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Refined trans-boundary Numerical groundwater Model and Report on Regional / trans-boundary Water budgets

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TABLE OF CONTENTS

1. Background	4
2. The conceptual model	5
2.1 The Western part	5
2.1.1 Geology	5
2.1.2 Construction of the model	9
2.2 The Eastern part	10
2.2.1 Geology	10
2.2.2 Construction of the model	10
2.2.3 Model Cross-Sections	11
2.3 The Alluvium	17
2.4 Regional hydrology	17
2.4.1 The Western part	17
2.4.2 The Eastern part	18
2.5 Boundary conditions	19
2.6 Replenishment Areas	21
2.7 Data	21
2.7.1 Springs Data	21
2.7.2 Meteorological Data	21
3. The computational model	23
3.1 The computational grid	23
3.2 Mathematical – Numerical Model	25
3.2.1 Mathematical Formulation	25
3.2.2 Boundary conditions	25
3.3 Initial values of hydraulic properties	26
4. Simulation Results	28
5. Conclusions	32

1. Background

A regional computational model, capable of reproducing the groundwater flow pattern within the project area was one of the key expected products of the SMART project phases. The logical steps required for the preparation of such a model, capable, of reliably predicting the groundwater flow behaviour included: 1) the definition of a conceptual, static, model; 2) translating the model into a computational one; 3) assigning values of the hydraulic and replenishment properties; 4) determining conditions and the model border; 5) identifying and representing outlets; and 6) conducting actual simulations under pristine conditions and later on conducting simulation in presence of the various well fields within the model area.

A necessary condition for proceeding was therefore the construction of a conceptual model. This critical phase included a number of tasks as follows:

1. Delineating the model extent, in the west and in the east;
2. Determining the geological layers (essentially the layers bearing water that could be utilized);
3. Producing a digital elevation model of the (elevation and thickness of the layers) of the area;
4. Identifying and representing the key geological features with potential impact on the groundwater flow pattern (faults and flexures);
5. Suggesting a practical approach to connect the rock aquifers in the west and the east with the alluvium of the Valley.
6. Preparing the digital data needed for the construction of the model.

The preparation of the conceptual model was planned to start at the early stages of the SMART/I project. The conceptual model in the eastern part of the domain was under the responsibility of partner Al Balqa University, while the preparation of the conceptual model in the west and its integration to the eastern one was a task to be carried out by Tel-Aviv University. De facto, work started at very late stages of SMART/I. Data was produced and supplied to us, prepared mainly, by Tel-Aviv University group. We then constructed a three dimensional computational mesh, incorporating the supplied data. Unfortunately, the resulting model was inconsistent: layers not located at proper depths, relevant faults were ignored while many non-necessary faults (from a groundwater flow point of view) were included, not clear and/or sound guidance on how to connect the western part to the eastern one was shared with us. Altogether, while the produced model could at first sight appear attractive, it had in our point of view no chance to produce sound groundwater flow pattern.

In SMART/II we therefore decided to rebuild the conceptual model. As it was clear that neither Tel-Aviv nor Al Balqa partners have the required degree of expertise to carry out this kind of task, we received key and substantial help from Dr. Joseph Guttman of Mekorot for the construction of the conceptual model in the West and of Dr. Julia Sawaneh, Professor Elias Salameh and Professor Heinz Hoetzel for the east.

For logistic reasons, work on the eastern part of the domain started in the spring of 2013 and finalized in the summer of the same year. The western part of the model was tackled after that, as we needed to construct it from scratch. It must be stressed that this work was conducted by all the involved partners without any billable time, as the construction of the conceptual model was not under the responsibility of either one of the abovementioned parties. In what follows we shall describe the steps taken for the construction of the model, the assumptions that were made and the resulting model.

2. The conceptual model

The area was divided into three parts:

1. The rock aquifers in the west;
2. The alluvium in the Valley;
3. The Rock aquifers in east.

The matching between the rock aquifers and the alluvium in the west and in the east was achieved by mapping the main faults that cross the model area from north to south. **Table 2.1** below describes the geological layers that were taken into consideration in both parts of the model.

Table 2.1: The layers included in the trans-boundary model.

Layer	Israel	Jordan
12	Neogene	Sediment filling
11	Avedat Gr.	Eocene - Balqa Group B4-B5
10	Mount Scopus	B3 Aquiclude -
9	No equivalent in Israel	B1, B2 Aquifer
8	Turonian	Turonian (A7, WSL)
7	Upper Cenomanian	A56
6	Upper Cenomanian	A4-A6
5	Middle Cenomanian (Moza, Bet Meir)	A3
4	Lower Cenomanian (Kesalon –Kefira)	A1-A2
3	Aptian	Kurnub
2	Lower Cretaceous	Kurnub
1	Jurassic	Azab - ZM

The model comprises 12 geological layers. In order to match the same layer structure in the model we divided the Upper Cenomanian in the west in two layers so we could include the Layers A56 and A4-A6 in Jordan. The Kurnub layer in the east was similarly divided in two layers in order to be able to incorporate the Aptian and Lower Cretaceous in the east.

2.1 The Western part

2.1.1 Geology

The essential guidance in the part of the work was provided by Dr. Joseph Guttman. The principal fault structure in the area is that of the Dead Sea – Jordan Rift Valley. Along the western side of the valley, the fault runs along the western shore of the Dead Sea up to Jericho city in direction N-S, then changes its direction to NW. In the mountain region the predominant elements governing the geological structure and flow regime are the anticlinal and synclinal structures crossing the entire study area. Structural features are presented on top of geological formations in **Figure 2.1**.

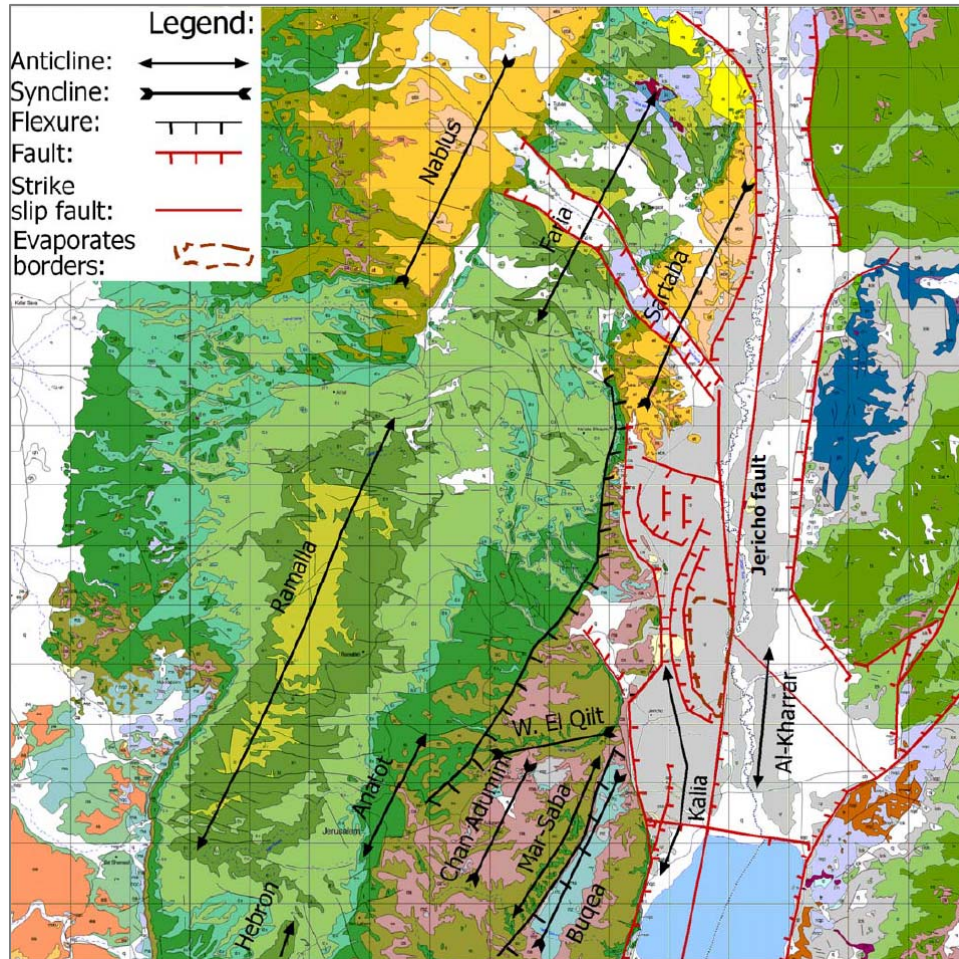


Figure 2.1: Tectonic map showing structures, folding and faulting features (Anker et al. 2009)

The Hebron & Ramallah anticline are the principal structural elements in the west. Its axis runs from the Hebron-Halhul area up to north of Ramallah in a general SW-NE direction. This anticline splits into Anbata - Um el Fahm and Fari'a anticlines. These anticlines axis represent the maximum elevation in the area. To the east and west there are minor folds, representing the descent of the structures towards the plain in the west and the Dead Sea in the east. The anticlines descend in the direction of the Jordan Valley and the Dead Sea in a series of undulations, forming secondary structures (Guttman et al. 2009). Among them are Chan Adumim and Bugea synclines which continue northward to Sartaba syncline, and the Marsaba anticline. Towards east, on top of the syncline structure, Younger formations of Mount Scopus Group, composed mainly of chalk and marls, exposed, whereas older formation of the Judea group exposed on anticline axes. The anticlines and synclines are asymmetric, with steepest inclinations to the eastern part of the anticlines (Yellin-Dror et al., 2009). The north part of the western side, around Vadi Fari'a region, is characterized by intensive fault systems that form grabens, horsts and step structures, exposing older layers of Jurassic and Lower Cretaceous age (**Figure2.2**).

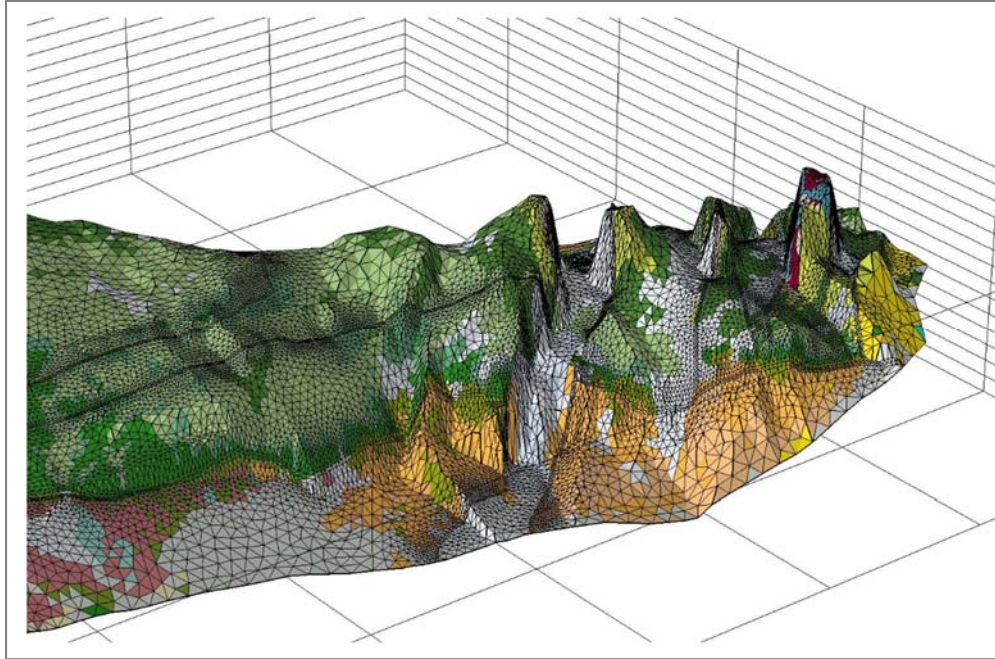


Figure 2.2: 3D illustration of Grabens & Horsts created by an intensive fault system, thus generating a complex geohydrology flow system (3D representation prepared with EWRE – VASP ModelGenerator module).

The stratigraphy profile exposed in the study area varies between the Lower Cenomanian age and much younger formations of the Holocene age. The exposed layers are: ancient formations of Cretaceous age composed mainly of limestone, at the vicinity of the Hebron anticline, in the west; formations of the Mt. Scopus Group, near the Jordan Valley and throughout the Judea Desert; young formations of Pleistocene-Holocene age in the Jordan Valley and along the shores of the Dead Sea as well as in inland wadis and valleys (**Table 2.2**). The Judea group is the main aquifer in the western side of the study area. The thickness of the Judea Group is about 800-850 m and is composed mainly of thick limestone and dolomite with interbedded marly, shaly and chalky horizons. In order to produce the needed digital elevation model, we produced maps of layer thicknesses for the layers comprised in the model.

Table 2.2: Stratigraphic table of rock unit in the study area (after Yellin-Dror et al., 2009)

Age	Group	Formation	Lithological Composition	Thickness [m]	Hydrology	Remarks
Plio-Pleistocene	Dead Sea	Lisan	Clays, silt, conglomerate, gypsum, chalk			Pebble horizons serving as local aquifers
Paleocene		Taqiye	Marl, chalk, clay, limonite concentrations		Aquiclude	
Maastrichtian	Mt. Scopus	Ghareb	Yellowish chalk		Aquiclude	Thickness varies from anticlinal margins to synclinal center
Campanian		Mishash	Chalk with black chert layers	100-400	Aquiclude	
Santonian – Campanian		Menuha	White chalk, some calcareous chalk		Aquiclude	
Turonian		Bina ⁽¹⁾	Fine grained limestone and dolomite	90-100	Aquifer	
		Veradim	Hard gray dolomite, porous	90-100	Aquifer	
Upper Cenomanian		Kefar Shaul	Chalky limestone, chalk, marl	30-40	Aquitard	
		Aminadav	Hard gray dolomite, porous	110-140	Aquifer	
		Moza ⁽²⁾	Marl, clay	10	Aquiclude	Not always present
Lower Cenomanian	Judea	Bet Meir ⁽²⁾	Chalky limestone, bluish clay, chert, dolomite in Bet Meir Lissan	120-140	Aquitard	Bet Meir Tongue constitutes an aquiferous layer
		Kesalon	Limestone and dolomite rich in fossils	30	Aquifer	Poor aquifer due to small thickness
Albian		Soreq	Limestone and marly dolomite, marl and some chert	110-170	Aquitard	Limestone and dolomite horizons constitute an aquifer
		Givat Yearim	Hard dolomite, at times also limestone	20-40	Aquifer	
		Kefira	Limestone alternating with marl	160-180	Aquifer	Profile at the base is marly
		Qatana	Marl with some limestone	50	Aquiclude	
Aptian	Kurnub	Ein Qinya	Limestone	60-70	Aquifer	
		Tammun	Limestone, marl and some sand	Base not Penetrated	Aquitard	

⁽¹⁾ The Bina Fm. divides into three formations in the eastern part of the study area, namely: Netzer, Shivta and Derorim Fms.

⁽²⁾ The Moza and Bet Meir Fms. are referred to as the Ein Yorge'am Fm. in the eastern part of the study area (Begin, 1976).

A series of West-East cross sections and sampling wells (**Figure**), combined with layer thickness data presented in **Table 2.2**, was used to estimate layer thickness above and below Bottom Judea

reference level. Cross sections were digitized to create digital elevation/thickness (xyz) data set which was then interpolated, creating representative surfaces of geological formations. The surface were then merged, generating a 3D geological model having its upper level truncated with the surface topography. Validation of the model achieved by comparing exposed geological formation with the geological map created by the Geological Survey of Israel.

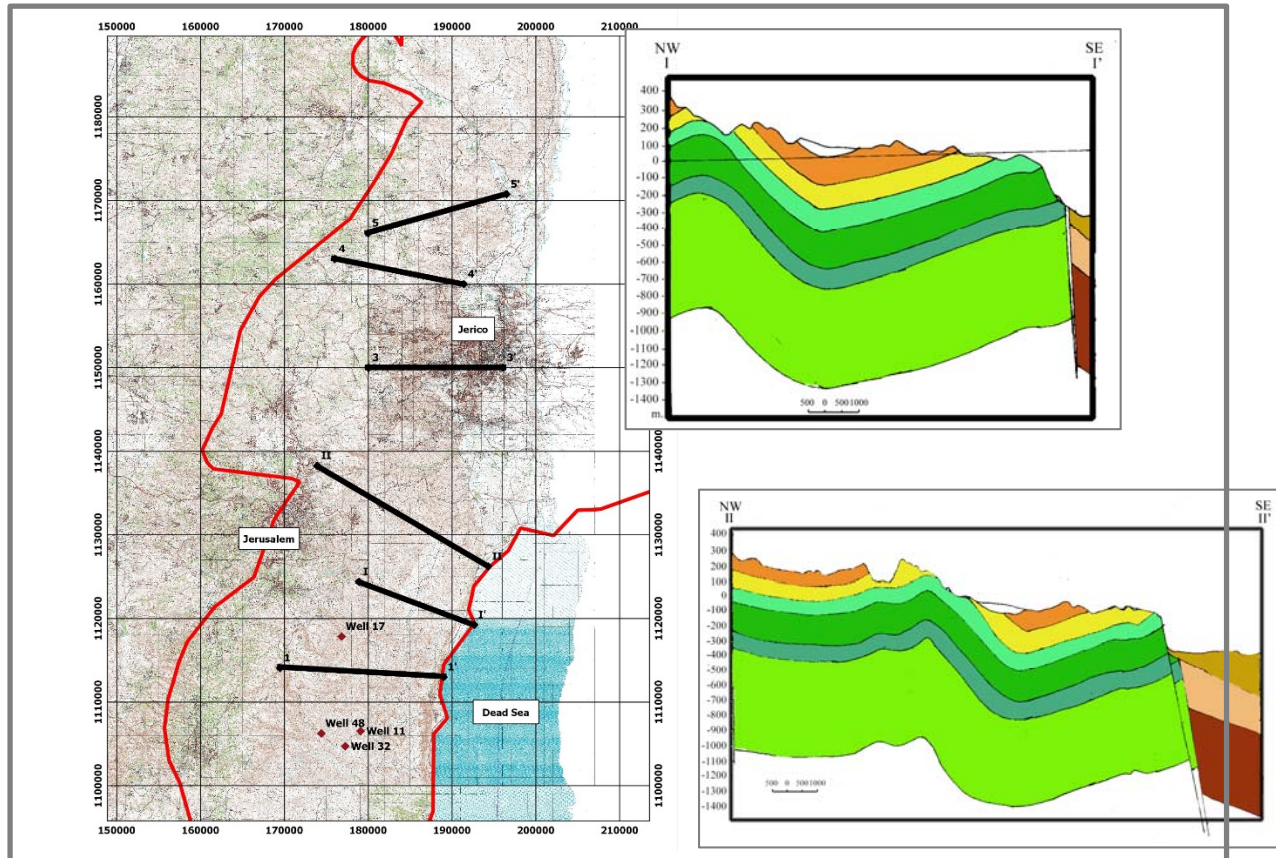


Figure 2.3: Western side cross sections layout (left) and examples (right).

2.1.2 Construction of the model

The model was constructed with EWRE-VASP software, which can create the computational mesh and incorporate digital elevation data of the various layers to be included in the model. The western side part of the model was constructed using Bottom Judea (Kfira formation) structural map (Guttman, 2000). This was chosen as a reference layer since it spreads over a major part of the model being the bottom layer of the main aquifer. Part of this map is illustrated in Figure 2.4. This is different from the approach adopted by the Tel-Aviv group, who actually selected the top of the Judea Formation as the base layer for the construction of the digital elevation model. The model was then constructed with an updated and highly reworked digital map of the bottom of the Judea formation as base layer, and a digital elevation model of ground surface topography (provided by J. Hall of the Israel Geological Survey), and maps of layer thickness above and below the base map. In the upper part of the model, the layers were truncated by the ground surface topography. VASP can then create a map of the exposed layers (outcrops) that could be then compared with the geological map. The construction was therefore iterative required substantial effort. It must be stressed that this area suffers from an acute lack of data and therefore the elevation of the bottom Judea formation had to be amended in order to produce a map of the exposed layers that could be satisfactorily compared to the geological map.

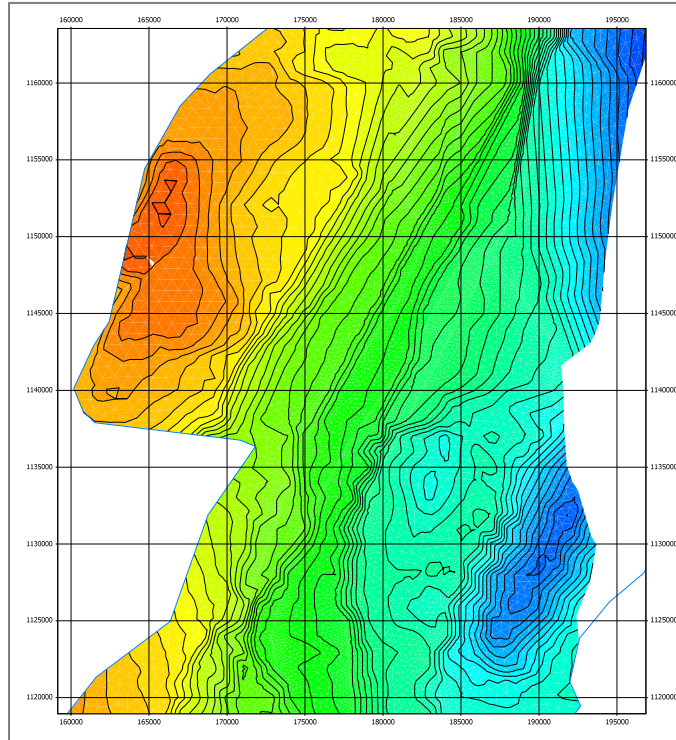


Figure 2.4: Part of Bottom Judea structural map

2.2 The Eastern part

2.2.1 Geology

The Eastern part of the model was constructed following a similar approach, by Dr. Julia Sawaneh. Here, the top Kurnub served as leading layer. As in the west, the ground surface topography served as a limiting layer. All The data regarding Kurnub topography, the layers thicknesses and the ground surface topography were supplied by Dr. Sawaneh, and are reported in her Doctoral Dissertation. These will not be reproduced in this document.

2.2.2 Construction of the model

The model was constructed in a similar way, using the VASP. First, we produced a computational mesh in the plane that could incorporate the major geological features, with potential impact on the groundwater flow pattern.

2.2.3 Model Cross-Sections

Id	Section_ID	X_Pal	Y_Pal
A	A1	199934	1145299
	A2	214355	1135856
B	B1	209621	1184036
	B2	226621	1139850
C	C2	233434	1164721
	C1	203404	1188401
D	D1	197583	1193164
	D2	226819	1193362
E	E1	197318	1212942
	E2	233434	1219887
F	F1	197252	1223988
	F2	231119	1224649
G	G1	197252	1221011
	G2	230788	1237019
H	H1	220072	1239466
	H2	220072	1137403

Geological Materials Key									
Alluvium_valley	B3	A7	A4	A1-A2	ZM				
JordanCascadesNS	B4	B1-B2	A5-A6	A3	Kurnub				

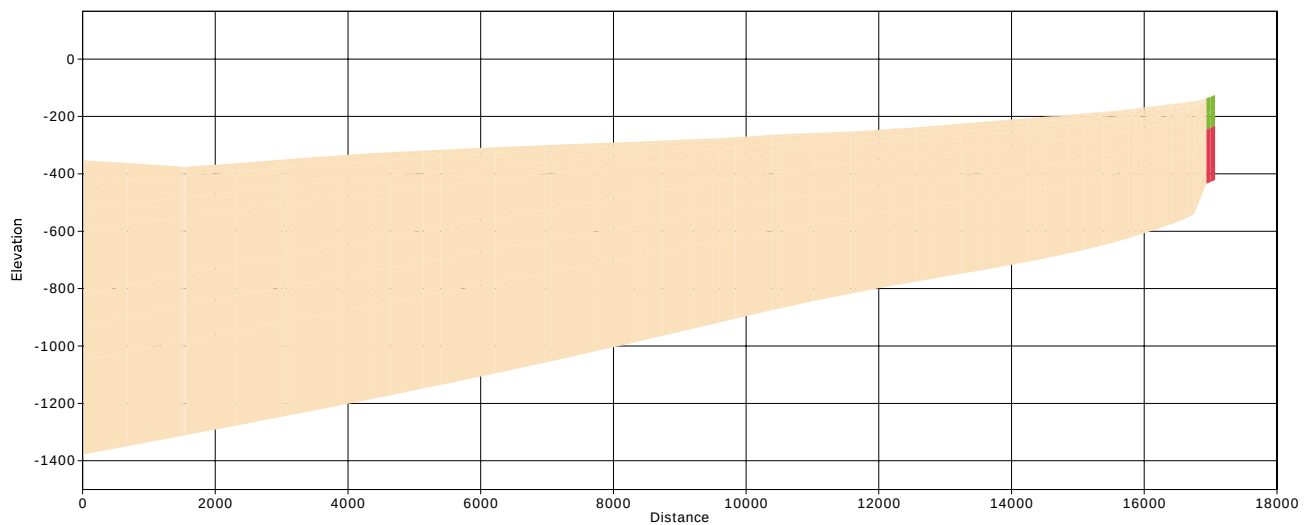


Figure 2.5: Cross-Section AA.

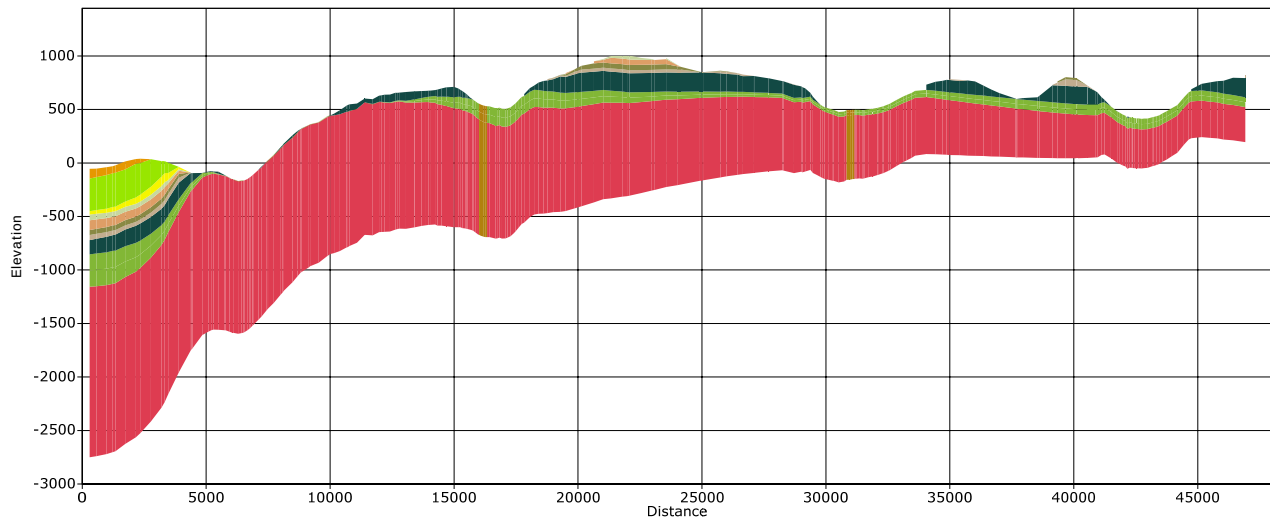


Figure 2.6: Cross-Section BB

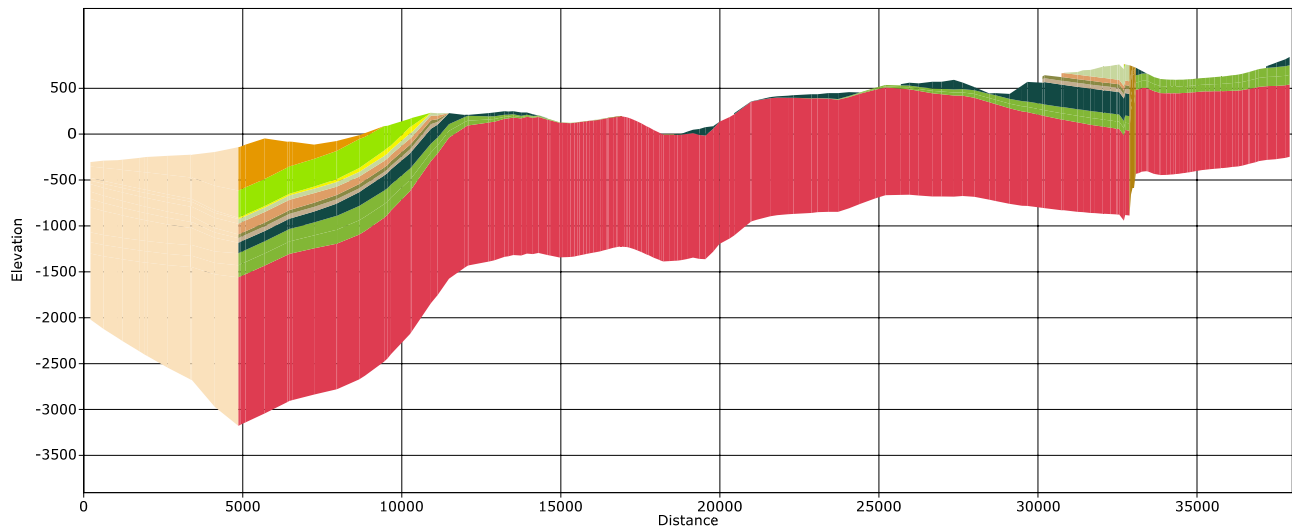


Figure 2.7: Cross-Section CC.

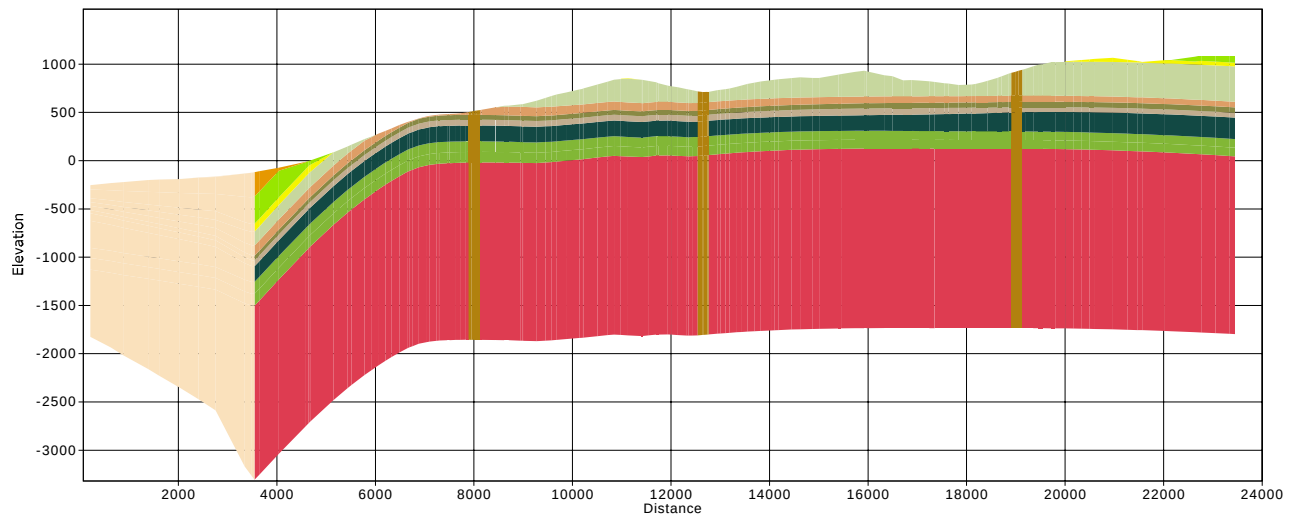


Figure 2.8: Cross-Section DD.

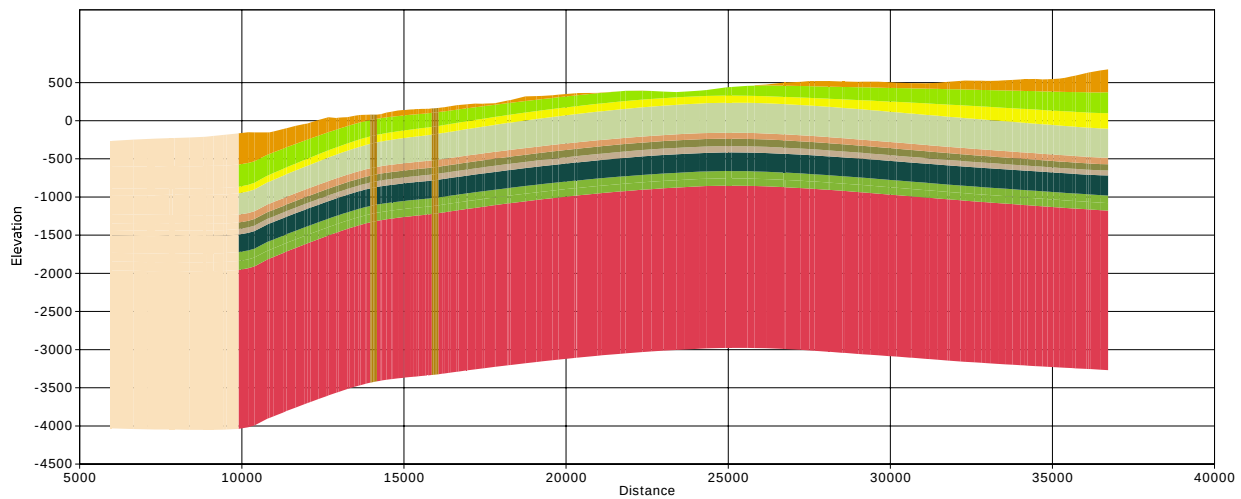


Figure 2.9: Cross-Section EE.

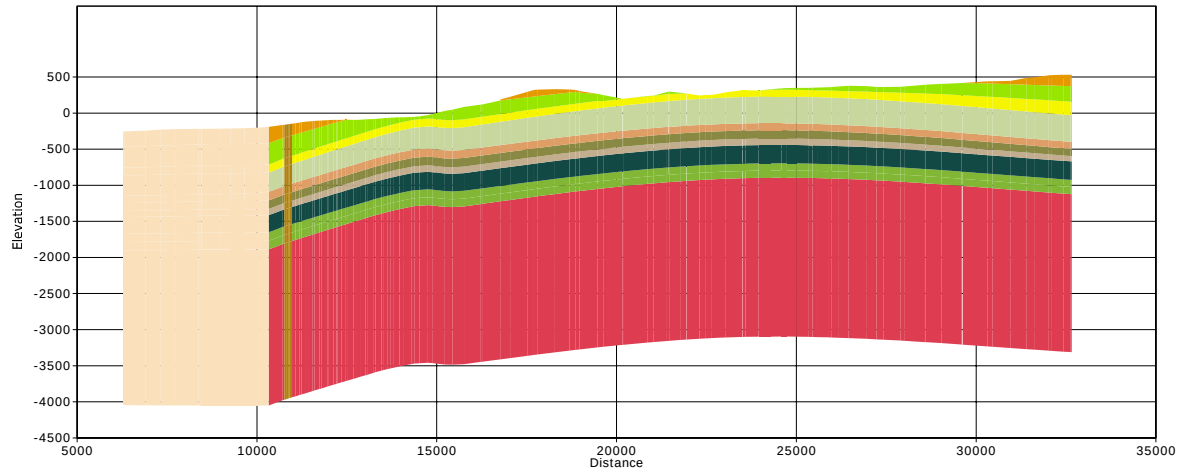


Figure 2.10: Cross-Section FF

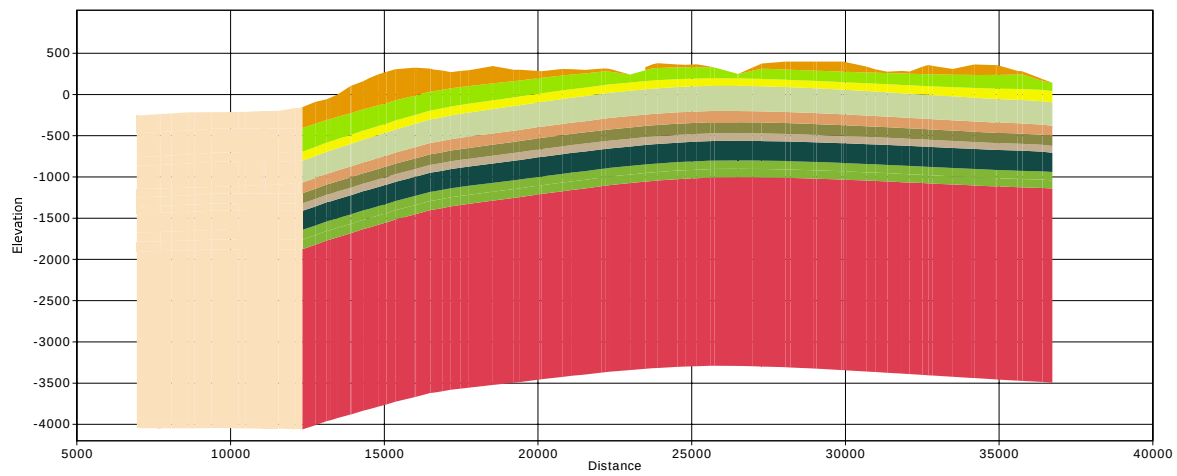


Figure 2.11: Cross-Section GG

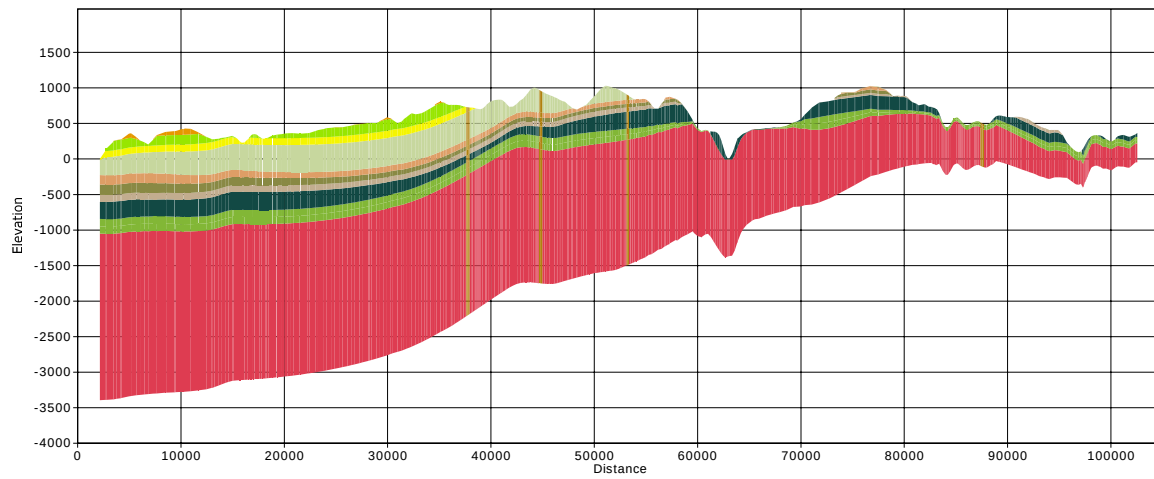
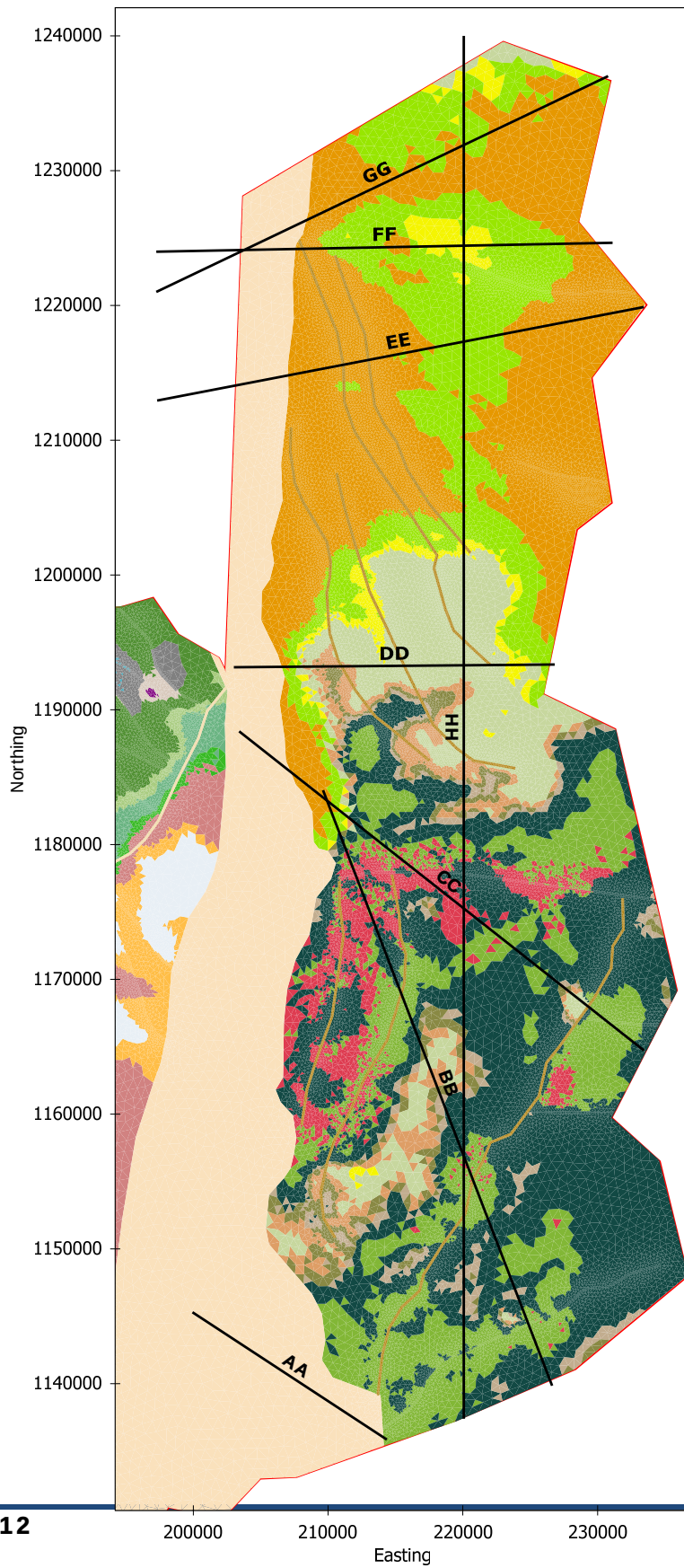


Figure 2.12: Cross-Section HH.



2.3 The Alluvium

The Alluvium in the Valley was then constructed between bounded on the east and the west by two major faulting systems, running from north to south. The models of the west and the east were then snapped to these faults.

2.4 Regional hydrology

2.4.1 The Western part

The current research mainly focuses on the the two regional sub-aquifers, the “Upper aquifer” (upper Cenomanian) and the “Lower Aquifer” (Lower Cenomanian). The separation between the two sub-aquifers is validated by significant differences in the groundwater piezometric heads. In most of the area mean water level in the upper aquifer is higher than in the lower aquifer.

Two major regional flow systems were identified, on the basis of geochemical and isotopic analyses (see bibliography list):

- An upper system which is not connected to the current research, known also as “The Springs System” equivalent to the Turonian Aquifer, and characterized by a well-developed Karstic system with high flow regime that drains mostly through the Wadi Kelt and the Jericho springs.
- The lower system also known as “The Well System” is characterized by slow flow regime. At the vicinity of the recharge area, the age of the water established by Kroitoru is 1,800 years in the Jerusalem-6 Borehole and 2900 years in the Jerusalem-4 borehole. According to Rosenthal (1992) the age found in the Jerusalem-4 is 5730 years. The “Well System” is equivalent to the Lower and Upper Aquifers. Rosenthal and Kronfeld (1992) made an effort to divide the Well System into two sub-systems in order to try and characterize the Upper Aquifer and the Lower Aquifer.
- Salinity concentrations in the west are low in both the upper and lower aquifers (an average of 30 mg Cl/L). In the east (Mizpeh Jericho and eastwards) there are differences in the water salinity between the two sub-aquifers. Salinity in the Upper aquifer in Mizpeh Jericho-3 and 5 and Jericho-2 wells is of 50-500 mg Cl/L and much higher in the lower aquifer up to 12,000 mgCl/L in the Jericho-2 well (Guttman, 2000).
- The springs in the research area can be divided into two main groups:
 - o The wadi Kelt and the Jerusalem springs acting as an outlet of the Uppermost Turonian Aquifer and were not included in the flow model.
 - o The Fesh’ha and the Dead-Sea springs acting as the outlets of the regional Upper and Lower Aquifers which are the subject of the current research.
- The geological structure dictates subsurface groundwater flow paths. The natural recharge of the aquifer is from rainfall penetrates to the layers in the western part of the model.

The geological structure dictates subsurface groundwater flow paths. The source of aquifer recharge is directly influenced by rainfall on the western exposed aquifer geological strata. In general the flow direction in the area is from west to east and the groundwater outlet is located in the Feshkha springs. Groundwater levels change from over +700m in the south - west part of the area to +450 m to +550 m (at the vicinity of the Jerusalem wells) in west. In the eastern boundary of the basin, close to the

Dead-Sea, the water level is about –400 m. The 1100 m difference in water levels from west to east over a relatively short distance of about 30 km means that the calculated flow gradient should be of ~ –3%. A close look at the water level data in the available wells reveals that the flow gradient cannot be constant and the change in the groundwater head elevation is the result of series of drops instead of a continuous change.

A relatively high gradient of more than -9% exists between the Jerusalem-5 well (+360 m) and the Azaria-1 well (-15 m) where the distance between the wells is about 4 Km. On the other hand a lower gradient of 0.8% was measured between Maale Adumim-2 well and the Mizpeh Jericho wells where the distance between the wells is about 6 Km and the water level difference is about 50 m.

This behaviour of the hydraulic gradient can be explained only by a geological structure in the form of underground “cascades”. The Cascades like structure is the result of the asymmetric geological structures crossing the area. The flexure (cascade) area is of low permeability, which causes a water level drop in the eastern lowermost areas of the flexure. The flow gradient in the uppermost areas of the flexure is relatively moderate. The current study defined four flexures crossing the model area from north to south. The flexure structure determines the flow system, the flow gradients and the water levels in the research area

There are many evidences that the geological structure influences the groundwater regime and flow directions in the study area. Data from the Mizpeh Jericho wells has shown that in the Marsaba Anticline, the Upper Aquifer geological strata (the Aminadav formation) is located probably above the regional water level. It could explain why the groundwater flow from the west turns to the north (and probably to the south) towards the Mizpeh Jericho well field located in a small syncline within the Marsaba Anticline. The groundwater flow continues from there to the Feshkha springs (Guttman, 2000).

In the vicinity of the Uja wells, north of Jericho, the base of the lower aquifer is located above or near the ground water table as a result of the Ein Samiya fault system and the monocline of En Far'a – Wadi Fari'a.

Consequently, a local hydrogeological barrier exists in the area. The local water divide creates conditions according to groundwater flow in the area to the north of the Uja wells is towards the Jordan Valley while groundwater flow in the area south of the Uja wells is towards the Dead Sea springs.

2.4.2 The Eastern part

Hydrogeologically, the different geological groups of the Mesozoic and Tertiary sediment sequence in the study area were divided into three **major aquifer systems**. These are: the Lower Aquifer System (Kurnub Sandstone Aquifer), and the Middle Aquifer System (Hummar A4, Na'ur A1-2 and Amman/ Wadi as Sir B2/A7 Aquifers) and the Shallow Aquifer System (B4/B5, Basalt and the Jordan Valley Aquifers). Each aquifer has different hydrogeological characteristics. These aquifer systems are serving as source of water for all types and uses in the study area.

The **Lower Aquifer System** (Kurnub Sandstone Aquifer) is the second most important aquifer in the study area. The aquifer receives direct and indirect recharge where it outcrops on the eastern escarpment of the Jordan Valley and the northern part of the Dead Sea. In Jarash, Al Baqa'a and along the Zarqa River and its tributaries direct recharge from precipitation occurs. In the Highlands recharge to the aquifer occurs by leakage from the Upper Cretaceous aquifers, percolating through fractures and faults. This aquifer is an unconfined-confined aquifer system, draining towards the Dead Sea, Jordan Valley and Yarmouk River. Waters from the Lower Aquifer System discharges along the Zarqa River due to the weathering of Kurnub Sandstone in that area. The groundwater flow within

this aquifer is predominantly vertical in the vicinity of the Jordan Rift Valley. The aquifer gains water through the downward leakage from the B2/A7 aquifer and losses water through upward leakage to the B2/A7 due to the high confinement degree and to the fact that the potentiometric surface of the Kurnub Aquifer is higher than that of the B2/A7. The upwards seeps from the Kurnub Aquifer to the surface, pass through the recent sediments forming saline springs (Wadi Mallaha).

In the study area the **Middle Aquifer Systems** (B2/A7, A4 & A1-2 Aquifers) is directly recharged from precipitation along their outcrops in the highlands and the slopes of the Jordan Valley. They are also recharged by leakage of runoff and irrigation return flow. The **B2/A7 aquifer** (Amman/Wadi as Sir Formations, separated by **B1**, Wadi Um Ghudran) is the major aquifer in the study area. It is directly recharged from precipitation along its outcrops in the highlands and the slopes of the Jordan Valley. Moreover the limestones of this aquifer are highly karstified therefore, it facilitates fast infiltration of rain water to the aquifer. The groundwater flow direction in the Upper Aquifer System is directed from the mounds in the area between Ajlun Mountain and Jarash, mainly to the northeast, to Ramtha Basin and Mafraq area and partly to the northwest to the western escarpment, to Wadi El-Arab and Mukheiba. Mainly, the groundwater flows in this aquifer come from the Syrian border in the north (Jabal Arab-Druze) to the area north and northeast of Mafraq, from there the water converges with the water coming from southwest and partially with water coming from Ajlun area. From there the water flows mainly, westwards to the Jordan Rift Valley and the Yarmouk River areas, where most of the discharge occurs. It partially flows towards the depressional area south of the Zarqa River after converging, due to high elevated structure of Ajlun structure. While, in the southeast of the study area i.e. the area southeast of Amman flexure, the groundwater flow within the B2/A7 aquifer system is directed partly northwest towards Zarqa River and partly southwest towards Wadi el Wala.

The outcrop area of the **A1-2 and A4 aquifers** is limited in extent and receives small amount of direct recharge in the study area. The minor aquifer (**A4**, Hummar & **A1-2**, Na'ur)/aquitards (**A3**, Fuheis & **A5-6**, Shueib) of the study area or what is known as A1-6 (Lower Ajlun) sequence behave very complex. Groundwater flow within A1-2 and A4 aquifers are localized within two areas characterized by high faulting and fracturing. These are the area NW of Zarqa River and the area between the southern eastern part of Zarqa River and Amman flexure. Generally, the faults and fractures increase the porosity and permeability of rocks in the study area as a result of extensional tectonics. Therefore, where faults occur the A1-6 sequence communicate with B2/A7 aquifer and/or the Kurnub aquifer and that communication is better with B2/A7.

The **Shallow Aquifer System** includes the B4/B5, Basalt and the Jordan Valley Aquifers. The **B4 aquifer system** is of local importance in the area north of Irbid and Ramtha. This area is characterized by deeply incised wadis, which act as drainage channels. Numerous springs mark spots of emergence of groundwater. The groundwater flow in the B4 aquifer system is mainly towards the Yarmouk River, but a small part also to wadi el 'Arab and the Jordan River.

2.5 Boundary conditions

The western and eastern boundaries of the model is assumed to match the groundwater divide that separates flow from the western and eastern parts of the mountain aquifer in Israel and Jordan. The northern and southern boundaries are assumed to be streamlines through which no flow takes place. The Dead Sea boundary deserves a much finer treatment. The subsoil along this segment is filled with brines. A precise representation of this boundary would have required taking into consideration density dependent flow and brine transport. However, since this approach is beyond the scope of the project, which deals only with the flow processes, a boundary condition of type I (fixed head) was assumed, across the full depth. Initial Conditions

Initial head map was automatically constructed based on well points static head data, which was then interpolated to the entire model regime using the Renka algorithm.

Map of the initial groundwater head in the model is presented in **Figure 2.13**.

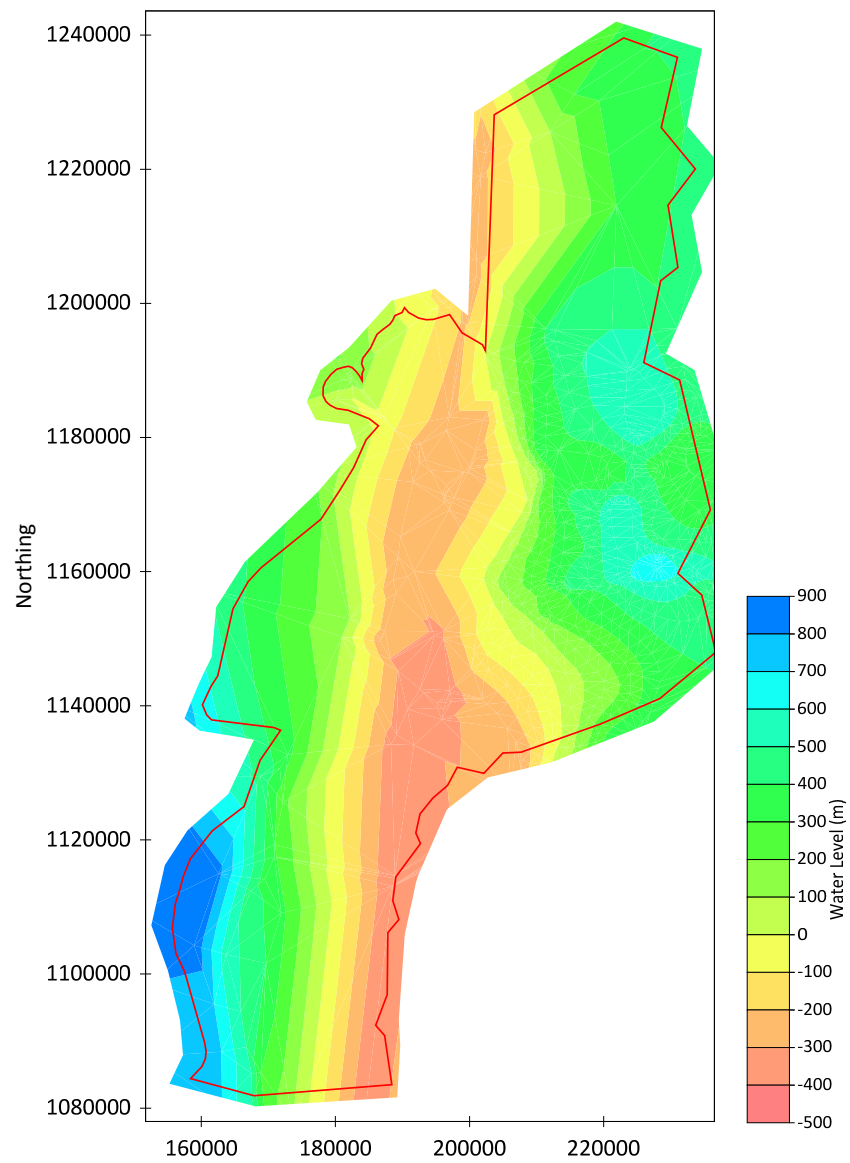


Figure 2.13: Groundwater head initial conditions

2.6 Replenishment Areas

Replenishment is from rainfall only and it occurs mainly in the edges of the western and eastern parts of the model. The replenishment areas are based on the mapping of the outcrops of the geological formations, hence representing the spatial variability of the model area.

Figure 2.14: replenishment un-calibrated coefficients.

Material	Name	α_p	Material	Name	α_p
1	ZM	0.3	101	Jurassic	0.2
2	Kurnub	0.3	102	LowerCretaceous	0.2
3	A1_A2	0.3	103	Aptian	0.2
4	A3	0	104	LowerCenomanian	0.3
5	A4	0.3	105	MiddleCenomanian	0.1
6	A5_A6	0	106	UpperCenomanian	0.3
7	A7	0.3	107	Turonian	0.3
8	B1_B2	0.3	108	Senon	0
9	B3	0	109	Avedat	0
10	B4	0.4	110	Neogene	0
11	Alluvium	0	1000	Alluvium_valley	0

2.7 Data

2.7.1 Springs Data

The main springs in the Israel side of the model are Feshkha (Zukim), Samar and Kane springs. These are located in the North-West shore of the Dead Sea. Springs water originates from the upper Cenomanian aquifer.

The Feshkha springs are not usually monitored, as these are surface springs, spread over a relatively large area of 3-4 km along the Dead Sea shore. It is extremely difficult to measure their discharge. Measurements vary from 32-40 MCM/Year (Tahal, 6 measurements during the period 1984-1986) to 80-85 MCM/Year (the Israel Hydrological Service, 1992-93). This discrepancy may also be due to the effect of the uncommonly rainy year of 1991-92.

The Kane and Samar springs have a discharge that is estimated to be of the order of 20-30 MCM/Year. Further south located the Ein Gedi and Sholamit springs which have total discharge of less than 5 MCM/year.

2.7.2 Meteorological Data

The amount of rainfall in the Israel Eastern part and in Jordan is governed mainly by the topographic elevation of a location. Rainfall decreases sharply from the 500-700mm/year in the western edge of the area (Hebron- 575 mm; Jerusalem – 554 mm; Ramallah – 647 mm) to less than 100-150 mm/year in the Jordan valley (Jericho – 163 mm, and less than 100 mm in the Dead-Sea shore), and increase again above the Jordanian mountain up to 600 mm/year.

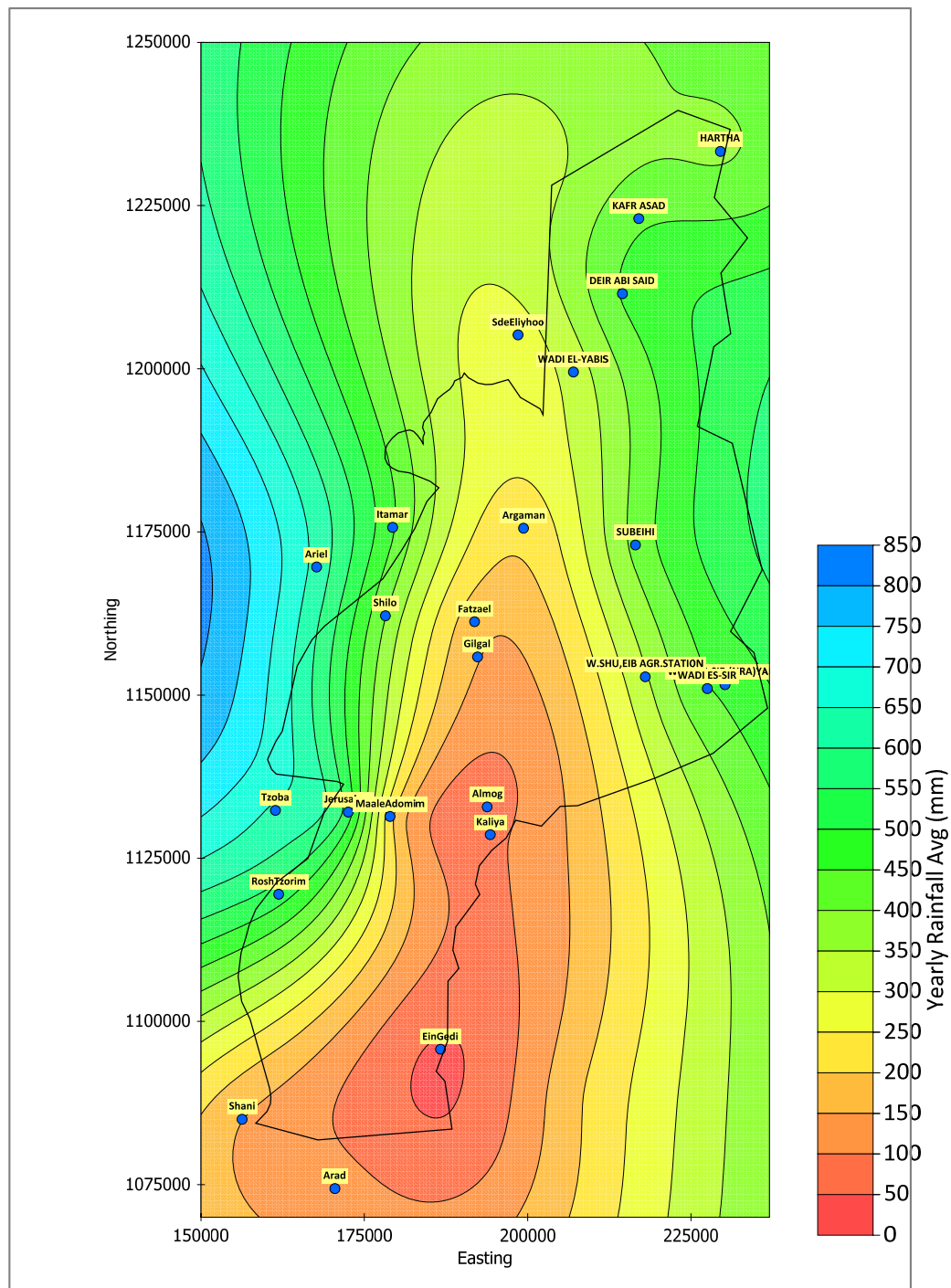


Figure 2.15: Yearly Rain average isohyets

The Israel Meteorological survey provided monthly rainfall data for the rain stations for the model west side, whereas meteorological data for the Jordanian side was obtained from J. Sahawneh. I. Rain stations with 10 years measurement period or longer were chosen. Rainfall and rain stations data were integrated into a separated database for further use by in the mode. The characteristics of these stations are summarized in **Table2.3**.

Table 2.3: Rain stations characteristics

	Station ID	Station name	Easting	Nothing	Yearly rain	AVG
Jordan	AB0002	DEIR ABI SAID	214500	1211500	454	
	AD0002	HARTHA	229500	1233300	393	
	AE0004	KAFR ASAD	217000	1223000	439	
	AH0002	WADI EL-YABIS	207000	1199500	322	
	AL0027	SUBEIHI	216500	1173000	415	
	AL0057	WADI ES-SIR (NRA)YARD	230200	1151600	460	
	AM0002	W.SHU,EIB AGR.STATION	218000	1152800	344	
	AN0002	WADI ES-SIR	227500	1151000	447	
Israel	241180	Itamar	179327	1175694	456	
	330240	Almog	193798	1132872	82	
	322655	Argaman	199363	1175569	216	
	323402	Gilgal	192335	1155850	153	
	244850	Jerusalem	172541	1132079	524	
	245460	MaaleAdomim	178935	1131399	219	
	331105	EinGedi	186661	1095741	45	
	251569	Arad	170490	1074391	124	
	323255	Fatzael	191870	1161240	171	
	330370	Kaliya	194276	1128617	91	
	247210	RoshTzorim	161894	1119486	526	
	241492	Shilo	178226	1162151	402	
	321800	SdeEliyhoo	198521	1205187	280	
	241410	Ariel	167690	1169626	632	
	244352	Tzoba	161391	1132337	642	
	251011	Shani	156290	1085000	151	

3. The computational model

3.1 The computational grid

The resulting computational model was created by snapping the models in the west and in the east to the mesh of the alluvial system. The model comprises 57,408 2D nodes and 114,129 2D elements (triangles) in the plane and 746,303 nodes and 1,369,548 elements (triangular prisms) in a 3D configuration. The model structure is illustrated by means of two cross sections, presented **Figure3.1** and **Figure 3.2**.

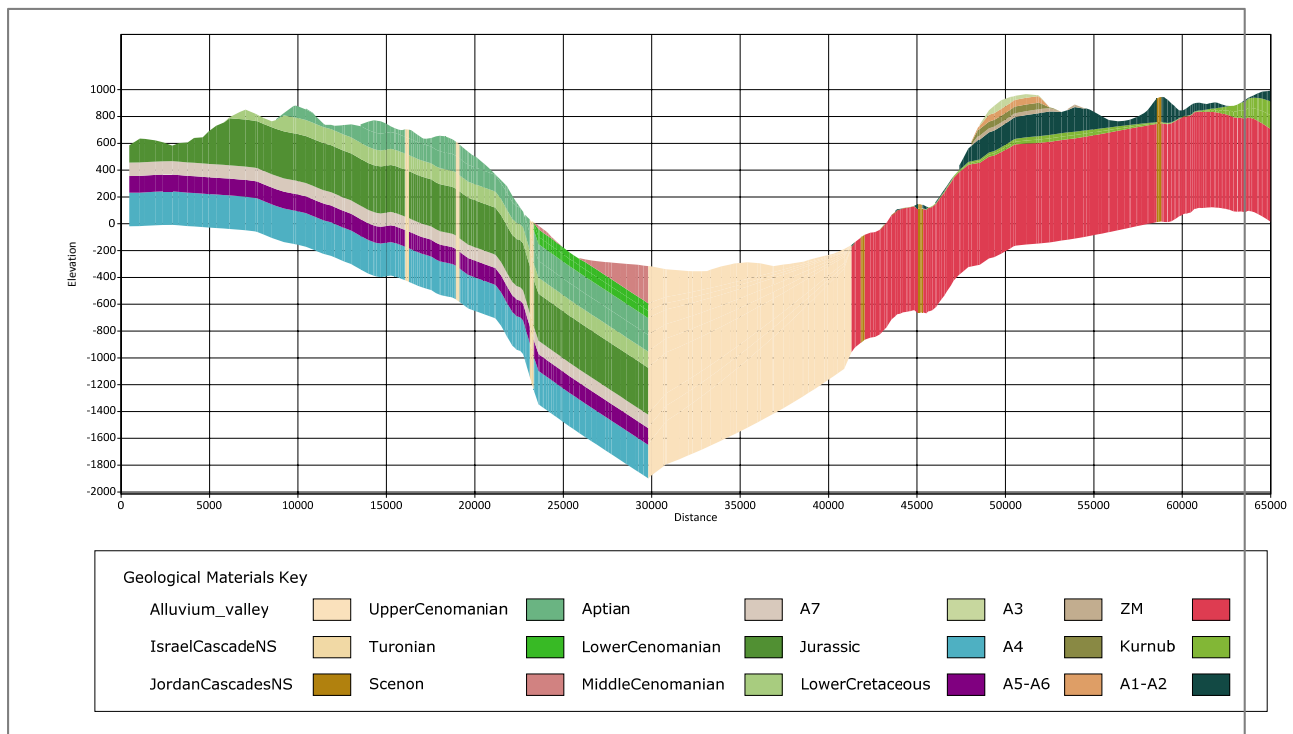


Figure 3.1: Cross section AA through the model

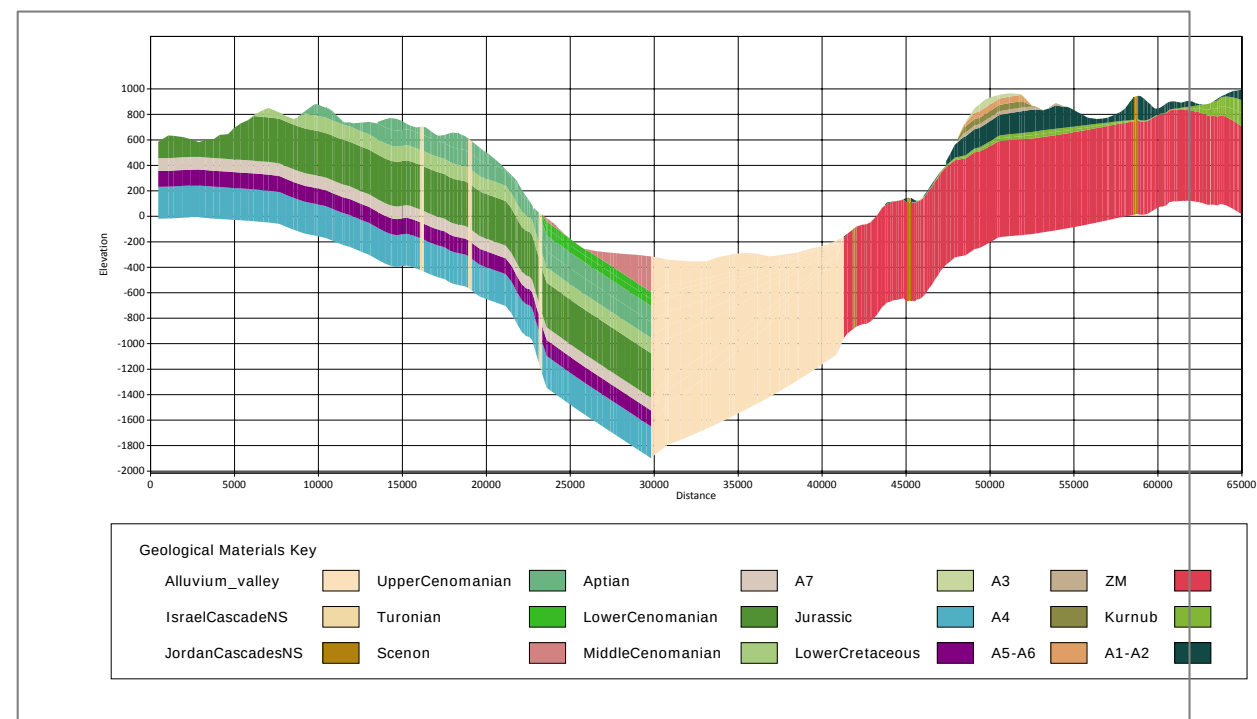


Figure 3.2: Cross section BB through the model.

3.2 Mathematical – Numerical Model

3.2.1 Mathematical Formulation

The mass balance equation solved by the model is:

$$S_0 \frac{\partial \varphi}{\partial t} = \nabla [K_{ij} \nabla \varphi] - \sum_i P_i(t) \delta(x - x_i) - Q_s(t)$$

Where:

S_0 Storativity coefficient

φ Piezometric Head

K_{ij} Hydraulic conductivity tensor

$P_i(t)$ Pumping rate at well i , at time t

$Q_s(t)$ Spring discharge at time t

The spring discharged is determined with the linear approximation:

$$Q_s(t) = \max(0, \alpha_s(\varphi_s(t) - \varphi_{s0}))$$

Where:

$Q_s(t)$ Spring discharge at time t

α_s Spring coefficient

$\varphi_s(t)$ Piezometric head at spring

φ_{s0} Threshold piezometric head, below which the spring dries out.

3.2.2 Boundary conditions

First Type Boundary Conditions

$$\varphi(x, t) = \varphi_\Gamma(x, t) \quad \forall x \in \Gamma_I$$

Where Γ_I is the portion of the model boundary over which a first type boundary condition is imposed and φ_Γ is a known function of space and time.

Second type boundary conditions

$$q_n(x, t) = q_n^\Gamma(x, t) \quad \forall x \in \Gamma_{II}$$

Where Γ_{II} is the portion of the model boundary over which a second type boundary condition is imposed, q_n is the groundwater flux entering (or leaving) the flow domain and q_n^Γ is known function of space and time.

Third type boundary conditions:

$$q_n(x,t) = -\kappa(x)(\varphi_T(x,t) - \varphi(x,t)) \quad \forall x \in \Gamma_{III}$$

Where Γ_{III} is portion of the model boundary over which a third type boundary condition is imposed, q_n is the groundwater flux entering (or leaving) the flow domain, φ_T is a known function of space and time and κ is a known coefficient.

Boundary conditions on the phreatic surface

On the phreatic surface two conditions must be satisfied:

- Groundwater flux continuity through the surface:

$$q_n = -\left(R(x,t) - S_y \frac{\partial \varphi}{\partial t}\right) n_z$$

- The pressure of the water at the phreatic surface is zero, i.e.,

$$\varphi(x,t) = \zeta_s(x,y,t)$$

Where q_n is the water flux entering (or leaving) the flow domain through the phreatic surface $R(x,t)$ is the replenishment flux entering through the phreatic surface and n_z is the vertical component of the vector normal to the phreatic surface.

3.3 Initial values of hydraulic properties

It is beyond the scope of our work to engage in a full calibration of the model, essentially due to a combination of lack of time, lack of resources and more importantly lack of data of adequate distribution in space and time. However, we shall run the model until it produces sound groundwater flow pattern and sound piezometric head values at locations where these are known. As a first step, we have gathered data and information on the values of the hydraulic parameters (porosity, hydraulic conductivity and Storativity). **Table 3.1** below, summarizes the information that has been gathered so far.

Table 3.1: Initial values of the hydraulic properties of the model formations.

Formation	Hydraulic Conductivity In the plane	Anisotropy	Effective Porosity	Storativity
	[m/day]		[-]	[m ⁻¹]
Neogene	< 1	10-100	5%	10 ⁻⁷
Avedat Gr.	< 1	10-100	5%	10 ⁻⁷
Mount Scopus	< 1	10-100	5%	10 ⁻⁷
Turonian	10-20	10-100	5%	10 ⁻⁷
Upper Cenomanian	5-10	10-100	5%	10 ⁻⁷
Middle Cenomanian (Moza, Bet Meir)	0.1 – 1	10-100	5%	10 ⁻⁷
Lower Cenomanian (Kesalon –Kefira)	1 – 5	10-100	5%	10 ⁻⁷
Aptian	0.1 – 1	10-100	5%	10 ⁻⁷
Lower Cretaceous	0.1 – 1	10-100	10-20%	10 ⁻⁷
Jurassic	0.1 – 1	10-100	5%	10 ⁻⁷
Balqa Group B4- B5	5	10-100	5%	10 ⁻⁷
Balqa Group B3	0.00001	10-100	5%	10 ⁻⁷
Balqa group B1- B2	2	10-100	5%	10 ⁻⁷
A7 (NA)	2	10-100	5%	10 ⁻⁷
A56	0.0001	10-100	5%	10 ⁻⁷
A4	2	10-100	5%	10 ⁻⁷
A3	0.0001	10-100	5%	10 ⁻⁷
A1_2	1	10-100	5%	10 ⁻⁷
Kurnub	3	10-100	5-10%	10 ⁻⁷
Azab	3	10-100	3%	10 ⁻⁷

4. Simulation Results

The constructed model was run under pristine conditions (prior to any pumping development). The basic reasons are that we wanted first to create a baseline information of the regional groundwater flow patterns. Additionally, little information is available on pumping wells in the Jordanian side (their location, depth and pumping rates).

In the west we had a three major outlets: 1) the Dead Sea; 2) the Marsaba-Feshcha Springs; and 3) the Kane and Samar springs. In the east we were not able to gather information on the outlets and therefore, in agreement with the partners, we decided to run without incorporating them. Possible impacts would result in higher than predictable piezometric heads in the various aquifers, including the alluvium.

The total discharge of the Marsaba-Feshcha springs in the model is equal to 70 MCM/Year. This is the last estimate of the springs discharge. The discharge of the Kane and Samar springs is of 30 MCM/Year.

The model was run for a period of 10 years using time steps of 1 month. However, the groundwater heads stabilized before that (after ~5 years) thus yielding a sort of quasi-steady state situation.

The resulting groundwater piezometric head elevation for the upper Cenomanian is presented in Figure 4.1.

The piezometric head in a vertical section stretching from West to East is presented in figure 4.2. What we can observe is that model produces in the west groundwater head elevations that are consistent with the measurements, i.e., ~+400 m in the western edges and ~-300 in the east, near the Jericho area. In the Jordanian side, we obtain a general groundwater flow pattern from east to west but an accumulation of water in the west, due to the lack of groundwater outlets. Also it is our point of view that the groundwater head elevation in the alluvium near the Jordan side is too high, once again due to the lack of outlets on this side.

Replenishment from rainfall is of ~260 MCM/Year. The total amount of water flowing to the Dead Sea is of ~420 MCM/Year. The latter value must be treated with caution because the real conditions are not truly represented at the dead-sea interface. In fact, the presence of brine in the Dead Sea prevents the flow of freshwater and probably limits it to a very small portion of the cross-section. In order to check the sensitivity of the boundary conditions at the Dead Sea we ran the model with fixed head only in the upper Cenomanian. The resulting groundwater heads were not significantly different but the flow out to the Dead Sea was reduced to ~35 MCM/Year. This figure is probably much closer to reality than the previous one. Our estimation is that the flow towards the Dead Sea is even smaller than that. Obviously additional work is required in order to determine an adequate representation of the conditions prevailing at the Dead Sea border.

Additional work has to be done in properly suggesting a surrogate for the hydraulic conditions prevailing at the Dead Sea. The most satisfactory way would have been to run a coupled model of groundwater flow and density dependent brine transport. However, the size of the model makes this task difficult to achieve. Another possibility would be to mimic the brine intrusion into the Dead Sea and to represent in this way the part of the cross section that is open to flow.

Altogether, despite the limitations the model is very near to be operational and can provide valuable information on the regional trends of the groundwater flow patterns, at basin scale, regional scale and trans-boundary scale. Of notable importance is the fact that we were able to properly represent the groundwater table elevation in the Jericho area, without any kind of special boundary conditions.

It is very well known that the vast majority of the models constructed in this area produce groundwater head elevation that are far higher than the ones actually measured.

Also the cross-section in figure 4.2 illustrates the impact of the cascades of hydraulic obstacles in breaking the steep hydraulic gradient in a step-wise manner.

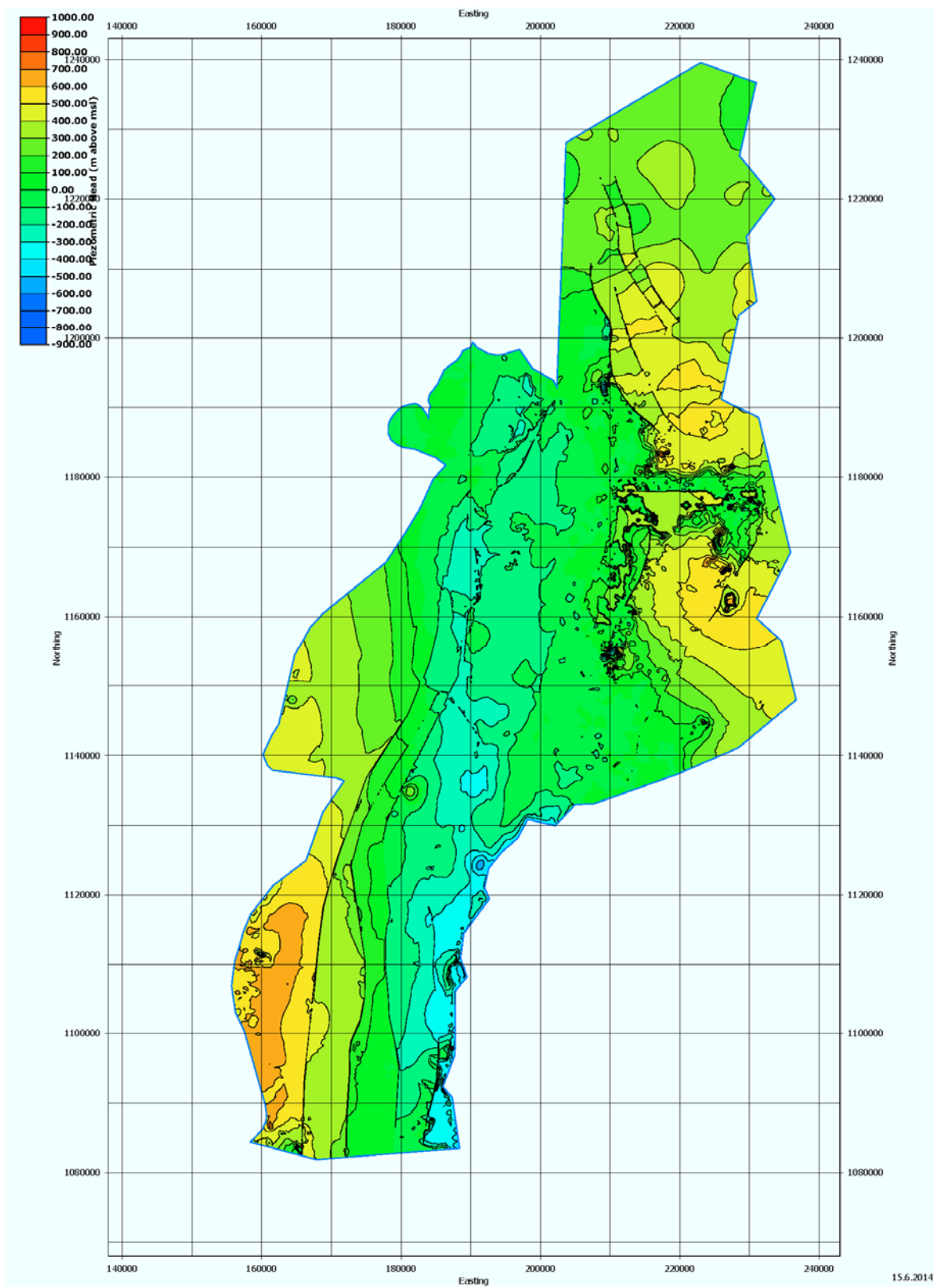


Figure 4.1: Piezometric head elevation in the upper Cenomanian (West) and corresponding aquifers in the East.

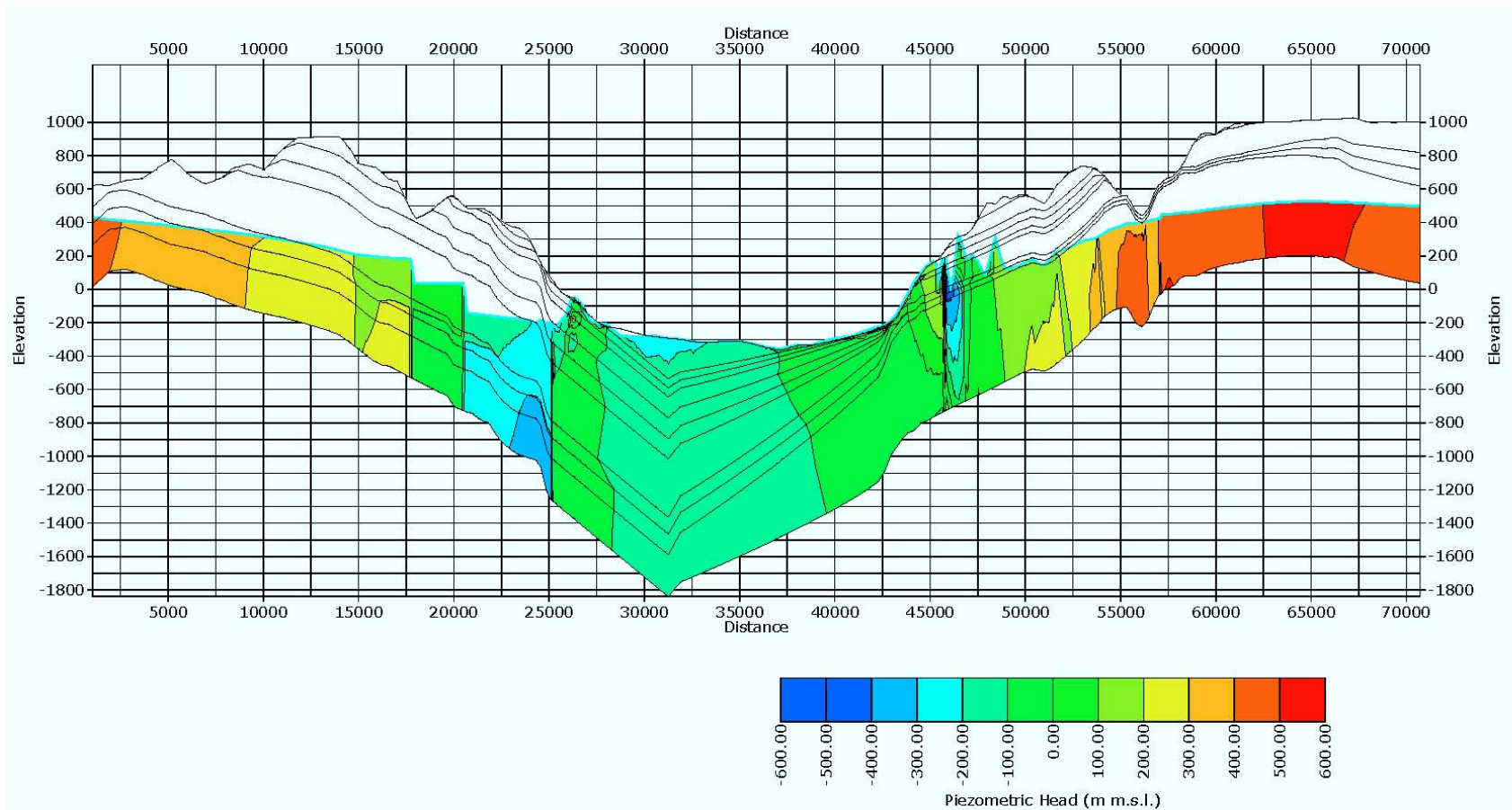


Figure 4.2: Piezometric head elevation in a vertical cross section from West to East .

5. Conclusions

This deliverable summarizes a substantial effort of constructing and validating a trans-boundary model for the analysis of groundwater flow in the LJV area in the main aquifers, on both parts of the Alluvial Jordan valley. The effort spanned the two phases of the SMART project, mainly due to the extreme difficulty of constructing a consistent static (geological) conceptual model in an area where data is sparsely available and where speculations play an important role. However, pending a proper representation of the outlets in the Jordan side, the model could be extremely valuable for a number of objectives:

1. Calculating the discharge of the rock aquifers to the alluvial aquifer;
2. Identifying the connections between the rock aquifers on both sides of the valley;
3. Developing groundwater production in the Cenomanian aquifers of the west and calculating the impact of the new development on existing well fields;
4. Developing groundwater resources in the deeper aquifers of the Jordan side, a task that does not seem so far to have been addressed.