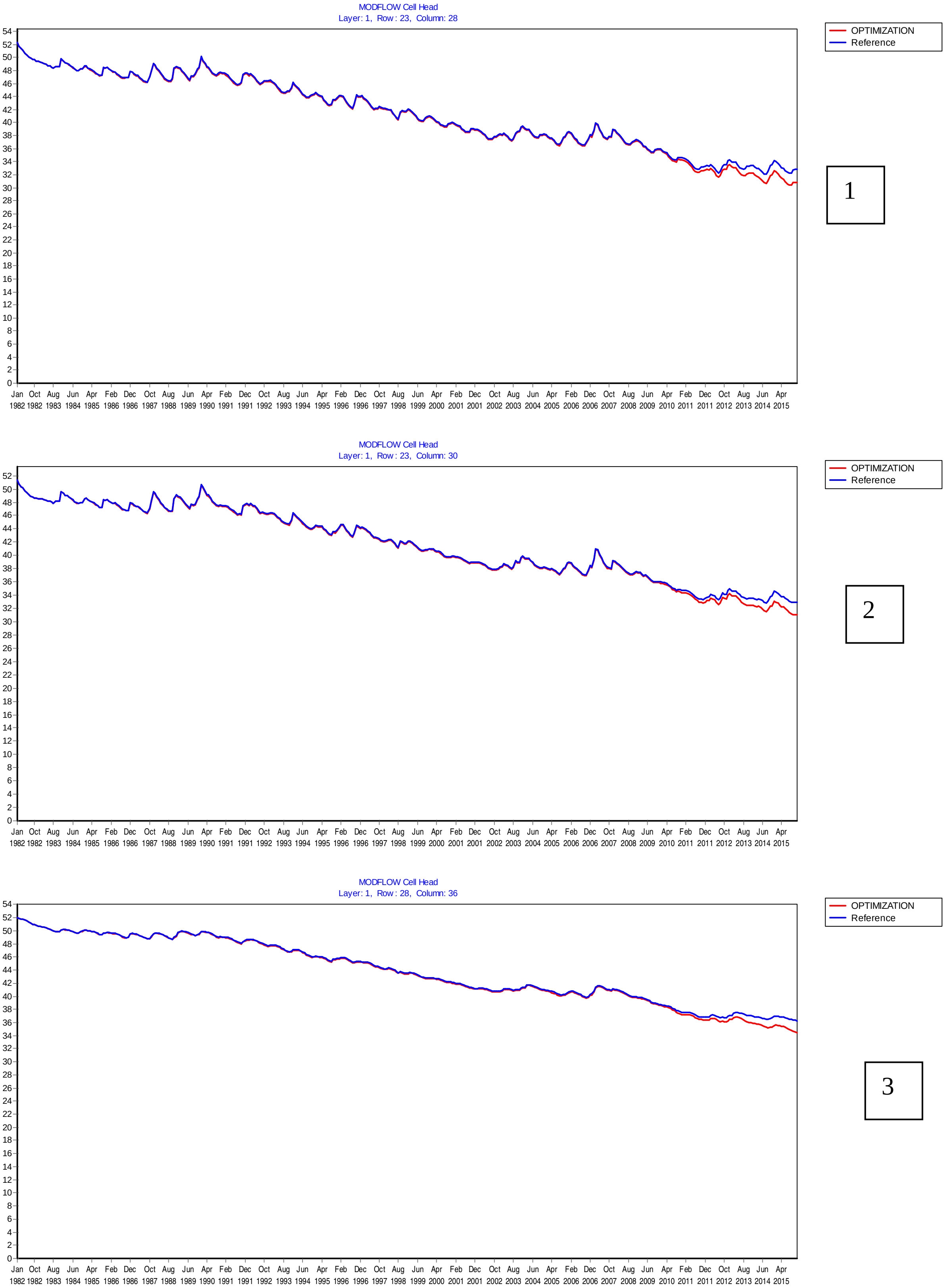


Figure 68. Optimized and Reference cells heads of the piezometers Glib Ettine (1), Koutine (2) and Ghabbey (3) with MODFLOW model.

6 Conclusions

This report has presented in the first part the elaboration of the WEAP-MODFLOW DSS for the “Zeuss Koutine” aquifer in Tunisia. The second part of the report has been reserved to demonstrate the use of the ***ALL_WATER_gw*** software to optimize the groundwater management.

At the end of this document, it is important to conclude that to lead to the groundwater management optimization step; it is required to ensure first the build of MODFLOW model. A monthly time step model will be the better to take profit from the optimization. The second requirement is the WAEP-MODFLOW DSS elaboration. User needs to be familiar with the WEAP functionalities and has to understand all the inputs and outputs of the elaborated DSS. At this level of skill, it will be easy to start using the ***ALL_WATER_gw*** software for groundwater optimization, following the user manual and the present report.

As presented her, the best option is to perform optimization of the case study without the use of the MODFLOW model, as first step. This allows getting long and fast runs to identify the best values of the parameter of the Genetic Algorithm and those for stopping the iterations.

One of the main steps of the optimization is the identification of the demand sites that need to be optimized. It is usually those supplied by more than one transmission link if the MODFLOW model is not used. When the MODFLOW model is used to compute the “Drawdown Minimization” objective function, all the demand site connected to the aquifer, through the linkage shape file, have to be considered, even if they are supplied by only one transmission link.

In the present study, it is required more than 8 hours to get the optimal solutions. This is the result of the problem complexity: 1152 decision variable to be defined. If there is hardware and/or time computing limitation, user has to simplify his problem. This can be done by reducing the number of the demand sites to be optimized, according to their consumption importance or when their optimal management is almost known. The second option is to reduce the optimization period. Indeed, optimize the groundwater management for long period can not be realistic. Physical and hydraulic condition can change over time. It is sufficient to optimize the groundwater management of only one year. There is also the option, offered by ***ALL_WATER_gw,*** to stop the optimization process and to get the identified optimal solution if the allocated time by user is finished.

About the case study results, it is possible to conclude that ***ALL_WATER_gw*** was capable to identify optimal solutions that can improve groundwater management. The simulated solution in WEAP-MODFLOW DSS demonstrated their capability to reduce the “Average Cost of Water”, in comparison with the “reference” scenario, while satisfying all the water demands and the quality requirements. When the MODFLOW model is used and the “Drawdown Minimization” is considered, the optimal solution ensures in addition a visible reduction of the cell head continue decrease. While the “Drawdown Minimization” objective function constitutes a time computing constraints for ***ALL_WATER_gw***, it has a valuated income in the water management optimization.

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