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Integration of Water Resources of the Upper Aquifer in Amman-Zarqa Basin Based on Mathematical Modeling and GIS, Jordan

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ABSTRACT

In this work, the geological, hydrogeological, hydrological, hydrochemical and environmental aspects of the most important groundwater basin in Jordan have been studied and investigated. In addition, geological and hydrogeological conceptual models were developed and a groundwater flow model was created, calibrated and evaluated. Amman-Zarqa Basin comprises an area of 3918 km^2, with 89% located in Jordan and 11% inside the Syrian territory. This basin is considered one of the most important basins in Jordan because of its location (transitional area between high lands in the west and desert in the east) and more than 60% of the total population of Jordan live inside this basin. The main aims of this study were calculation of the surface and groundwater water budget, prediction the aquifer reactions due to groundwater withdrawal, determining the safe yield, specifying the source and the type of pollutants and proposing solutions and alternatives for the current problems of groundwater resources in terms of quantity and quality.

The age of the outcropping formations in the study area ranges from Lower Cretaceous to recent age. Based on the structure contour maps, which were drawn, a three-dimensional geological model was built. Three main structures are distinguished in the study area: Amman Syncline, Zarqa-Fault and Ramtha-Wadi Sirhan Fault.

Based on the surface water budget, the average annual direct recharge in the study area is between 22.4 and 60.4 $*10^6$ m^3 for normal and wet hydrological years, respectively.

To find the maximum monthly annual flood to be considered for the design of protection structures (such as dams) in Amman-Zarqa Basin, frequency analysis was done based on runoff data over more than 30 years. The recommended flood comes to 51 $*10^6$ m^3.

The main aquifer of the study area is formed by Basalt flows underlain by a carbonate rock sequence of the Amman and Wadi As Sir Formations (B2/A7). In addition, the lower aquifer (Kurnub aquifer) was considered in this study in order to determine the amount of leakage. Based on pumping tests analysis, the transmissivity of Basalt ranges from 4.3 to 29,700 m^2/d, the average is about 7000 m^2/d, corresponding to a mean permeability of 20 m/d. The transmissivity of B2/A7 aquifer varies between 4.7 and 2200 m^2/d, the average is about 467 m^2/d, corresponding to a mean permeability of 7 m/d. The upper aquifer is unconfined and the dominant direction of groundwater flow is from southwest and northeast to the far northwest, east and central parts (Seil el Zarqa) of the study area.

Based on the statistical analysis, the hydrochemical data of the analyzed water samples can be divided into three groups. Group-1 represents the well fields between Amman and Ruseifa regions. This group characterizes low salinity and high concentration of NO_3. Group-2 shows moderate salinity and low concentration of NO_3. This group represents the well fields between

Ruseifa and Zarqa regions as well as the far northeast well fields in the study area. Group-3 shows high salinity and moderate value of NO_3. This group includes most of the well fields close to Khaldiya and Dhuleil regions. To find out the main factors of influence within the analyzed water samples, factor analysis was conducted. The method of interpretation was the Varimax rotation method. Three main factors of influence to groundwater were found. These factors are salinity, pollution and carbonate.

A three-dimensional groundwater flow model was built and calibrated for steady state and time dependent in order to calculate the water budget, to calibrate the aquifer characteristics and to predict the aquifer response (drawdown) if the current abstraction would be continued over the next 20 years. The maximum accumulative drawdown will reach more than 70 m by the year of 2025. That means some wells will become completely dry by the year of 2025, particularly, the well fields between the towns of Khaldiya and Um El Jumal. According to the water budget, 61.8 $*10^6$ m^3/yr flows into the upper aquifer as underflow from Jabal Al Arab through the Basalt and 45.5 $*10^6$ m^3/yr as renewable recharge from excess rainfall. On contrast, 66 $*10^6$ m^3/yr and 3.4 $*10^6$ m^3/yr outflow as cross boundary from the upper aquifer into Azraq and Yarmouk Basins, respectively. Also, there is 26.8 $*10^6$ m^3/yr as underflow towards Zarqa River and natural spring discharge. The leakage into the lower aquifer is about 12.2 $*10^6$ m^3/yr. The optimal use of groundwater resources of the upper aquifer will be in the range of 60 $*10^6$ m^3/yr.

ZUSAMMENFASSUNG

Die geologischen, hydrogeologischen, hydrologischen, hydrochemischen und die Umweltaspekte des Amman-Zarqa Beckens wurden untersucht und erforscht. Es wurde ein geologisches Konzeptmodell und darauf aufbauend ein Grundwasser Strömungsmodell erstellt und kalibriert.

Das Amman-Zarqa Becken umfasst ein Gebiet von ungefähr 3900 km², wovon 89% auf jordanischem Territorium liegen und 11% auf syrischem Staatsgebiet. Dieses Becken gilt als eines der bedeutendsten in Jordanien wegen seiner verbindenden Lage zwischen Bergland und Wüste und weil mehr als 60% der jordanischen Bevölkerung darin leben. Die Hauptziele dieser Untersuchung sind die Berechnung des Oberflächen- und des Grundwasserhaushalts, die Vorhersage von Reaktionen des Aquifers auf Grundwasserentnahmen, die Ermittlung der möglichen Entnahme und die Bestimmung von Herkunft und Art der Grundwasserverunreinigungen. Es sollen Lösungen für die gegenwärtigen Schwierigkeiten mit dem verfügbaren Grundwasser im Hinblick auf Menge und Qualität vorgeschlagen sowie Alternativen für eine bessere Bewirtschaftung des Wassers aufgezeigt werden.

Die ausstreichenden Formationen im Untersuchungsgebiet reichen von der Unterkreide bis in die Neuzeit. Von diesen wurden Strukturkarten erstellt und auf dieser Basis ein dreidimensionales geologisches Modell aufgebaut. Drei Hauptstrukturen lassen sich im Untersuchungsgebiet unterscheiden, die Ammaner Mulde, die Zarqa-Störung und die Ramtha-Wadi Sirhan-Störung.

Aus dem Oberirdischen-Wasserhaushalt ergab sich eine jährliche Grundwasserneubildung zwischen 22,4 mio m³ für normale Jahre und 60,4 mio m³ für niederschlagsreiche Jahre.

Um den höchsten monatlichen Abfluss während eines Jahres zu finden, der für den Entwurf von Schutzeinrichtungen (z.B. Deiche) berücksichtigt werden muss, wurden Abflussdaten von mehr als 30 Jahren mit einer Frequenzanalyse untersucht. Es ergab sich ein höchster Wert von 51 mio m³.

Der Hauptaquifer des Untersuchungsgebietes wird von Basaltdecken gebildet, unter denen eine carbonatische Abfolge der Amman- und Wadi As Sir Formationen liegt (B2/A7). Zusätzlich wurde der tiefere Aquifer (Kurnub Aquifer) betrachtet, um die Versickerung nach unten (Leakage) festzustellen. Pumpversuche ergaben für den Basalt eine Transmissivität von 4,3 bis 29700 m²/Tag, im Mittel 7000 m²/Tag. Die entsprechende mittlere Durchlässigkeit beträgt 20 m/Tag. Die Transmissivität des B2/A7-Aquifers variiert von 4,7 bis 2200 m²/Tag, im Mittel 467 m²/Tag. Die entsprechende mittlere Durchlässigkeit beträgt 7 m/Tag. Der obere Aquifer hat eine freie Grundwasseroberfläche. Die Haupt-Fließrichtungen verlaufen von

Südwesten und Nordosten in die entfernten Teile des Nordwestens und die zentralen Gebiete (Seil el Zarqua) des Beckens.

Statistische Auswertungen erlauben eine Einteilung der Grundwasseranalysen in drei Gruppen. Gruppe 1 gilt für die Brunnenfelder zwischen Amman und Ruseifa. Für diese Gruppe sind eine niedrige Salinität und hohe Nitrat-Konzentration typisch. Gruppe 2 wird durch mäßige Salinität und niedrige Nitrat-Konzentration gekennzeichnet. Diese Gruppe umfasst die Analysen aus den Brunnenfeldern zwischen Ruseifa und Zarqua sowie aus den Brunnen im fernen Nordosten des Untersuchungsgebietes. Für die Analysen der Gruppe 3 sind hohe Salinität und mäßige Nitrat-Konzentration charakteristisch. Die Gruppe umfasst die meisten Brunnenfelder in der Nähe der Gebiete Khaldiya und Dhuleil.

Um die Haupteinflussfaktoren bei den Wasseranalysen herauszufinden, wurde eine Faktorenanalyse durchgeführt. Die Auswertung nach der Varimax Rotations Methode ergab die drei Faktoren Salinität, Kontamination und Carbonat.

Mit dem dreidimensionalen Grundwasser-Strömungsmodell wurden die Kennwerte des Aquifers kalibriert und der Grundwasserhaushalt untersucht. Die Haushaltsbetrachtungen ergaben folgende Mengen: 61,8 mio m^3/Jahr Zufluss in den oberen Aquifer als Grundwasserabfluss vom Jabal Al Arab durch den Basalt und 45,5 mio m^3 Grundwasser-Neubildung aus Niederschlägen. 66 mio m^3/Jahr fließen aus dem oberen Aquifer über die Gebietsgrenze in's Azraq Becken und 3,4 mio m^3/Jahr in's Yarmouk Becken. 26,8 mio m^3 fließen als Grundwasserabstrom in den Zarqua-Fluss ab bzw. über natürliche Quellaustritte. Die Versickerung in den unteren Aquifer beträgt etwa 12,2 mio m^3.

Weiterhin wurden die künftigen Absenkungen als Folge fortgesetzter Grundwasser-Entnahme über die nächsten 20 Jahre berechnet. Bei fortgesetzter Entnahme im heutigen Umfang wird die Absenkung im Jahre 2025 mehr als 70 m erreichen. Das würde bedeuten, dass eine Reihe von Brunnen trocken fielen. Besonders die Brunnenfelder zwischen den Städten Khaliya und Um El Jumal wären betroffen. Wollte man die Grundwasserabsenkung etwa auf dem heutigen Stand halten, dürfte die optimale Grundwasserentnahme aus dem oberen Aquifer bei 60 mio m^3 pro Jahr liegen.

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LIST OF SYMBOLS AND ABBREVIATIONS

A1-2	Naur formation (aquifer)
A1/A6	aquitard layer
A4	Hummar formation (aquifer)
A5-6	Shueib formation (aquitard)
ABY	Abyad soil type
AJL	Ajlun soil type
ALI	Abu Salih soil type
ALL	Tell Alluba soil type
ANJ	Anjara soil type
ASWWTP	As Samra wastewater treatment plant
ATT	Attarat soil type
Avg.	average
AYD	Aydoun soil type
B1	Wadi Umm Ghudran formation (aquifer)
B2	Amman-Al Hisa formation (aquifer)
B3	Muwaqqar formation (aquitard)
B4	Umm Rijam formation (aquifer)
B5	Wadi Shallala formation (aquifer)
B2/A7	Amman Wadi As Sir formation (aquifer)
BAN	Hisban soil type
BAQ	Baq'a soil type
BGR	Federal Institute for Geosciences and Natural Resources
BIR	Jabir soil type
BOD_5	biological oxygen demand (five days)
BUQ	Bureiqa soil type
CLWAJ	Central Laboratories of Water Authority of Jordan
COD	chemical oxygen demand
CP	pan coefficient
d	day
DD	drawdown
DEI	Mudeises soil type
DHU	Dhuleil soil type
DO	dissolved oxygen
DOS	Department of Statistics
E	east
EC	electrical conductivity
EP	potential evaporation
ET	potential evapotranspiration
Fig.	figure
FUL	Fulug soil type
GAB	Ghabawi soil type
GIS	Geographic Information System
GMS	Groundwater Modeling System
GTZ	German Agency for Technical Cooperation
GWF	groundwater flow process
GWW	Groundwater Software for Windows
h	head in the well
HAB	Rihab soil type
HAL	Hallabat soil type

HAT	Qihat soil type
hr	hour
Ia	initial abstraction
IAP	ion activity product
IBB	Ibbin soil type
Id.	Identification
i.e.	that is
IRI	Tel Umeiri soil type
J	Jacobian matrix
JDWQS	Jordanian Drinking Water Quality Standards
JER	Jarash soil type
JICA	Japan International Cooperation Agency
JISM	Jordanian Institute of Standards and Metrology
JMD	Jordanian Meteorological Department
JV	Jordan Valley
JVA	Jordan Valley Authority
K	Kurnub
K_{eq}	equilibrium constant
K_f	permeability
K_{SP}	solubility product of the mineral
K_{xyz}	components of the hydraulic conductivity tensor
KTR	King Talal Reservoir
l	cell length
m	meter
masl	meter above sea level
Max.	maximum
mbgl	meter below ground level
mbsl	meter below sea level
ME	Ministry of Environment
Min.	minimum
MOA	Ministry of Agriculture
MPN	most probable number
MWI	Ministry of Water and Irrigation
N	north
n	number of observation wells
NIS	Nisab soil type
No.	Number
NRA	Natural Resources Authority
OBS	observation process
P	precipitation
ppm	part per millions
PEST	parameter estimation
PM	Processing Modflow
PMWIN	Processing Modflow for Windows
Q	well discharge
Q_L	volume of leakage
R	recharge
RSS	Royal Scientific Society
S	south (direction)
S	storage coefficient
Sc	specific capacity

Ss	specific storage
Sy	specific yield
SAB	Sabha soil type
SAK	Sakhra soil type
SAR	sodium adsorption ratio
SCS	Soil Conservation Service
SEN	sensitivity analysis
SI	saturation index
SIS	Mudeisisat soil type
SSP	soluble sodium percentage
Std. Dev.	standard deviation
STP	sewage treatment plants
T	transmissivity
TAR	Tarmah soil type
TDS	total dissolved solids
TH	total hardness as $CaCO_3$
THA	Ramtha soil type
TSS	total suspended solids
TTCC	total thermotolerant coliform count
USAID	United States Agency for International Development
ν	specific flow rate
VCONT	vertical leakance
W	west
w	cell width
WAJ	Water Authority of Jordan
WAY	Huwaynit soil type
WHO	World Health Organization
WIS	Water Information System
WMO	World Meteorological Organization
WWTP	wastewater treatment plants
YAD	Yaduda soil type
yr	year
ZAR	Zarqa soil type
ZAY	Uzaymi soil type
ΔS	change of groundwater storage
Δv	layer thickness

1 INTRODUCTION

1.1 Background

The Hashemite Kingdom of Jordan is located between latitudes 29° 11' and 33° 22' North and longitudes 34° 19' and 39° 18' East and covers an area of about 90000 km^2. Approximately 80 percent of the country is steppe and desert. A great part of Jordan (about 90%) is located in arid and semi arid climate which has led to the limitation of water resources, in particular in groundwater resources. Accordingly, the country has and will be facing challenges in its water sector.

Water resources in Jordan depend mainly on rainfall precipitating during the winter season. More than 90% of the territory rainfall is flashy irregular and is below 200 mm per year. Only about 2% of the country receiving a yearly rainfall exceeding 350 mm. So, agriculture is heavily depending on irrigation. Population growth rate (about 2.8 per cent) is very high and is considered as one of the highest rates in the world that imposed a challenge to achieve balance between resources and population caused as a result deterioration in living standards (ME 2002). The total population of Jordan (5,480,000 inhabitant, DOS 2003) has trebled in the last 25 years. The demand for water in this arid country is high and steadily growing with all sectors (Domestic, industrial and agricultural) competing for limited supplies of costly water.

Due to the limitation of surface water resources in Jordan, the groundwater basins are subjected to exploitation caused by extensive over pumping from wells owned by governmental and private sectors to supply water for drinking and agricultural purposes which had increased significantly in the last few decades. Groundwater forms the main water resources in Jordan. The total amount of water recharge into the groundwater basins from the excess rainfall is estimated to be about $275 * 10^6$ m^3/yr. However, the current abstraction of groundwater has been exceeded more than $475 * 10^6$ m^3/yr. Consequently, the depletion and deterioration of the groundwater have been occurred.

The study area (Amman-Zarqa Basin) is the most important basin in Jordan because this basin is one of the transitional areas between high lands in the west and desert in the east. This is not only reflected in the climatological changes from wet to dry but also in different landuse patterns and also in large changes of habitat. While the western hilly areas are relatively densely populated, the southeast of the basin is fully desert and almost without population and more than 60% of the population of Jordan (3,720,000 inhabitant, DOS 2003) is located inside this basin.

According to the international weather classification, the climate of this area has semi arid conditions except for some wet years when precipitation exceeds 1000 mm. The total annual average precipitation volume in Amman-Zarqa Basin is calculated to be about $925 * 10^6$ m^3/yr (1937-2001).

Geologically, Amman-Zarqa area is composed of the outcrop of carbonate series, limestone with chert and limestone crystalline rocks of Belqa Series (B1/B7) and Ajloun Series (A1/A7), changing towards Baq'a valley to marl and marly limestone, dolomatic limestone and sandstones of Kurnub Group. Wadi Dhuleil area is a graben surrounded by two main faults. It is composed of basalt at the top covering the major part of the area. The outcrop of the horst area is limestone and limestone with chert.

Hydrogeologically, the study area is divided into two separate basins, one of them is Amman-Zarqa and the other is Wadi Dhuleil including Northeastern Desert area. They are separated by two big faults uplifting the area between Wadi Dhuleil and Amman-Zarqa subbasins.

The groundwater resources have been exploited since 1950s by government and private sectors with few wells to reach more than 1000 wells by 2003. Consequently, the aquifer balance is disturbed and a major decline in water level accompanied by deterioration in groundwater quality has taken place.

Therefore, in the last 25 years two major problems have occurred in this basin, the first was the declining of groundwater levels due to over pumping exceed the recognized safe yield. The other was the increasing of total dissolved solids (TDS) from 300 part per millions (ppm) to more than 2500 ppm at present. NO_3 concentration in some wells has reached more than 200 milligrams per liter (mg/L), recently. However, to avoid such irreversible environmental impact, depletion and deterioration of groundwater should be prevented.

In order to manage a groundwater reservoir sustainable and wisely, geographic information system (GIS) and numerical groundwater modeling tools (groundwater flow and groundwater solute transport) are essential.

1.2 Location

The study area (Amman-Zarqa Basin) comprises an area of about 3918 km^2, where 89% is located in Jordan and 11% inside the Syrian territory (Fig. 1.1). This basin is located between the Palestine Grid Coordinates, 215 – 306 E (East) and 140 – 201 N (North).

1.3 Slope and topography

The general slope in the basin changes from west to east where hilly areas comprise a large part of the western and surrounding areas along the boundary of the basin. Altitudes gradually decrease towards the center of the basin and towards the outlet of the catchment to Jordan Valley near Deir Alla in the west.

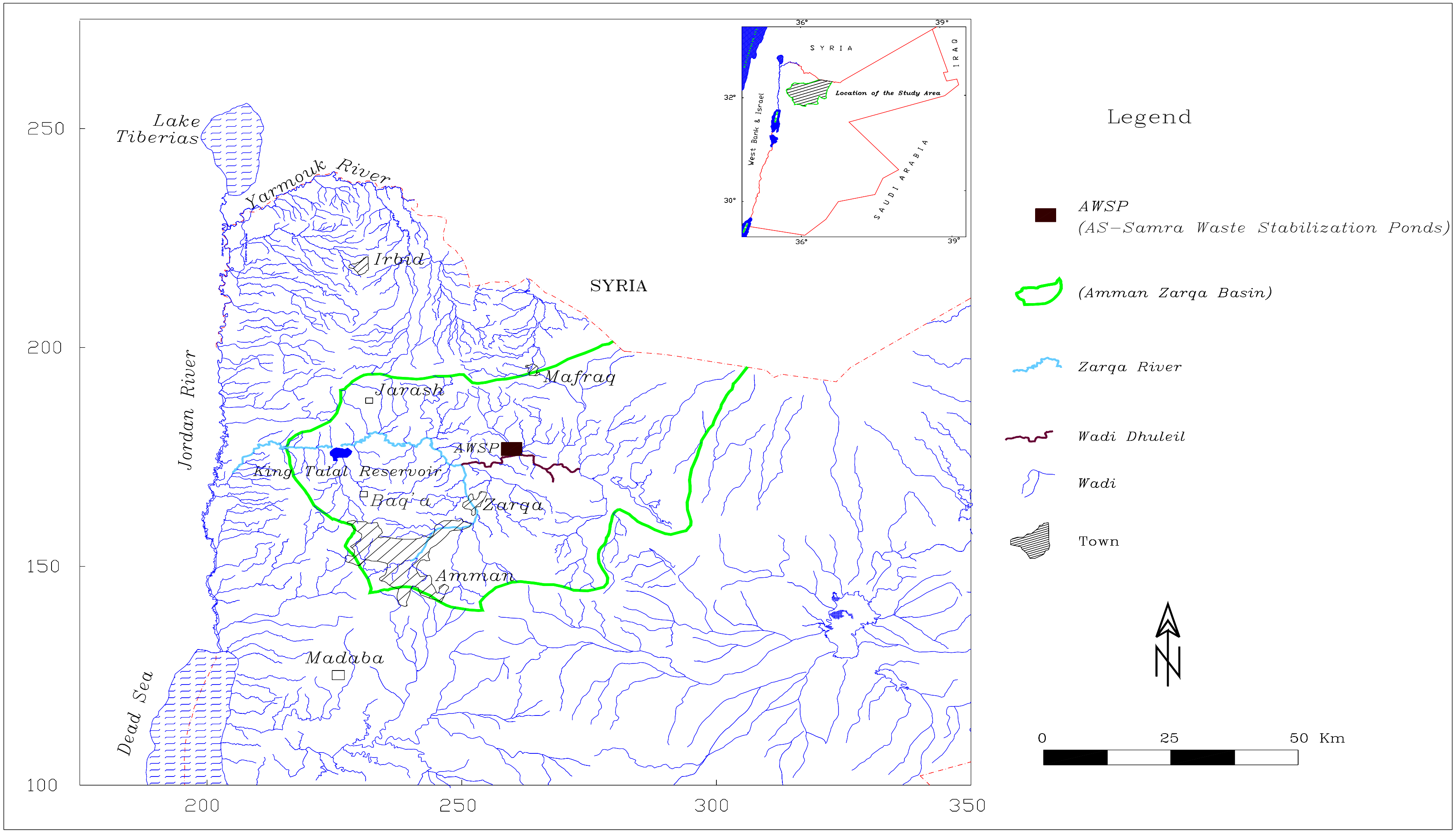

Fig. 1.1: Location map of the study area.

From the center, the altitudes increase towards the northeast into Syria where the highest point of the basin is 1570 m in Jabal Al Arab located at the north of Salkhad. The lowest point of the basin is about 140 m below mean sea level near Deir Alla (Fig. 1.2).

1.4 Soil and landuse

Soil is the uppermost layer of the earth crust developing considerable slowly as a result of weathering process. Amount of water, wind, solar radiation, temperature, vegetation and landuse are important parameters besides the type of rock exposed determining the type of soil which develops at distinct sites.

Generally, four soil groups can be distinguished in Jordan (Bender 1974):

1- Grey desert soils (Sierosem), formed under arid conditions (<150 mm precipitation/yr).
2- Red mediterranean soils, formed under subhumid conditions (>600 mm precipitation/year) and semiarid conditions (precipitation between 300 and 600 mm a year).
3- Yellow steppe soils, formed under semiarid and arid conditions (between 150-300 mm precipitation/yr).
4- Yellow mediterranean soils (transitional type of soil between the red mediterranean soils and the yellow steppe soils), formed under semiarid climate (250-350 mm precipitation/yr).

Distribution of soil types in Amman-Zarqa Basin is illustrated in Fig. 1.3. Huwaynit (WAY) and Zumlat (ZUM) soil types dominate the eastern and northeastern parts of the study area.

The Huwaynit soil unit is very gently undulating quaternary lava plain with coarse sub-parallel drainage. It characterized by shallow to moderately deep (25-80 cm) silt loam and silty clay loam overlying basalt with very high calcareous and weak saline with gradients less than 5%. The Zumlat soil unit is undulating, occasionally rolling, plain of Quaternary lavas with rocky interfluves and broad alluvial basins. It composed from silty clay and silty clay loam overlying basalt with depth more than 80 cm. It is highly calcareous and non-moderately saline. On the other hand, stony-very stony silty clay loam (very highly calcareous and moderately saline) with depth less than 25 cm (gradient less than 8%) in other parts.

Nisab (NIS) and Abu Salih (ALI) soil types dominate central, northern and western parts of the study area. The Nisab soil unit is dissected plateau in Belqa Group limestones producing narrow interfluve crests and long valley slopes with gradients between less than 10 and 20%. It contains silty clay loam and clay loam (very high calcareous and weakly to moderately saline) with depth more than 80 cm. On the other hand, it contains very stony slity clay loam (with very high calcareous and weakly saline) with depth less than 50 cm.

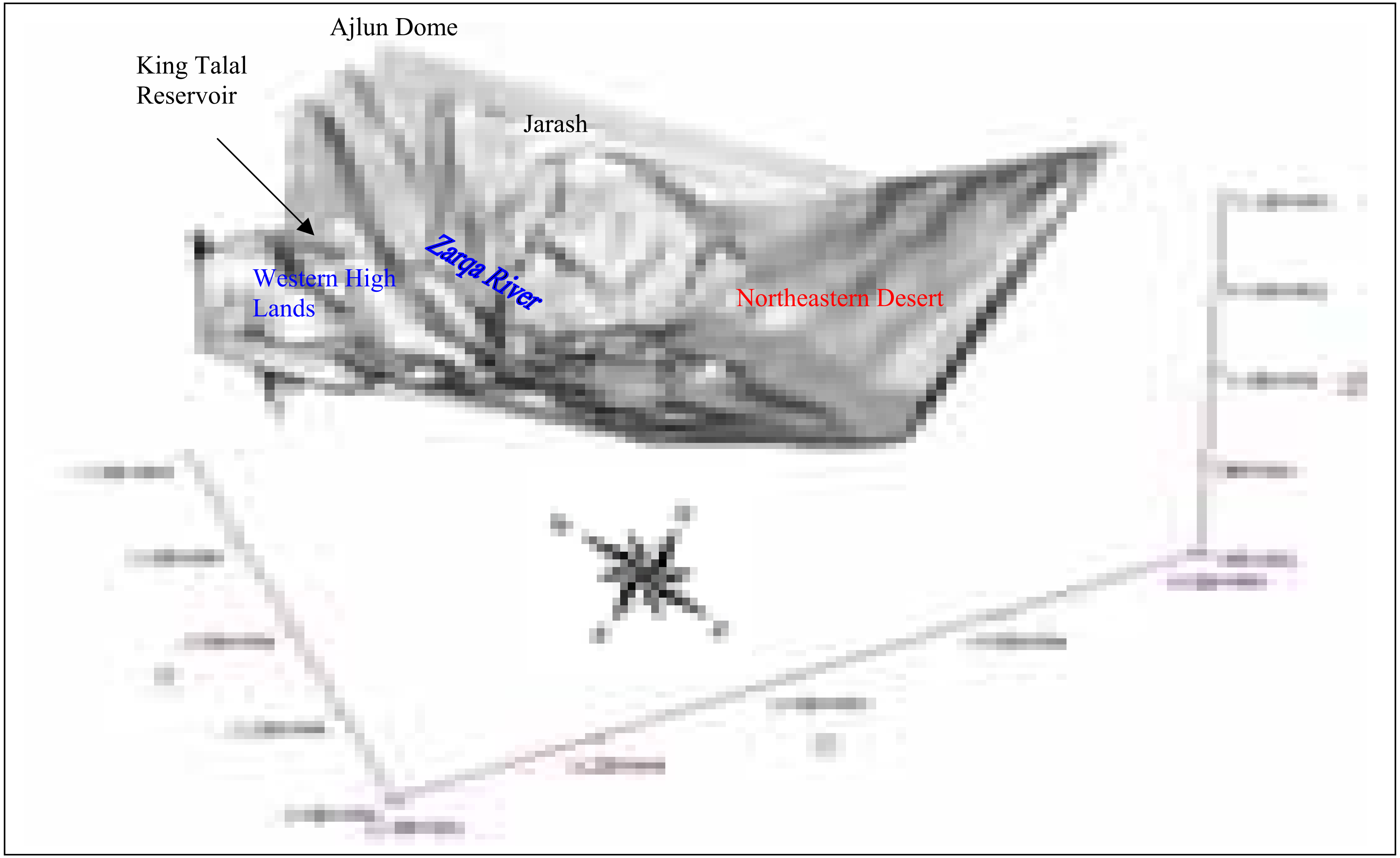

Fig. 1.2: A three-dimensional topographic map of Amman-Zarqa Basin.

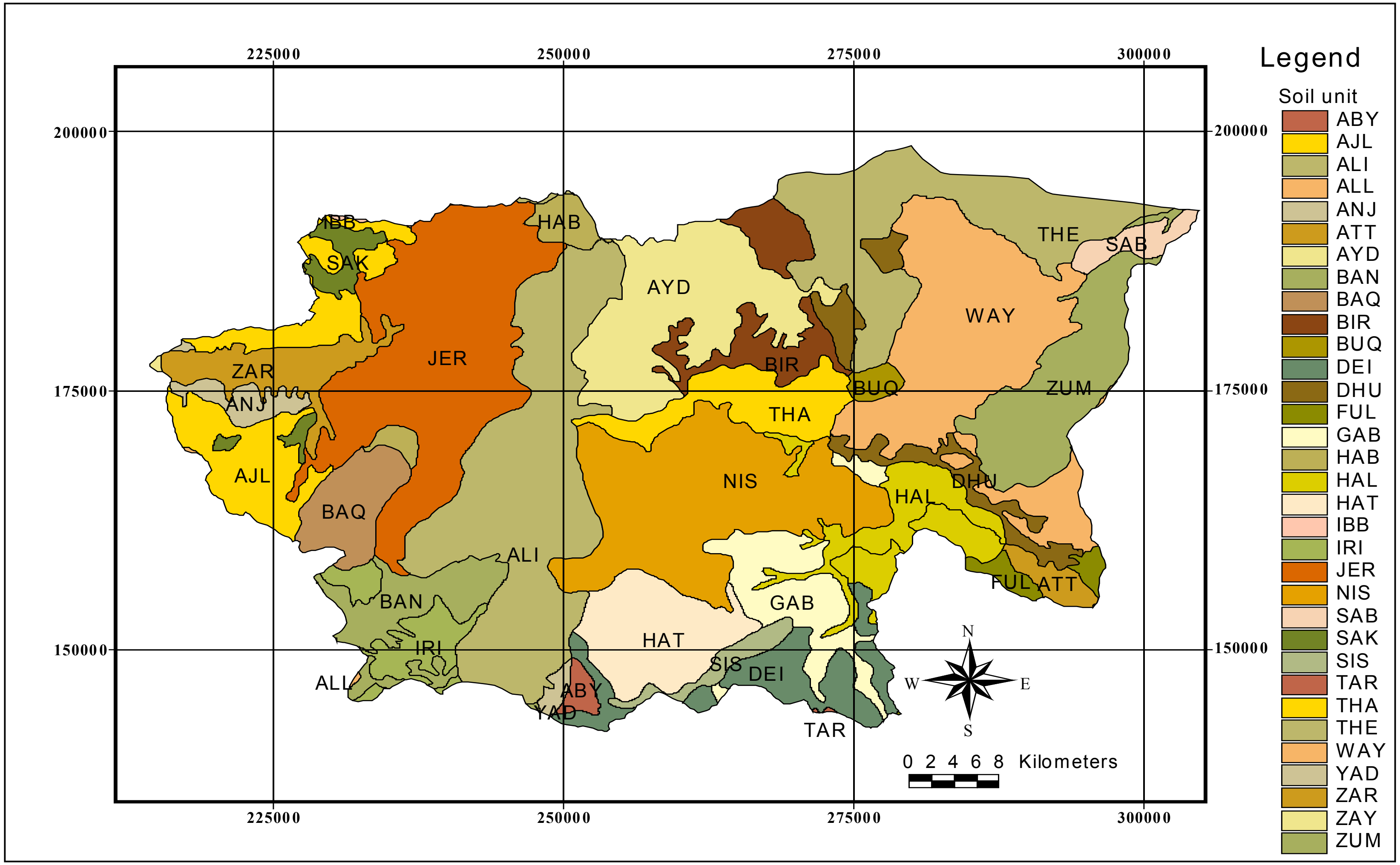

Fig. 1.3: Soil map of Amman-Zarqa Basin (modified after MOA 1994).

The Abu Salih soil unit is finely dissected limestone uplands and slopes with gradients range 5-35 % with some valley sides to 70 %. It characterized by deep (more than 80 cm) silty clay with highly calcareous and non-saline in some parts and very shallow (less than 25 cm) gravelly silty clay loam on limestone with highly calcareous and non-saline. In addition, Jarash (JAR), Ajlun (AJL) and Zarqa (ZAR) soil types are covered the western and northwestern parts of the study area. The Jarash soil unit is deeply dissected plateau on limestone of the Ajloun Group with very steep slopes in upper catchments and gentler slopes (with colluvial mantle) in lower part of the catchments. Its gradient is generally ranging 5-40 % with some valley sides to 53 %. It contains deep (more than 80 cm) clay and silty clay with moderate to strong calcareous and non-saline. However, it is moderately deep (50-80 cm) stony and very stony clay and clay loam in other parts with strongly calcareous and non-saline. The Ajlun soil unit is deeply dissected limestone plateau with colluvial filled valleys and long, steep, rocky slopes to valleys with gradients range 2-60 %. It characterized by moderately to deep (more than 50 cm) stony, stony silty clay, silty clay and clay with non-moderately calcareous and non- saline. The Zarqa soil unit is very deeply dissected gorge and valley floor of Zarqa River cut into Kurnub sandstone. Its gradient is ranging 10-40 % with some valley sides up to 70 %. It characterized by moderately to deep (more than 80 cm) clay loam, silty clay loam and fine sandy clay loam with highly to strongly calcareous and non-weakly saline. Appendix 1.1 contains the description of all soil units in Amman-Zarqa Basin.

Climate, topography, soil type and other parameters affect the types of vegetation in Jordan. Jordan is divided into three regions: subhumids, semiarids and arids regions. The predominant vegetation in the subhumid regions is forest while the steppe vegetation and Saharon covers the arid regions and climax vegetation covers the semiarid regions (Bender 1974).

The landuse and the vegetation types of Amman-Zarqa Basin are shown in Fig. 1.4. The western and the northeastern parts of the study area contain more than 90 % of agricultural activities and vegetation. According to the National Soil Map and Landuse Project of Jordan, the landuse of Amman-Zarqa Basin varies from urban and non-agricultural land, non-vegetated and sparsely vegetated land (bare rocks and Basalt) to rained agricultural land (open field crops and fallow lands).

Based on the satellite imagery, which was done by USAID 2001 Project, the total amount of irrigated land (Highlands, Wadi Dhuleil and Khaldiya areas) is about 17,000 dunums (1.700 ha).

According to the Fig. 1.4, the landuse types of Amman-Zarqa Basin contain the following: 65 % as bare rock, thin soils and urbanization and 35% as natural vegetation, forest, irrigated agriculture (cereals, vegetables, fruit trees, olives, bananas and citrus) and rained agriculture (cereals, vegetables, fruit trees, olives, bananas and citrus).

1.5 Previous studies

Numerous studies for different purposes have been conducted in the study area since mid sixties, to determine groundwater recharge, aquifer characteristics, sources of pollution and to get some information about the interaction between this basin and the adjacent basins in order to utilize the water resources in sustainable way. However, three-dimensional numerical model (based on 0.5 by 0.5 km mesh size) for groundwater flow and solute transport simulation was not conducted in the study area. No GIS was applied either. The following studies have been carried out in the study area:

MacDonald and Partners (1965), conducted a study about on soil survey, hydrogeological situation and more detailed for extensive assessment of the groundwater reserves from part the study area to construct agricultural irrigation investigation project.

Raikes & Partners (1971), carried out two-dimensional groundwater flow model for the Wadi Dhuleil area (central part of the study area). The model showed that the water available in the Wadi Dhuleil area is approximately $22 * 10^6$ m^3/yr.

Rimawi (1985), presented his Ph.D thesis entitled “Hydrogeochemistry and Isotope Hydrology of the Groundwater and Surface Water in North Jordan (North-Northeast of Mafraq, Dhuleil-Hallabat, Azraq Basin)”. He found that that the sources of groundwater salinization originated according to the following reasons:

- extensive Pumping
- mixing of groundwater with partially evaporated
- irrigation return flow

GTZ (1989), carried out a study on “soil salinization in North-East part of the study area” (Wadi Dhuleil and Wadi Arja). This study proved that Wadi Dhuleil irrigation project was seriously affected by salinization, mainly caused by the increasing salt content of the irrigation water.

USAID & WAJ (1989), prepared three reports to cover Yarmouk, Azraq and Amman-Zarqa basins. The main purpose was to evaluate the water potential available. This study showed that the deterioration of groundwater in some parts of Amman-Zarqa basin is serious and the government is not able to take any effective action, because the exact cause of the deterioration is not known.

BGR & WAJ (1994-1996), within the framework of a technical cooperation project between the Water Authority of Jordan (WAJ) and the Federal Institute for Geosciences and Natural Resources (BGR) in Germany, a hydrogeological assessment study of the groundwater resources of northern and central Jordan carried out. The main objectives of this study were: the preparation of thematic maps on important aspects of the

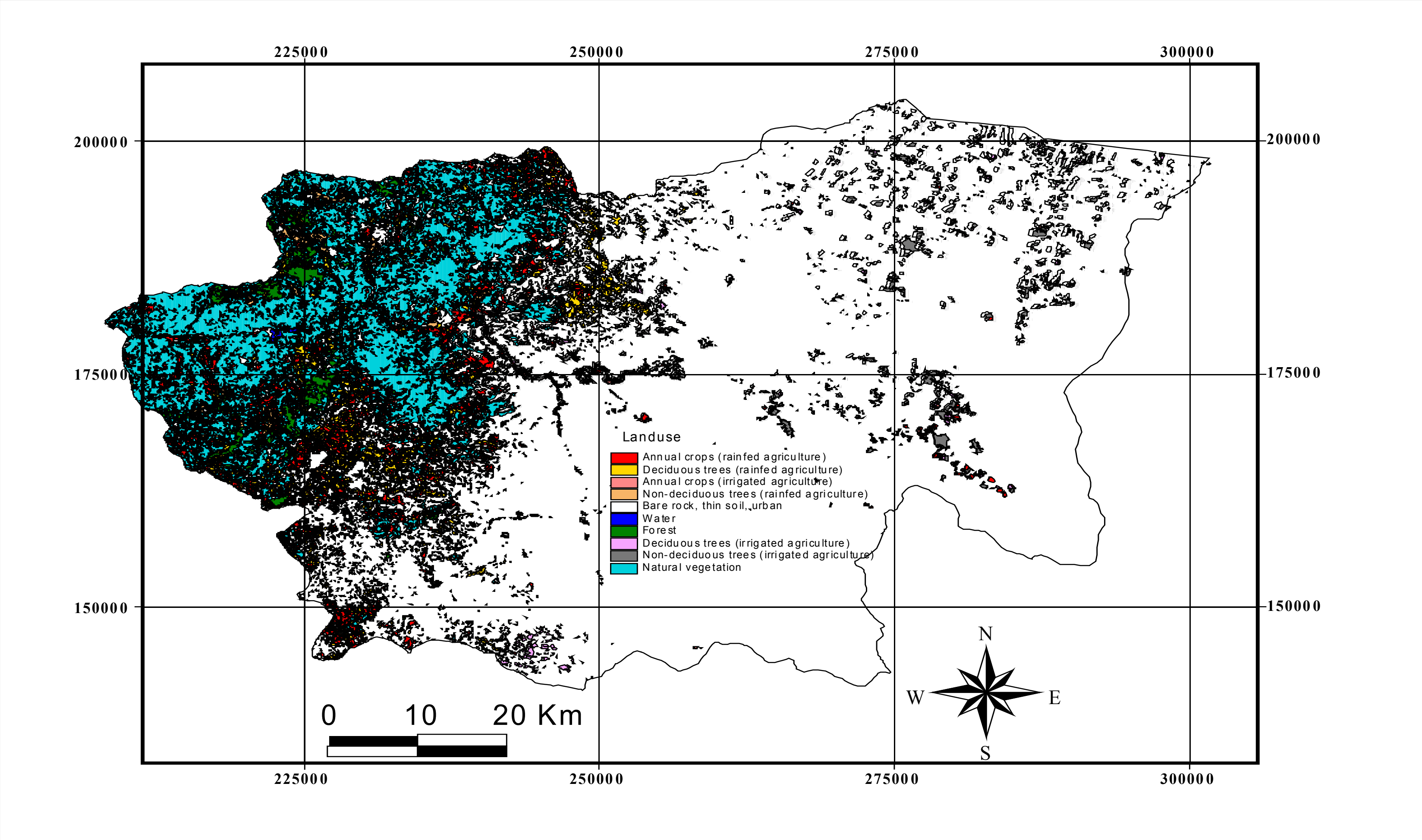

Fig. 1.4: Landuse map of Amman-Zarqa Basin (modified after MOA 1994).

hydrogeology of the area, the preparation of documents relevant to the assessment and exploitation of the groundwater resources and groundwater models. The results of this project are being presented in a series of technical reports.

Awad (1997), carried out a study on “Environmental study of the Amman-Zerqa Basin”. The main objectives of this study were to evaluate the water quality in Zarqa River, efficiencies of Khirbit Es Samra treatment plant and industries treatment plants. The main results of this study were that water quality of Zarqa River is poor and not suitable for potable supply. Zarqa River is contaminated with Pb, Cr, Fe, Al and Mn. Agricultural and industrial activities are the main source of pollution for Zarqa River.

Bajjali (1997), prepared a report entitled “Using ArcView GIS to determine the origin of groundwater salinity in Dhulei-Hallabat and Samra areas of Jordan”. The main purpose of this study was to define the characteristics of the groundwater hydrochemistry and to define the sources of salinity in some wells in the study area. This study showed that irrigation return flow was the main source for salinization problems and the occurrence of nitrate (NO_3) in the groundwater due to inorganic fertilizer activities.

Al Mahamid (1998), conducted a study of “Three Dimensional Numerical Model for Groundwater Flow and Contaminant Transport of Dhuleil-Hallabat Aquifer System”. The main objectives of this study were to calculate water budget, estimate the safe yield and define the source of salinization. This study showed that the total recharge to the groundwater system was about 9 $*10^6$ m^3/yr (the inflow from Jabal Al Arab through the Basalt formation was about 6.7 and from the irrigation return flow and excess rainfall was about 2.3 $*10^6$ m^3/yr. Also, the main source of the salinity in the study area has been originated from the irrigation return flow (more than 95% contributed) and less than 5% contributed from the aquifer itself.

Mac Gregor (1998), conducted a study entitled “The geochemistry of selenium in sedimentary environments: examples from the UK and Jordan”. The main goal of this study was to study water, soil and sediment from three different areas in relation to selenium geochemistry. It is found that a number of wells sampled from Amman-Zarqa basin contained selenium concentrations up to twelve times the World Health Organization (WHO) safety limit of 10 mg/L. However, the lack of elevated selenium concentrations in the soils is due to the dilution of the polluted waters through mixing with non-polluted waters before use in irrigation. Generally, the selenium content of the sediments in Amman-Zarqa basin is highly variable as a function of organic matter content.

Martens (2001), presented a Diploma thesis entitled “Groundwater Study of the Wadi Zerqa Catchment Area”. The main objectives of this study were to present a geological map scaled 1:120,000 generated by TNT-Mips, collecting chemical water samples and isotopes samples for interpretation and create a 3D hydrogeological model using FEMWATER in combination with the graphical interface GMS. This study showed that seven clusters of chemical water samples can be distinguished. According to the isotopes analysis, all samples of the Ajlun aquifer contain Tritium, which might be explained by the circumstance that all samples were taken at springs so that the aquifer also is exposed and a local recharge with young meteoric water is presumable. Most of the Kurnub aquifer samples do not contain any Tritium and the samples of Zerqa group almost contained no Tritium. The groundwater recharge varies between 0-65 mm/yr and there is interaction between the upper aquifer (A7/B2) and the lower aquifers (Kurnub and Zerqa).

BGR & MWI (2001), carried out a comprehensive study on groundwater resources of northern and central parts of Jordan. The main aims of this study were to evaluate the information relevant to the assessment and exploitation of the groundwater resources and to prepare the thematic maps of the hydrogeology of the area to show important aspects as: potential of groundwater exploitation, distribution and the outcrop areas of the main aquifers, the groundwater recharge and discharge areas, groundwater flow pattern and the flow directions in the main aquifers, a review of aquifer parameters and information on the spatial distribution of groundwater salinity. The project results provide important basic data for the water information system of the Ministry of Water and Irrigation (MWI) and for the ongoing updating of the National Master Plan of Jordan.

USAID (2001), prepared a report for resource policy support plan for managing water reuse in the Amman-Zarqa basin and the Jordan Valley. The main goals of this study were to use reclaimed water, to exchange for present and future uses of freshwater, and to maximize the using of reclaimed water resource. The main results reached by this study were that the volume of reclaimed water available in Amman-Zarqa basin is expected to grow from 60 $*10^6$ m^3/yr in 2000 to more almost 180 $*10^6$ m^3 by 2025. In addition, the main constituents of present concern for irrigated agriculture are salts, microbiological, contamination, and nitrogen. The levels of trace elements and metals in the effluent are lower than those specified by the relevant Jordanian standards.

1.6 Aims of the study

The main aims of this study are:

- Calculation of the water balance of the Basin which includes the following informations:

  1. Recharge from rainfall.
  2. Leakage between upper and lower aquifers.
  3. Flow across the boundaries of the aquifers.
  4. Water released from storage in the main aquifer due to decline of the water level.

- Prediction of the reactions of the hydraulic system due to groundwater withdrawal.

- Determination of the Safe Yield of the basin.

- Specifying the type of pollutants and the sources of pollution.

- Determination of the relationship between the groundwater withdrawal and the increasing of salts.

- Identifying the groundwater resources affected by pollutants and any possible contamination in the future.

- Propose solutions and alternatives for the current problems of groundwater resources in terms of quality and quality.

1.7 Methodology

a. Literature review and data collection: collect all data available related to geological, hydrogeological, hydrological, hydrochemical, landuse and other related environmental data documented in technical reports, papers, journals or other references.

b. Field work: geological, hydrogeological, hydrological, hydrochemical and other related data were collected during this work in order to confirm the data collected and to compile the missing data. These data contains: rainfalls, runoffs, base flows, evaporations, elevations, coordinates, pumping rates, static and dynamic water levels, pumping test analysis and brief geological investigations will carry out. Water sampling sites were carefully selected to cover most of the aquifers in the study area and to fulfill the main aims of this study. Eighty-seven water samples were collected between the years of 2003 and 2004 as shown in Fig. 5.1. The chemical analysis for the major cations, anions and heavy metals were carried out in the Laboratories and Quality Department of the Ministry of Water and Irrigation (MWI).

c. Data evaluation: all physical data were checked and evaluated by field surveying and statistical handling (correlation coefficients, type of distribution, etc). Missing data were replaced based on the similarity and the correlation coefficients between data. Ninety-five pumping tests analysis were evaluated for the aquifer systems in order to calculate the aquifer characteristics (transmissivity, permeability and storage coefficient). These evaluations were done using commercial computer software (Aquifer Test). The analyses of water samples were checked and the accuracy of the analysis is based on the sum of positive and negative charges in the water must balance (difference less than 5%). The evaluation of the water quality data was carried using PHREEQC for Windows and AquaChem softwares.

d. GIS database: all relevant data was tabulated (attributes) and was used to create the shape files under ESRI-GIS software to cover the geological, hydrogeological, hydrological, hydrochemical and environmental aspects in the study area. Structured contour maps, drainage boundary, groundwater flow systems and the topographic map was digitized and converted into shape files (themes). Formation thickness, saturation thickness and depth to water levels were calculated.

e. Compilation of raster, vectors and database in GIS: TNT-mips version 6.8 was used to georeference all imported Raster Images into Vector Images. The location of wells, springs, wastewater treatment plants, water samples in the study area were added as points to the active theme based on their coordinates.

f. Groundwater model

Generally, steps for any groundwater modeling cover the following items: conceptual model, code selection, model design, calibration, verification, sensitivity analysis and prediction (Appendix. 7 .1).

1. Conceptual model

It consists of a set of assumptions that minimize the complicated real system to simplified view to reach the model objectives. Generally, it contains the hydrostratigraphic units, water budget, flow system and data needed to assign values. Based on the data compilation and interpretation of topographic, geological and hydrogeological situation, the conceptual model of Amman-Zarqa was developed.

2. Computer program (modeling software)

MODFLOW (a modular three-dimensional finite-difference groundwater flow model of the U.S. Geological Survey) was used to describe and predict the behavior of groundwater flow systems have increased significantly over the last years.

Processing Modflow Pro (PMWIN Pro) software version 7.0.13 (Chiang and Kinzelbach 2003) is a three-dimensional groundwater flow software based on finite difference approach. This software was used to simulate the groundwater flow system and the effects of groundwater abstraction on the groundwater systems in Amman-Zarqa Basin. PMWIN Pro is an enhanced version of Processing Modflow for Windows, supported MODFLOW-2000 and several codes of useful modeling tools and comes with a professional graphical user-interface.

3. Discretization (model design)

Processing Modflow Pro (PMWIN) is based on the block-centered finite difference approach for modeling design. The block-centered grid considered that the flux boundaries are located at the edge of the block. In the block-centered finite difference approach, an aquifer system is represented by a discretized domain consisting of an array of nodes and associated finite difference blocks (cells) as shown in Fig. 7.2. The nodal grid represents the framework of all numerical model calculations. Thus, the hydrostratigraphic units and the thickness of each model cell can be specified in terms of layers, rows and columns.

According to the conceptual model and other related data, the model design was established. In order to reach the main aims of this study, the model design contained the upper, middle and lower layers. Also, the mesh size (0.5 by 0.5 km) of the model reflects the actual hydraulic response and to eliminate the superposition of drawdown in the same cell as much as possible. The flux boundary was carefully selected in order to guarantee no any flow boundary would exclude in the model domain.

Model parameter values were assigned into the model by three methods: Cell-by-Cell, Polygon and Vector Trans methods. The first two methods was a part of the model software and the Vector Tans method is a part of GIS software.

4. Boundary conditions

Three types of hydrogeological boundaries are dominant in the groundwater system:

a. Specified head boundaries (Dirichlet conditions)
At least one point in a modeled domain to insure that there is a uniqueness of the solution.

b. Flow boundaries (Neumann conditions)
This type of boundary means the gradient of head (flux) across the boundary is given.
A special case of this boundary is the impervious boundary where the flux is zero.

c. Head-dependent flow boundaries (Cauchy or mixed boundary conditions)
Linear combination of head and flux at boundary where the flux across the boundary is calculated given a boundary head value.

5. Assigning parameter values

The geometry of the aquifer systems was assigned in the model domain. First, topographic map and structural maps of all layers were digitized. Second, transformation polylines to points then assign to the model as ASCII file. Then, the thematic maps (vector graphics) were imported into the model by using Cad Reader (DXF format) so that all of input data could be checked.

Processing Modflow Pro (PMWIN) has three methods for specifying parameter values: Cell-by-cell (since the elevation of the base of a hydrogeological unit has a different value in each cell, the data needed to enter into the model cell by cell), Polygon (when the elevation of the base of a hydrogeological unit is homogeneous) and Polyline method. These methods were applied for few data at certain locations.

Hydrogeological parameters were assigned in the model domain by the following method: First, the horizontal hydraulic conductivities were assigned in the model domain as initial values based on the pumping tests analysis results. Second, by using Field Interpolator (Gridding method-Kriging) filling all cells in the model domain where pumping tests were not available.

6. Theoretical background of the mathematical model

Theoretical background of the mathematical model will be discussed in detail in chapter seven. However, the dominant flow equations of the groundwater system should be related to continuity and Darcy's law. Generally, continuity requests the conservation of water mass (outflow-inflow = change in storage) and Darcy's law (1856) states that the specific flow rate (filter velocity) is proportional to the negative head gradient in the isotropic porous medium.

7. Model calibration

7.1 Steady state

Steady state calibration was performed by comparison piezometric heads of the upper and lower aquifers (initial states) and the calculated hydraulic heads of the model results.

Calibration of the steady state in the upper aquifer (Basalt and B2/A7) was based on the water-table map which represents the groundwater situation in the beginning of seventies and on some spot observations made in 1996. The same methodology was applied for the lower aquifer.

7.2 Transient simulation

The steady state calculations were used as input data to build up the transient simulation. The main benefit of the building of transient simulation is to simulate the current drawdown and to predict the situation of the hydraulic system on a long-term average. The year of 1970 was considered as the year in which water production started and further development of the transient groundwater flow will simulate until the year of 2001. The time period of 32 years was divided into 32 stress periods in order to cover the pumping period from 1970 to 2001. The seasonal variations of the production rates were neglected for modeling purposes.

Time dependent calibration was based on long-term (1970-1995) and short-term (1996-2001) of drawdown in the observation wells.

8. Inverse model

Inverse model, it is often referred to as automatic calibration, or parameter estimation. PEST is external parameter estimation software on the basis of finite parameter differences. PEST tries to reach the optimum parameter values based on the sum of squared deviations between model-calculated and observed hydraulic heads or drawdowns at the observation boreholes.

Inverse modeling will apply for upper and lower aquifers in order to minimize the difference between calculated and measured water levels and to improve the model results.

9. Sensitivity analysis

To minimize the uncertainty in the estimation of aquifer parameters, sensitivity analysis was conducted in this study. Also, the sensitivity analysis was conducted in this study to test the effect on the model domain if one parameter is changed whereas all other parameters are kept constant

Sensitivity analysis was applied for steady and non-steady states in the upper and lower aquifers.

10. Model prediction

Further model runs were carried for the next 20 years of abstraction. Multi scenarios were adopted in this study in order to reach the sustainability use of the water resources. In addition, these scenarios give alternative solutions and strategies for future plans.

2 HYDROLOGY

2.1 Hydrometeorological network

The hydrometeorological monitoring network in the area investigated consists of rainfall, evaporation and runoff stations. Fig. 2.1 shows the distribution of the meteorological stations in the study area. Rainfall monitoring network in Amman-Zarqa Basin consists of 56 stations. Table 2.1 summarized the name of rainfall stations, their locations, type of stations, averages annual rainfall, altitudes and their approximate period of records. Most of the rainfall stations include Class-A pan to measure the evaporation rate from open surface, anemometer to measure the wind speed, sunshine recorder and relative humidity sensor. There are six stream gauging stations located in the study area. The stream flow data measurement has been started in Amman-Zarqa Basin by Ionides in 1938 at old Jarash Bridge. In the beginning of sixties, the current meter and stage observation started to perform for discharge measurements (USAID and WAJ 1989).

2.2 Climate

The climate in Jordan is predominantly of the Mediterranean type: hot and dry summer and cool wet winter with two short transitional periods in autumn and spring. During the short transitional periods most convective activity occurs producing thunderstorms. Precipitation pattern is both latitude and altitude dependent. Rainfall decreases from North to South, from West to East and from higher elevation to lower ones (JMD 2003).

Amman-Zarqa Basin is bordered by the high lands in the west and the foothills of Jabal Al Arab in the Northeast. Thus, the basin is located in a rain-shadow area, where moist air masses can only enter through two different conditions, one near Amman–Zarqa and the other near Mafraq. Hence, Amman-Zarqa Basin is located between humid climatic conditions in West and Saharian type of arid climate in the Southeast and East regions (USAID and WAJ 1989).

The average annual rainfall varies from less than 200 mm Northeast to more than 500 and 600 mm Northwest close to Bal'ama station and West close of Salt station over the basin, respectively. The average of maximum rainfall is 61.8 mm/d in January, the average daily temperature is 12.4 °C during the wet season (from November to April) and 23.2 during the dry season (from May to October), whereas the average daily minimum temperature in the basin occurred in January is about 4.1 °C and about 33.1 °C as an average daily maximum temperature. The prevailing wind direction in the study area is west-southwestern in winter and shifting to west-northwestern in summer. The average daily wind speed is 2.1 m/s, ranging between 1.9 and 2.3 m/s in winter and 1.6 and 2.4 m/s in summer. The average daily relative humidity varies from 65.2 to 82.6% in winter and from 59.2 to 71% in summer.

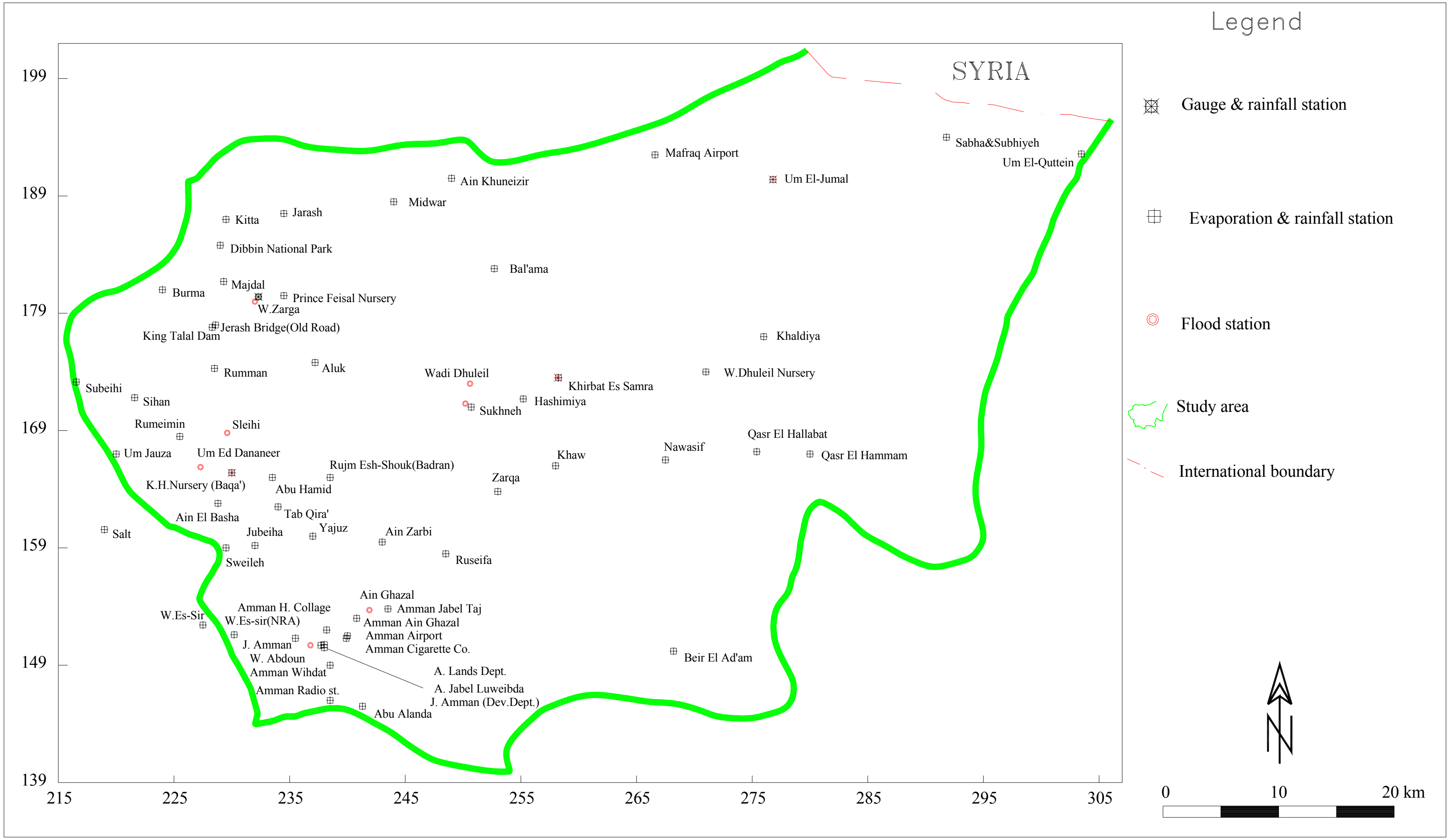

Fig. 2.1: Map of meteorological stations in the study area.

Table 2.1: List of representative rainfall stations in the study area.

Station Id.	Station name	Coordinates (Palestine Grid)		Altitude	Annual average rainfall	Type of station	Period of records
		East [km]	North [km]	[m]	[mm]		
AL0003	Bal'ama	252.7	182.8	695	205.5	N*	1970-2002
AL0004	Jarash	234.5	187.5	585	347.2	R** & N	1970-2002
AL0015	Zarqa	253	163.8	610	131.2	R & N	1970-2002
AL0016	Ruseifa	248.5	158.5	655	147.5	N	1970-2002
AL0019	Amman Airport	243.5	153.8	790	255.0	R & N	1970-2002
AL0049	Q. El-Hallabat	275.4	167.2	610	102.6	R & N	1970-2002
AL0059	UM El-Jumal	276.8	190.4	650	120.3	R & N	1970-2002
F0001	U. El-Quttein	303.5	192.6	986	137.1	R & N	1970-2002
AM0001	Salt	219	160.6	1100	569.9	R & N	1970-2002
AN0002	W. As-Sir	227.5	152.4	800	541.4	N	1970-2002

* Nonrecording: standard gauge (measures daily).

** Recording: records rainfall on chart automatically.

The average daily sunshine hours ranges between 5.3 and 8.2 hours/day in winter and between 8.3 and 11.1 hours/day in summer. Table 2.2 summarized the climatic parameters over the basin.

2.3 Precipitation

Rainfall is the most important parameter in the hydrological cycle. Generally, the amount of rainfall is mainly governed by the topographic elevation of a location. In addition, the dominant conditions for precipitation to form may be summarized as follows: supply of moisture, cooling to below point of condensation, condensation and growth of drops.

2.3.1 Rainfall stations

The first rainfall station in Jordan was established in Amman Airport which is located in Amman-Zarqa Basin during the year of 1922/23. The density of the rainfall stations is 62 km^2/station. According to the World Meteorological Organization Guide (WMO 1994), this density is sufficient to evaluate the hydrological situation in the study area. However, because of lack in documentation of rainfall data, measurement accuracy and incomplete data set, not all rainfall stations have been selected to represent and evaluate the hydrological situation in the study area. All of rainfall stations in Amman-Zarqa Basin are daily measurement with recording gauges.

Table 2.2: Averages of the climatic parameters in the study area (1970-2002).

Parameters	**Months**											
	Oct.	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**
Minimum daily temperature °C	13.3	8.9	6.1	4.1	4.7	6.7	9.7	13.1	16.0	18.0	17.8	16.3
Maximum daily temperature °C	27.5	20.4	16.3	13.6	15.9	18.3	23.9	28.4	31.5	33.1	32.5	31.4
Mean daily temperature °C	20.4	14.7	11.2	8.8	10.3	12.5	16.8	20.7	23.7	25.6	25.2	23.9
Sunshine duration (hrs/day)	8.3	6.8	5.4	5.3	6.2	7.2	8.2	10.1	11.1	11.4	10.8	9.3
Wind speed (m/s)	1.6	1.9	1.9	1.9	2.2	2.2	2.3	2.3	2.4	2.4	2.1	1.7
Wind direction	W SW	W SW	W SW	W SW	W SW	W NW	W NW	W NW &NE	W NW &NE	W SW	W SW	W SW
Relative humidity (%)	71.0	73.4	81.1	82.6	81.1	73.5	65.2	59.2	59.8	63.7	68.0	69.3
Rainfall (mm)	7.3	25.1	48.9	61.8	55.1	42.9	12.8	1.9	0.0	0.0	0.0	0.0
Class-A pan (mm/d)	7.6	5.2	3.2	2.8	3.8	5.2	8.1	11.0	12.5	13.4	11.8	10.0
Potential evapotranspiration (mm/d)	4.2	2.5	2.3	2.1	2.6	3.9	5.7	6.8	7.6	8.1	7.2	5.6

Therefore, by using statistical software (SPSS FOR WINDOWS 2001) missing values for some specific years have been filled during the period of (1970/71-2001/02) among the stations. The missing data have been filled based on the similarity and the correlation coefficients between stations. Table 2.1 summarized the general information of the representative rainfall stations in the study area. Generally, the rainfall begins in October and ends in May.

2.3.2 Types of rainfall precipitating over the study area

There are two types of precipitation distinguished in the study area according to the factor mainly responsible for lifting the air mass causing the required large-scale cooling of significant amounts of precipitation (USAID and WAJ 1989):

1- Frontal precipitation
2- Nonfrontal precipitation

Frontal precipitation occurs as a result from the lifting of warm air on one side of a frontal surface over colder and denser air on the other side. This kind of precipitation can have two types: **First**, warm-front precipitation which occurs when the warm air is advancing upward over a colder air mass. This type is characterized by light to moderate and continuous rainfall till the end of the front. **Second**, cold-front precipitation which occurs when the warm air forced upward by an advancing mass of cold air, of which the leading edge is the surface cold front. This kind of precipitation is generally much higher, heavier amounts and intensities occur near the front surface. This type of rainfall is considered the main source of the precipitation over the study area.

Nonfrontal precipitation occurs in three types: The **first** type occurs under low pressure condition which lets the air move into low pressure areas from surrounding areas then displaces low pressure air upward to cool and precipitate. This type of precipitation is rarely occurring in the colder months. **Second** type is the Convective precipitation; it develops from day long heating of moist air. An instability state into the air creates a bubble of rising warmer lighter air in the colder denser surroundings which may cause an increasing in the speed of the upward and downward motions followed by rapid saturation. This type of precipitation is usually distinguished by showers and thunders and sometimes hails. Usually this type occurrs in the warmer months during the winter season. **Third** type is the Orographic precipitation occuring as a result of moving moist air mass toward a mountain and then deflecting upward by the mountain. This type of precipitation is regarded as an enhancement of the annual precipitation and observed on the western mountains of Amman-Zarqa Basin.

Thus, the main source of precipitation in the study area is delivered throughout the above mentioned two types of precipitation during the winter months (from October to May).

2.3.3 Mean precipitation over the study area

There are mainly three techniques such as arithmetic, Isohyetal and Thiessen polygons to convert the point sampling of the rainfall gauges into the average value in order to complete the hydrological analysis. The arithmetic method is the simplest one to achieve the average depth of rainfall but this method is good in flat areas if the gauges are uniformly distributed and the individual gauge catches do not vary widely from the mean (Ta'ani 1992). The Thiessen polygons simply assume linear variation of precipitation between stations and attempts to allow for nonuniform distribution of gauges by providing a weighting factor for each gauge (Appendix 2.1). The Isohyetal method had been applied to find the mean rainfall depths and their volumes over the study area because this method is most common and accurate to represent the nonuniform of the areal pattern of precipitation from complex weather situations as Amman-Zarqa Basin or varied topography from point of view. The monthly and annual rainfall observations for the period of 33 years (1970/71-2001/02) are shown in Appendices 2.2A-2.2H. Thus, Thiessen method has been used in this study in order to evaluate the daily rainfall. However, it was not possible to apply Kriging or Isohyetal methods for each daily storm. Also, Thiessen method has been adopted in order to classify the water years into dry, wet and normal conditions.

Based on the Thiessen polygons results (Table 2.3) and Isohyetal maps results for dry, normal and wet years (Figs. 2.2-2.4, respectively), the total amounts of rainfall were calculated as shown in Tables 2.4, 2.5 and 2.6 for dry, normal and wet years, respectively. It is concluded that from Fig. 2.2 the annual rainfall distribution for dry year (1998/99) over the study area varies from less than 50 mm in eastern and northeastern part of the basin to more than 200 mm in the western and northwestern parts of the study area. Fig. 2.3 represents the normal hydrological year (1984/85), it is shown that the annual rainfall depth ranges between less than 100 mm in the eastern and northeastern part and more than 500 mm in the western and more than 450 mm in northwestern parts of the study area. Moreover, Fig. 2.4 shows that the wet hydrological year (1991/1992) which has rainfall depth varies from less than 200 mm in the eastern and northeastern parts to more than 750 mm in the northwestern parts and more than 1000 mm in the western parts of the study area.

The rainfall distribution and total amount over the study area have been calculated as mentioned above for dry, normal and wet years. Table 2.4 shows that the volume of rainfall in the dry year for a period of 33 years (1970/71-2001/02) is about 272.9 $*10^6$ m^3 over the study area (3489.5 km^2). On the other hand, the rainfall volume in the wet year for the same period is about 1343.3 $*10^6$ m^3 over the study area as shown in Table 2.6. In addition, Table 2.5 shows that the rainfall amount in the normal year for the same period is about 705.9 $*10^6$ m^3. Fig. 2.5 shows the distribution of the mean monthly rainfall over the study area. The maximum average rainfall occurred in January with rainfall depth around 62 mm and with less than 5 mm in May.

Table 2.3: The average annual rainfall of the study area.

Water Year	Salt Area 7.9%	Jarash Area 11.6%	Amman Airport Area 9%	Zarqa Area 18.2%	Bal'ama Area 12.4%	Qasr El-Hallabat Area 21.2%	Um El-Jumal Area 13.7%	Um El-Quttein Area 6.0%	Weighted Avg. Annual Rainfall
	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
70/71	718.0	523.8	293.9	107.0	364.3	110.6	143.2	258.5	267.2
71/72	619.9	358.1	311.6	148.0	245.5	174.8	211.3	212.0	254.7
72/73	349.5	229.7	195.1	96.1	158.5	71.0	102.7	85.5	143.2
73/74	793.0	443.8	447.9	238.9	301.2	147.3	200.4	277.0	310.6
74/75	504.2	298.1	237.3	138.4	167.3	126.1	132.2	189.3	197.9
75/76	472.6	263.6	195.0	110.4	199.0	90.9	116.5	137.4	173.7
76/77	417.3	264.8	190.4	80.4	155.3	58.4	76.0	104.4	143.8
77/78	561.1	267.1	248.6	87.4	157.9	82.6	83.4	95.1	167.8
78/79	420.8	145.0	134.2	52.7	125.1	56.0	70.7	97.1	114.6
79/80	914.2	564.7	504.0	310.2	377.2	200.5	216.1	255.2	373.7
80/81	640.3	324.0	301.1	105.9	203.2	150.3	118.5	158.6	217.4
81/82	494.1	266.3	194.9	119.5	160.4	104.4	118.7	92.7	173.1
82/83	829.2	421.9	422.0	193.7	309.5	70.0	144.8	108.0	267.2
83/84	482.3	323.6	200.2	86.3	147.1	70.0	104.8	107.0	163.2
84/85	542.6	285.0	279.5	104.3	222.3	108.7	161.7	182.3	203.8
85/86	396.6	189.5	108.9	84.7	132.3	60.8	46.9	124.9	121.7
86/87	599.2	352.2	264.2	172.7	242.9	107.1	148.2	129.6	224.3
87/88	706.7	526.8	359.3	250.1	324.0	189.4	219.7	190.6	316.7
88/89	568.7	297.2	243.7	149.8	200.0	176.6	101.5	97.6	210.6
89/90	512.5	277.8	156.2	130.3	140.6	99.8	117.9	168.2	175.3
90/91	535.7	241.5	197.9	88.1	87.4	82.6	114.7	148.0	157.1
91/92	1200.7	668.7	539.9	258.2	239.5	205.1	191.4	162.5	377.2
92/93	666.5	462.8	256.8	97.9	138.0	79.7	92.9	127.0	201.6
93/94	442.7	279.7	160.5	107.7	128.6	47.2	53.4	83.5	139.7
94/95	598.4	414.2	278.8	146.3	186.8	66.0	141.0	96.5	209.3
95/96	492.6	298.5	178.2	96.1	162.5	96.6	68.0	70.5	161.2
96/97	600.4	423.1	268.6	123.9	266.2	72.2	91.3	101.6	210.2
97/98	518.3	460.0	258.6	143.9	326.7	106.0	108.2	204.4	233.8
98/99	223.4	196.8	107.2	48.0	82.0	21.0	17.0	16.0	76.8
99/00	330.3	327.2	172.1	63.5	213.5	70.2	46.4	64.5	142.7
00/01	411.6	297.7	176.5	100.6	199.7	70.4	129.4	110.0	165.3
01/02	672.0	416.2	277.7	157.0	210.8	110.8	160.5	131.4	234.4
Average	**569.9**	**347.2**	**255.0**	**131.2**	**205.5**	**102.6**	**120.3**	**137.1**	**204.1**

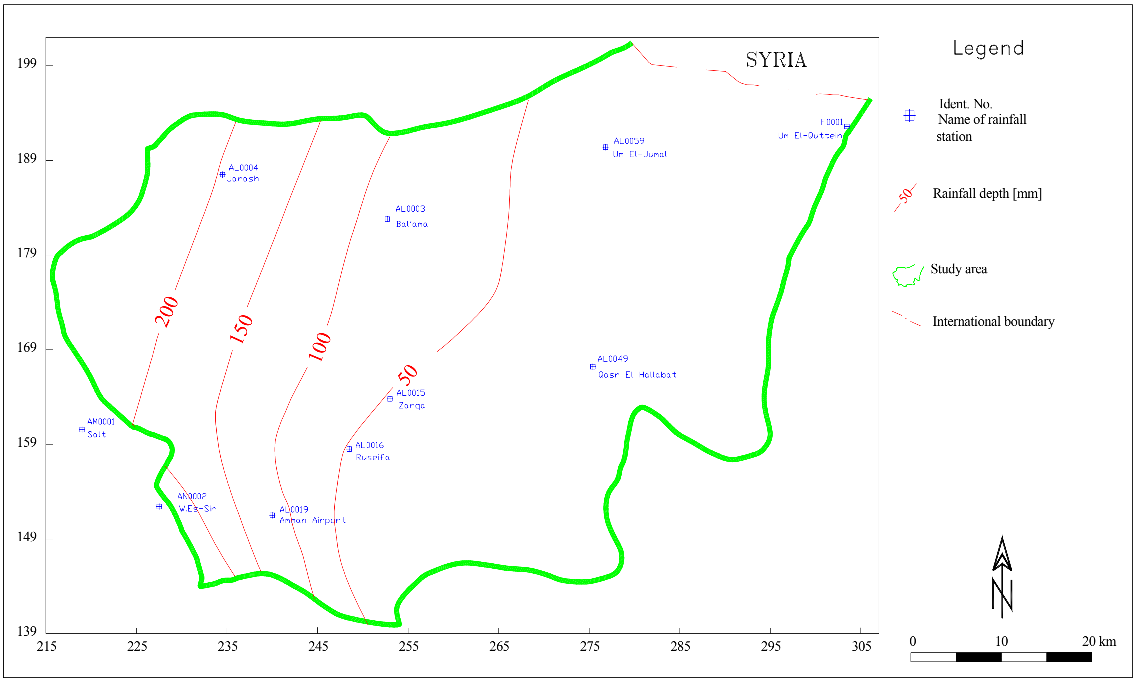

Fig. 2.2: Contour map of precipitation for an average dry year of Amman-Zarqa Basin (1998/99).

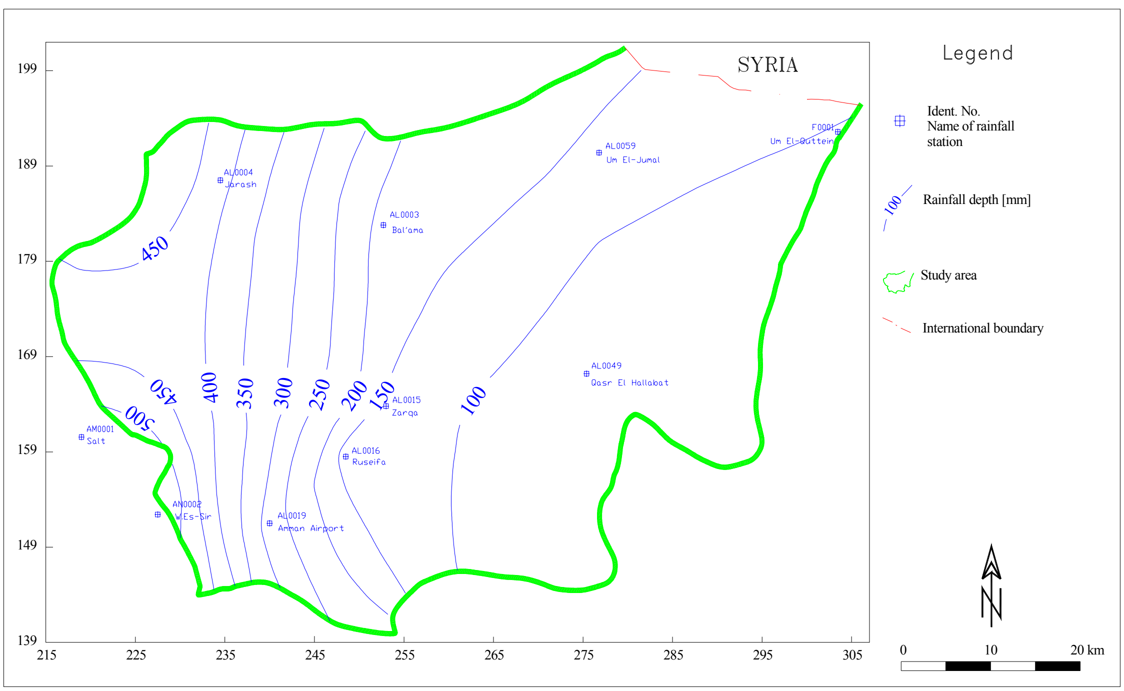

Fig. 2.3: Contour map of precipitation for an average normal year of Amman-Zarqa Basin (1984/85).

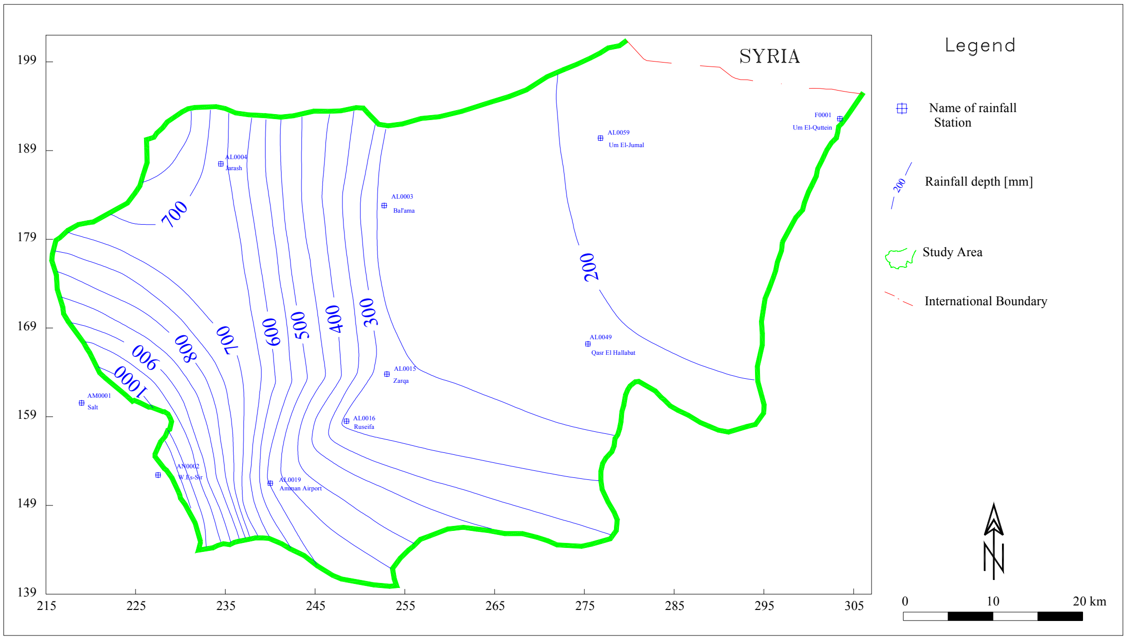

Fig. 2.4: Contour map of precipitation for an average wet year of Amman-Zarqa Basin (1991/92).

Table 2.4: Averaged rainfall for dry year.

Rainfall depth [mm]	Covered area [km^2]	Mean annual rainfall [mm]	Annual rainfall volume [10^6 m^3]
<50	1843.5	25	46.1
50-100	589.3	75	44.2
100-150	371.0	125	46.4
150-200	360.5	175	63.1
>200	325.3	225	73.2
Total	**3489.5**		**272.9**

Table 2.5: Averaged rainfall for normal year.

Rainfall depth [mm]	Covered area [km^2]	Mean annual rainfall [mm]	Annual rainfall volume [10^6 m^3]
<100	987.3	75	74.0
100-150	770.4	125	96.3
150-200	449.4	175	78.6
200-250	211.8	225	47.7
250-300	189.5	275	52.1
300-350	191.2	325	62.1
350-400	180.1	375	67.5
400-450	313.8	425	133.4
450-500	175.9	475	83.6
>500	20.2	525	10.6
Total	**3489.5**		**705.9**

Table 2.6: Averaged rainfall for wet year.

Rainfall depth [mm]	**Covered area [km²]**	**Mean annual rainfall [mm]**	**Annual rainfall volume [10^6 m^3]**
<200	802.8	175	140.5
200-300	1103.6	250	275.9
300-400	360.8	350	126.3
400-500	278.2	450	125.2
500-600	200.9	550	110.5
600-700	286.1	650	186.0
700-800	232.0	750	174.0
800-900	116.5	850	99.1
900-1000	81.0	950	77.0
>1000	27.6	1050	29.0
Total	**3489.5**		**1343.3**

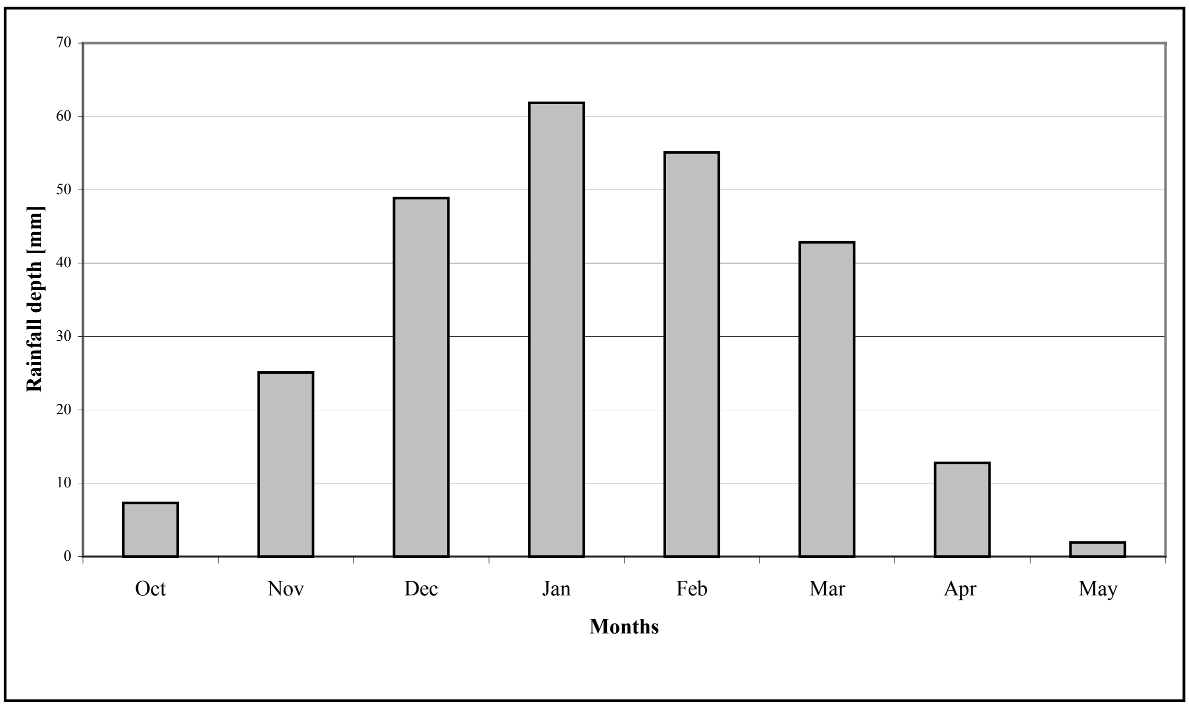

Fig. 2.5: Histogram of the mean monthly rainfall distribution over Amman-Zarqa Basin.

2.3.4 Frequency analysis for rainfall

This analysis was performed to compute the rainfall frequencies for different return periods (2,5,10,25,50,100 and 200 year-return period).

The calculated rainfall values were analyzed for all events (1970-2002). The monthly peak of each flood was selected in order to conduct the frequency analysis on monthly basis. The yearly monthly maximum rainfall values for Amman-Zarqa Basin were calculated. The largest sample size of these data was found as 32 events from November until March. In the other months, this sample size was found to be 30 events in April, 28 events in October and 18 events in May.

For the frequency analysis, monthly annual maximum series and the partial series for the whole data were analyzed individually using six different distributions (i.e., Normal, 2 Parameters log Normal, 3 Parameters Log Normal, Pearson type III, Log Pearson type III and Gumbel Type I Extremal) were run using the software package SMADA 6.3 (1997) and the best fit was chosen.

The results of frequency analyses were presented in Figs. 2.6 and 2.7 and illustrated in Tables 2.7 and 2.8.

The results of 2-years return period rainfall (which represents the average yearly condition) using frequency analysis for both annual monthly maximum series and the partial series (Tables 2.7 and 2.8) are 74.5 mm and 24.6 mm, respectively.

According to the measured monthly maximum rainfall value (155 mm) which corresponds to 50-return period according to the predicted data in Table 2.7. However, it is difficult to decide in which month the peak of rainfall might occur.

Therefore, the long-term average of the annual rainfall over the study area has a continuous decline in rainfall depth. During the period of 33 years (1970/71-2001/02) the rainfall depth has been declined within the range between 25 and 30 mm as shown in Fig. 2.8 (confidence interval 95%).

2.4 Evaporation

Evaporation is the transfer process of water from liquid state into water vapor which requires energy to provide the latent heat of vaporization (Chow et al. 1988). The combination process of the evaporation from surface ground and plants is known as evapotranspiration.

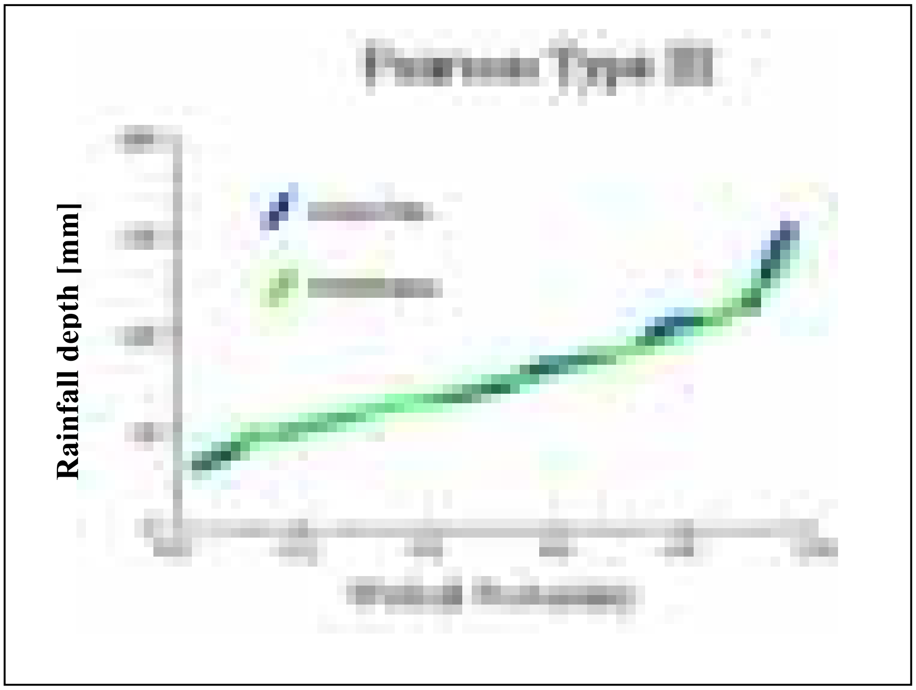

Fig. 2.6: Distribution analysis for the monthly maximum rainfall using Pearson Type III.

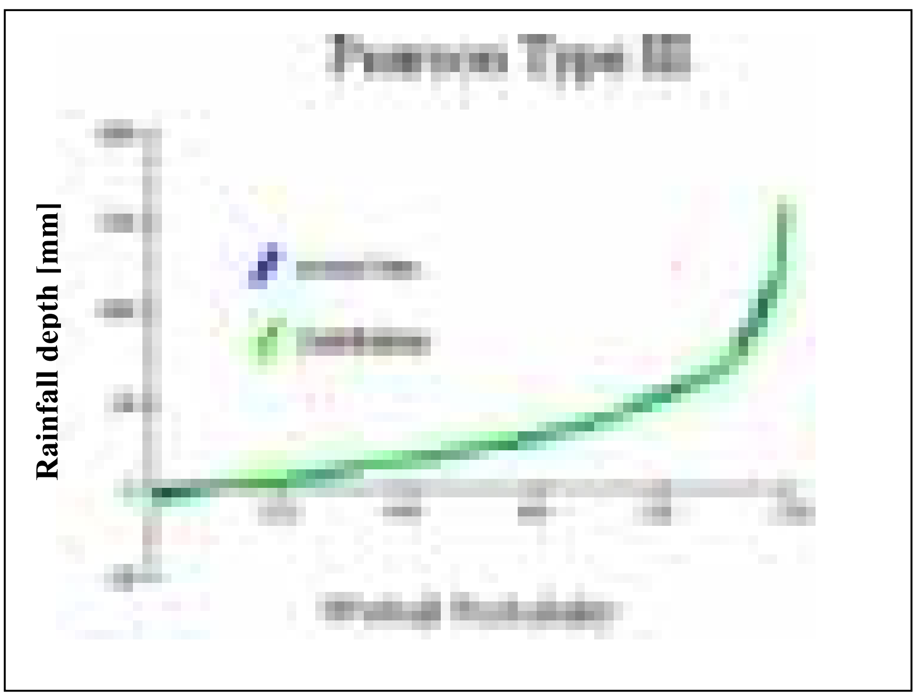

Fig. 2.7: Distribution analysis for the partial series of rainfall using Pearson Type III.

Table 2.7: Predictions of rainfall based on monthly maximum values.

Exceedence probability	Return period	Calculated value	Standard deviation
0.995	200	179.8	30.7
0.990	100	166.6	25.1
0.980	50	152.9	19.9
0.960	25	138.7	15.1
0.900	10	118.6	10.0
0.800	5	101.7	7.5
0.667	3	87.7	6.6
0.500	2	74.5	6.0

Table 2.8: Predictions of rainfall based on partial values.

Exceedence probability	Return period	Calculated value	Standard deviation
0.995	200	151.0	18.9
0.990	100	132.8	14.8
0.980	50	114.5	11.1
0.960	25	96.2	7.9
0.900	10	71.5	4.8
0.800	5	52.3	3.6
0.667	3	37.4	3.2
0.500	2	24.6	2.7

Generally, three main factors influencing evapotanspiration from an open water surface are (Chow et al. 1988):

- Supply of energy to provide the latent heat of vaporization. The main source of energy supply is solar radiation.

- Ability to transport the vapor away from the evaporative surface. This process depends on the wind speed velocity and the specific humidity gradient in the air.

- Supply of moisture at the evaporative surface.

According to the location of Jordan in arid and semi arid zone, the evapotranspiration (ET) plays an essential role in order to evaluate the hydrological situation (aside from the surface runoff) and to estimate the infiltration rate.

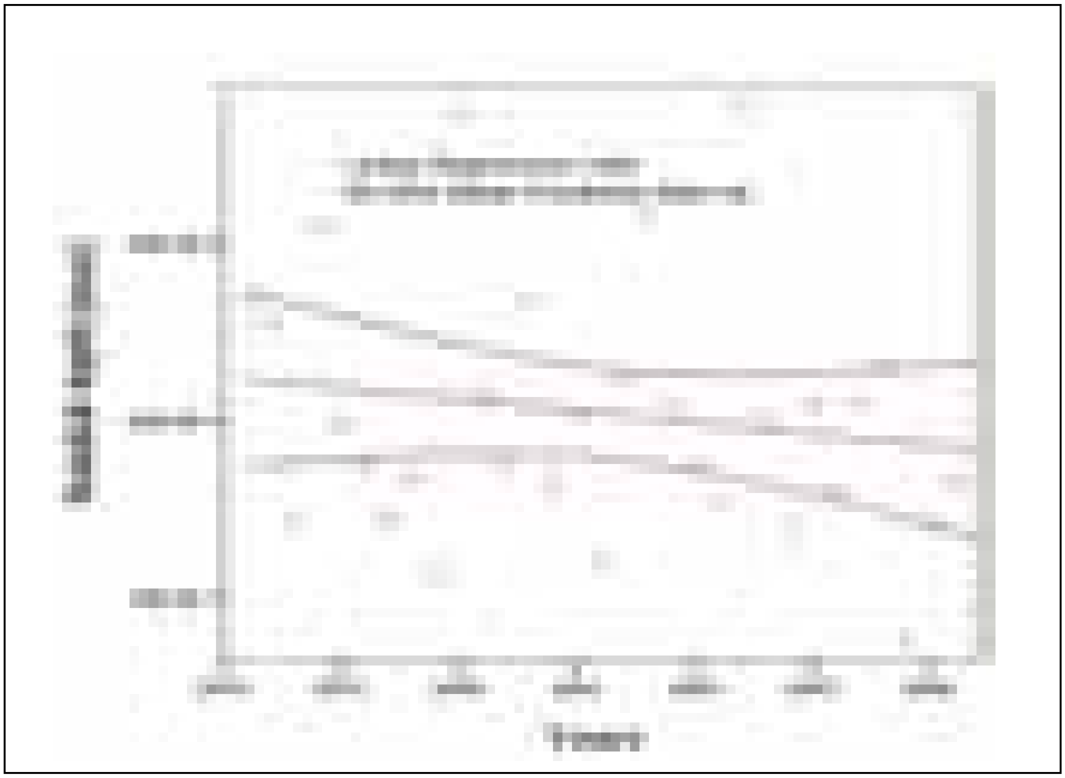

Fig. 2.8: Trend of long-term average rainfall over Amman-Zarqa Basin.

2.4.1 Evaporation stations

The first evaporation station established in Amman-Zarqa Basin was Amman Airport station in 1959 (USAID and WAJ 1989). During the sixties three other stations were installed in the study area (AL0035: King Husein Nursery, AL0059: Um El-Jumal and AL0053: King Talal Dam). Moreover, during the seventies three stations were added in the study area (Mafraq Airport, AL0004: Jarash Bridge and AL0055: Wadi Dhuleil). In 1985, another station was added (AL0066: Khirbet As-Samra Evap. Station) parallel with the biggest treatment plant built in Jordan (Khirbet As-Samra). According to the WMO standards, the density of the evaporation stations over the study area is sufficient (436 km^2/station) because the minimum network required in arid areas is one station per 30000 km^2.

Two methods have been applied to evaluate and analyze the process within the evaporation and evapotranspiration in this study; i.e. evaporation pan (Class-A pan) and Penman's equation.

2.4.2 Evaporation pans

The standard of USA Weather Bureau Class-A pan evaporation (EP) is widely used in Jordan. It consists of a galvanized iron pan, 122 cm in diameter, 22.4 cm deep and is placed 15 cm above ground on a wooden frame that allows air to circulate under it. Generally, water level is kept between 19 and 20 cm (MWI 2003). Also, Piche Evaporimeter used to measure the evaporation amounts but it is not commonly used for computations of water budget but it could be used to check the Class-A pan or to cover the gaps in the pan measurements.

Fig. 2.1 shows the location of all evaporation stations over the study area. All of them are equipped by Class-A pan and Piche Evaporimeter. According to the lack of data, only five evaporation stations (AL0019: Amman Airport, Al0035: King Husein Nursery, AL0053: King Talal Dam, AL0059: Um El Jumal and AL0066: Khirbit As-Samra) out of eight have been taken for hydrological evaluation over the study area. Appendices 2.3A-2.3E include all evaporation stations with average monthly and annual evaporation measured by Class-A pan during the period of investigation (1970/71-2001/02).

Missing data were completed using the relation between the Piche and Class-A pan evaporation as first step and by regression equation (SPSS FOR WINDOWS 2001) between stations as second step.

It is found that the annual maximum potential evaporation was 3104 mm/yr measured at Um El-Jumal station in the northeastern part of the study area where arid climate is prevailing. However, the annual minimum evaporation was 2077 mm/yr observed at Khirbit As-Samra located close to the treatment plant pools of the biggest treatment plant in Jordan. Generally, the long-term average of monthly evaporation ranges between 52 and 105 mm in January and between 310 and 431 mm in July.

Fig. 2.9 shows the isohyetal contour map of the long-term annual Class-A pan evaporation during the period of 33 years (1970/71-2001/02) excluded Khirbet As-Samra evaporation station because of this station has been operated in the mid of eighties.

According to the Class-A pan evaporation measurements, the long-term average of annual evaporation varies from less than 2500 mm in the southwestern parts to more than 3200 in the northeastern and eastern parts of the study area. In addition, the shape of the evaporation contours lines have been changed in the southwestern parts because of the transitional zones between the high lands in the west to desert in the east. Since the temperature increases from west (hills zone) to east (desert zone).

2.4.3 Potential evapotranspiration

In order to estimate the infiltration volumes of the study area, the total evaporation (evapotranspiration) has to be computed over a hydrological year. The potential evapotranspiration (ET) was calculated based on Penman's equation (Jensen and Allen 1990).

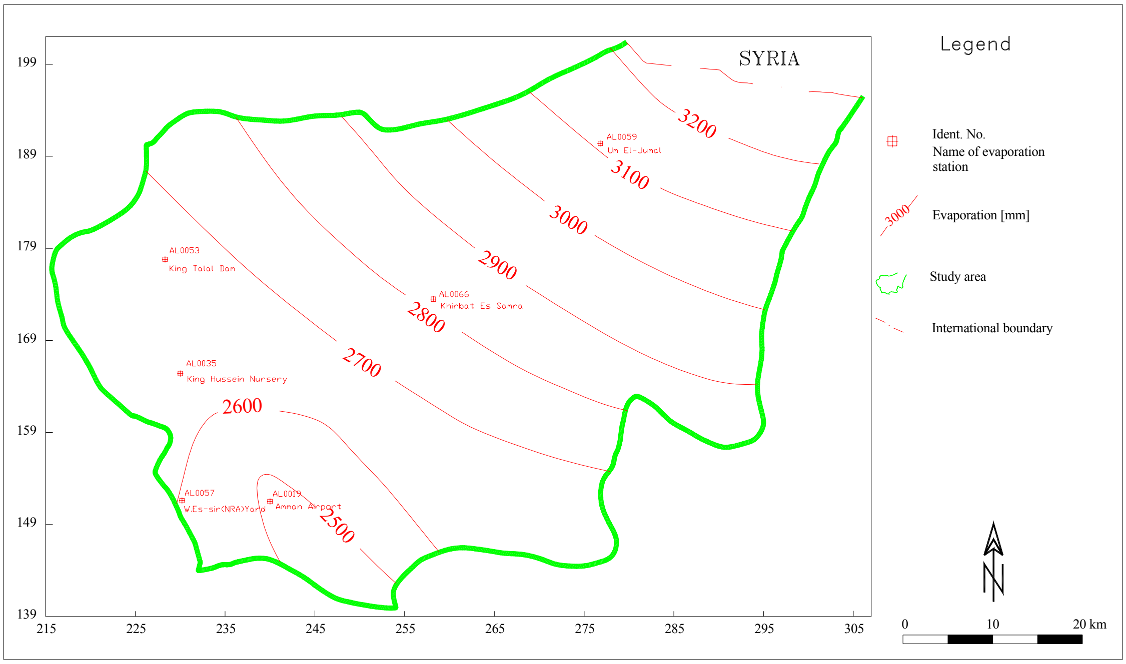

Fig. 2.9: Contour map of long-term average annual Class-A pan evaporation over Amman- Zarqa Basin.

According to Penman's equation, the potential evapotranspiration (ET) was calculated for the period (1970/71-2001/02). Table 2.9 shows the long-term average monthly evapotranspiration over the study area. It is concluded that the evapotranspiration according to Penman ranges between 65 and 170 mm/month in winter season (from the first of November tell the end of April) and between 129 and 250 mm/month in summer season (from the first of May tell the end of October).

For water budget calculation over the study area, the contour lines of potential evapotranspiration for wet and normal (long-term) water years were plotted for the period of (1970/71-2001/02) as shown in Figs. 2.10 and 2.11, respectively. It is found that the potential evapotranspiration in winter season (normal year) varies from less than 380 mm in the southwestern parts to more than 640 mm in the northeastern parts of the study area (Fig. 2.10). In addition, the potential evapotranspiration (wet year) varies from less than 540 mm in the southwestern parts to more than 680 mm in the northeastern parts of the study area (Fig. 2.11).

2.4.4 Pan coefficient

According to the different models of large reservoirs, evaporation pans have differ in the heat storing capacity and heat transfers from their sides and bottom. The sunken and floating pans aim to reduce this deficiency (Ta'ani 1996). It is found that there is correlation between Class-A pan evaporation (EP) and actual evapotranspiration with a regression coefficient over 97% (Doorenbos and Pruitt 1977) using the following formula:

Table 2.9: Long-term monthly averages of ET, EP and PC for Amman-Zarqa Basin.

Months	**Class-A pan evaporation [mm]**	**Evapotranspiration [mm]**	**Pan Coefficient**
October	236	129	0.55
November	156	76	0.49
December	99	71	0.72
January	88	65	0.74
February	106	74	0.70
March	160	120	0.75
April	244	170	0.70
May	340	212	0.62
June	375	227	0.61
July	415	250	0.60
August	365	224	0.61
September	299	167	0.56

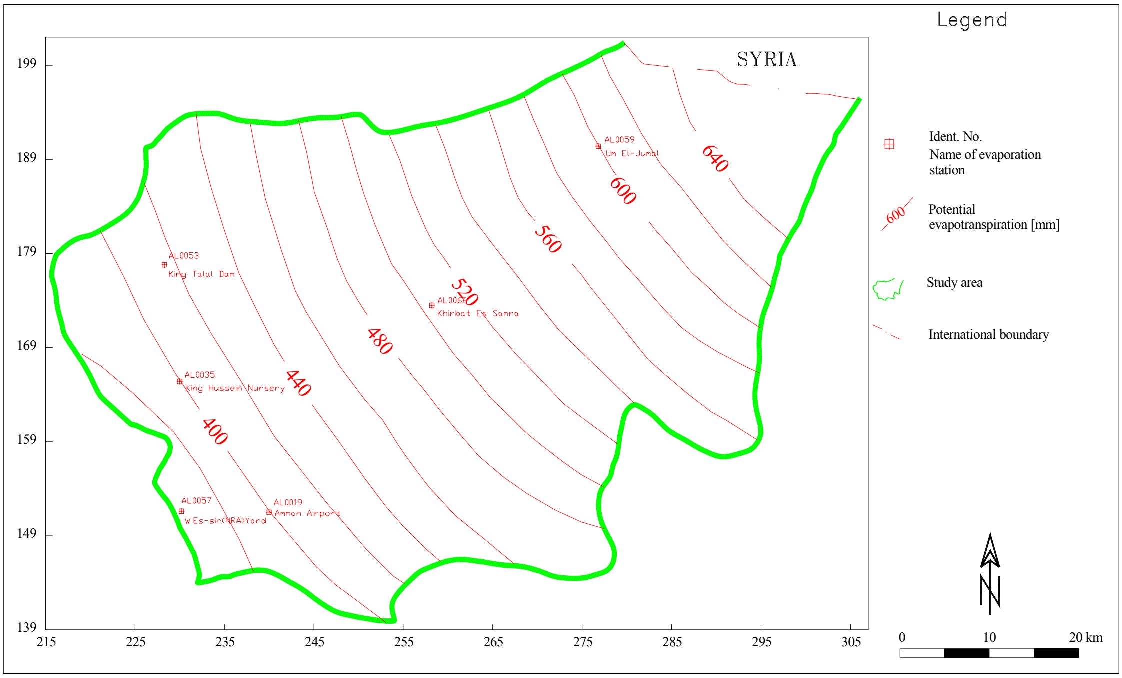

Fig. 2.10: Contour map of potential evapotranspiration in mm for normal year (wet season) over Amman-Zarqa Basin (1984/85).

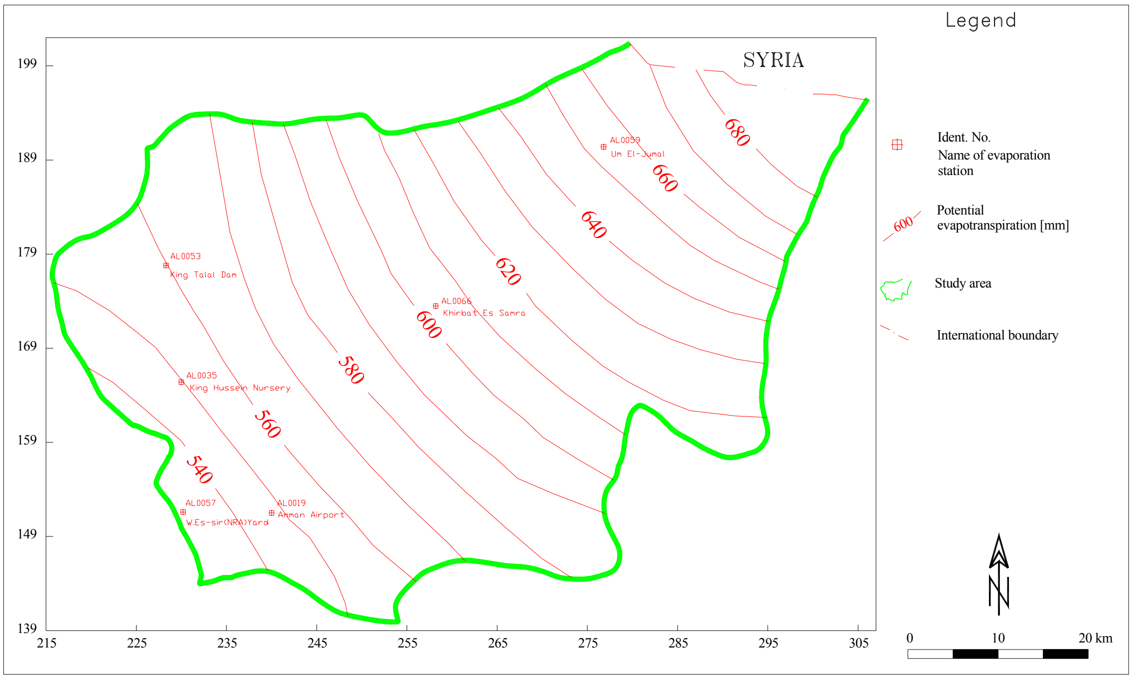

Fig. 2.11: Contour map of potential evapotranspiration in mm for wet year (wet season) over Amman-Zarqa Basin (1991/92).

$$ET = EP * CP$$

Where:

ET: evapotranspiration, EP: pan evaporation and CP: is the pan coefficient. It is found that the correlation between the monthly ET to EP for the period of (1970/71-2001/02) ranges from 0.49 to 0.75 in winter and from 0.55 to 0.62 in summer as shown in Table 2.9. This ratio has been used to replace the monthly missing data for each station.

2.5 Runoff

In order to estimate the water budget of the study area, the runoff parameter is considered as an important element for computation of water budget.

Three main flow streams occurred in the study area: 1. Wadi Dhuleil (flood flows), which drains the eastern parts of Amman-Zarqa Basin, 2. Seil el Zarqa (flood and base flows), which drains the western parts of Amman-Zarqa Basin and 3. Zarqa River (the second largest river in Jordan), discharges Wadi Dhuleil and Seil el Zarqa after confluence at Sukhna area (Fig. 2.12).

There are six gauging stations distributed over the study area (Fig. 2.1). However, the distribution of the stream flow gauging network does not cover all the subcatchments areas specifically in the northern parts of the study area.

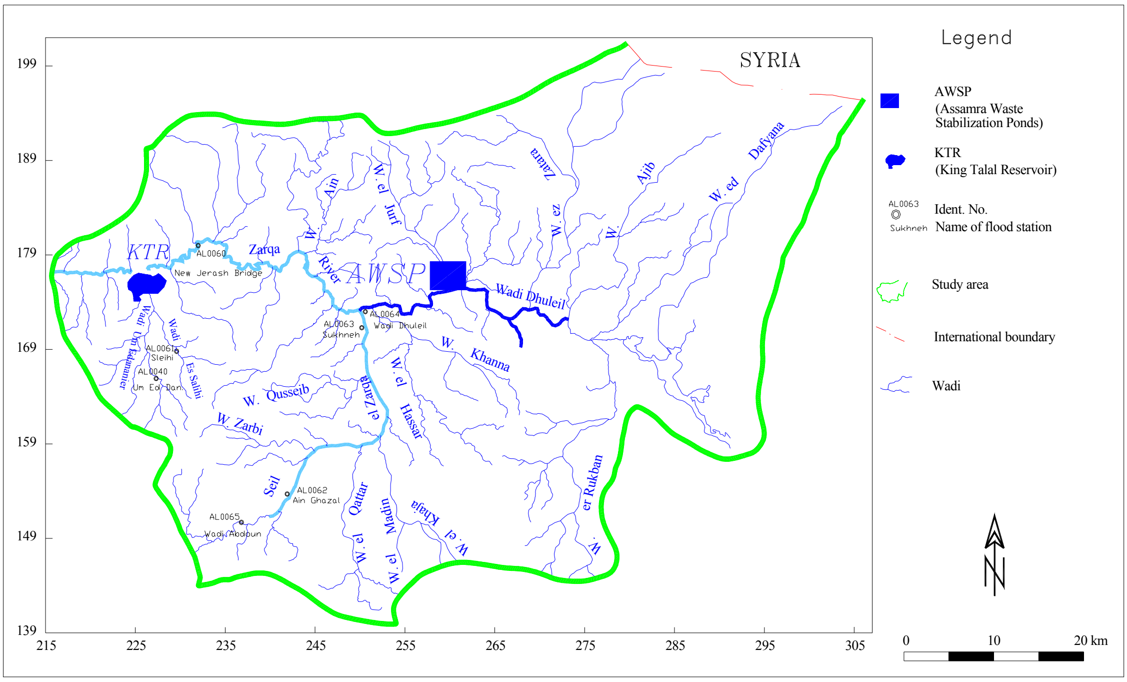

Fig. 2.12: Drainage system of Amman-Zarqa Basin.

More than 94% of the total catchment area of Amman-Zarqa Basin drains into Jarash Bridge gauging station which is located few kilometers from King Talal Dam (KTD), the largest dam in Jordan, thus this station represents the upstream measurements of KTD.

Appendix 2.4 shows the total flow recorded during the period of (1970/71-2001/02) of Jarash Bridge gauging station over Amman-Zarqa Basin. The highest total flow (flood flow) was recorded in 1979/80 with a volume of 115 $*10^6$ m^3, while the lowest flow was recorded in 1976/77 with a volume of 1.8 $*10^6$ m^3. The long-term average of annual flow (33 years) was calculated to be 26.6 $*10^6$ m^3. In addition, the long-term average of highest flood flow was recorded in December with a volume of 5.8 $*10^6$ m^3 and the lowest flood flow was recorded in May with a volume of 0.3 $*10^6$ m^3 (Fig. 2.13).

The runoff coefficients were calculated to range between 2 and 6 for normal and wet years, respectively.

2.5.1 Flood frequency analysis

This analysis was done to compute the runoff frequencies for different return periods (2,5,10,25,50,100 and 200 year-return period).

The calculated runoff values were analyzed for all events (1970-2002). The monthly peak of each flood was selected in order to conduct the frequency analysis on monthly basis. The yearly monthly maximum runoff values for Amman-Zarqa Basin were calculated. The largest sample size of these data was found as 31 events in February and 3 events in May.

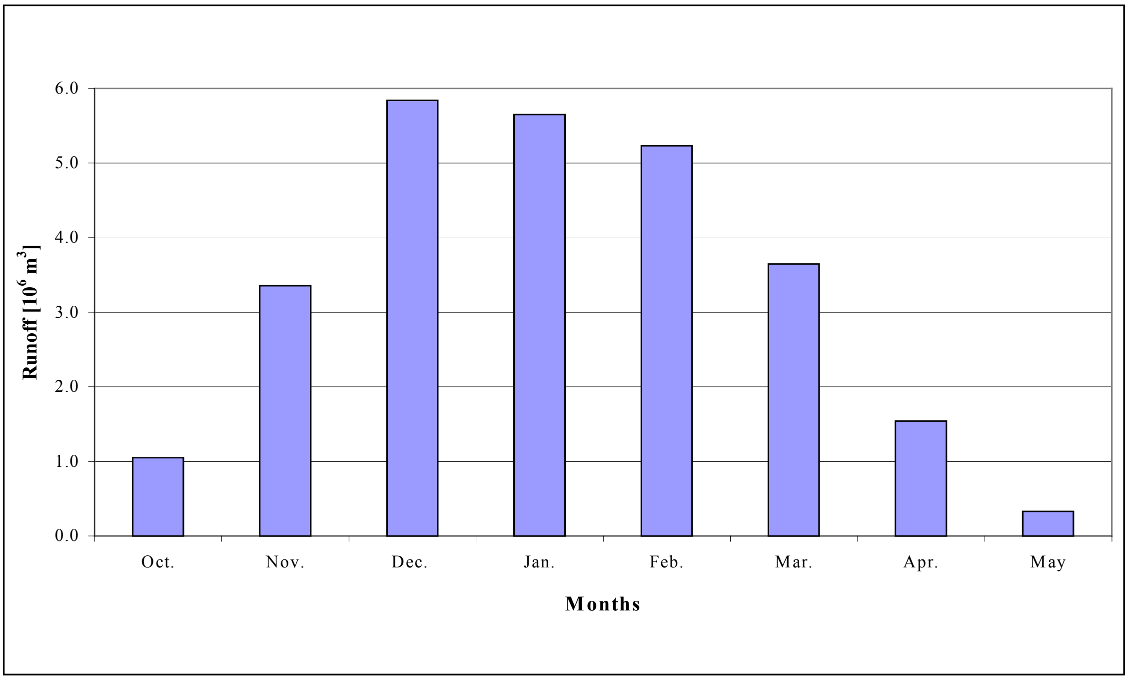

Fig. 2.13: Histogram of the long-term average monthly runoff over the study area (1970/71-2001/02).

In the other months, this sample size was found to be 28 events in January, 28 events in March, 21 events in December, 16 events in November, 12 events in April and 11 events in October.

Six different distributions (i.e., Normal, 2 Parameters log Normal, 3 Parameters Log Normal, Pearson type III, Log Pearson type III and Gumbel Type I Extremal) were tested to reach the best fit. The results of these analyses were presented in Table 2.10 and Fig. 2.14. The results of 2-years return period runoff (which represents the average yearly condition) using frequency analysis for annual monthly maximum series is $10 * 10^6$ m^3.

The maximum measured of runoff value was found about $50.6 * 10^6$ m^3 which corresponds to 50-return period according to the predicted data in Table 2.10. It is difficult to decide in which month the peak flow might occur. The design flood for 50-years frequency (2% risk) period flood is expected to occur during November to February. Therefore, the recommended flood to be considered in the design of the protection structure in Amman-Zarqa Basin is about $51 * 10^6$ m^3. The predicted 2-year return period and 50-year return period suggest the design flood for these return periods should be considered as yearly maximum values.

2.6 Infiltration

Since there are no direct infiltration measurements (lysimeters) in the study area, a water budget approach has been applied to estimate the amount of infiltration over the study area as follows:

Table 2.10: Predictions of runoff based on monthly maximum values.

Exceedence probability	Return period	Calculated value	Standard deviation
0.995	200	63.8	22.0
0.990	100	55.7	17.0
0.980	50	47.7	12.5
0.960	25	39.6	8,7
0.900	10	29.1	5,1
0.800	5	21.1	4.0
0.667	3	15.0	3.6
0.500	2	10.0	2.9

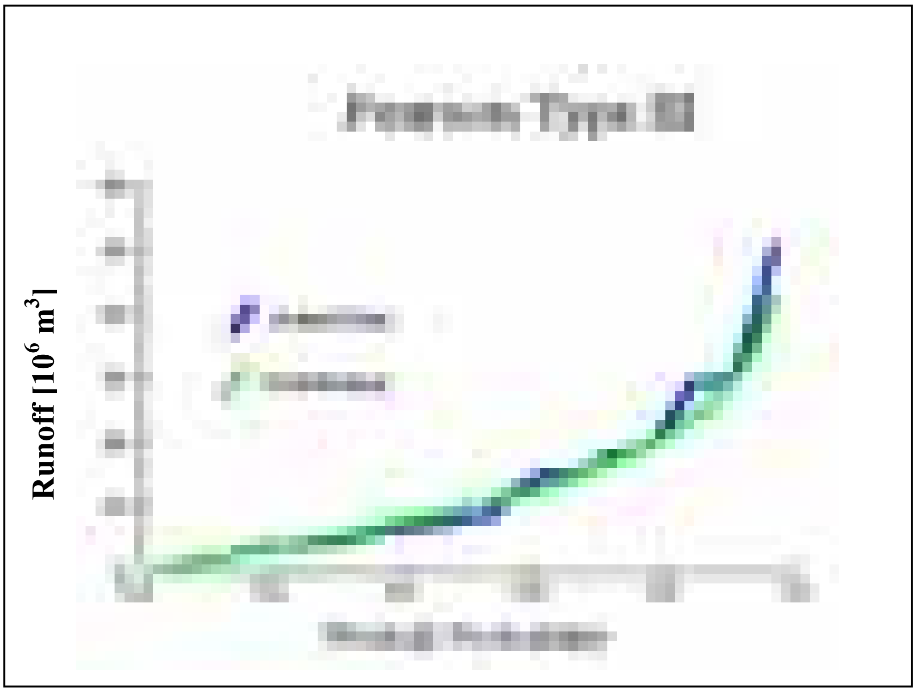

Fig. 2.14: Distribution analysis for the monthly maximum runoff using Pearson Type III.

$$\Delta S = P - ET - R - Ia$$

Where:

ΔS: change of groundwater storage [mm/yr] (Infiltration), P: precipitation [mm/yr], ET: evapotranspiration [mm/yr], R: runoff [mm/yr] and Ia: initial abstraction [mm/yr]. The initial abstraction is calculated (30 mm/yr) based on US Soil Conservation Service method (SCS) for long-term average (1970/71-2001/02).

The water budget was done based on the contour maps of precipitation and evapotranspiration for the same years of wet and normal years over the period of 33 years (1970/71-2001/02), whereas in dry hydrological year condition there was no any events for infiltration has been found as a result of comparison between contour maps of rainfall and evapotranspiration for the same year (1998/1999).

Thus, the volumes of surplus for wet and normal years have been calculated by defining the areas which have more rainfall than evapotranspiration then the areas between every two surplus lines were calculated and finally by multiplying these areas by mean surplus depth to convert it into volumes. Table 2.11 summarized the surface water budget for Amman-Zarqa Basin. Moreover, Figs. 2.15 and 2.16 show the recharge areas of Amman-Zarqa Basin for normal and wet years, respectively. It is found that the total of surplus area in a normal year (long-term) was 457 km^2 with an average excess rainfall depth 125 mm, i.e. the volume of infiltration in a normal year is 22.4 $*10^6$ m^3 after subtract the amount of runoff in the same year (34.7 $*10^6$ m^3). The total of surplus area in a wet water year was 808.7 km^2 with an average excess rainfall depth 175 mm, i.e. the volume of infiltration in a wet year is 60.4 $*10^6$ m^3 after subtracting the amount of runoff in the same water year (81.1 $*10^6$ m^3).

Table 2.11: Surface water budget over Amman-Zarqa Basin (1970/71-2001/02).

Water Year	**Rainfall [10^6 m^3]**	**Runoff [10^6 m^3]**	**Runoff Coefficient [%]**	**Surplus (P-ET) [10^6 m^3]**	**Infiltration [10^6 m^3]**
Wet	1343	81	6	142	60.4
Normal	706	35	5	57	22.4
Dry	273	6	2	-	-

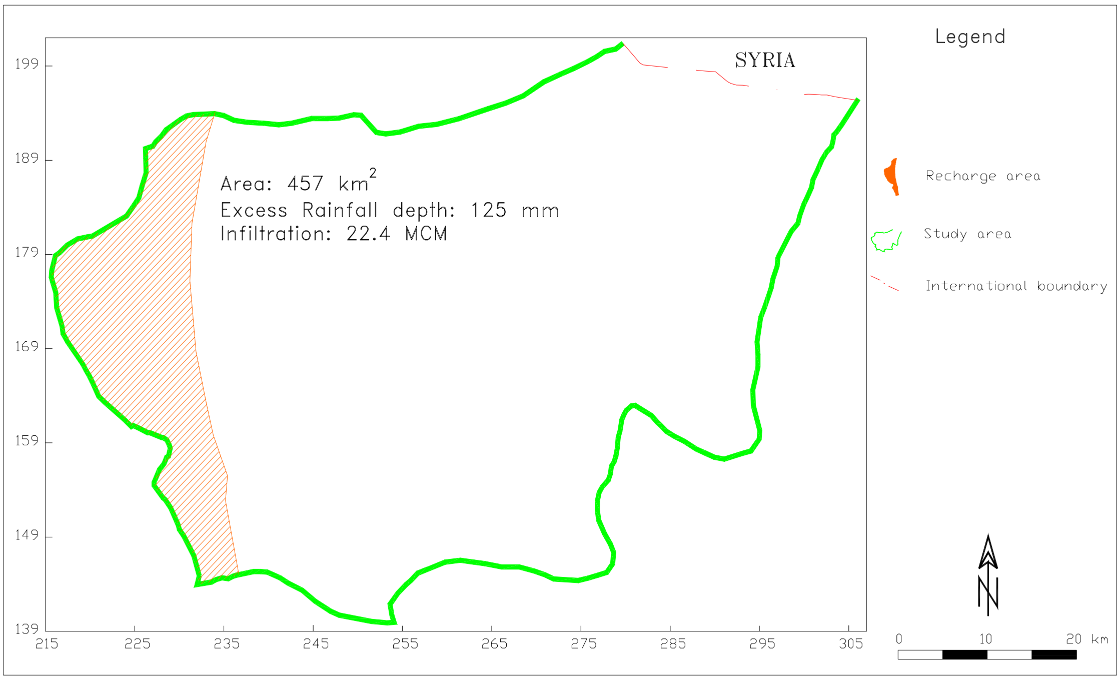

Fig. 2.15: Map of recharge area for normal hydrological year of Amman-Zarqa Basin.

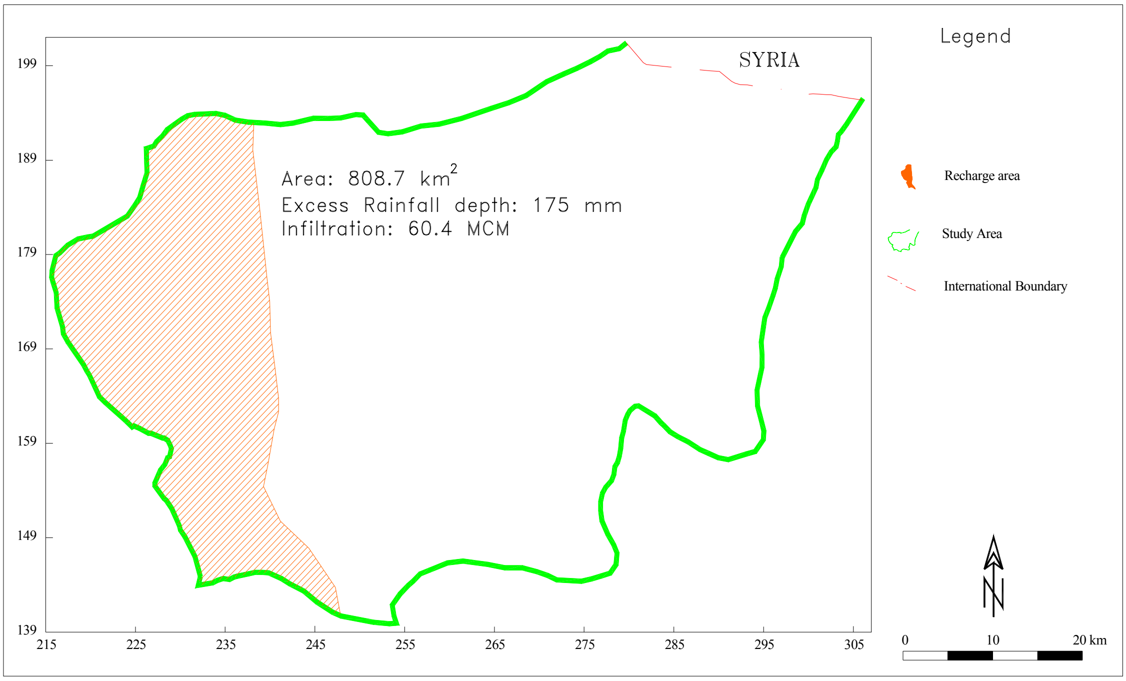

Fig. 2.16: Map of recharge area for wet hydrological year of Amman-Zarqa Basin.

3 Geology

3.1 Geological setting

Jordan lies in the northern area of the Arabian Shield and is divided into two main structural zones: the Rift (Wadi Araba-Dead Sea-Jordan Valley Graben), generally is a part of NNE-SSW faulting network along the African – Arabian Red Sea structure and the Jordan platform. Rifting, northward movement, tilting and uplifting in the lower Miocene to Pleistocene resulted in landscape formations (CES and ACE 1993).

The outcropping rock units in Jordan are from pre-Cambrian to recent. Calcareous sediments of the Upper Cretaceous and Lower Tertiary are exposed in the Eastern Highland of Jordan. Limestone, dolomite, limestone with marl, shale, chalk and chert of the same age occur in the eastern highlands and the eastern plateau covering an area of about 45000 km^2 with 150-800 meters thickness (JICA and MWI 2000). Sandstone and sandy facies formation with some shale cover an area about 8000 km^2 with 1900 meters thickness (1600 meters belong to Early Paleozoic and 300 meters belong to Lower Cretaceous). The Basalt overlies the fluviatile gravels of the Middle Pleistocenes is outcropping from the southern extension of Jabal Al-Arab in Syria till Wadi Sirhan Depression (near the border of Saudi Arabian).

Most parts of Wadi Arab-Jordan Valley Depression, Jafer and Azraq Depressions are filled by coarse clastics of marine to continental origin belonging to Neogene-Quaternary ages. The pre-Cambrian basement complex is mostly covered the southwestern parts of Jordan along the Gulf of Aqaba and the eastern escarpment of Wadi Araba with an area about 70 km^2. Table 3.1 shows the geological and hydrogeological classification of rock units in Jordan.

3.2 Lithostratigraphy

The outcropping of Amman-Zarqa Basin extends from Lower Cretaceous (except for the wadi fill deposits which are of Quaternary) to recent age, which is belonging to the Ajlun and Belqa Groups according to Jordanian classification (Table 3.1 and Fig. 3.1). However, the Kurnub Group (Lower Cretaceous) is usually found at certain depths except outcrops at the western parts of the study area (Baq'a Valley) along the axis of Suweileh anticline. In addition, the older Zarqa Group (Jurassic-Triassic age) occurs at considerable depth (Howard Humphreys 1983).

Lithologically, Amman-Zarqa Basin includes the following (from old to young):

i. Zarqa Group: this group consists of sandstone, shale, dolomite and dolomitic limestone, marl, gypsum and intercalation of volcanic ash. Its thickness reached up to 1000 meters as encountered at Wadi Rimam (south of Amman).

Table 3.1: Geological and hydrogeological classification of rock units in Jordan (modified after Margane et al. 2002).

System	Epoch	Group	Formation	Symbol	Lithology	Thickness	Aquifer unit
QUATERNARY	Holocene	JORDAN VALLEY	Alluvium	Qal	clastics		ALLUVIUM (AQUIFER)
	Pleistocene		Lisan	JV3	marl, clay, evaporites	> 300 m	BASALT (AQUIFER)
TERTIARY	Pliocene Miocene Oligocene		Samra	basalt JV1-2	conglomerate with silicious cement, sand, gravel	100 - 350 m	
			Neogene				
	Eocene	BELQA	Wadi Shallala	B5	chalky and marly limestone with glauconite	0 - 555 m	B4/5 (AQUIFER)
			Umm Rijam	B4	limestone, chalk, chert	0 - 311 m	
	Paleocene / Maastrichtian		Muwaqqar	B3	chalky marl, marl, limestone, chert	80 - 320 m	B3 (AQUITARD)
UPPER CRETACEOUS	Campanian		Amman-Al Hisa	B2	limestone, chert, chalk, phosphorite	20 - 140 m	A7/B2 (AQUIFER)
	Santonian		W.Umm Ghudran	B1	dolomitic marly limestone, marl, chert, chalk	20 - 90 (*)	
	Coniacian / Turonian	AJLUN	Wadi as Sir	A7	limestone, dolomitic lst., chert, marl	60 - 340 m	
			Shuayb	A5/6	marl, limestone	40 - 120 m	A1/6 (AQUITARD)
	Cenomanian		Hummar	A4	limestone, dolomite	30 - 100 m	
			Fuheis	A3		30 - 90 m	
			Naur	A1/2	limestone, dolomite, marl	90 - 220 m	
LOWER CRETACEOUS		KURNUB	Subeihi	K2	sandstone, shale	120 - 350 m	KURNUB (AQUIFER)
			Aarda	K1	sandstone, shale		
JURASSIC		ZARQA	Azab		siltstone, sandstone, limestone	0 - >600 m	ZERQA (AQUITARD)
TRIASSIC			Ramtha		siltstone, sandstone, shale, limestone, anhydrite, halite	0 - >1250 m	
PERMIAN			Hudayb		siltstone, sandstone, shale, limestone	0 - >300 m	
SILURIAN		KHREIM	Alna		siltstone, sandstone, shale	0 - >1000 m	KHREIM (AQUITARD)
			Batra		mudstone, siltstone	0 - >1600 m	
ORDOVICIAN			Trebeel		sandstone	0 - 130 m	
			Umm Tarifa		sandstone, siltstone, shale	0 - >1200 m	
			Sahl as Suwwan		mudstone, siltstone, sandstone	0 - 200 m	
CAMBRIAN		RAM	Amud		sandstone	0 - >1500 m	RAM SANDSTONE (AQUIFER)
			Ajram		sandstone	0 - ca. 500 m	
			Burj		siltstone, dolomite, limestone, sandst.	ca. 120 m	
			Salib		arkosic sandstone, conglomerate	0 - >750 m	
PRECAMBRIAN			Unassigned clastic unit		sandstone, argillaceous, siltstone, claystone	0 - 1000 m	BASEMENT COMPLEX
			Saramuj		conglomerate, sandstone	up to 420 m	
			Crystalline Basement				

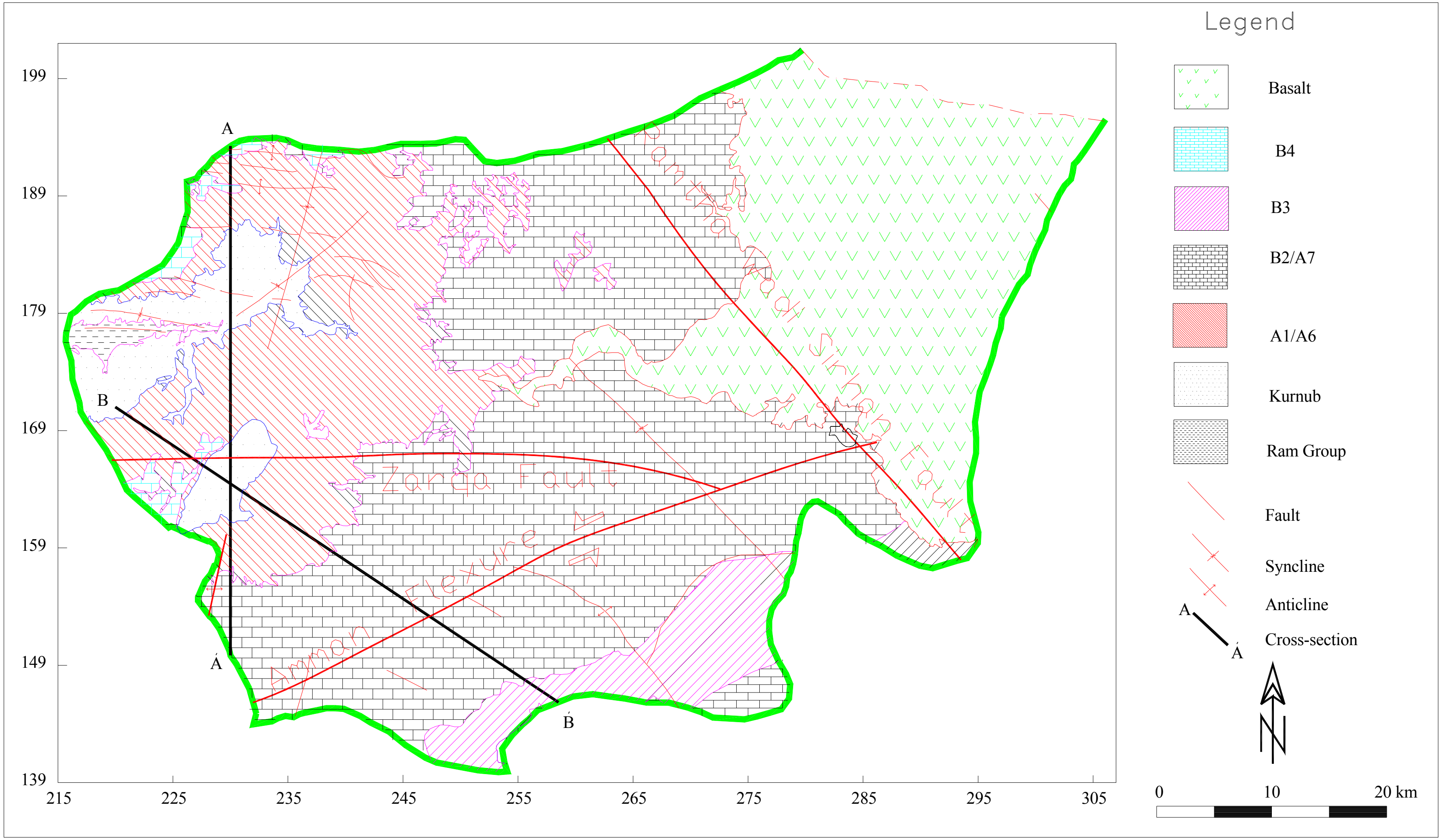

Fig. 3.1: Geological map of the study area (modified after BGR and WAJ 1994).

ii. Kurnub Group: this group is exposed in the western parts of Amman-Zarqa Basin at Baq'a Valley. It mainly consists of white, gray and multicolored sandstone (weakly cemented fine-medium and coarse grained) with red silts, shales and dolomite streaks. The top of this group is known as the Subeihi Formation, which mainly consists of red-brown varicolored sandstone with a large portion of marl, clay and siltstone. On the other hand, the lower part of this group is known as Aarda Formation which consists of yellow-white sandstone with shale partings and dolomite streaks.

The thickness of Kurnub Group has been encountered between 200-300 meters (USAID and WAJ 1989). The age of this formation is Lower Cretaceous.

iii. The Ajlun Group overlays the Kurnub Group and consist of five formations, namely: the Naur (A1-2); the Fuheis (A3); the Hummar (A4); the Shuayb (A5-6) and the Wadi as Sir (A7).

1. The Naur and Fuheis Formations consist of marl, limestone, marly limestone and shale. Both formations outcrop in the northern and western parts of Amman-Zarqa Basin. Their ages are Lower Cenomanian and Middle Cenomanian with thickness between 150 and 60 meters, respectively (USAID and WAJ 1989).

2. The Hummar Formation forms a narrow outcrop northwest part of the study area (along the Zarqa River). It comprises limestone and dolomitic limestone. Its age is Cenomanian. Generally, the thickness of this formation is between 30 and 60 meters.

3. The Shuayb Formation outcrops to the north of Amman-Zarqa Basin with thickness about 200 meters of marl and limestone. In average, the thickness is about 50 meters. The age of this formation is Upper Cenomanian.

4. The Wadi as Sir Formation outcrops in most parts of Amman-Zarqa Basin. It consists of about 100 meters of thinly bedded limestone and chalky limestone with occasional chert beds and nodules. Its age is Turonian.

iv. The Belqa Group overlays the Ajlun Group and consists of five formations, namely: Wadi Umm Ghudran (B1); Amman-Al Hisa (B2); Muwaqqar (B3); Umm Rijam (B4) and Wadi Shallala (B5). However, Wadi Shallala formation is not represented in the geological of Amman-Zarqa Basin.

1. Wadi Umm Ghudran Formation comprises mainly marl with an average thickness of about 15 meters. Its age is Santonian.

2. Amman-Al Hisa Formation outcrops in most parts of Amman-Zarqa Basin. Generally, this formation is mostly mixed with Wadi as Sir Formation (A7) and

presented in most geological maps of Jordan as B2/A7 (BGR and MWI 2001). It consists of limestone with chert interbedded with phosphatic layers and marl. Its age is Campanian. The thickness of Amman Formation ranges from few meters to 150 meters depending on depth of erosion.

3. Muwaqqar Formation outcrops in the southeastern parts of Amman-Zarqa Basin. It consists of marl, chalk and chert. Its age is Meastrichtian with thickness ranging from 60 to 80 meters (USAID and WAJ 1989).

4. Umm Rijam Formation consists of limestone (partly phosphatic), chalky limestone, chalk with beds and nodules of brown to black chert. The thickness of this formation is less than 15 meters and it outcrops in the northern and western parts with limited areas. Its age is Eocene.

v. Basalt outcrops in the eastern and northeastern parts of Amman-Zarqa Basin. Its age is ranging from Miocene to Pleistocene. It consists of black olivines, basalt interbedded with clay beds and volcanic ashes. Most of basalt flow surface is mantled by sub-rounded boulders of basalt and in other places by local alluvium (USAID and WAJ 1989). The thickness of basalt ranges from 30 meters to 100 meters in Wadi Dhuleil and generally becomes thicker to north and northeast of Amman-Zarqa Basin to reach 400 meters thickness in Wadi Al Agib area (Fig. 3.2).

vi. The Wadi Fill Deposits form the bed and terraces of the Seil el Zarqa. They consist of sands and gravels with clays and have a variable thickness up to 20 meters at different places of Amman-Zarqa Basin.

Fig. 3.3 illustrates the 3-Dimensional view of the geological model covering the whole Amman-Zarqa Basin showing the stratigraphy of major subsurface geology. Also, two cross sections have been drawn over the study area (Figs. 3.4-3.5). The portions of these cross sections are shown in Fig. 3.1.

3.3 Structure

Most of the formations in Amman-Zarqa Basin are affected by orogenessis movement especially by the Alpine orogenessis which its last stage ended in the Maestrichian causing folding, faulting, synclines and anticlines (USAID and WAJ 1989). Fig. 3.1 shows the geological structure map of Amman-Zarqa Basin. There are three main geological structures occurring in Amman-Zarqa Basin, namely: Amman-syncline (Amman Flexure), Zarqa-Fault and Ramtha-Wadi Sirhan Fault.

The Amman synclinal structure is dominated in Amman-Zarqa Basin, whose axis is aligned southwest to northeast, commencing south of Amman and continuing in a roughly north easterly direction along Seil el Zaraq. The northern limb of this structure is situated to the north-east merging with the Suweileh anticline in the Baq'a Valley. On the other hand, the southern limit of this structure (Amman syncline) is presented by Amman Flexure which runs parallel to the synclinal axis (Howard Humphreys 1983).

As a result of the Amman synclinal structure, there are numerous smaller anticlinal-synclinal folds aligned along similar directions with regional dip (shallow between 5-6 degrees with much greater angles of dip in some locally minor folds) is generally to the south-west towards Seil el Zarqa.

As a result of the major two faults in Northeast-Southwest and Northwest-Southeast directions, the big graben or Wadi Dhuleil has been developed in Amman-Zarqa Basin.

Ramtha-Wadi Sirhan Fault is a major fault affected the Northeastern parts of Amman-Zarqa Basin. Its direction is Northwest-Southeast (Fig. 3.1).

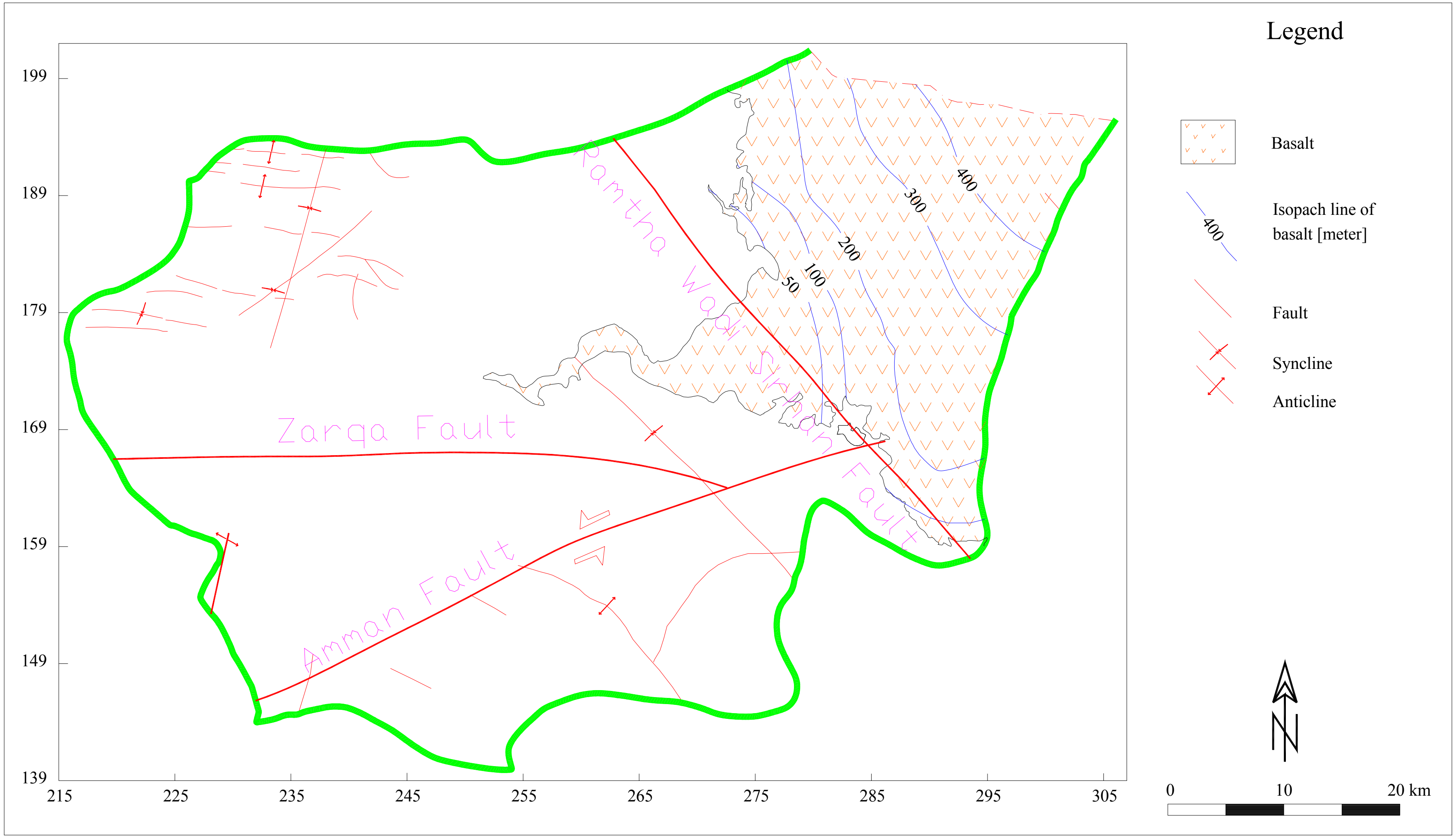

Fig. 3.2: Isopach map of the Basalt aquifer in Amman-Zarqa Basin (modified after BGR and WAJ 1994).

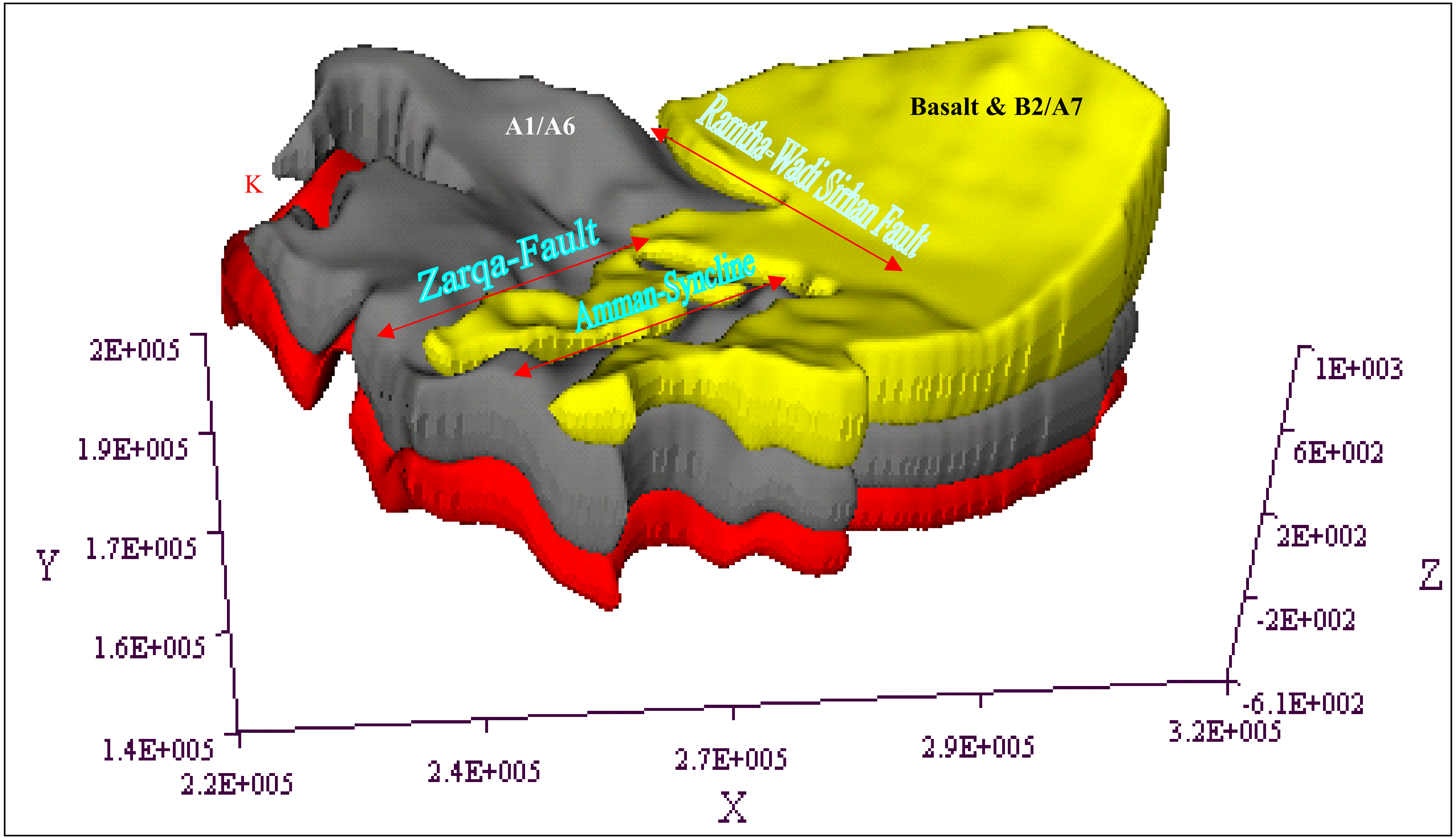

Fig. 3.3: A three-dimensional geological model of Amman-Zarqa Basin.

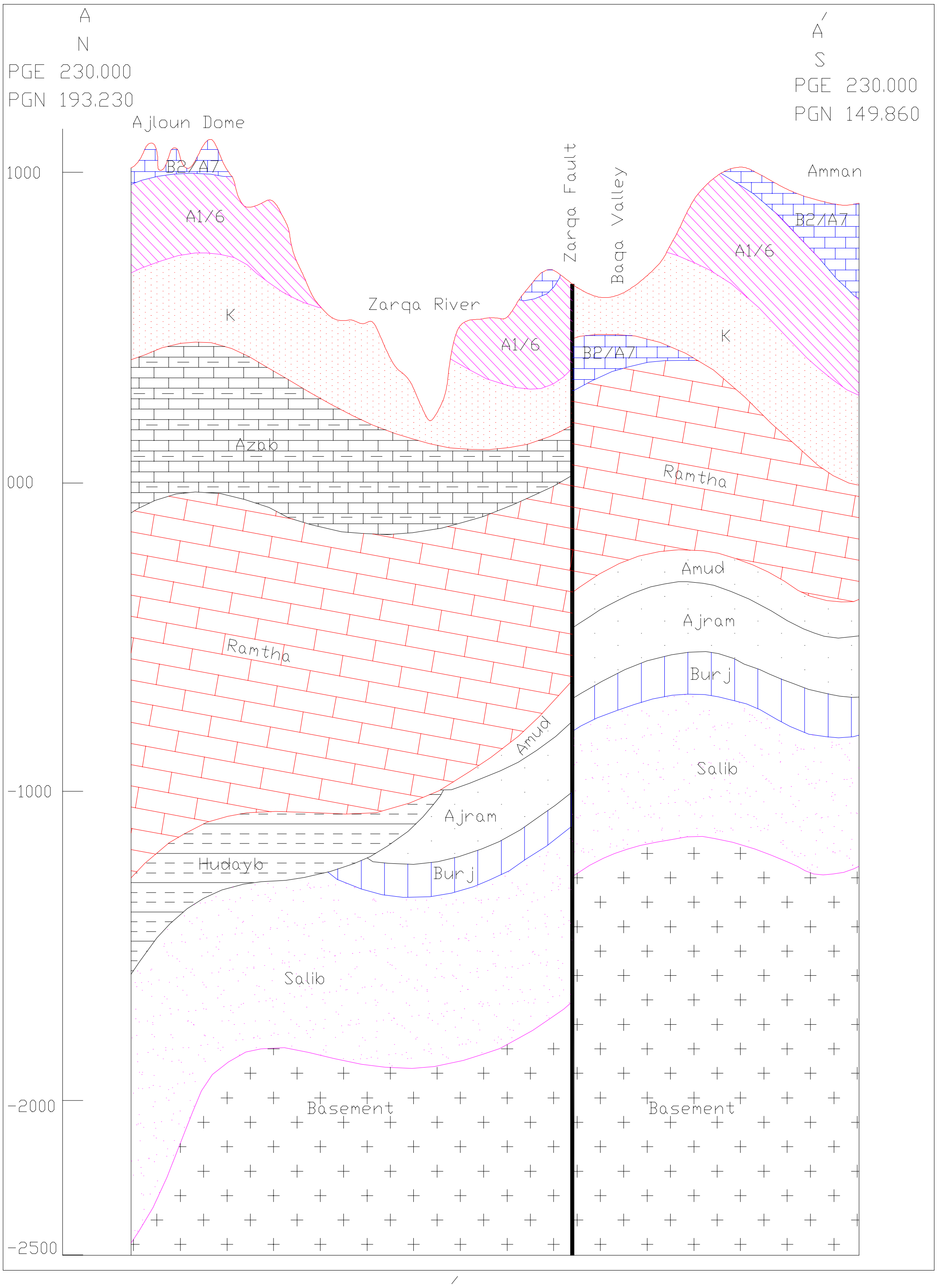

Fig. 3.4: Geological cross-section A-A´ (modified after BGR and WAJ 1994).

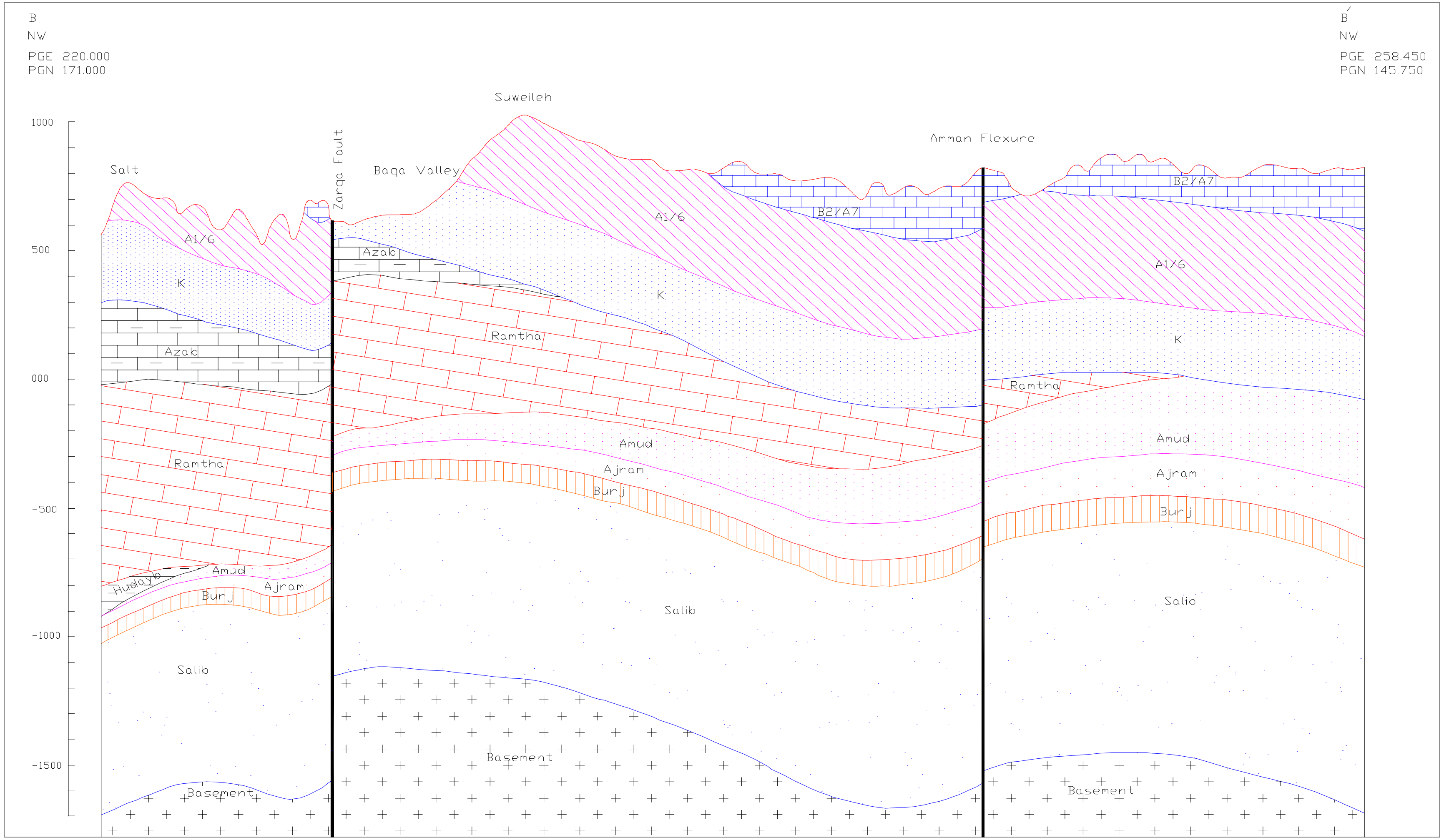

Fig. 3.5: Geological cross-section B-B´ (modified after BGR and WAJ 1994).

4 HYDROGEOLOGY

4.1 Hydrogeological setting

The hydrogeological setting in Jordan is generally controlled by the geological set-up, which also controls the piezometry, occurrence and movement of the groundwater and the distribution of productive areas in the aquifers.

The main part of the country consists of bedrock aquifers, which are the main groundwater sources. The main aquifers in Jordan are (Master Plan 2003):

- Sandstone aquifers like the Ram sandstone aquifer ("Disi-aquifer") and the Kurnub aquifer.
- Carbonate aquifers like B2/A7 and B4/B5 aquifers.
- Basalt aquifer.

Unconsolidated aquifers, like fluvial deposits in the Jordan Valley, are of less importance compared to the bedrock aquifers in Jordan.

On a regional scale, the aquifers in Jordan can be divided into three major aquifer systems based on their spatial distribution, lithology and the age of the geological units (Master Plan 2003). According to Jordanian classification (Table 3.1), these aquifer systems are from bottom to top:

1. **Ram-Zarqa-Kurnub Aquifer System**: It includes the Ram aquifer, the Khreim aquitard, the Zarqa aquifer and the Kurnub aquifer.

2. **Upper Cretaceous Limestone Aquifer System**: It includes the A1/2 aquifer, the A3 aquitard, the A4 aquifer, the A5/6 aquitard and the B2/A7 aquifer.

3. **Tertiary–Quaternary Shallow Aquifer Systems**: They include the B3 aquitard, the B4/5 aquifer, the Basalt aquifer and the alluvial deposits.

The outcropping formations of Amman-Zarqa Basin are dominated by sedimentary Ajlun and Belqa Groups (Fig. 3.1). The Kurnub-Zarqa formations are outcropping in the western parts of the basin (Baq'a valley). In addition, the wadi-fill deposits of Quaternary age and basalt flows cover the Wadi Dhuleil and the north-eastern parts of the basin.

4.2 Aquifer systems

According to the potentiality of water bearing, three aquifer systems are available in Amman-Zarqa Basin:

- Upper aquifer system, which includes Basalt and underlying Amman-Wadi As Sir (B2/A7) formation.

- Middle aquifer system, consisting of Hummar (A4) and Naur (A1/2) formations.
- Lower aquifer system (Kurnub Group).

4.2.1 Upper aquifer system

4.2.1.1 Basalt aquifer

Basalts are outcropping in various parts of Jordan, specifically along the eastern margin of the Dead Sea (Wadi Zarqa Ma'in, Wadi Heidan, north of Wadi Mukheiris, Wadi Dardur and the plateau area north and south of Wadi Mujib). Also, they outcrop at the rims and on the plateaus facing of the Yarmouk Valley and in the lower Wadi Al Arab as well as at the subsurface of the Jordan Valley and in the vast Harrat-Ash Shaam basaltic province north and east of Azraq. Those kinds of basalts are associated with the formation of the Red Sea-Dead Sea-Jordan Rift and the relative northward movement of the eastern plate that governed the area from Oligocene to recent times (Margane et al. 2002). However, the most frequently encountered age of basalt extrusions on the eastern margin (Red Sea-Dead Sea-Jordan Rift) is Pleistocene (Bender 1974). The basalts extend from Azraq and Wadi Dhuleil region in Jordan (11,000 km^2) to Jabal Al Arab in Syria.

During the Miocene and Oligocene ages, there were volcanic activities and the low areas (such as: Wadi Dhuleil and Northeastern Desert) where filled with lava. The boundaries of this aquifer are generally dominated by active faults, such as: Ramtha-Wadi Sirhan falut which acts as barrier between Northeastern parts and Bal'ama area (USAID and WAJ 1989).

The thickness of basalt increases from north-eastern parts in Jordan (maximum observed thickness is 479 m in the Mukeifteh wellfield in the upper Azraq basin) towards Jabal Al Arab in Syria to reach about 1500 m (Wolfart 1966). Fig. 3.2 shows the isopach of basalt aquifer in Amman-Zarqa basin where the maximum thickness is found to be approximately 400 m in far north-eastern parts while the minimum thickness is found to be less than 50 m in the central parts of Amman-Zarqa basin. In addition, Fig. 4.1 shows the structure contour map (base of basalt). The base of the basalt is peaking to the north part of the study area and around 500 m above sea level (masl) as an average value in the most parts of the outcropping area of basalt within Amman-Zarqa Basin.

This aquifer represents the main aquifer in Wadi Dhuleil area and even to the north and north-east of the study area. It was concluded that the basalt as a whole is a potential aquifer to the east of Wadi Ez'atri where the water bearing zone comprises a highly porous and scoriaceous reservoir (Al Mahamid 1998).

Therefore, there is a hydraulic connection between the Basalt and the underlying of Wadi As Sir formation (B2/A7) and they are considered as one hydraulic unit (USAID and WAJ 1989). The Basalt with the B2/A7 aquifer is the main aquifer in Amman-Zarqa Basin.

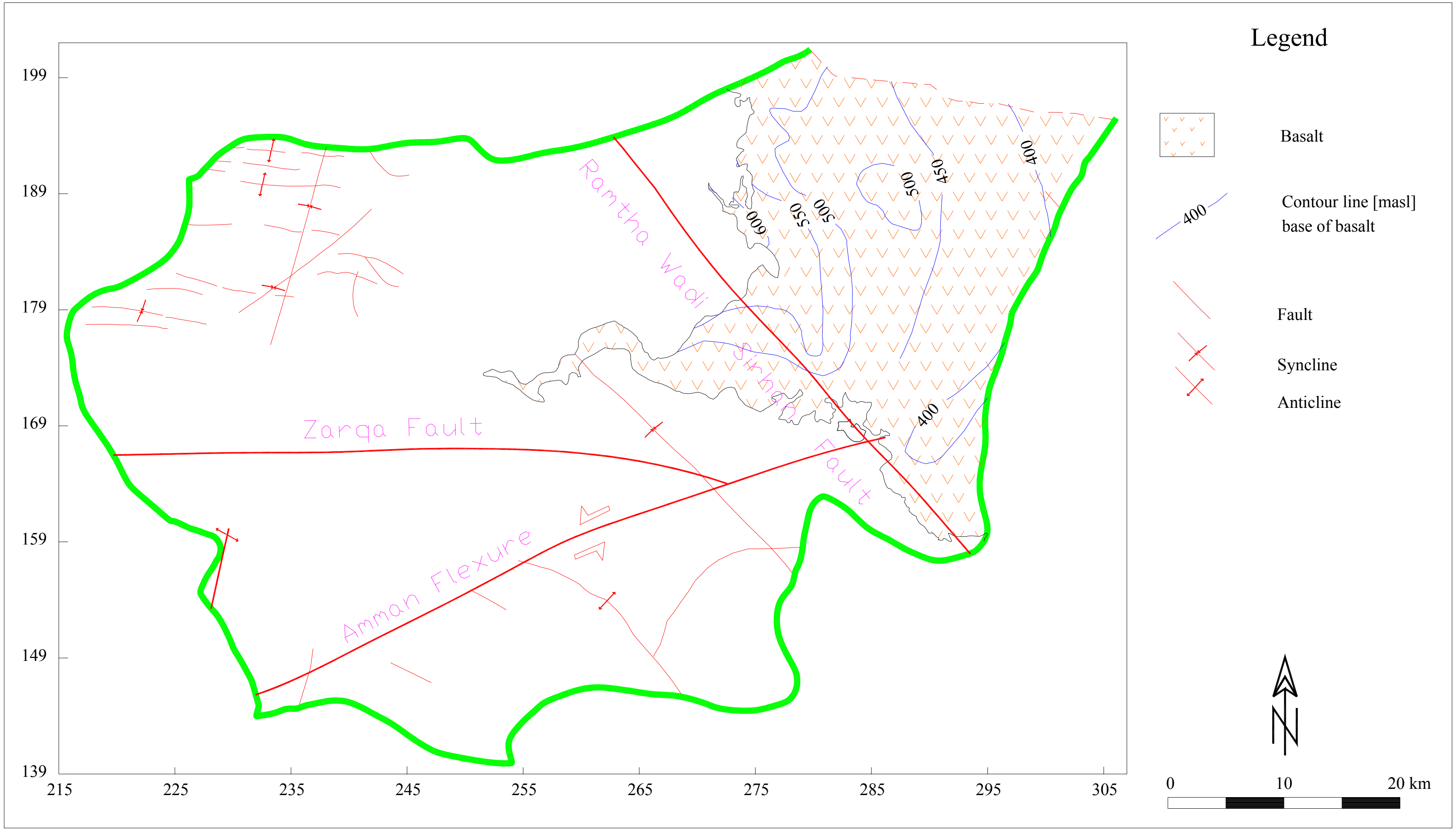

Fig. 4.1: Structure contour map base of Basalt (modified after BGR and WAJ 1994).

4.2.1.2 Amman-Wadi As Sir (B2/A7) aquifer

Amman-Wadi As Sir aquifer comprises of two carbonate formations, Amman-Al Hisa (B2) and Wadi As Sir (A7). There are hydraulic connections between B2 and A7 in certain locations and along Zarqa River where these formations are overlain with wadi-fill deposits (composed with sands and gravels) forming a minor aquifer (Howard Humphreys 1983). This aquifer consists of massive limestone, dolomitic limestone and dolomite with intercalated beds of sandy limestone, marl, chalk, chert and phosphorite.

The B2/A7 aquifer (Amman-Wadi As Sir aquifer system) is the most important aquifer system in Jordan in terms of productivity and areal extension. It consists of Upper Cretaceous (Turonian to Campanian) carbonate rocks forming large outcrops in the highlands where the highest recharge rates in Jordan are occurring. This aquifer extends beneath the basalt flows in the northeastern parts of Jordan (Amman-Zarqa Basin) and occurs at a certain depth beneath of younger sediments in the central of Jordan (CES and ACE 1993).

The thickness of the B2/A7 unit is mostly reflecting the high tectonic activity during the deposition time of these formations. Generally, the thickness is extremely high in the area around Azraq, in a down-faulted tectonic block delineated by the W-E striking Siwaqa fault, the WSW-ENE striking Zarqa Main-Azraq fault, and the NW-SE striking Fuluq Fault and Wadi Sirhan fault systems. The maximum thickness of the B2/A7 was found more than 3000 m in the Hamza Graben, immediately west of the Fuluq Fault (East Jordan) then the thickness becomes thin towards to the west. Also, the thickness of B2/A7 decreases from NW to SE and reaches a minimum of only about 40 m in the Risha area (Hammad Basin, far east of Jordan). In addition, the thickness of the B2/A7 unit decreases from more than 300 m in the area close to the south of the Siwaqa fault (south Jordan), in southerly and south-easterly directions. In the northwestern part of Jordan, the B2/A7 thickness trends to increase towards north and towards the Rift Valley. Generally, the B2/A7 unit outcrops mainly from the structural high of the Ajloun Dome (North-West of Jordan) and its eastern extension towards Mafraq (North Jordan) then into Amman and the Rift Valley in the southern parts of Jordan (BGR and MWI 2001).

In Amman-Zarqa Basin, the B2/A7 unit outcrops in the central and northern parts as shown in Fig. 3.1. The B2/A7 formations is mostly joined and fissured with solution channels and karstic features on a local scale. It is noted that the intensity of jointing increase near the faults and in the vicinity of Amman Synclinal axis (Parker 1977, Mudallal 1973 and VBB 1977). The boundaries of the saturated thickness of B2/A7 aquifer are Wadi Dhuleil as northern boundary, Amman flexure as south and east boundaries. The western boundary is believed as the outcropping of the elder formation (USAID and WAJ 1989). The B2/A7 aquifer is an unconfined aquifer in most parts of Amman Zarqa Basin. In general, the underlying A5/6 (Shuayb Formation) unit forms the base of the B2/A7 aquifer and there is a vertical downward leakage into the underlying Hummar (limited areas) or Kurnub through the aquitard layer (A1/A6). The thickness distribution of B2/A7 aquifer is shown in Fig. 4.2. The average thickness of B2/A7 aquifer is about 200 m. There is an obvious trend of the B2/A7 thickness over Amman-Zarqa Basin, it is concluded that the thickness of B2/A7 aquifer trends to increase north-east to reach about 500 m and south-east to reach about 400 m.

The base of the B2/A7 reaches its highest elevations of roughly 1,000 masl in the area of the Ajlun Dome (Fig. 4.3). From there it drops to the Jordan Valley in the west, the Yarmouk River in the north and the Azraq area in the east. Note that, there is no individual base map for A7 and B2, because there are a hydraulic connection between two these formations (USAID and WAJ 1989).

4.2.2 Middle aquifer system

4.2.2.1 Hummar and Naur aquifers

Hummar Formation (A4) is a part of the lower Ajloun Group (A1/A6) which overlies the Kurnub Group and comprises a Late Cretaceous (Cenomanian-Turonian) sequence dominated by limestone, dolomite and marl. The A1/A6 is originally subdivided into four Formations as mentioned in the previous chapter: Naur (A1/2), Fuheis (A3), Hummar (A4) and Shuayb (A5/6) Formations. It is most frequently outcropping in the northwest of Amman in the hilly area surrounding the Zarqa River valley. Generally, the thickness of the A1/A6 is increasing from SW to NE and varies from about 30 m in the Hammad area to more than 638 m in the Mukheiba area (also more than 500 m has been found in Qastal, Azraq, Irbid and the lower Yarmouk Valley areas) according to drilling records of the Mukheiba deep well and becomes relatively thin in the Ajloun, the Dhuleil and the southern part of the Jordan valley (BGR and MWI 2001).

The A4 Formation can be found to the north of Wadi Mujib and extends eastwards at depth into the Azraq basin. On a local scale, this aquifer is important in Amman-Zarqa Syncline where it outcrops in a narrow 100 – 800 m wide strip, then dips towards the Seil el Zarqa to reach depth of 200 m below the Shuayb marly aquiclude (A5/6) (CES and ACE 1993). This aquifer consists of limestone with an average thickness of 45 m in the Amman-Zarqa Synclinal area. It is found that the thickness of A4 aquifer trends to increase north-west to reach about 60 m and north-east to reach about less than 20 m. Recharge is limited to an area of about 20 km^2 extending from Sukhna through Suweileh and around the south-western edge of the Amman-Zarqa Syncline (Master Plan 2003).

The depth to A4 ranges between 100 and 300 m along Seil el Zarqa (Kilani 1997). The A4 aquifer is confined by Shuayb Formation (A5/A6). The natural boundaries of A4 aquifer are groundwater divide in the western parts, Amman-Zarqa flexure in the southern parts, limit of saturation in the northern parts, Fuheis Formation (A3) as lower boundary and Shuayb Formation (A5/A6) as upper boundary (VBB 1977).

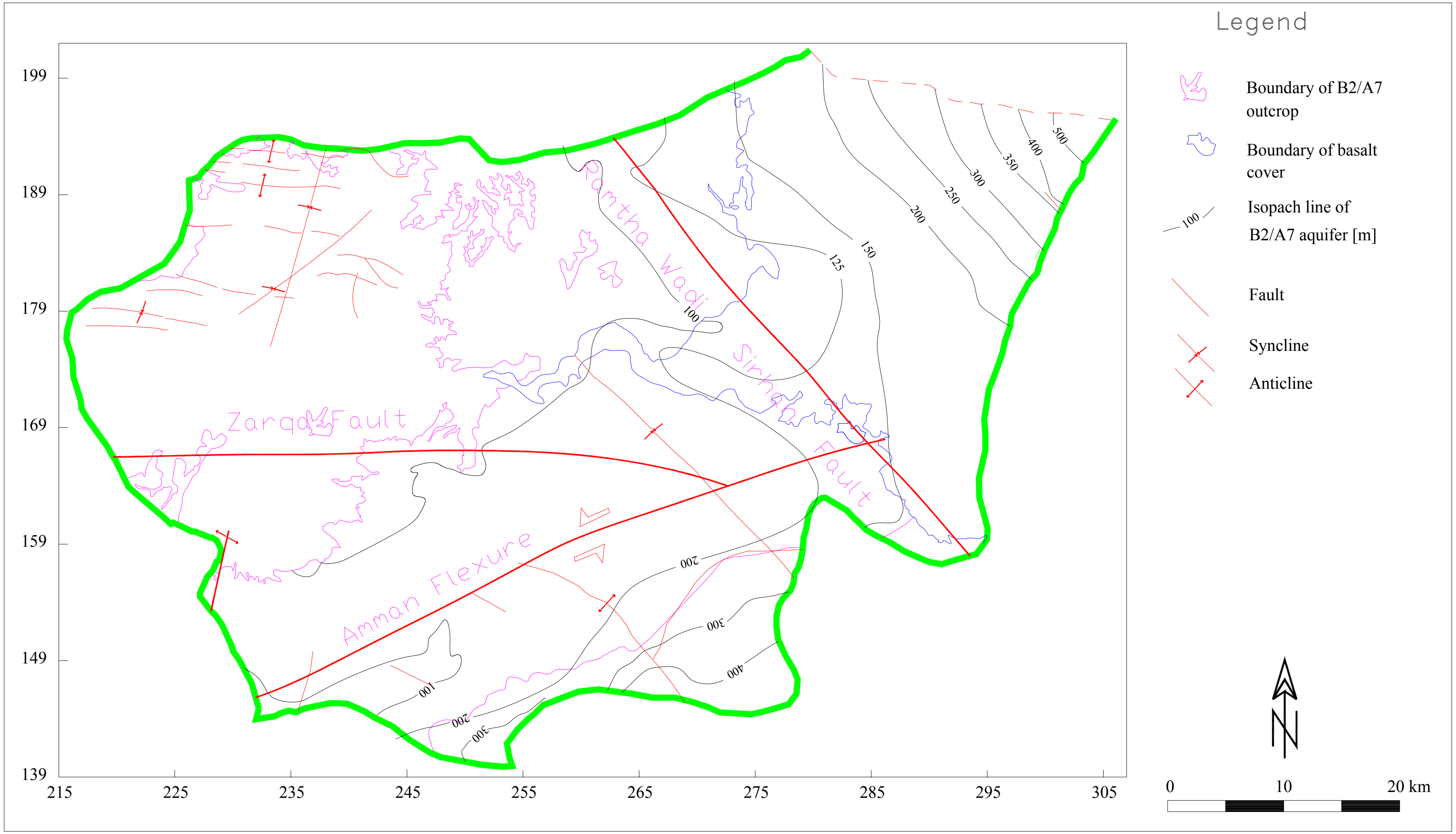

Fig. 4.2: Thickness distribution of B2/A7 aquifer of Amman-Zarqa Basin.

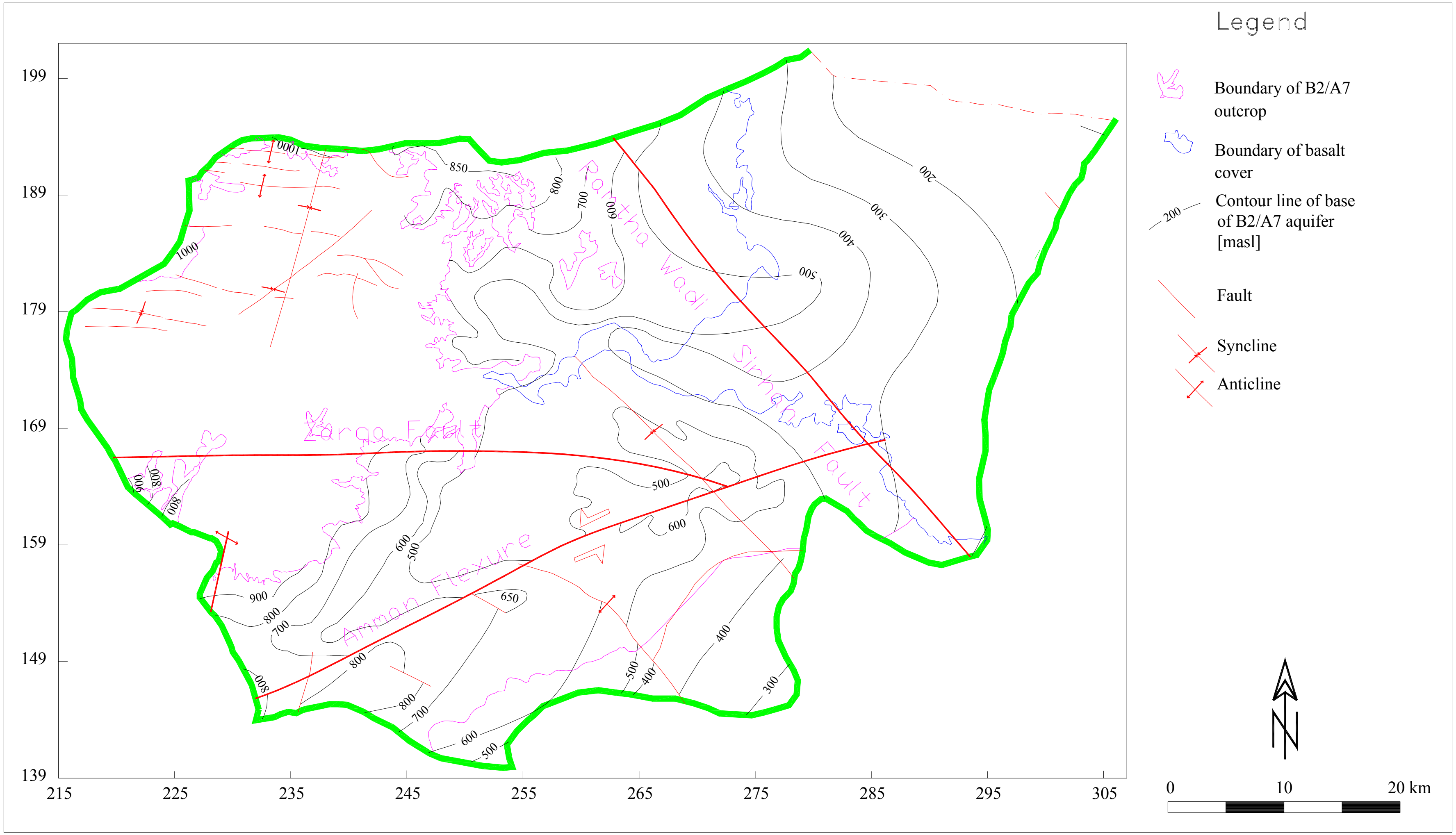

Fig. 4.3: Structure contour map base of B2/A7 aquifer (modified after BGR and WAJ 1994).

The A1/2 Formation overlies the Kurnub Group directly and comprises a Late Cretaceous (Cenomanian) sequence dominated by limestone, dolomite and marl. The A1/2 Formation can be found separately in some parts of the area south of Zarqa River. The outcrops of A1/2 are limited in extent and receives small amount of direct recharge in northwest. The thickness of the A1/2 varies between 30 and 40 meters (Master Plan 2003). It appears to be hydraulically connected to the Amman-Wadi As Sir (B2/A7, the overlying aquifer) and slightly connected to the lower Kurnub aquifer which means downward leakage from the B2/A7 into the A1/2 and from the A1/2 into the Kurnub aquifer (CES and ACE 1993). The number of productive drilled wells in A1/2 is very limited so that the information for the thickness and groundwater movement in Amman-Zarqa Basin are still unknown.

The limestone layers of Hummar (A4) and Naur Formations (A1/2) form potential aquifers of significant local importance where the B2/A7 aquifer is missing. Direct recharge of these aquifers is limited due to small outcrop areas and they are almost under artesian conditions with piezometric level at or close to the ground surface in some localities. Thus, in many cases and on regional scale studies, the formations from A1 to A6 are considered as one formation called the A1/A6 aquitard.

4.2.3 Deep aquifer system

4.2.3.1 Kurnub aquifer

The Kurnub Formation extends almost over whole Jordan. It mainly crops out in the lower Zarqa River (Baq'a Valley) and along the eastern flanking escarpment of the Jordan Valley, Dead Sea and Wadi Araba Graben (JICA and MWI 2000). Also, it crops out in the deeply eroded cores of anticlines in the areas of Wadi Sir, Naur and Wadi Hisban. The Kurnub Formation is of Lower Cretaceous age and consists mainly of sandstone (white, multi-colored and gray with medium to coarse grained size) and shale. However, in the northern and central parts of Jordan the Kurnub Formation is characterized by very fine-to coarse-grained, partly carbonaceous sandstones with intercalations of sandy dolomite. Dolomitic limestone, siltstone and shale are common.

Generally, the thickness of the Kurnub Formation decreases from the northwestern to the southeastern part of Jordan and is absent in the extreme southeastern part of Jordan. In general, the Kurnub aquifer dips gently to the east and to the north at about 5 degrees (Master Plan 2003).

Most of wells drilled in Jordan reaching the Kurnub aquifer have neither good yielding nor quality except in the Baq'a Valley (part of Amman-Zarqa basin).

The bottom of the Kurnub Group is underlain by the aquitard of the Khreim Group. The Kurnub-Zarqa aquifers can be found in hydraulic connection with older or younger formations to form one single aquifer in the western part of Jordan where the Khreim Group is absent.

In Amman-Zarqa Baisn, the Kurnub aquifer represents the lower aquifer system and outcrops only in Baq'a valley along the Suweileh anticline. It consists of sandstone, white or varicolored with layers of reddish silt and shale. Because of the presence of clay layers in Kurnub aquifer, there are variations in horizontal and vertical permeability. The depth to the Kurnub aquifer is approximately 480 m south of Amman and 530 m near to the Zarqa area (Howard Humphreys 1983). Fig. 4.4 shows the distribution thickness of Kurnub aquifer over Amman-Zarqa Basin, it is found that the thickness of Kurnub aquifer trends to increase north-west to reach about more than 400 m and about 200 m to the north-east of the study area. Moreover, the average thickness of Kurnub over Amman-Zarqa Basin is found about 300 m. In addition, Fig. 4.5 shows the structural contour map base of Kurnub aquifer. It is concluded that at the eastern part of the study area the base of this formation is less than 400 m below seal level (mbsl or less). On the other hand, in the north-west it is found more than 500 masl at Ajloun Dome and about less than 0 m (sea level) at the central part of the study area.

4.3 Aquifer characteristics

The principle of pumping test is to pump water from a well and measure the discharge and the drawdown in the well with known piezometers at distances from the well. Then these data will substitute into appropriate well-flow equation and the hydraulic characteristics of the aquifer can be calculated (Kruseman and de Ridder 1991). The effect of pumping on the groundwater heads at and in the vicinity of the pumped well is recorded. Proper analysis of these effects lead to the determination of hydraulic constants such as, transmissivities (T) or permeabilities (K_f), vertical resistances and storage coefficients.

In general, pumping tests in Jordan are carried out by the Water Authority of Jordan (WAJ). Commercial computer software was used for the evaluation of the test (mainly JACOBFIT and since 1996 Aquifer Test has been used). Since WAJ was focused to determine the yield and the efficiency of drilled well, the evaluation of pumping test result in most cases was not evaluated. Since the drawdown was very small with respect to the yield, Raikes and Partners (1971) have found empirical formula to calculate the transmissivity at Wadi Dhuleil and Hallabat areas. These areas are located at the central part of the study area where the Basalt and B2/A7 form as one aquifer system. The empirical formula was as follows:

$$\mathbf{T\ (m^2/day) = Sc\ (m^2/h) * 34} \qquad \text{(Raikes and Partners 1971)}$$

Where:
T: Transmissivity and **Sc**: Specific capacity.

In the current study, more than ninety pumping tests have been evaluated using specific softwares for analysis (Aquifer Test ver. 2.57 and GWW 1996). The pumping tests have been performed for the upper, middle and lower aquifers using different methods to calculate the aquifer characteristics. The methods of analysis and fitting curves are shown in Appendices 4.1A-4.1F for selected wells.

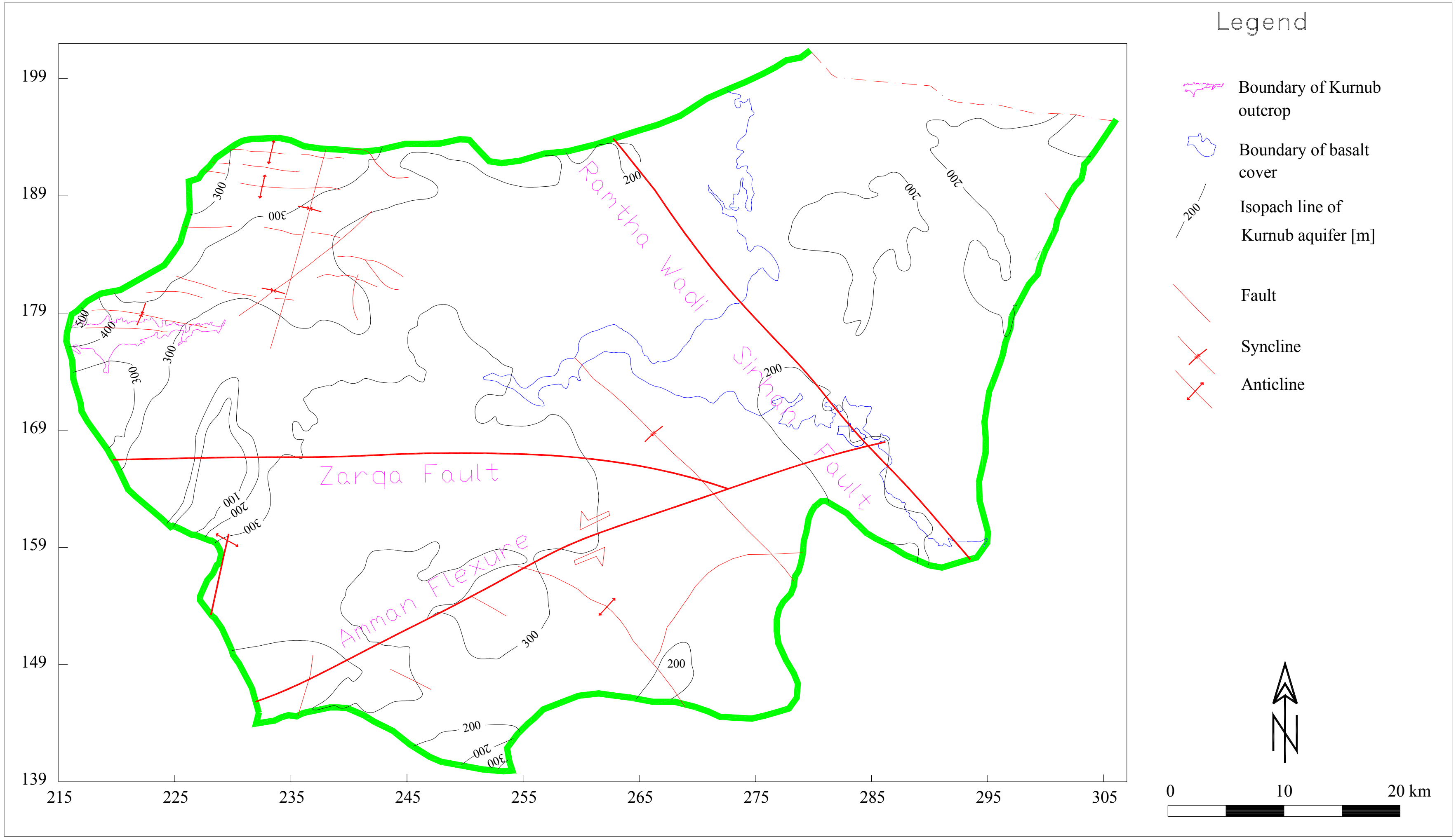

Fig. 4.4: Thickness distribution of Kurnub aquifer of Amman-Zarqa Basin.

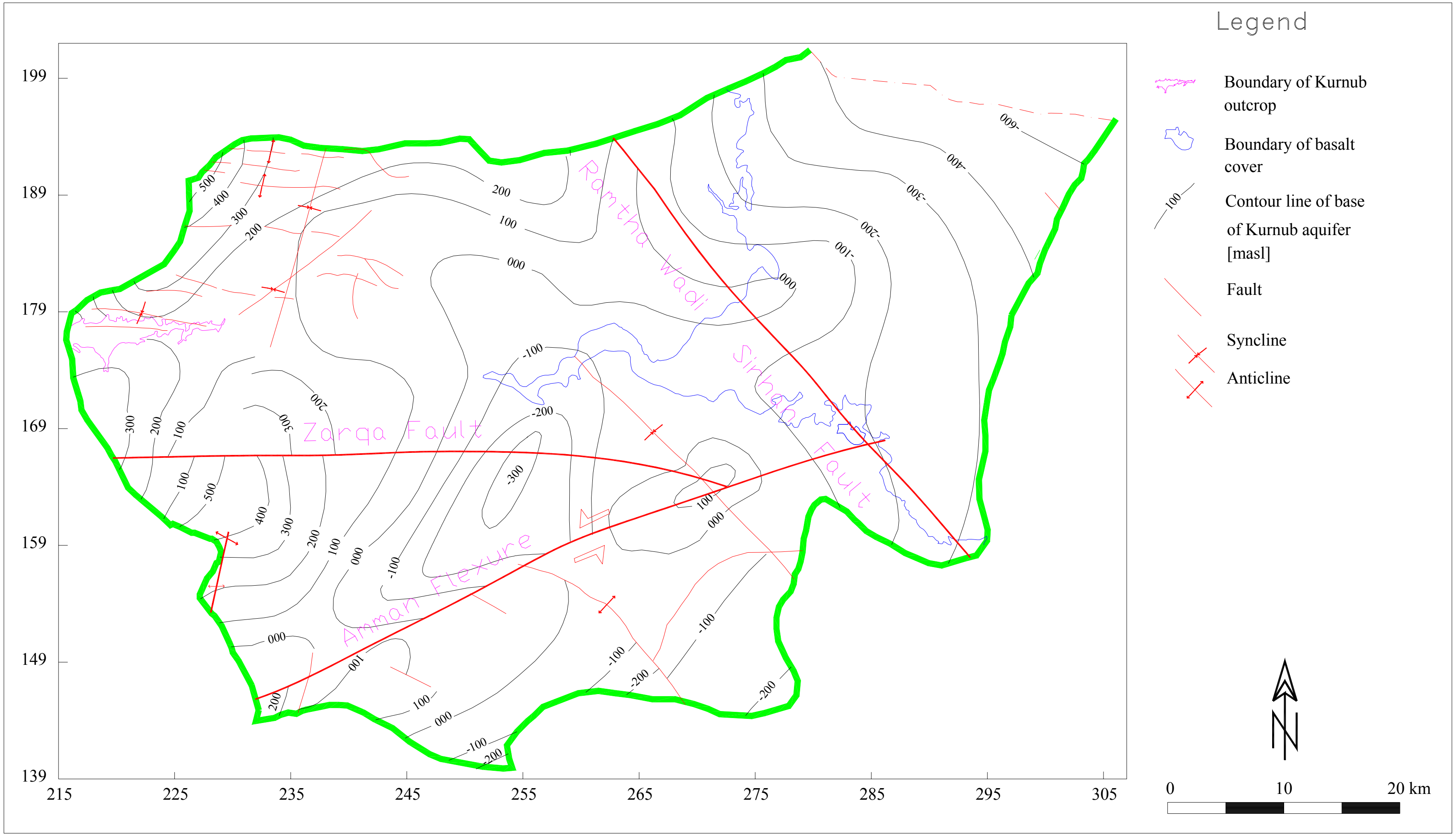

Fig. 4.5: Structure contour map base of Kurnub aquifer (modified after BGR and WAJ 1994).

4.3.1 Upper aquifer (Basalt and B2/A7)

The average yield of wells in the B2/A7 aquifer is around 50 m^3/h (cubic meters/hour) and permeability is around 1.7 m/d while in the Basalt aquifer yield is around 100 m^3/h and permeability 34.6 m/d (BGR and MWI 2001). Also, pumping tests indicate a wide range of hydraulic characteristics: transmissivity (T) varies from 9 to 900 m^2/d and yields from few liters per second to 504 m^3/h with an average of 122 m^3/h and specific yield between 12 and 22% of the Basalt aquifer while T varies from 10 m^2/d in the East to 6300 m^2/d in the West of Jordan for the B2/A7 aquifer (El Naser 1991) and storage coefficient in the confined conditions vary from 10^{-3} to 10^{-5} with specific yield of more than 30% (CES and ACE 1993).

63 pumping tests analysis have been evaluated for Basalt and B2/A7 aquifer in the study area (Appendix 4.2). Transmissivty of Basalt ranged from 4.3 to 29,700 m^2/d with an average about 7000 m^2/d, corresponding to a mean permeability (K_f) of 20 m/d. On the other side, the transmissivity of B2/A7 varies between 4.7 and 2200 m^2/d with an average of about 467 m^2/d, corresponding to a mean permeability of 7 m/d. The transmissivity map of the Basalt and B2/A7 aquifer of the Amman-Zarqa Basin drawn from 63 analyses is shown in Fig. 4.6. The highest transmissivity values were found in the north-east areas where the Basalt and B2/A7 are encountering. On the other hand, the lowest tranmissivity values were found in the northern and western parts where the B2/A7 is distributed.

Due to the complexity of the aquifer structures, the range of transmissivity values have a wide range from less than 4 m^2/day to more than 29,000 m^2/day over the study area.

The reason for high transmissivity is related to the distribution of scoria within the basalt sequence. Generally, the carbonate rocks have low transmissivity except in a zone where the water flows from the scoriaceous zone into the limestone.

The frequency of transmissivities distribution of Basalt and B2/A7 vary in a very wide range. There is no trend for increase or decrease in transmissivity. However, VBB 1977 found that the general hypothesis of transmissivities being high in the vicinity of the Seil el Zarqa where the carbonate aquifer is overlain by wadi-fill deposits with the generally accepted view that in carbonates permeability is enhanced along structurally disturbed areas (where the groundwater flow produces solution channels and karstification) and become low-very low elsewhere.

4.3.2 Middle aquifer (Hummar and Naur aquifers)

Pumping tests analysis (along Seil el Zarqa) of A4 aquifer showed a wide range of transmissivity from 230 to 2800 m^2/d which leads to permeability ranges from 0.5 to 60 m/d with an uncertain estimation of storage coefficients between 10^{-3} and 10^{-4} and 10% as specific yields (CES and ACE 1993). Also, it was reported by BGR and MWI 2001 the permeability of A4 aquifer in average is about 2 m/d in the central and northern parts

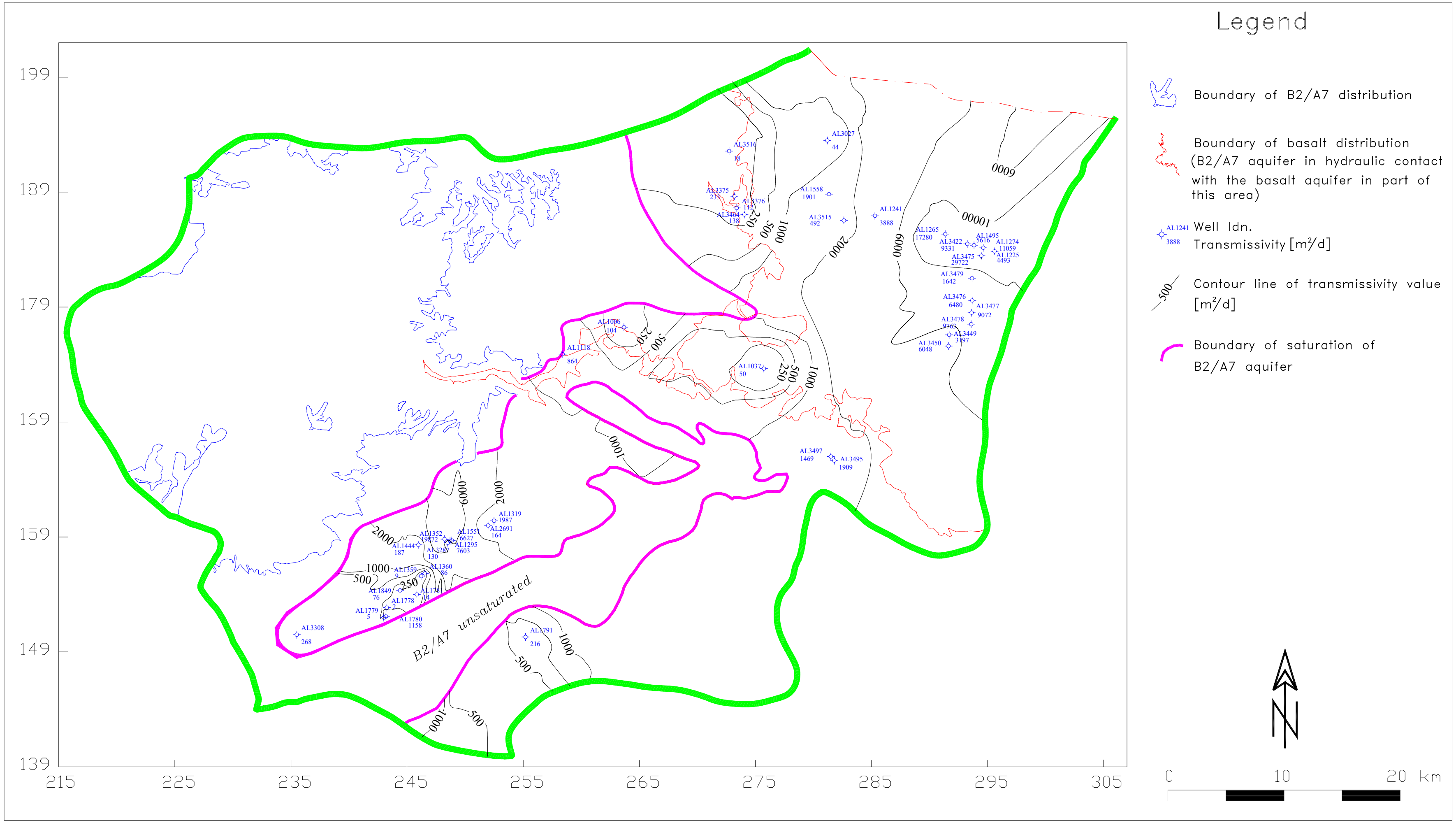

Fig. 4.6: Transmissivity distribution of the Basalt and B2/A7 aquifer in Amman-Zarqa Basin.

of Jordan. BGR and MWI 2001 the permeability of A4 aquifer in average is about 2 m/d in the central and northern parts of Jordan.

Only six pumping tests analyses have been evaluated for A4 aquifer concluding that the transmissivty of the A4 aquifer ranges from 40 to 1500 m^2/d with an average of about 510 m^2/d, corresponding to a mean permeability of 10 m/d. In addition, Parker (1970) has used pumping tests and specific capacity data to estimate the A4 properties in the Amman-Zarqa area. He found that the transmissivities in the A4 aquifer range from 230 to 2800 m^2/d corresponding to permeabilities of approximately 0.5 to 60 m/d with high distribution of permeabilities along Seil el Zarqa (which is attributed to increase of karstification arising from large quantities of water flowing) and less to the north and south directions (around the Amman flexure area).

There are only two pumping tests analyses have been done for the A1/2 aquifer in the study area. The transmissivity of A1/2 was found between 250 and 300 m^2/d, which lead to a mean permeability of 8.6 m/d.

4.3.3 Lower aquifer (Kurnub)

According to the pumping tests analysis, the Kurnub aquifer is poorly productive on the regional scale except the Hisban-Kaffrein regions where the flow is artesian. The transmissivity was reported in the phreatic conditions to be 200 m^2/d (25-3500 m^2/d in Amman-Zarqa Basin) and 2040 m^2/d under confined conditions with storage coefficients between 10^{-3} and 10^{-4} (CES and ACE 1993). Also, it was reported by BGR and MWI 2001 that the permeability of Kurnub aquifer in average is about 2.6 m/d in the central and northern parts of Jordan.

24 pumping tests analyses have been evaluated of the Kurnub aquifer in the study area (Appendix 4.2). The transmissivity of the Kurnub under phreatic conditions (Baq'a Valley) ranges from 13 to 1210 m^2/d with an average of about 325 m^2/d, corresponding to a mean permeability of 2.3 m/d. On the other hand, the transmissivity of the Kurnub aquifer under confined conditions (4 pumping tests analysis) varied between 59 and 1382 m^2/d with an average of about 656 m^2/d, corresponding to a mean permeability of 1.9 m/d. The transmissivity map of the Kurnub aquifer of the Amman-Zarqa Basin drawn from 24 pumping tests analysis is shown in Fig. 4.7. The transmissivity values of Kurnub aquifer tend to increase west-east to reach the value of more than 1000 m^2/d at the central parts of the study area. In the eastern parts where no pumping tests have been done, the transmissivity have been extrapolated based on the surroundings average permeability. Since no observation wells have been used during the pumping tests, the specific yield or storage coefficient of Kurnub aquifer is unknown. However, the specific yield has been obtained by laboratory tests and has a value in the range of 30-35% and the storage coefficients in the order of 10^{-3} to 10^{-6} (Howard Humphreys 1983).

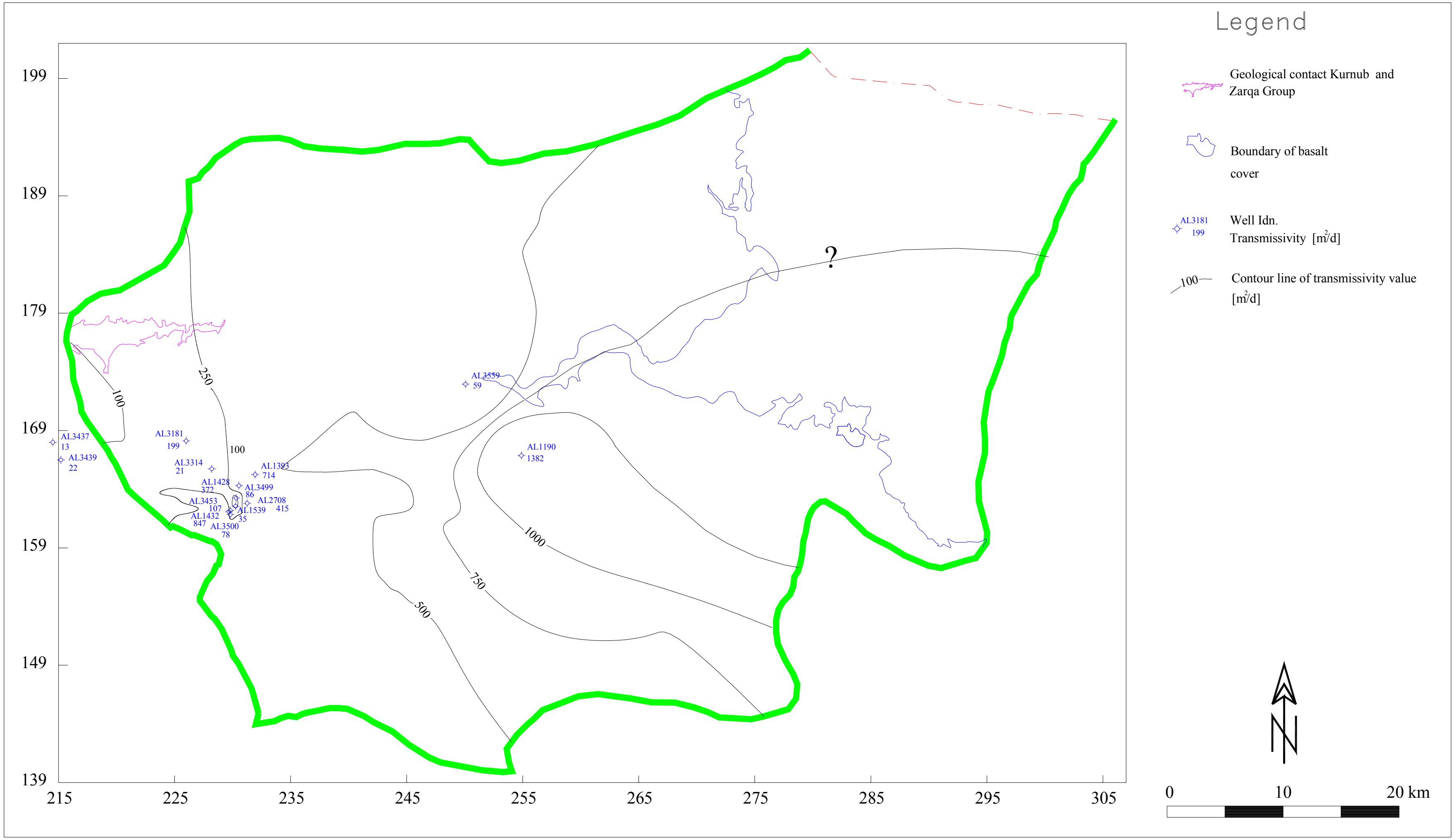

Fig. 4.7: Transmissivity distribution of Kurnub aquifer in Amman-Zarqa Basin.

4.4 Groundwater flow system

There are three groundwater flow systems in Amman-Zarqa Basin which can be distinguished.

4.4.1 Upper aquifer (Basalt and B2/A7)

A detailed water level map of Basalt and B2/A7 is given in Fig. 4.8. Based on the groundwater flow pattern of Basalt and B2/A7 aquifer, the groundwater flow directions are from south-west of Amman-Zarqa Basin to Wadi Dhuleil and Azraq Basin in central and eastern parts, respectively, and from south-west where recharge occurs into Seil el Zarqa north-west of the study area. In addition, the groundwater is moving from northeast directions through the plateau of basalt into the Yarmouk and Azraq Basins in northwestern and eastern parts of Amman-Zarqa Basin, respectively. The depth to water table varies from 50 m in the southwest (closed to As-Samra wastewater treatment plant) to more than 400 m in the north-east and about 100 m at the central parts of the study area (Fig. 4.9). Moreover, the elevation of the water surface varies from more than 750 masl in the south-west, and more than 675 masl in the south to less than 500 masl in the north (towards Yarmouk Basin), east (towards Azraq Basin) and central (towards Seil el Zarqa) of Amman-Zarqa Basin. The effect of Amman Flexure and Zarqa fault on the movement of water table still remain unknown except the investigation done by VBB 1977, proposing that at the vicinity of Zarqa fault overflow occurs from the B2/A7 aquifer into the A4 aquifer.

Groundwater in Basalt and B2/A7 is under phreatic conditions over the most parts of the Amman-Zarqa Basin, which is confirmed by wells drilling, however, in some specific wells there is indication to confined or semi-confined conditions occurred such as well D.P 14. The dominant direction of groundwater flow of Basalt and B2/A7 in Amman-Zarqa Basin is from south-west and north-east to the far northwest, east and center (Seil el Zarqa).

4.4.2 Middle aquifer (A4)

The piezometric map of A4 aquifer has been drawn based on the springs and Yajuz boreholes in the north; Amman Flexure and some boreholes to determine the saturation limit of the aquifer in the south. According to the groundwater movement of the A4 aquifer, the groundwater flow directions are from west to the east except close to the Zarqa area where the groundwater flow towards to the northeast. The depth to water table varies from 50 m in the southwest to more than 100 m in the east and 106 m in the northeast of the study area. Moreover, the elevation of the water surface varies from less than 450 masl in the east to more than 750 masl in the west. Therefore, the A4 aquifer is almost confined between the overlying marly Shuayb Formation (A5/6) and the marly lower Naur Formation (A1/2) except the outcropping areas.

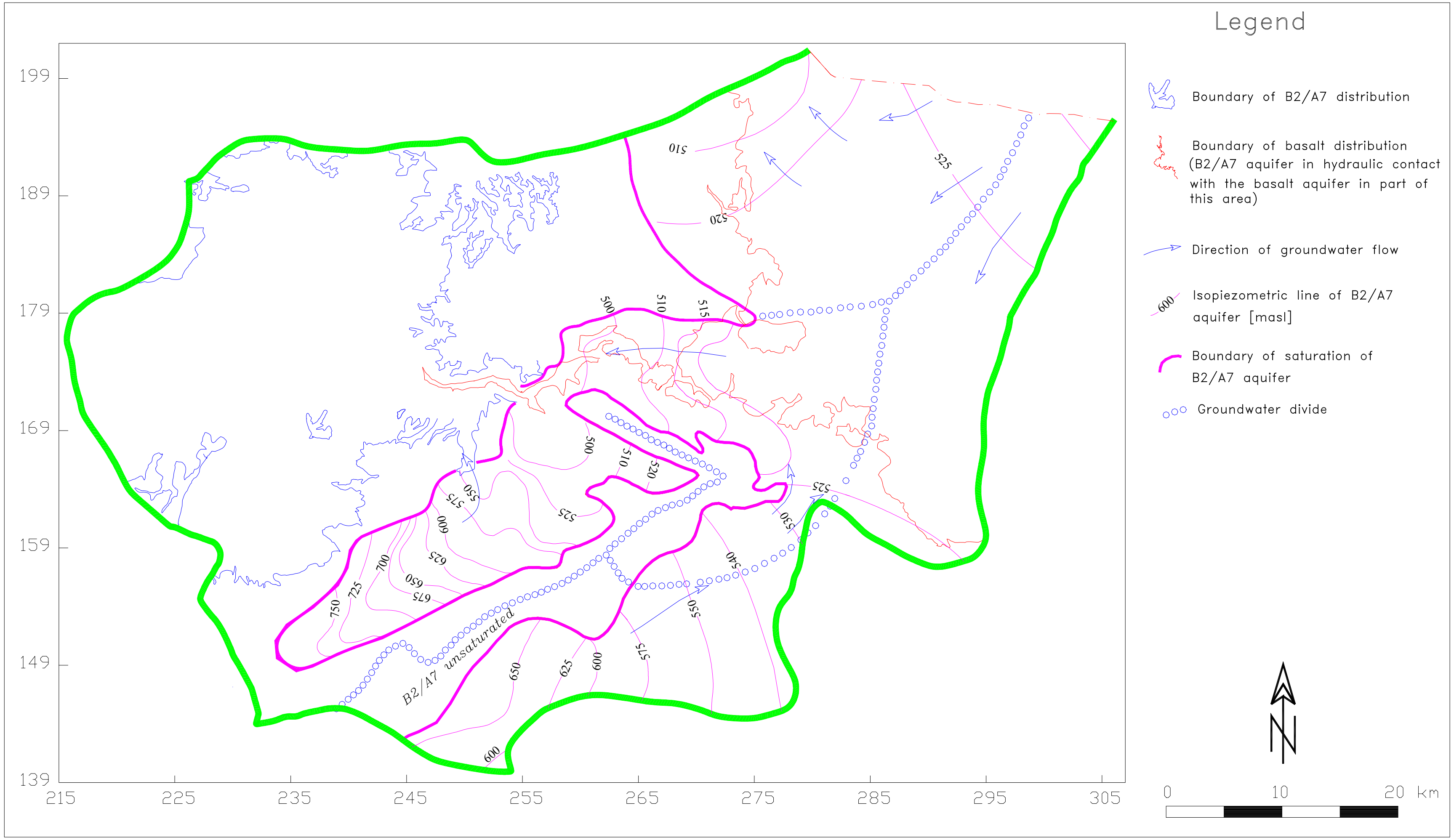

Fig. 4.8: Groundwater flow pattern of Basalt and B2/A7 aquifer (modified after BGR and WAJ 1996).

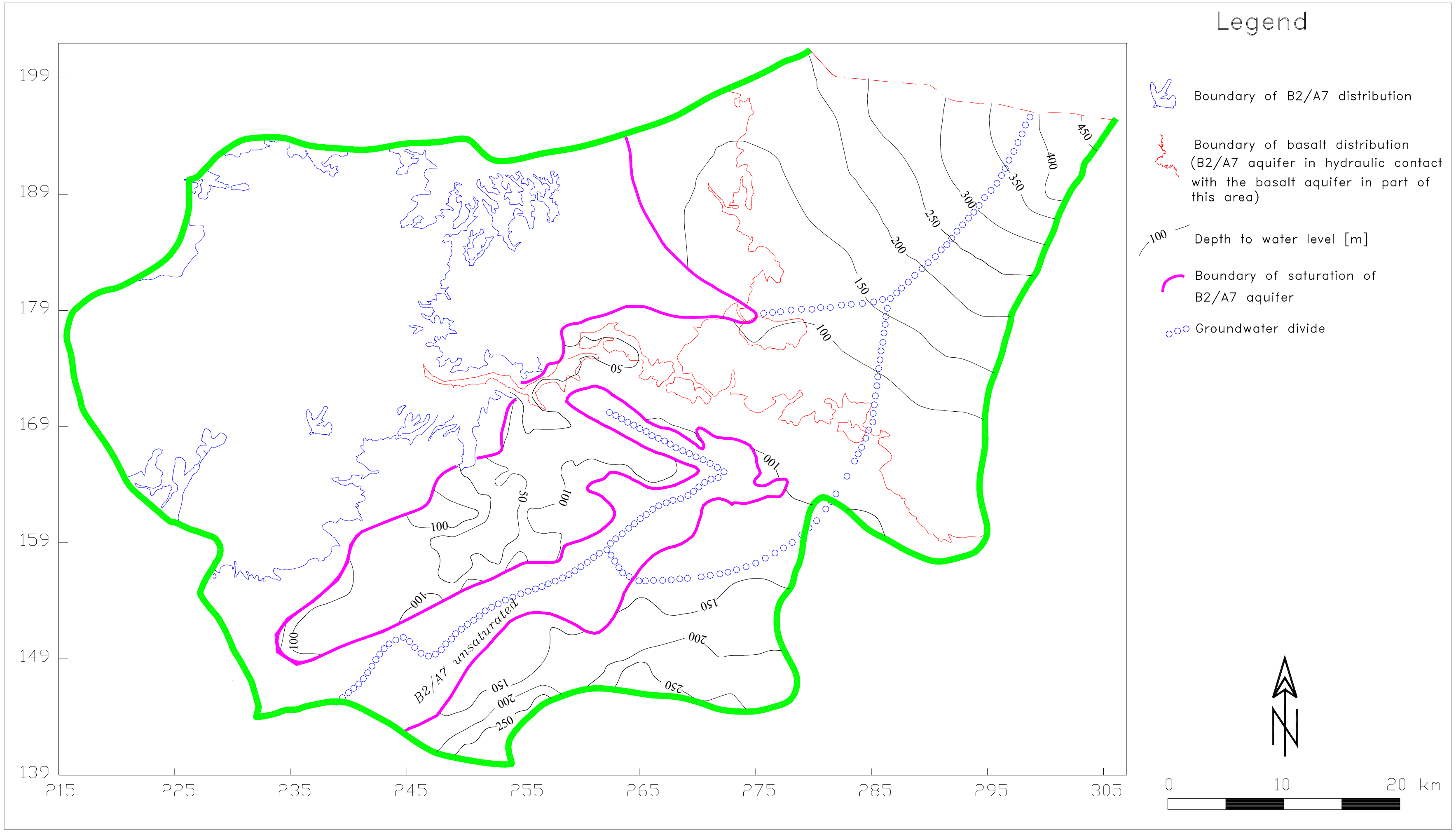

Fig. 4.9: Depth to the water level of Basalt and B2/A7 aquifer in Amman-Zarqa Basin.

4.4.3 Lower aquifer (Kurnub)

Generally, the flow pattern in the Kurnub aquifer (sandstone aquifer) in Jordan points from all directions towards the Dead Sea (the deepest base level on the earth).

As mentioned before, the Kurnub aquifer in the study area outcrops only in the Baq'a valley. Three water tables have been identified in this aquifer: shallow aquifer, deep unconfined phreatic aquifer and deep confined aquifer (CES and ACE 1993). Since the limited numbers of drilled wells into the Kurnub aquifer in the study area, especially in the central and northeastern parts, the water levels of Kurnub aquifer need more modifications. However, the boreholes which reached the Kurnub aquifer (such as: boreholes in Azraq Basin) surroundings the Amman-Zarqa Basin provide a good evidence of the regional distribution of the Kurnub aquifer to complete water levels map of the Kurnub aquifer (Fig. 4.10). The depth to the piezometric level varies from less than 100 mbgl (below ground level) in the southwest, 150 m surrounding the Baq’a Valley and to more than 400 m and 500 m north-west (Ajloun Dome) and north-east (North Badieh), respectively (Fig. 4.11). Thus, the type of groundwater in the Kurnub aquifer is unconfined (phreatic conditions) in the Baq'a valley and confined conditions elsewhere.

4.5 Groundwater recharge

Few studies give a good estimation on groundwater recharge overall Jordan. According to GTZ and NRA (1977) the total natural recharge reached approximately 462 $*10^6$ m^3/yr of which 168-200 $*10^6$ m^3 discharges as spring flow from different aquifers. However, WAJ (Bilbeisi 1992) has estimated the total recharge (renewable groundwater resources) to be only 275 $*10^6$ m^3/yr. The common approach of groundwater recharge determination in Jordan can be classified into four approaches (BGR and MWI 2001):

1- Water Balance
2- Water level fluctuations
3- Spring flow measurements
4- Flow-net analysis

The sources of groundwater recharge in Amman-Zarqa Basin can be distinguished into two parts:

- Natural recharge: within this kind of recharge it can be distinguished between direct recharge (direct infiltration of rainfall) and indirect recharge (which takes place when water percolates to the water table in localized areas through fracture or in areas where the soil cover is very thin or not existing).

- Artificial recharge: which takes place directly at the point of activities. It consists of resources such as irrigation return flow, physical losses and leakage from water supply networks and effluent of waste water treatment, etc.

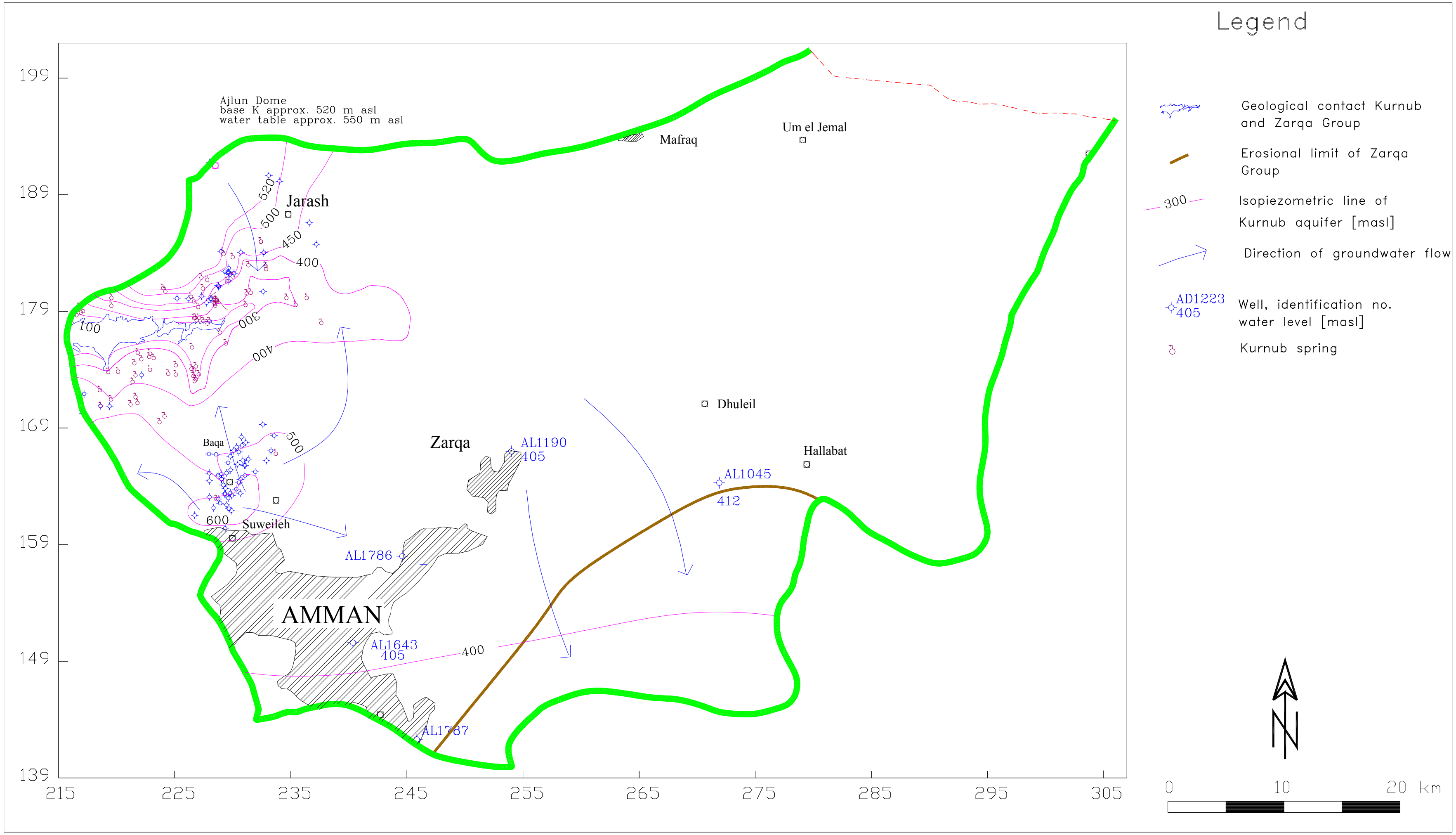

Fig. 4.10: Groundwater flow pattern of Kurnub aquifer (modified after BGR and MWI 2001).

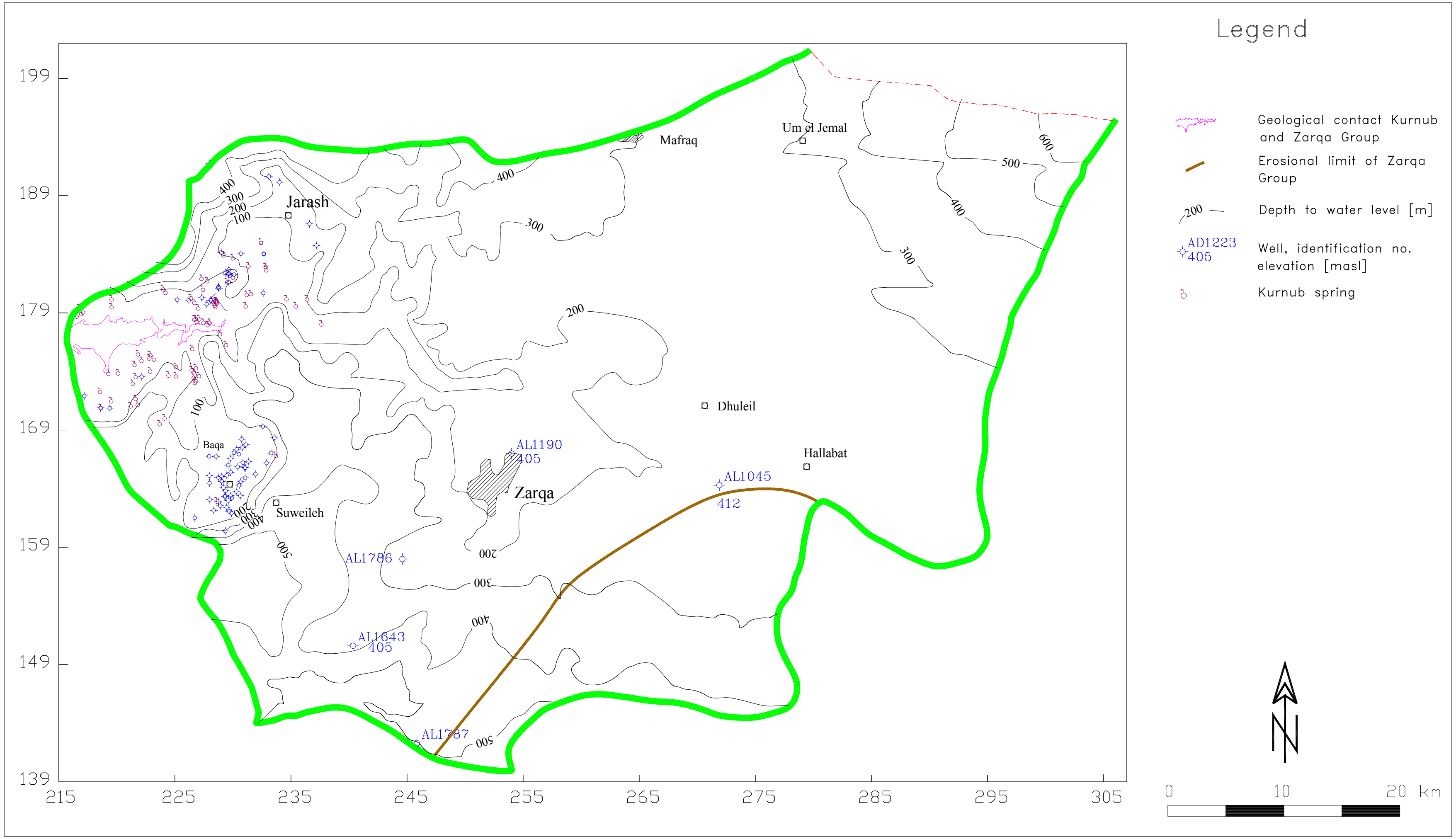

Fig. 4.11: Depth to the water level of Kurnub aquifer in Amman-Zarqa Basin.

Based on the surface water balance (chapter 2), the natural recharge (direct recharge) into the groundwater reservoir has been calculated. It is found that during the normal hydrological year the total natural recharge is about 22.4 $*10^6$ m^3 and 60.4 $*10^6$ m^3 during the wet water year. However, indirect recharge and artificial recharge will be estimated during the implementation of mathematical model calibration of Amman-Zarqa Basin.

4.6 Groundwater discharge

Most of the springs in Amman-Zarqa Basin are emerging from two major aquifers (USAID and WAJ 1989):

- Amman-Wadi As Sir formations and recent alluvium (major springs are: Ras el Ain and Ruseifa).

- Hummar and Naur aquifers (major springs are: Zarbi, Sukhneh, Fawwar, Suleihi, Maghasil, Nimra, Qunayyah and El Tannour).

About 155 springs are presently monitored in Amman-Zarqa Basin out of 800 springs in Jordan. Based on aquifer type, the springs are grouped into four types: B2/A7 spring (4 springs), A4 spring (54 springs), A1/2 spring (61 springs) and Kurnub and Zarqa springs (35 springs). The distribution of springs according to aquifer type is presented in Fig. 4.12. The total spring discharge ranges from 8.3 $*10^6$ m^3 to 24.5 $*10^6$ m^3 during the time period of 11 years (1990-2001). The maximum total discharge of the springs emerges from A4 aquifer is 9 $*10^6$ m^3 which was measured in 1995 whereas the springs discharge of Kurnub aquifer is 0.6 $*10^6$ m^3 which was measured in 2001. Table 4.1 illustrates the spring discharge from all aquifers in Amman-Zarqa Basin based on the average of 11 years (1990-2001). It is concluded that the spring discharge has been extremely declined from 25.5 $*10^6$ m^3 in 1995 to less than 9 $*10^6$ m^3 in 2001 as results of local or regional overexploitation of the aquifers in the past 10 years, decreased amount of rainfall in the past 10 years and the fact that some part of spring discharge has been used for domestic purposes.

As mentioned before (chapter two), more than 94% of the total catchment area of Amman-Zarqa Basin drains into Jarash Bridge gauging station. Based on the long-term average (33 years) the amount of baseflow (contains outflow from sewage treatment plant of Khirbit As-Samra) recorded at Jarash Bridge station was about 44.4 $*10^6$ m^3. In addition, the maximum of baseflow has been recorded in March with recorded value of about 5.9 $*10^6$ m^3.

Thus, most of springs and streams baseflows have generally been affected by overexploitation of groundwater resources in Amman-Zarqa Basin which is indicated by the general declines or even drying up some of springs such as Sukhneh and Zarqa springs.

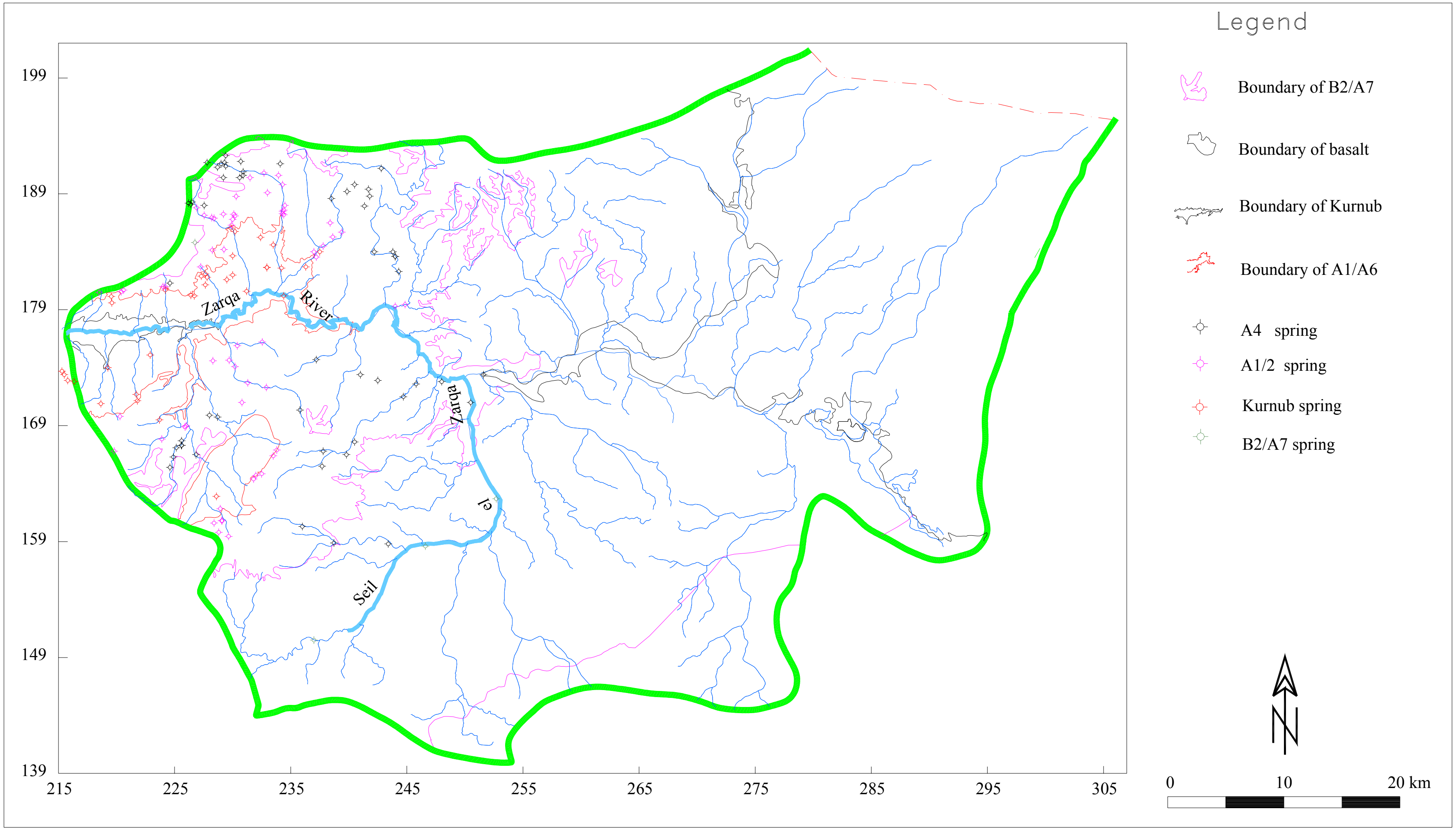

Fig. 4.12: Map of spring distribution by aquifer type in Amman-Zarqa Basin.

Table 4.1: Long-term average of spring discharge by aquifer type (1990-2001).

Aquifer type	**Discharge [10^6 m^3]**
A4	9
A1/2	6.4
B2/A7	4
K	1.5

4.7 Groundwater withdrawal

Generally, the total water consumption in Jordan increased from 640 $*10^6$ m^3 in 1985 to more than 900 $*10^6$ m^3 in 2002 (about 55% from groundwater resources). Consequently, severe overexploitation of the groundwater resources occurred so that the Ministry of Water and Irrigation (MWI) introduced new regulation to control the amount of abstraction.

The total of groundwater abstraction from the renewable aquifers exceeds more than 480 $*10^6$ m^3/yr (35% domestic, 55% agriculture and 10% industrial and other activities) whereas the safe yield was estimated between 250-300 $*10^6$ m^3/yr over the whole of Jordan based on the Water Information System (WIS) in the MWI. More than 2400 registered wells are tapping groundwater excluding the illegal drilled wells especially in Amman-Zarqa and Azraq Basins. The B2/A7 aquifer is the most used aquifer for wells tapped (more than 40% of the total abstraction) whereas the B4/B5 is still the minority aquifer for wells tapped (1% of the total abstraction) in Jordan (JICA and MWI 2000).

Until recently, groundwater withdrawal from the private wells was roughly estimated. In 1993, the Water Basin Project has been created in the Water Authority to collect the field data on groundwater abstraction from private wells by questioning of the farmers, then the Water Authority of Jordan (WAJ) decided that all private wells should be equipped with flow meters to control the abstraction from these wells.

Amman-Zarqa Basin is the groundwater basin in Jordan with highest abstraction, i.e. more than 28% of total abstractions in Jordan come from this basin. The following compilation of groundwater abstraction in Amman-Zarqa Basin is based on WIS (Appendix 4.3).

According to Appendix 4.3, the total numbers of production wells are ranging from 600 to 713 wells distributed over Amman-Zarqa Basin during the years of 1995-2003 with a total abstraction of approximately 142-138.6 $*10^6$ m^3/yr, respectively. Fig. 4.13 shows the groundwater abstraction from the different aquifer types according to the water budget of 2003 (138.6 $*10^6$ m^3). The figure shows, the total number of productive wells are 673 wells of which 456 wells tapping Basalt and B2/A7 aquifer (79.6%), 81 wells tapping Kurnub aquifer (7.2%), 63 wells tapping A4 aquifer (9.7%), 27 wells tapping A1/2 aquifer (2.5%) and 46 wells tapping Alluvium aquifers (1%). Fig. 4.14 shows the groundwater abstraction amount based on the water budget of 2003 which includes: 5.9% industrial (65 wells), 38.6% agricultural (434 wells) and 55.5% domestic (174 wells). In addition, Fig. 4.15 shows the distribution of productive wells over the Amman-Zarqa Basin. It is noticed that the highest density of abstraction wells is located in the northeastern parts of Amman-Zarqa Basin where the most of agricultural activities have been found.

Therefore, most of productive wells tapping Basalt and B2/A7 aquifer, specifically in the northeastern parts of Amman-Zarqa Basin.

The amount of groundwater abstraction for domestic purposes exceeds the amount of groundwater abstraction for agriculture and industry activities where more than of 60% of the total population in Jordan lives there.

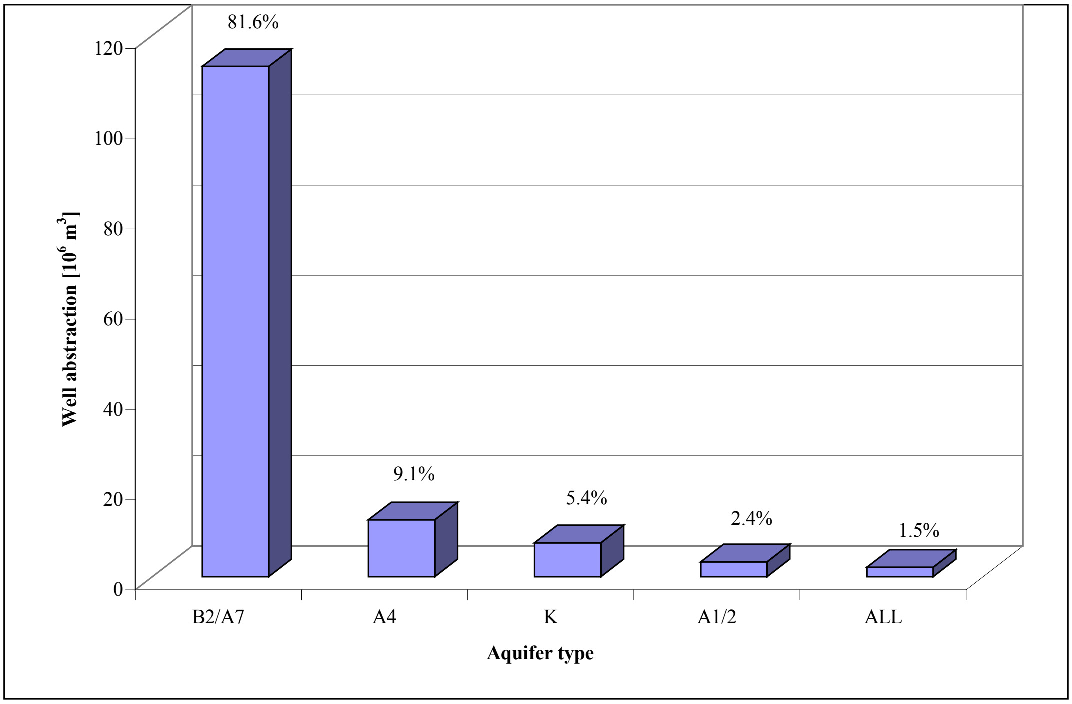

Fig. 4.13: Groundwater abstraction (water budget 2003) based on aquifer type in Amman-Zarqa Basin.

4.8 Monitoring of groundwater levels

Monitoring of groundwater levels are mainly concerned with observations of water levels fluctuations or the collection of the hydrochemical data. The monitoring of groundwater levels usually concerned with one of the following targets: first, to observe the long-term fluctuation of the groundwater table; these data reflect the long-term changes in the water balance of groundwater resource. Second, to study the correlation between the annual groundwater level fluctuation and rainfall.

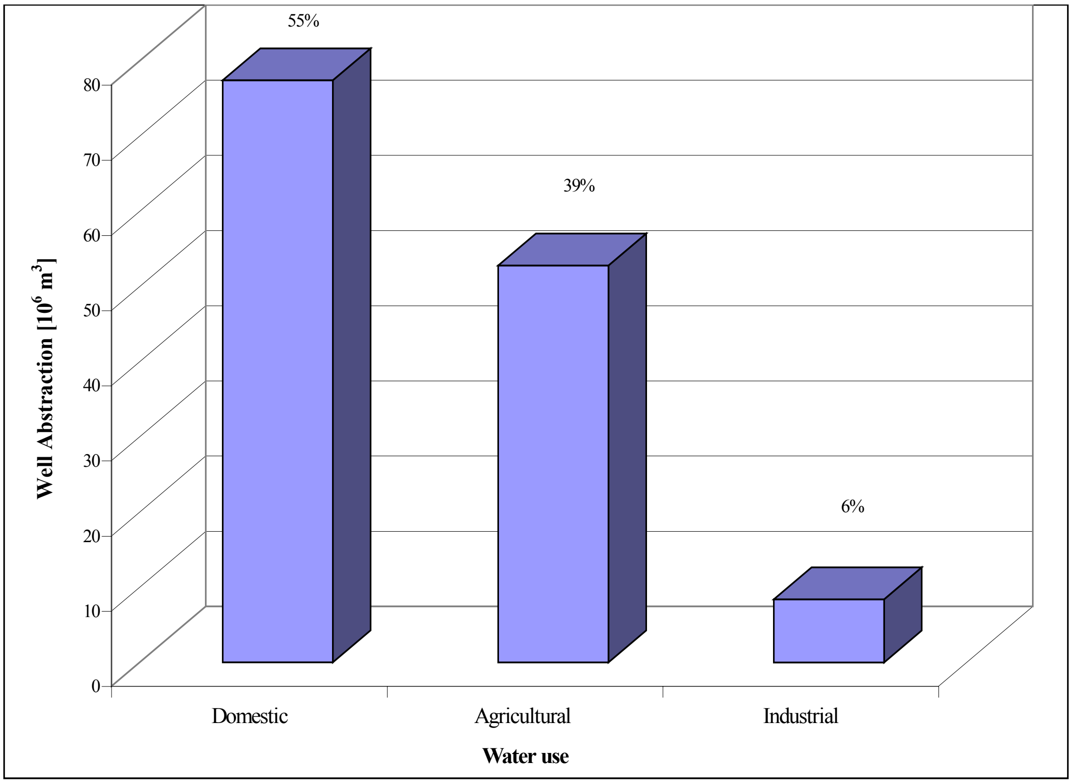

Fig. 4.14: Groundwater abstraction based on water use (water budget 2003) over Amman-Zarqa Basin.

Groundwater level monitoring in Jordan has been conducted by different institutions before the 80's until the foundation of Water Authority of Jordan (WAJ) in 1984. In the beginning of the 90's the groundwater level monitoring of wells in the Jordan Valley and Wadi Araba was carried out by Jordan Valley Authority (JVA). Nowadays the monitoring of groundwater levels over the whole of Jordan is carried out by the Groundwater Monitoring Division under the activities of Ministry of Water and Irrigation (MWI). The most important objectives of groundwater monitoring wells in Jordan are focused on long-term movement of the groundwater table, which is necessary for groundwater simulations and modeling surveys, in order to define the regionally effective specific yield of aquifers and to calibrate the required hydrogeological models. Therefore, these data will be used to study the changing in the water balance of a groundwater resource and serve as a planning tool on the regional scale for groundwater management.

About 198 observation wells are being monitored throughout the country, 119 of those equipped with automatic recorders, 55 with manual measurements which are taken at irregular time intervals and 26 with dynamic water level (Master Plan 2003). According to the aquifer, there are more than 80 observation wells serving as monitors for the water level fluctuation in the B2/A7 aquifer.

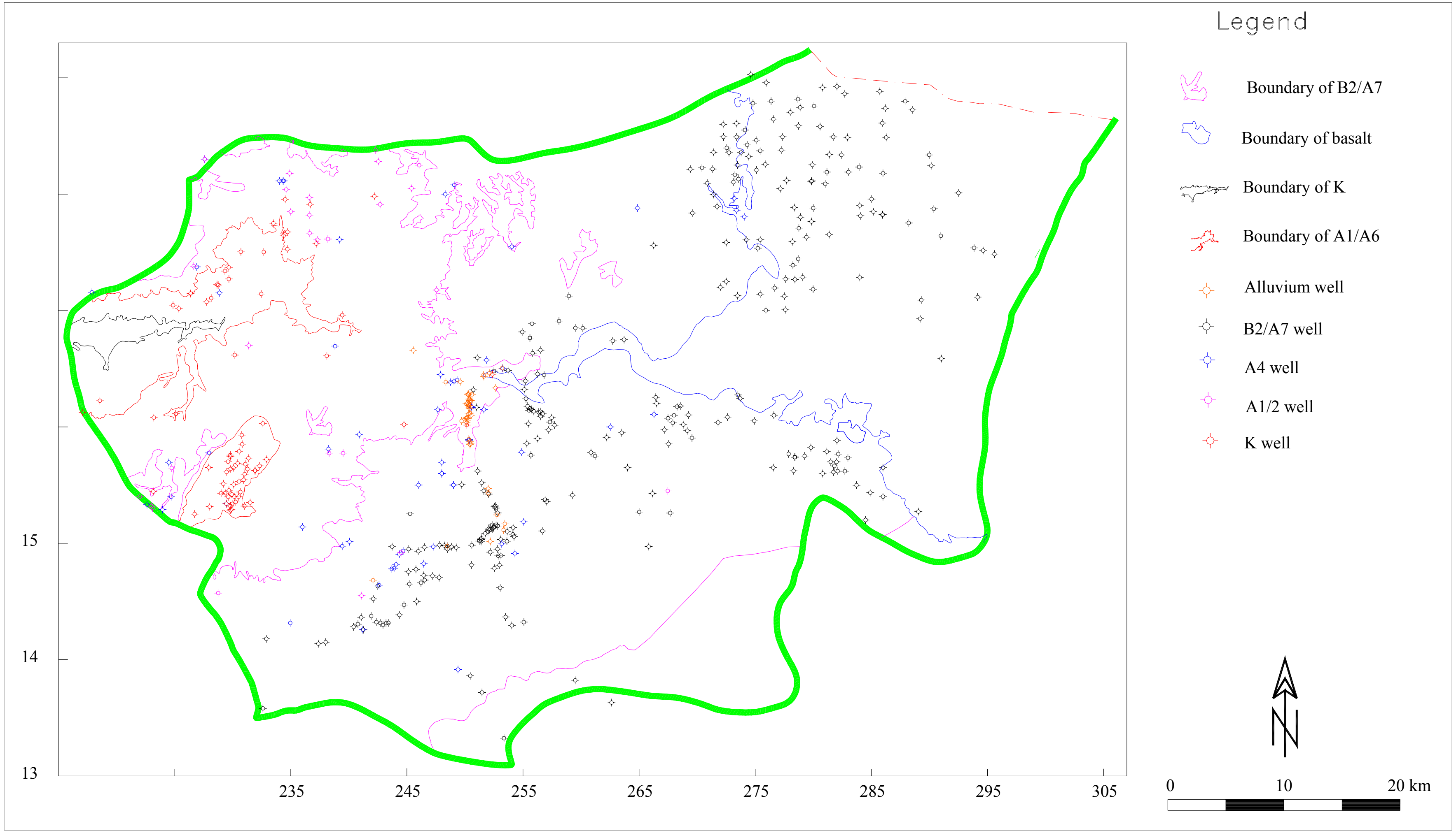

Fig. 4.15: Map of productive wells based on aquifer type in Amman-Zarqa Basin.

In Amman-Zarqa Basin, there are 65 observation wells distributed as shown in Fig. 4.16. Some wells have been closed down or worked for a short time only because of technical problems or completed technical project. All observation wells in Amman-Zarqa Basin have been listed in Appendix 4.4. Based on the Appendix 4.4, Fig. 4.16 and the hydrographs, the groundwater fluctuations in Amman-Zarqa Basin have the following characteristics.

4.8.1 Upper aquifer (Basalt and B2/A7)

Most of water levels monitoring wells in Amman-Zaraq Basin are located in the Basalt and B2/A7 aquifer, i.e. about 40 wells out of 65 monitoring wells. The first well has been drilled to monitor the water level in Basalt and B2/A7 aquifer was Wadi Dhuleil Well No. TW-5 (AL1040) since 1968 (Appendix 4.4). Most of hydrographs show relatively moderate depletion rates of water level. Based on the hydrographs of Basalt and B2/A7 aquifer, the maximum depletion of groundwater level reached 15 m/yr at Ain Ghazal Station No. 2 (east of Amman) but this hydrograph does not reflect the real water level fluctuations in the aquifer because the measured water level is dynamic not static. However, in the northeast parts of Amman-Zaraq Basin (Hallabat, Wadi Dhuleil, Khaldiyeh, etc.) the average drawdown of water level is about 1.1 m/yr (far northeast) and the maximum drawdown is reaching about 2.8 m/yr at Hallabat area (Hallabat No. 5). On the other hand, the average drawdown is less than 1 m/yr (0.5-1 m/yr) in the other parts of Amman-Zarqa Basin. In addition, it is concluded that water level surrounding the As Samra wastewater treatment plant (ASWWTP) area is rising between 0.05-0.25 m/yr (Appendix 4.4). Also, it is concluded that there was sharp increase in the declining of water level until the beginning of the 90’s where the drilling of new wells become forbidden. Thus, a study conducted by WAJ & BGR (1995) revealed that water levels in the B2/A7 aquifer in the central and northern parts of Jordan are declining at rates of 1 – 1.5 m per year.

4.8.2 Middle aquifer (A4)

There are seventeen monitoring wells for the A4 (14 wells) and A1/2 (3 wells) aquifers over the study area. Monitoring of water level in A4 aquifer has been started in 1989 at Nadi Es-Sebaq observation well No. 13 (AL1782). Unfortunately, most of the monitoring wells in the A4 aquifer are still new. However, in the early 60's many wells in the A4 aquifer were showing artesian heads of up to 70 m above the ground (Howard Humphreys 1983) and nowadays having pressure heads. Based on the hydrographs of A4 aquifer, the maximum depletion of groundwater level reached between 7 and 9.5 m/yr at Seil Ruseifa (east of Amman), but this hydrograph does not reflect the real water level fluctuations in the aquifer because the measured water level is dynamic not static. However, based on long-term monitoring data of well No. AL1782 the average drawdown of water level is approximately 0.5 m/yr and becomes more than 2 m/yr at Ruseifa monitoring well No. 1 (AL3523).

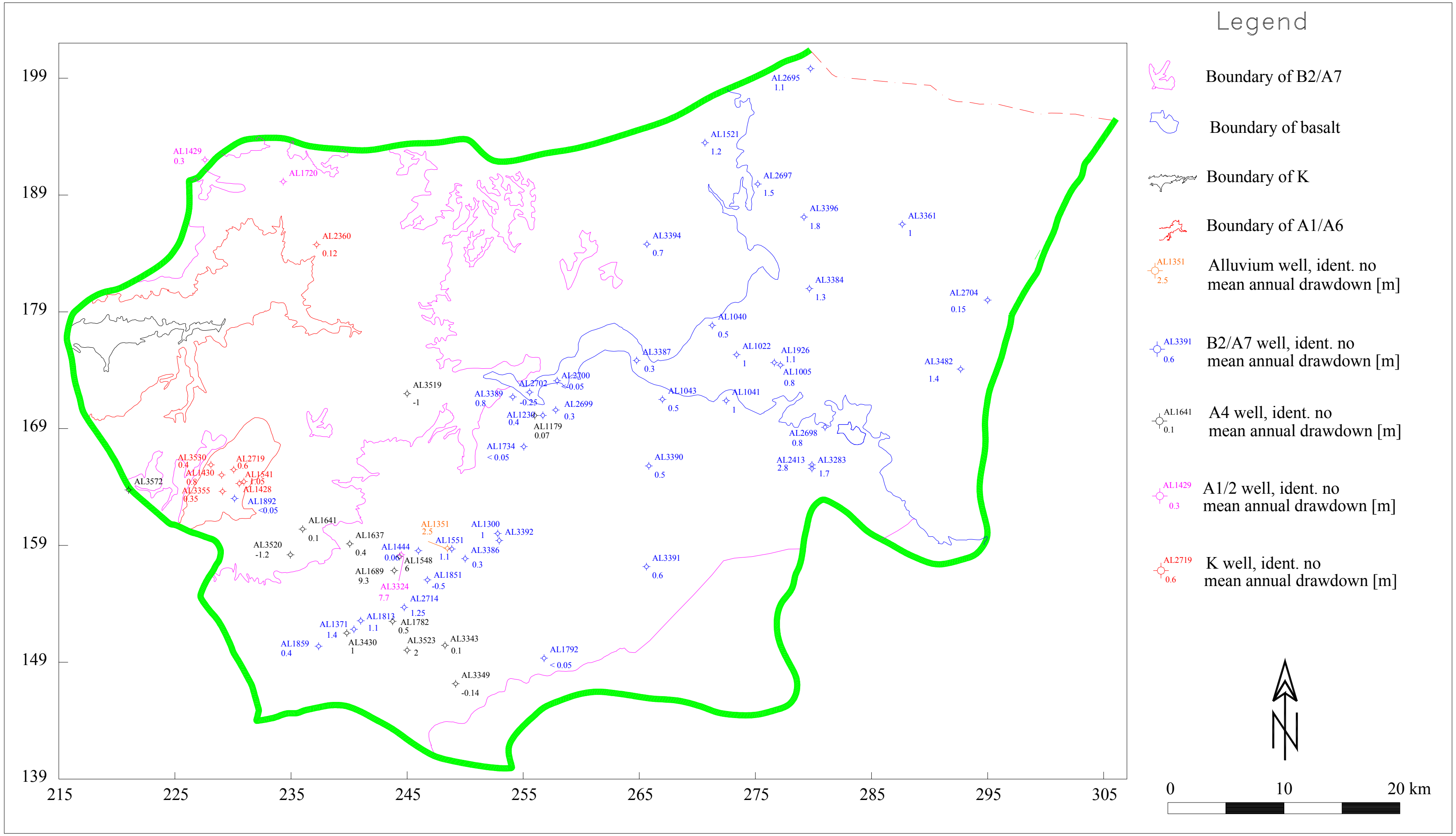

Fig. 4.16: Location of observation wells in Amman-Zarqa Basin.

However, it is found that there is rising of water level in Yajouz well No. 1 (AL3520), Wadi El Qattar well No. 7 (AL3349) and Sukhneh well (AL3519) because of direct recharge either from excess rainfall (natural leakage) or irrigation return flow. Therefore, the recording of data of water level monitoring in the A4 aquifer is still not sufficient to evaluate the regional distribution of the behavior of water level fluctuations in the A4 aquifer.

The A1/2 aquifer has only three monitoring wells. Unfortunately, all of them started monitoring in the beginning of 2000's as dynamic water level type. However, the average drawdown was found to be about 0.3 m/yr in the western parts of Amman-Zarqa Basin (Souf Municipality well No. 1) and more than 5 m/yr at Seil el Zaraq area (Ain Ghazal Deep well No. 4).

4.8.3 Lower aquifer (Kurnub)

There are only seven monitoring wells for the Kurnub aquifer. The monitoring of water level fluctuations in the Kurnub aquifer has been started in 1985 (Baq'a No. 3) at Baq'a Valley where the Kurnub is outcropping. Based on the hydrographs of the Kurnub aquifer, the maximum depletion of groundwater level on long-term recording data reached about 0.8 m/yr at Baq'a well No. 3 with an average reaching about 0.5 m/yr. Therefore, the data of water level monitoring in the Kurnub aquifer indicates continuous depletion of groundwater level.

Therefore, the water level monitoring network in the Amman-Zarqa Basin shows that the groundwater depletion is still in progress. Often monitoring wells in Amman-Zarqa Basin have been not continuity of water levels measurements (e.g. Ruseifa Municipality No. 4). Some monitoring wells have been changed into production wells (e.g. Race Club No. 29) temporarily or permanently since water shortage occurred. More than 25% of observation wells in Amman-Zarqa Basin monitored the dynamic water levels with variable amount of groundwater withdrawal which resulting in high uncertainty for the interpretation of the water level fluctuations for short time as well as for long-time data recording.

5 HYDROCHEMISTRY

Water has unique properties such as solvent for many salts and some types of organic matter, very high dielectric constant and its molecules tend to combine with ions to form hydrated ions, etc. As a result of chemical and biological interactions between groundwater and the rocks through which it flows, and to a lesser extent because of contributions from the atmosphere and surface water bodies, groundwater contains a wide variety of dissolved inorganic chemical constituents in various concentrations. In addition, the dissolved organic matter with low quantity also contributes in the groundwater quality (Freeze and Cherry 1979).

Water quality is the main key that is likely to affect the sustainability of resources for multi-purposes. Most of domestic water in Jordan comes from groundwater resources. In the early sixties, the quality of groundwater in the Amman-Zarqa Basin was suitable for all water uses (domestic, agricultural and industrial), however due to the over-pumping of the groundwater and intensive agricultural activities, the chemical composition of groundwater changed to the worse and got unusable for many purposes; for example: the electrical conductivity (EC) increased from 700 μS/cm in 1965 to more than 5800 μS/cm in 2004. The water salinity (EC) is a good indicator for increasing of the concentrations of main cations and anions in the groundwater system. On the other side, the concentration of nitrate (NO_3) is often an indicator of water deterioration due to agricultural impact. The concentration of nitrate was below the Jordanian and World Health Organization (WHO) standards in the middle of sixties whereas in 2004 the concentration has reached in some areas more than 100 mg/l.

Fig. 5.1 shows the map of representative sampling wells that were monitored between 2003 and 2004. The chemical analyses for those samples include chemical major and minor ions, physical parameters and trace elements for 87 groundwater samples. The chemical analyses were carried out at the Central Laboratories of Water Authority (CLWAJ) and the historical data were obtained from data bank and open files of the Ministry of Water and Irrigation (MWI) (Appendix 5.1). Only data with an error of less than 5% in the balance of total cations and anions has been used for the assessment. Evaluation of water quality of the wastewater treatment plants and dams are described in chapter six, environmental features.

5.1 Calculation of chemical parameters

Different parameters have been calculated based on the chemical analysis of the groundwater samples. The most common computed parameter is saturation indices that reflect the interaction between water and rocks in terms of dissolution and precipitation processes. These processes are controlled by the solubility products of certain minerals (such as: calcite, dolomite, aragonite, gypsum, etc). These calculations have been done using the computer software (PHREEQC for Windows ver. 2.10) (Parkhurst and Appelo 2004).

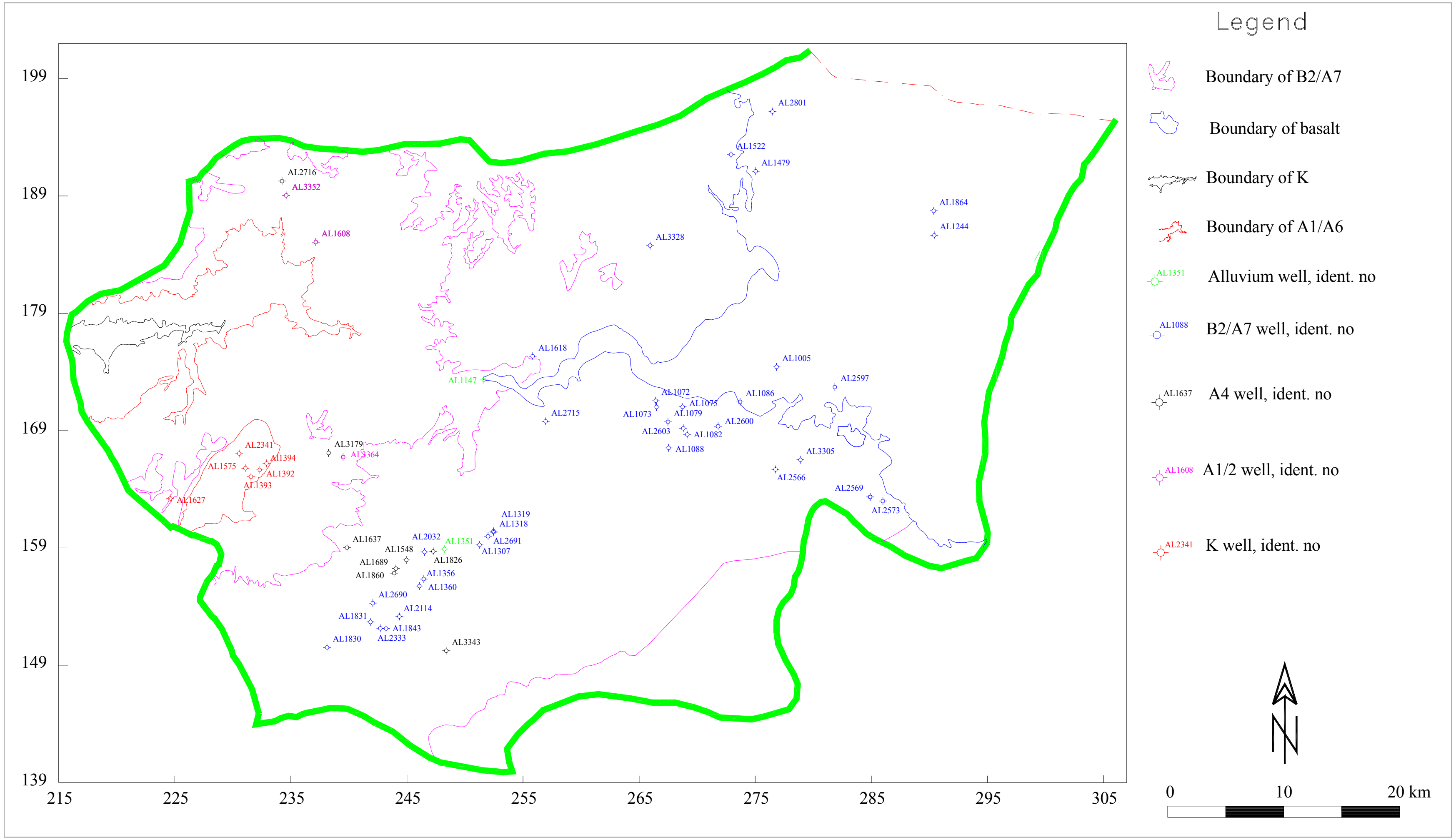

Fig. 5.1: Map of representative wells of water samples in Amman-Zarqa Basin.

5.1.1 Chemical equilibrium and saturation indices

Equilibrium thermodynamics predicts the concentration (more precisely: activities) of various species and phases if a reaction reaches equilibrium (Ebey 2004). Mass action law defines how constituents are reacting and what are the products of the reaction (Freeze and Cherry 1979). It states that for a reaction:

$$aA+bB \longrightarrow cC+dD$$

At the equilibrium between the species at the left and the right is described as:

$$K_{eq} = \{C\}^{c} * \{D\}^{d} / \{A\}^{a} * \{B\}^{b}$$

where K_{eq} is the equilibrium constant and the bracketed quantities denote activities "effective concentration" and A, B, C and D refer to the stoichiometric coefficients of the chemical constituents.

The saturation indices (SI) are commonly used to express the state of saturation of water sample in terms of minerals. The importance of determining the saturation indices is to know the state of water rock interaction (equilibrium, undersaturation or supersaturation).

The state of saturation indices of groundwater sample for any mineral can be obtained by applying the following formula:

$$SI = Log\ (IAP / K_{SP}) \qquad \text{(Freeze and Cherry 1979)}$$

Where:

SI : Saturation index

IAP : Ion activity product

K_{SP} : Solubility product of the mineral

For SI = 0, there is equilibrium between the mineral and the solution, SI < 0, there is an undersaturation and SI > 0 this refers to a supersaturtion.

The saturation indices of the major mineral phases for the all collected samples were calculated using PHREEQC. Table 5.1 shows the average saturation indices of the upper, middle and lower aquifer as well as the descriptive statistics for the main chemical compositions.

Based on the results as shown in Table 5.1, all of groundwater is still undersaturated with respect to anhydrite, brucite, gypsum, halite, hydromagnesite and magnesite. This means that the dissolution process will continue in the carbonate rocks, but the process is a function of time. The saturation indices of dolomite and calcite are supersaturated in the middle and lower aquifers while being in equilibrium in the upper one. Dolomite and calcite are the main minerals that represent the major sediments of the aquifer system structures in Amman-Zarqa Basin.

Table 5.1: Descriptive statistics of the averages of the chemical compositions and computed parameters of the aquifer systems.

Parameter	Upper aquifer (56 samples)			Middle aquifer (18 samples)			Lower aquifer (10 samples)		
	Mean	**Min.-Max.**	**Std. dev.**	**Mean**	**Min.-Max.**	**Std. dev**	**Mean**	**Min.-Max.**	**Std. dev**
Ca (mg/l)	92.7	24.3-192.5	34.9	72.3	51.7-94.6	13.9	66.8	41.7-83.4	11.7
Mg (mg/l)	49.2	7.5-129	27.7	34.9	22.5-46.1	7.9	32.4	23.1-44.5	7.1
Na (mg/l)	163.4	25.5-422.1	111	44.1	19.3-79.6	22.3	59.2	20.5-117.1	28.7
K (mg/l)	8.2	2-15.6	3.0	2.8	0-7.4	1.6	4.7	1.6-9.4	2.6
HCO_3 (mg/l)	211.5	66.5-366	102.0	290.3	248.9-372	27.8	257.1	133-321.5	52.3
SO_4 (mg/l)	108.5	17.3-495.4	105.6	33.5	15.4-65.3	15.2	67.2	24.5-207.8	51.1
Cl (mg/l)	338.4	43.3-958.5	232.6	89.5	27.3-163.3	49.3	92.4	42.6-204.8	46.8
NO_3 (mg/l)	46.8	3.5-107.2	25.5	33.0	7.7-66.9	17.7	26.0	5.8-80	29.6
EC (µS/cm)	1679	500-3680	827.1	830.5	536-1176	214.8	818.1	650-1211	182.9
TDS (mg/l)	904.6	234-2002	457.5	450	302-622	114.1	477.3	340-684	102.6
pH	7.4	6.2-8.5	0.6	7.7	7.3-7.9	0.2	7.5	6.4-8	0.5
SAR	3.3	0.6-6.6	1.7	1.0	0.5-1.8	0.5	1.5	0.5-2.8	0.7
TH (mg/l)	430	92-905	178.5	324.2	246-402	53.7	300	233-375	38.2
$SI_{anhydrite}$	-2.0	-2.6-(-)1.2	0.4	-2.4	-2.8-(-)2.1	0.2	-2.2	-2.7-(-)1.7	0.3
$SI_{Brucite}$	-5.1	-7.3-(-) 3.1	1.2	-4.5	-5.4-(-) 4.1	0.3	-4.9	-7.2-(-) 3.9	1.0
$SI_{Calcite}$	0.01	-1.4-0.74	0.6	0.48	0.1-0.9	0.2	0.2	-1.2-0.7	0.6
$SI_{Dolomite}$	0.02	-2.7-1.5	1.2	0.8	-2.2-1.7	0.8	0.5	-2.4-1.4	1.1
SI_{Gypsum}	-1.8	-2.4-(-)1	0.4	-2.3	-4.9-(-)1.8	0.7	-1.9	-2.5-(-)1.4	0.3
SI_{Halite}	-6.1	-7.5-(-) 5.1	0.6	-7.1	-7.8-(-) 6.5	0.5	-6.9	-7.7-(-) 6.2	0.4
$SI_{H.magnesite}$	-13.8	-21.4-(-) 9	3.5	-10.8	-14-(-) 2.2	2.4	-12.7	-20.7-(-)10	3.3
$SI_{Magnesite}$	-0.5	-1.9-(-) 0.2	0.6	-0.7	-11.5-(-) 0.3	2.7	-0.3	-1.8-0.2	0.6

5.1.2 Total dissolved solids

Concentrations of cations and anions in the water samples are related to the total dissolved solids (TDS). This means that the increasing of TDS signifies a degradation of water quality. With increasing of TDS water becomes more salty and corrosive.

According to the TDS values, the groundwater can be classified into four types as shown in Table 5.2

Table 5.2: Classification of groundwater based on TDS values (Caroll 1962).

Type of water	**TDS [mg/L]**
Fresh	0-1000
Brackish	1000-10000
Saline	10000-100000
Brine	>100000

Since no measurements or analysis of TDS have been done in this research, the TDS was calculated (Table 5.1) using the following equation (Freeze and Cherry 1979):

TDS (mg/L) = $Ca^{2+} + Mg^{2+} + Na^{+} + K^{+} + SO_4^{2-} + Cl^{-} + NO_3^{-} + 0.5HCO_3^{-}$

By reviewing the Table 5.1 and Appendix 5.1, it is noticeable that in the upper aquifer the TDS ranged between 234 and 2001 mg/L with an average about 905 mg/L. The highest value of TDS was found close to Dhuleil and Khaldiya well fields (central parts of Amman-Zarqa Basin) in wells AL1082, AL1088, AL2715, AL1075, AL1005 and AL2579 as a result of over abstraction and irrigation return flow (Al Mahamid 1998). On contrast, the TDS for middle and lower aquifers is less than 1000 mg/L.

Generally, the TDS value can be estimated from electrical conductivity (EC) measurements in most cases whereas both EC and TDS represent the total salt content in water. Fig. 5.2 shows the correlation between TDS and EC with correlation coefficient 0.99, i.e., TDS (mg/L) = 0.54 EC (µS/cm).

5.2 Classification of groundwater samples

Classification of the analyzed groundwater samples in the Amman-Zarqa Basin has been done by using the software AquaChem (Calmbach 1997). These classifications were done in order to determine the water types and the variations of water quality. The hydrochemical data of groundwater samples were represented for interpretation using Piper diagram (Piper 1944), Durov and Wilcox diagrams.

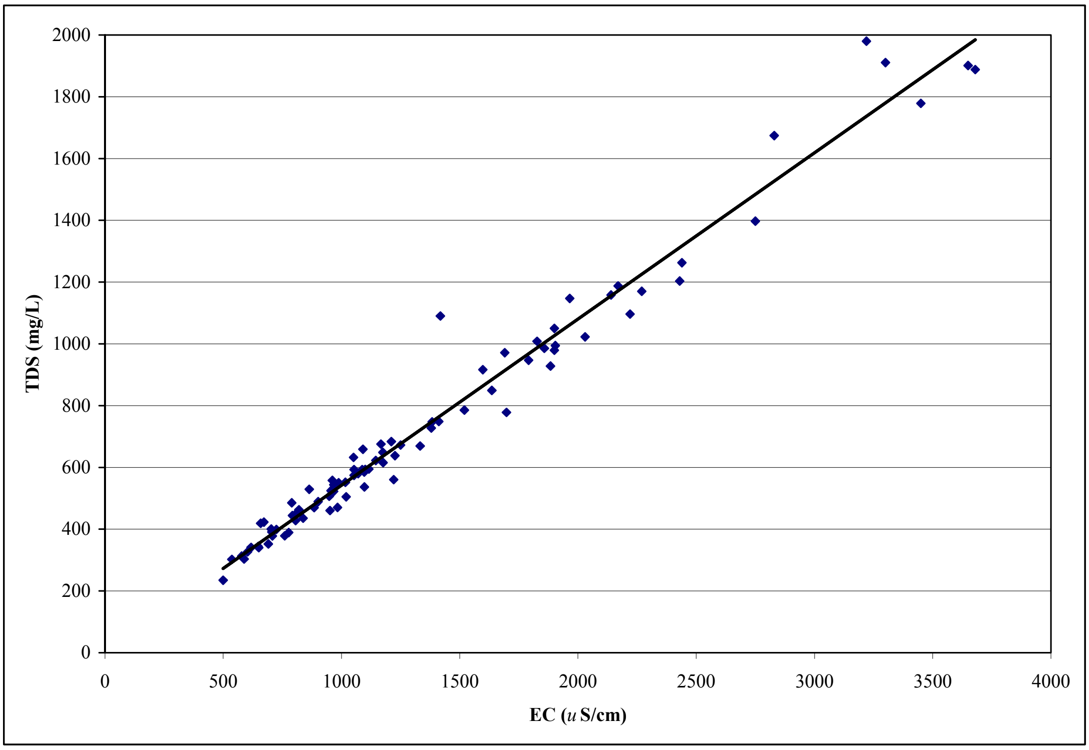

Fig. 5.2: TDS concentration compared with EC values of the all samples analyzed.

5.2.1 Classification of groundwater samples using Piper diagram

The relations between rock types and groundwater composition are commonly displayed in the so-called Piper diagram. The Piper diagram is an ingenious construction that consists of two triangular diagrams that describe the relative compositions of cations (sodium, potassium, magnesium and calcium) and anions (bicarbonate, sulphate, chloride and nitrate) and a diamond shaped diagram that combines the compositions of cations and anions (Piper 1944).

According to Langguth (1966), the groundwater samples of the study area can be classified for the upper, middle and lower aquifers (Figs. 5.3 and 5.4) as follows:

Type 1-upper aquifer:

Based on the Piper diagram, less than 4 % of the groundwater samples are belonging the normal earth alkaline water with prevailing bicarbonate (only B2/A7 aquifer). This type of water (Ca-Mg-HCO_3) shows a low salinity over the analyzed samples and it can be expected for recently recharged in a limestone aquifer. Thus, this type of water is highly effect by the infiltration of precipitation.

Type 2-upper aquifer:

Type 2 waters are earth alkaline water with increased portion of alkalies with prevailing bicarbonate. This type of water makes about 32% of the total groundwater samples. Also, this type is common distinguished by moderate salinity (1000-2000 μS/cm) and is

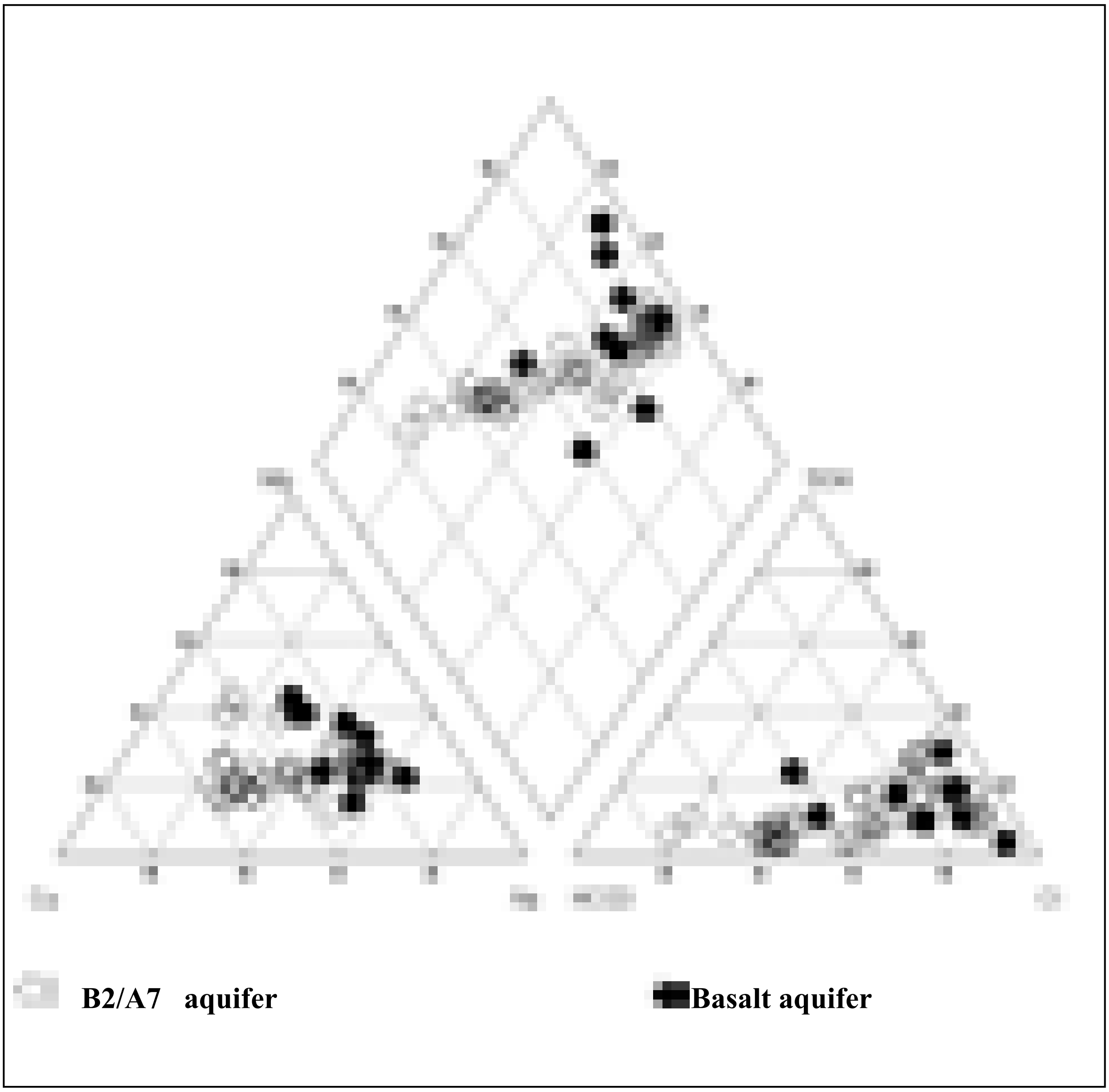

Fig. 5.3: Piper diagram for the major ions of the groundwater sampled of the upper aquifer.

classified as Ca-Na-HCO_3-Cl type. The reason of relatively high sodium in this water is due to ion exchange capacity of sodium with Ca^{2+} and Mg^{2+} in clay layers during the infiltration process.

Type 3-upper aquifer:

Type 3 waters are earth alkaline water with prevailing sulphate and chloride. About 64% of the groundwater samples fall within this type. This type of water is characterized by relatively high salinity values and is classified as Na-Cl type. The characteristics of water chemistry of this type are:

$$Na^{+}>Ca^{2+}>Mg^{2+} \text{ and } Cl^{-}>SO_4^{2-}>HCO_3^{-}$$

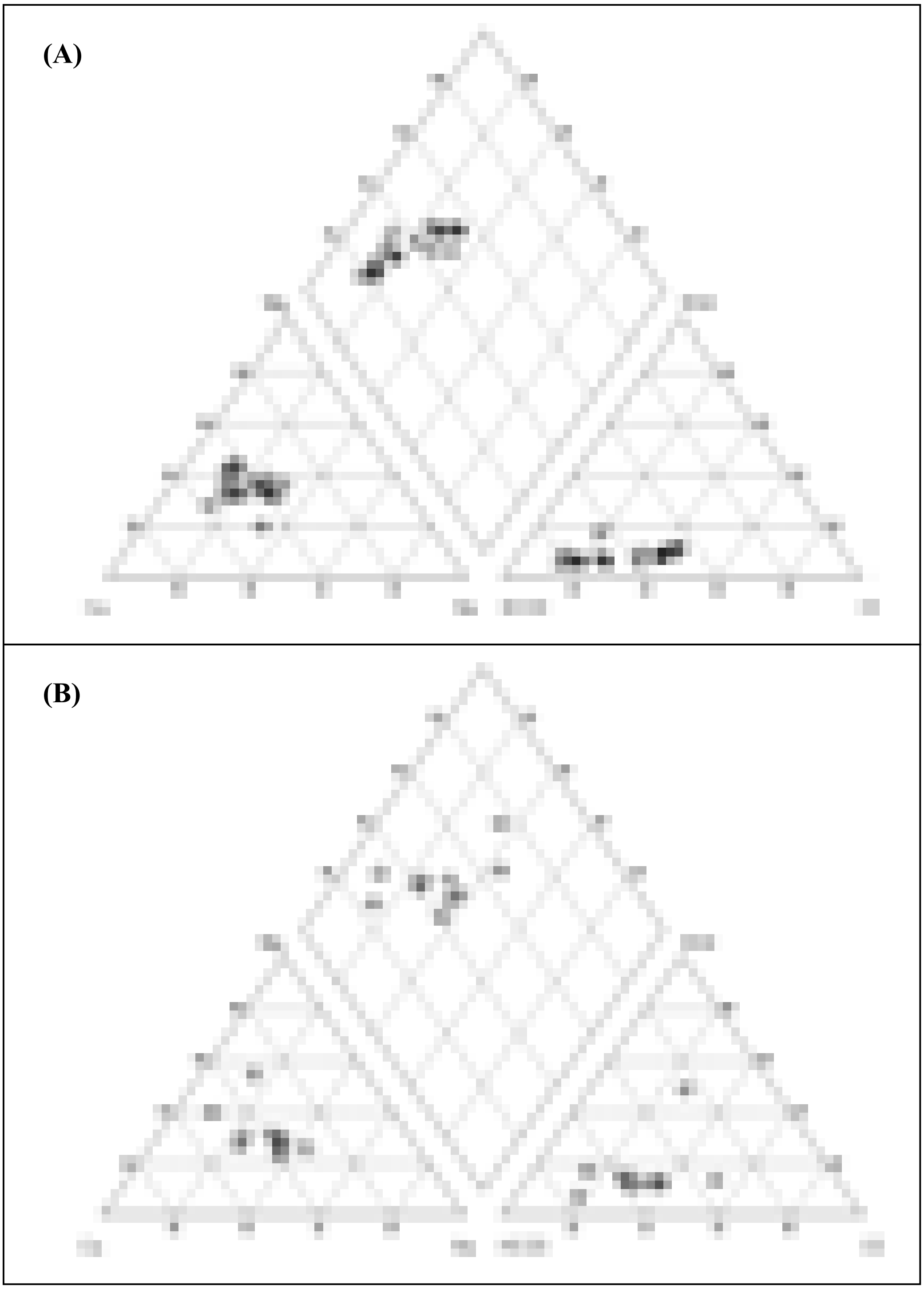

Fig. 5.4: Piper diagram for the major ions of the groundwater sampled of the middle (A) and Lower (B) aquifers.

Therefore, the most interesting result in this interpretation is that most of the Basalt samples are located in the same chemical zone as B2/A7 aquifer. This means that there is a strong hydraulic connection (mixing process) between the B2/A7 and Basalt aquifers in the northeastern parts of the study area. Thus, the B2/A7 and Basalt aquifers are forming one aquifer system.

Type 1-middle aquifer:

Type 1 in the middle aquifer is normal earth alkaline water with prevailing bicarbonate. This type represents about 50% from the total groundwater samples. This type of water ($Ca-Mg-HCO_3$) shows a low salinity in the range of 700 μS/cm and it can be expected for recently recharged. Thus, this type of water is highly effect by the infiltration of precipitation.

Type 2-middle aquifer:

Type 2 in the middle aquifer is earth alkaline water with prevailing bicarbonate. There is about 50% of the total groundwater samples fall within this type. Also, this type is common distinguished by relatively moderate salinity (1000 μS/cm) and is classified as $Ca-Mg-Na-HCO_3-Cl$ type.

Type 1-lower aquifer:

Less than 20 % of the groundwater samples belong to the normal earth alkaline water with prevailing bicarbonate. This type of water ($Ca-Mg-HCO_3$) shows a low salinity and it can be expected for recently recharged. Thus, this type of water is highly effect by the infiltration of precipitation.

Type 2-lower aquifer:

Type 2 in the lower aquifer is earth alkaline water with increased portion of alkalies with prevailing bicarbonate. This type of water represents the majority of groundwater samples (about 64%). Also, this type is common distinguished by low salinity (700 μS/cm) and is classified as $Ca-Mg-Na-HCO_3-Cl$ type.

Type 3-lower aquifer:

This type is an earth alkaline water with prevailing sulphate and chloride. Less than 20% of the groundwater samples fall within this type. This type of water is characterized by relatively moderate salinity values (about 1000 μS/cm) and is classified as $Na-Ca-Mg-Cl-HCO_3$ type.

5.2.2 Classification of groundwater samples using Durov diagram

This method has been adopted in order to evaluate the water types from the geochemical process that could have been affected the water type. Durov diagram (Lloyd and Heathcoat 1985) consists of two triangular diagrams that describe the relative compositions of the major cations and anions and a square shaped diagram that represents the geochemical process and the dominant constituents of the water samples.

Figs. 5.5 and 5.6 show the Durov diagrams for all groundwater samples in the upper and lower aquifers, respectively. Most of groundwater samples of B2/A7 and Basalt are located on the mixing line that confirmed that there is a mixing process between them. Also, some of the groundwater samples of the upper aquifer (only B2/A7) and lower aquifer are located on the mixing line. The mixing process in the deep aquifer is limited at the outcropped areas whereas most of the deep aquifer is not exploited yet.

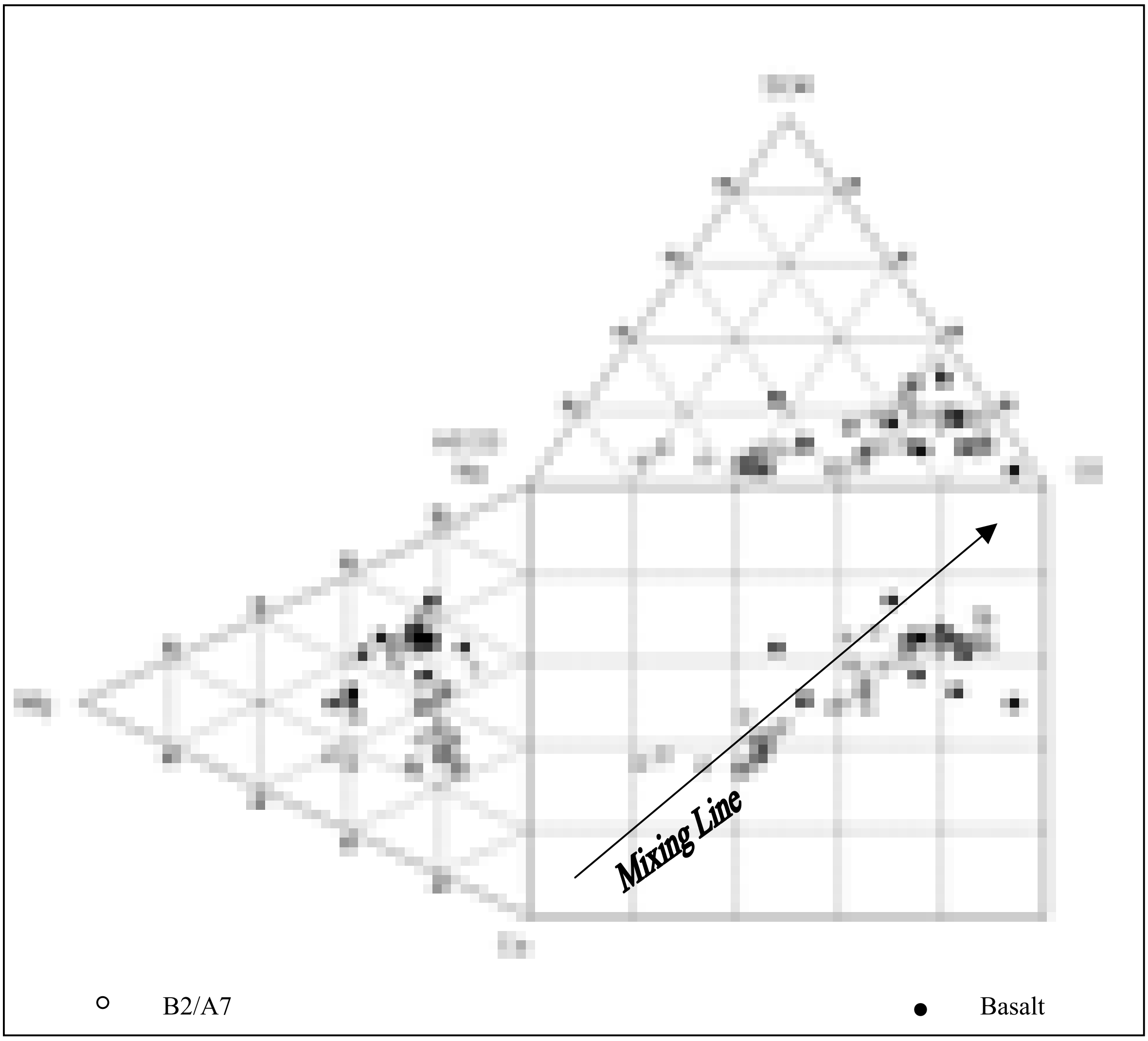

Fig. 5.5: Durov diagram of the groundwater sampled in the upper aquifer.

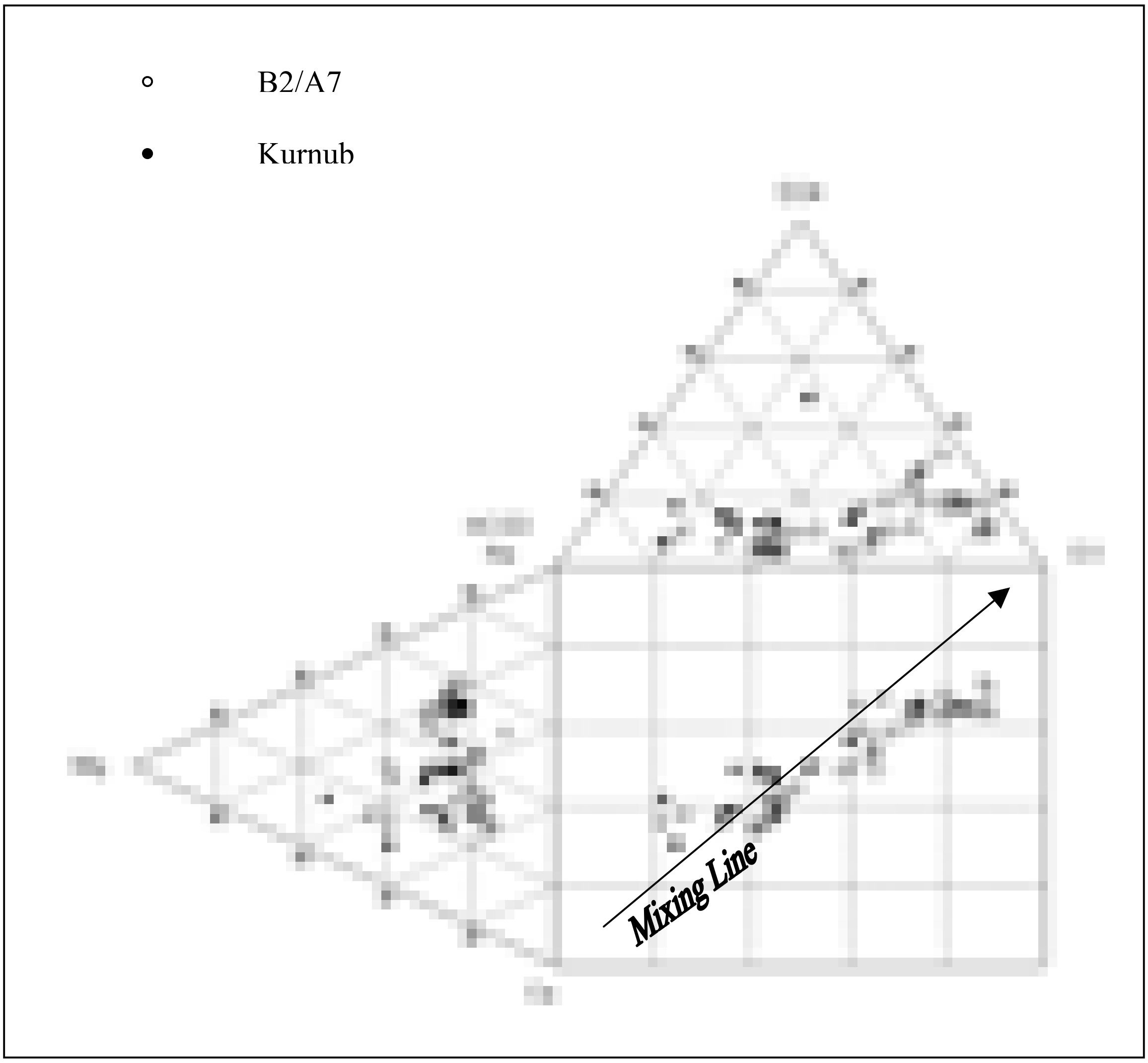

Fig. 5.6: Durov diagram of the groundwater sampled in the lower aquifer (K) and B2/A7 aquifer.

5.3 Evaluation of water quality

Since the potentiality of water use constraints by the chemical constituents, several parameters have been calculated to determine the possibility of groundwater use for a certain use.

The evaluation of groundwater resources in Amman-Zarqa Basin will focus only for domestic and irrigation purposes. Also, the evaluation will be limited to the groundwater sampled that were analyzed and collected in 2003 and 2004.

5.3.1 Domestic use permissible

Based on the calculated average values of groundwater samples (Table 5.1) and Appendix 5.1, the following results can be reached:

For the upper aquifer, all waters are potable (on the average scale) based on World Health Organization guidelines (WHO 1996) and Jordanian Drinking Water Quality Standards (JDWQS 2001) (Appendix 5.2). However, the TDS and Cl values exceeded the allowable value of JDWQS and WHO but are still below the maximum allowable values. Also, based on the maximum values of constituents few samples (local scale) are far from the WHO and JDWQS with respect to SO_4 (495 mg/L), NO_3 (107 mg/L), Na (422 mg/l), K (15 mg/L) and TDS (2000 mg/L). As mentioned before, the highest value of TDS (>1200 mg/L) was found closed to Dhuleil and Khaldiya well fields (central parts of Amman-Zarqa Basin) as a result of over abstraction and irrigation return flow. High concentration (>70 mg/L) of nitrate (NO_3) was found closed to Ain Ghazal area (south-east parts) in the following wells: AL1830, AL1832, AL1843 and AL2690. The main source of high nitrate contents is related to high population density (infiltration of sewage water from sewage treatment plants (STP) and household for the wells in this area).

Generally, the chemical composition of Basalt aquifer is usually low and better than the water quality of B2/A7 aquifer. The concentrations of analyzed trace elements for all groundwater samples were very low (sometimes below detection limits) comparing with JDWQS and WHO standards.

For the middle aquifer, according to JDWQS and WHO guidelines all waters in the middle aquifer are potable and its constituents are relatively low.

For the lower aquifer, all waters in the lower aquifer are potable by comparing the constituents with JDWQS and WHO guidelines except well No. AL2341 due to high nitrate concentration. The main source of high nitrate in this well is related to intensive cultivation with abundant use of fertilizers. The well may be affected as well from the wastewater treatment plant of Baq'a.

According to Sawyer and MacCarty (1967) (Table 5.3), all groundwater samples analyzed were classified as moderately to very high hardness as shown in Table 5.1. The total hardness was calculated as $CaCO_3$ based on the following equation (Todd 1980):

$$TH = 2.5\ Ca + 4.1\ Mg$$

Where:

TH: total hardness in mg/L, Ca and Mg concentration in mg/L.

Table 5.3: Classification of water based on hardness (Sawyer and McCarty 1967).

Hardness [mg/L]	Water class
0-75	Soft
75-150	Moderately hard
150-300	Hard
>300	Very hard

5.3.2 Irrigation use

According to the ionic exchange between water constituents and soil structure, the physical properties of the soil will be changed. The physical properties are highly impacting of plants and soils.

The sustainability of groundwater use for irrigation purposes is common related to the salinity and sodium concentration. From the irrigation water use point of view, Wilcox diagram was developed (at the U.S. salinity laboratory 1954) to classify the waters into groups based on the electrical conductivity (EC) and the sodium adsorption ratio (SAR).

Soils with a high concentration of Na^+ in solution are notorious for having a bad physical structure. The permeability is reduced and heavy agricultural machinery is not supported. The effects are related to a high degree of swelling of the clays, which in turn is caused by extending double layers around the clay particles. Diffuse double layers will increase in thickness (Appelo and Postma 1993).

The sodium content is usually calculated in terms of the soluble sodium percentage as below:

$$Na\ \% = (Na^{+} + K^{+}) / (Na^{+} + K^{+} + Mg^{2+} + Ca^{2+}) * 100$$

where all ionic concentrations are expressed in milliequivalents per liter (meq/L). Table 5.4 shows the classification of irrigation water based on soluble sodium percentage (SSP) according to Todd (1980). In addition, there is another important formula to determine the suitability of water for irrigation purposes called sodium adsorption ratio (SAR), which is calculated by:

$$SAR = Na^{+} / ((Mg^{2+} + Ca^{2+}) / 2)^{0.5}$$

Where, the concentration of ions is expressed in meq/L.

Table 5.4: Classification of irrigation water based on SSP (Todd 1980).

Water Class	**SSP**	**EC [µS/cm]**
Excellent	< 20	< 250
Good	20 – 40	250 – 750
Permissible	40 – 60	750 – 2000
Doubtful	60 – 80	2000 – 3000
Unsuitable	> 80	> 3000

Based on the Wilcox diagram (Fig. 5.7) for the groundwater sampled in the upper aquifer, the following results have been found:

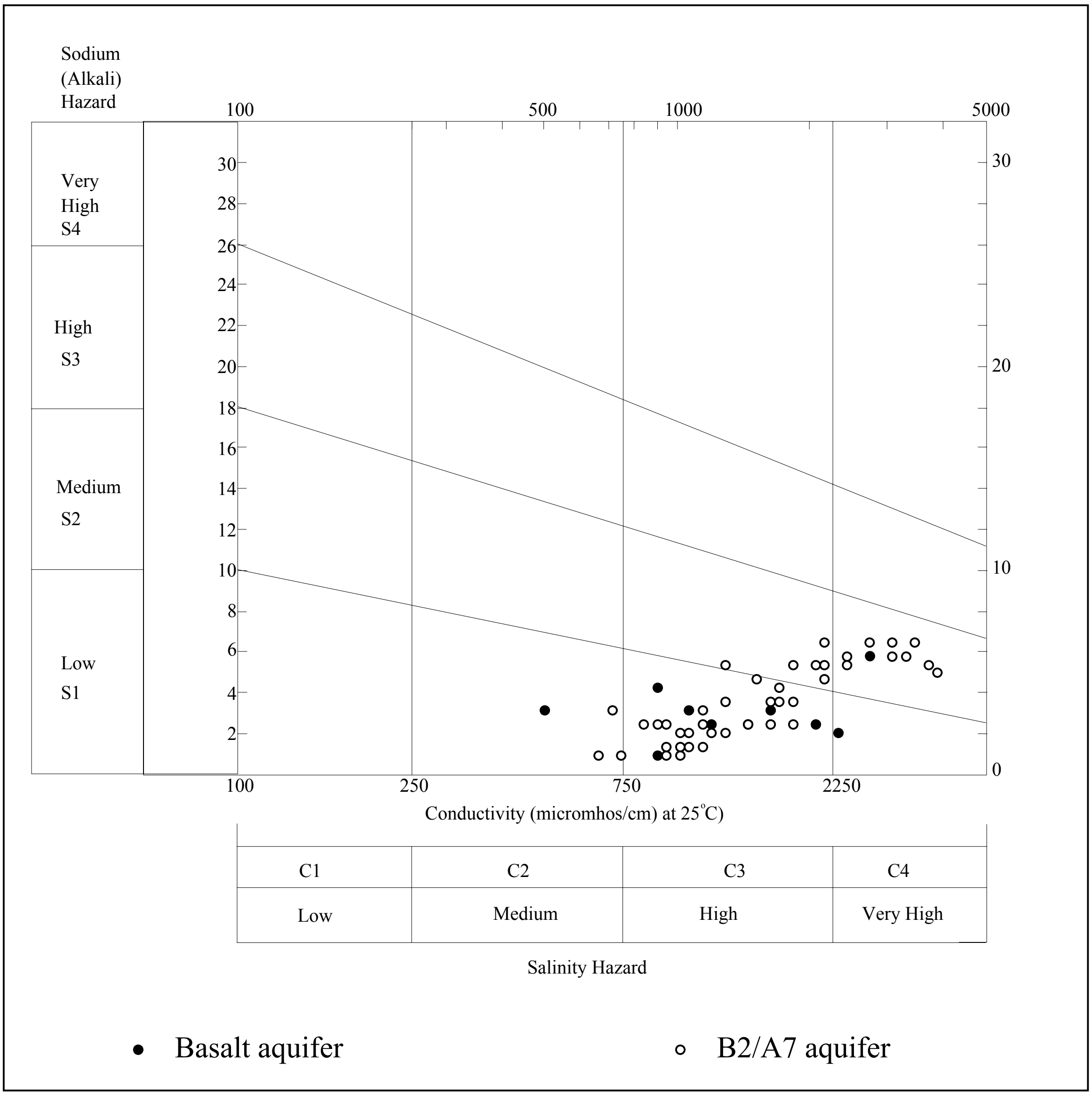

Fig. 5.7: Wilcox diagram for the classification of groundwater samples in the upper aquifer based on SAR and EC.

- All Basalt water samples have low sodium hazard and medium to high salinity (600- 2000 μS/cm).

- About 85% of the groundwater samples of the B2/A7 aquifer have low-medium sodium hazard and medium-high salinity (750-2200 μS/cm). This type of water needs special management for salinity control and the type of plant should be selected based on salt tolerance.

- Only 15% of the groundwater samples show medium-sodium hazard with very high salinity (>2250 μS/cm). This type of water is not recommended for irrigation. The location of this type of water is surrounding the Dhuleil and Khaldiya well fields.

The main reason of degradation the water quality in this region was due to the over-pumping and mismanagement of land use.

Regarding the middle and lower aquifers, all groundwater samples showed low sodium hazard and medium salinity. Thus, the middle and lower aquifers are classified as good irrigation water type in the study area.

Based on the SSP (Table 5.5), most of the groundwater samples in the upper aquifer showed permissible to doubtful water type (20-60 SSP). From the SSP values point of view, all groundwater in the upper aquifer is suitable for irrigation purposes except a few well fields. Also, the middle and the lower aquifers showed good water qualities for irrigation purposes.

Table 5.5: Classification of all groundwater sampled based on SSP.

Aquifer	**SSP (%)**	**EC [µS/cm]**	**Water class**
Upper	16-64	750-2200	Permissible-doubtful
Middle	15-35	700-1000	Good-permissible
Lower	11-44	800-1100	Good-permissible

5.4 Statistical analysis

Statistical analysis was performed in this study in order to assess if the classification is statistically significant. Also, in order to evaluate the relation between the different chemical parameters and to define the water quality grouping and genesis. The statistical analysis was done by using SPSS for windows 11 (2001).

The descriptive statistics of all groundwater samples are shown in Table 5.1 that includes the mean, minimum, maximum and standard deviation.

All chemical parameters have been checked for normal distribution. Kolmogorov-Smirnov One-Sample Test was used to test the hypothesis that a sample shows a certain distribution (uniform, normal, or Poisson). It was found that the following parameters showed normal distribution: Ca, Mg, Na, K, Cl, NO_3, EC, pH, SAR and TH. However, HCO_3 and SO_4 showed non-normal distribution.

The Pearson's correlation coefficient between the different parameters was calculated (Appendix 5.3). The Pearson’s correlation coefficient is a measure of linear association and has been adopted because most parameters were normal distributed. Table 5.6 illustrates the summarized correlation matrix of positive (+) and inverse (-) significant correlations between the variables.

5.4.1 Cluster analysis

Cluster analysis is a statistical technique which was used to manage multi-elements data sets. The correlation coefficients between the variables are used as similarity measures and the highest similarities are ranked first.

Table 5.6: Summarized of correlation coefficients between the chemical constituents of the upper aquifer.

Parameter	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	EC	SAR	TH
Ca											
Mg	+										
Na	+	+									
K	+	+	+								
HCO_3	+	-	-	-							
SO_4	+	+	+	+	-						
Cl	+	+	+	+	-	+					
NO_3	+	+	-	+	+	+	+				
EC	+	+	+	+	-	+	+	+			
SAR	+	+	+	+	-	+	+	-	+		
TH	+	+	+	+	-	+	+	+	+	+	

+: Positive significant correlation
-: Inverse significant correlation

A Hierarchical Cluster Analysis method was selected to identify relatively homogeneous groups of cases (or variables) based on aquifer type. The Ward's method with squared Euclidean distance (to specify the similarity measure to be used in clustering) was conducted. Based on the Dendrogram, which can be used to provide information about the appropriate number of clusters, three clusters have been distinguished for all groundwater sampled (Appendix 5.4) in the upper aquifer. The descriptive statistics of the chemical constituents of the three groups are shown in Fig. 5.8.

Based on the Dendrogram and bar diagrams, group-1 was identified to have low salinity (1050 µS/cm) and high concentration of NO_3 value (>60 mg/L). Most of wells in this group are located between Amman and Ruseifa regions. The main source of the high nitrate concentration was originated from the effect of Seil el Zarqa, which includes wastewater, and high population density surrounding the well field. 33% of the total water samples fall in this group. Regarding group-2, this group showed moderate salinity (1370 µS/cm) and low concentration of NO_3. This group represents the well fields between Ruseifa and Zarqa regions as well as the far northeast well fields in the study area. About 24% of the total water samples were distinguished in this group. However, group-3 showed high salinity (more than 2000 µS/cm) and moderate NO_3 concentrations (> 40 mg/L). The concentration of NO_3 is still beyond the maximum permissible value of JDWQS standards.

Most of the well fields close to Khaldiya and Dhuleil regions fall in this group representing about 43% of the total water samples.

Kruskal-Wallis and Mann-Whitney tests have been conducted in order to assess and compares two or more groups of cases. It was found that the mean of all groups was considerable differed from other groups for all chemical parameters except Ca^{2+}. However, this type of test shows only the difference in the means among the groups and did not show the significant difference level between them. Thus, with Mann-Whitney the significance between the groups was tested. The group-3 showed significant differences from groups 1 and 2. Differences between group-1 and group-2 were showed less significant differences and more similarities. .

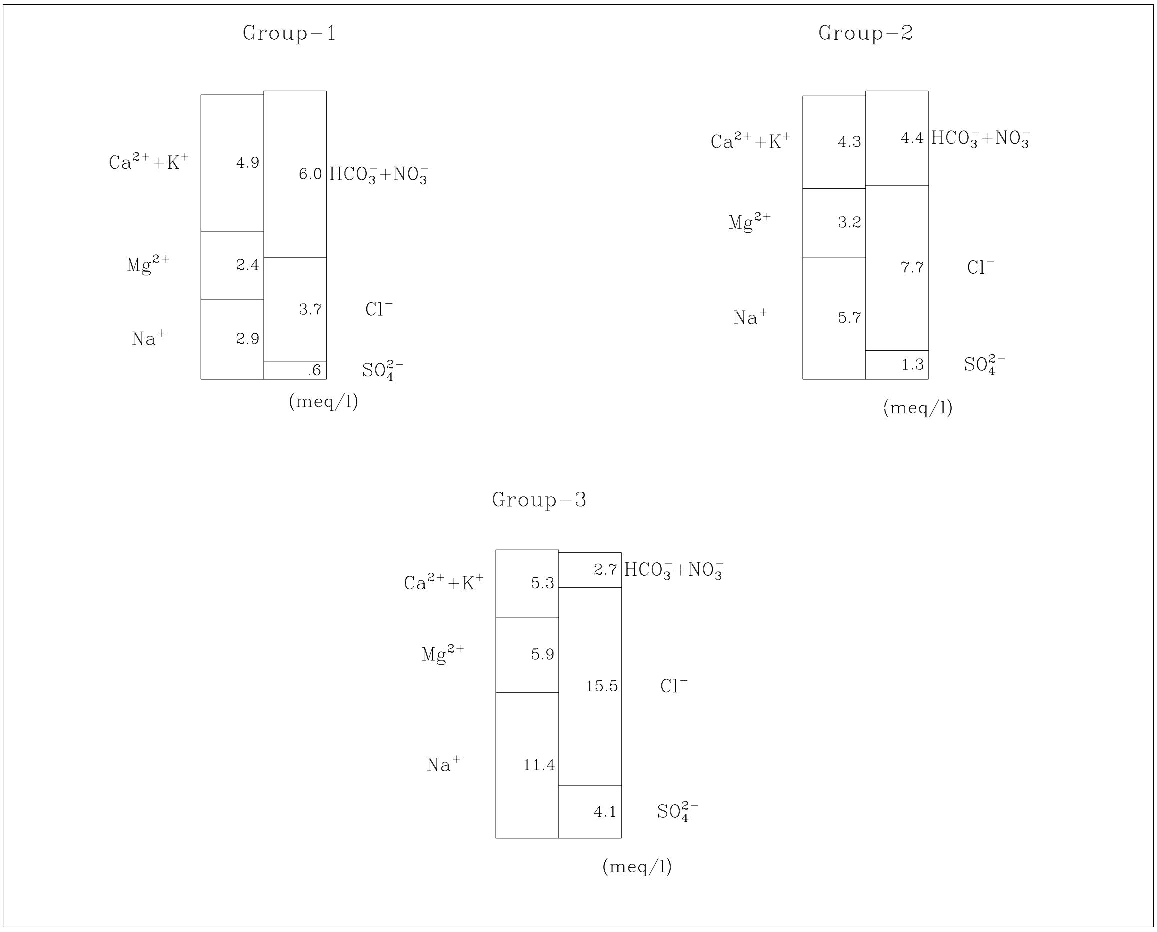

Fig 5.8: Bar diagram for the characteristics of all water groups.

5.4.2 Factor analysis

Factor analysis attempts to identify underlying variables, or factors, that explain the pattern of correlations within a set of observed variables (SPSS 2001). Factor analysis is successful in reducing considerable large quantities of data to identify a small number of factors that explain most of the variance observed in a much larger number of manifest variables.

The factor analysis was conducted in this study using SPSS 11 for windows. The data has been analyzed using Varimax rotation method (one factor will be declared only through one variable). Three factors were distinguished in the study area as shown in Table 5.7. The first factor can be considered as salinity factor due to the dominant positive relation of the salinity components. The second factor can be seen as pollution factor (nitrate and potassium were considered of anthropogenic source in the form of used fertilizers). The third factor can be considered as carbonate factor which was improved by the positive and direct relation between pH-value and SI-calcite.

Table 5.7: Factor analysis of the water sampled based on Varimax rotation.

Parameter	Factor-1	Factor-2	Factor-3	Communalities
Ca	0.48	0.84		0.93
Mg	0.90			0.82
Na	0.98			0.96
K	0.74	0.2		0.62
HCO_3				0.79
SO_4	0.83			0.72
Cl	0.97			0.95
NO_3		0.86		0.74
EC	0.97			0.98
pH			0.96	0.96
SAR	0.92			0.92
TH	0.85			0.92
$SI_{Calcite}$			0.93	0.98
SI_{Halite}	0.95			0.92
SI_{Gypsum}	0.87			0.82

5.5 Variations of salinity and nitrate

During the middle of sixties of Wadi Dhuleil area (central part of the study area) the groundwater quality in terms of salinity and nitrate was very good and less than the JDWQS and WHO guidelines. By reviewing the historical groundwater quality, the increase in nitrate was often accompanied by an increase in groundwater salinity in most cases. The salinity of the groundwater (expressed as electrical conductivity) was reported to range about 750 µS/cm and the nitrate was about 42 mg/L. However, due to over-abstraction, irrigation returns flow (which represents the excess flows from the cultivated areas) and evaporation the groundwater salinity has been increased reaching about 5900 µS/cm as a maximum value based on the data in 2004. Also, due to the infiltration of irrigation return flow, leakage of wastewater from the treatment plants, industrial waste and poorly designed cesspits the nitrate concentration was raised to reach more than 300 mg/L at the downstream of As-Samra wastewater treatment plants (WWTP) based on the historical data in 2004.

According to the groundwater samples analyzed in 2003 and 2004 and few additional data that was analyzed by the Ministry of Water and Irrigation (MWI), the salinity map of upper aquifer has been drawn (Fig. 5.9). As mentioned above, the highest salinity occurred around Dhuleil and khadiya well fields with 3500 µS/cm on average values. Generally, the groundwater salinity of the upper aquifer increases gradually from the recharge areas and along the direction of the groundwater flow. Also, the nitrate map (Fig. 5.10) was drawn based on the analyzed data and few additional data that was analyzed by MWI. As mentioned before, high nitrate concentration was found closed to As-Samra WWTP as well as the well field along the Seil el Zarqa and Ain Ghazal area as a result of leakage of wastewater. Generally, all hydrochemical constituents of Seil El-Zarqa were increased along the direction of flow. Also, the well field close to Dhuleil area showed high concentration of nitrate as a result of irrigation return flow.

The salinity and nitrate values in the middle and lower aquifers are still low and within JDWQS and WHO guidelines for potable use.

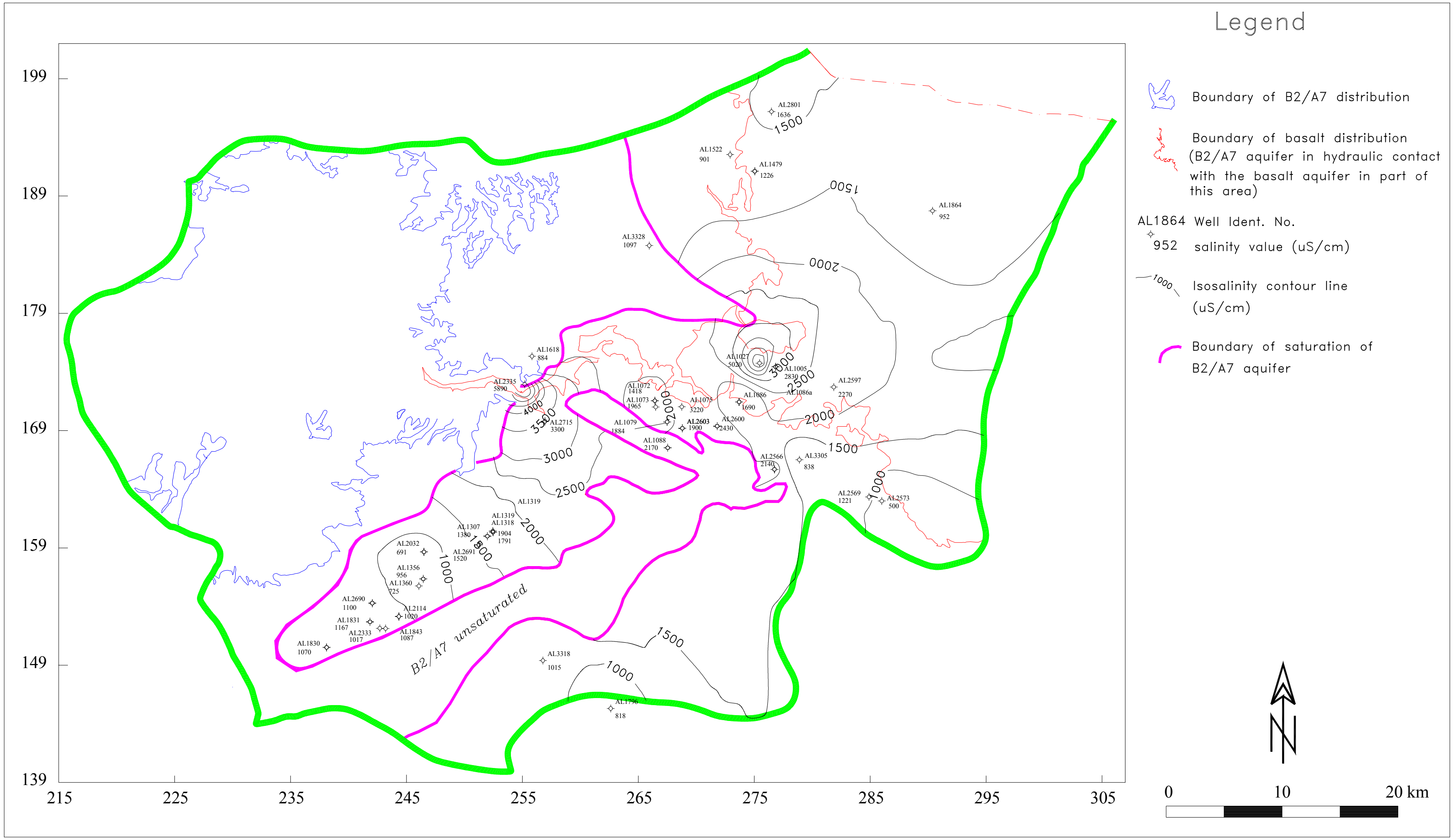

Fig. 5.9: Groundwater salinity of the upper aquifer (Basalt and B2/A7).

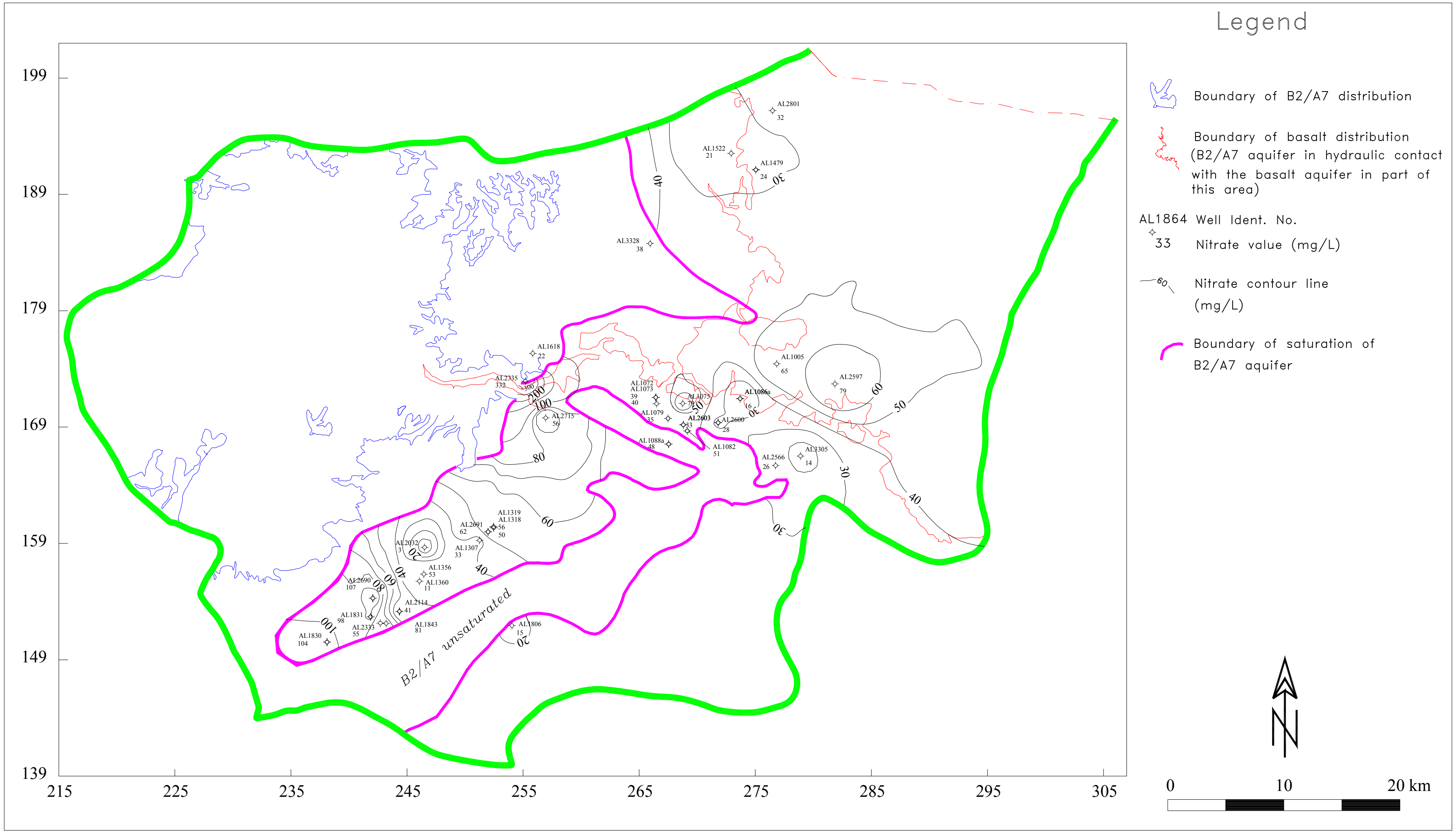

Fig. 5.10: Nitrate concentration of the upper aquifer (Basalt and B2/A7).

6 ENVIRONMENTAL ASPECTS

6.1 Background

Since more than 60% of the total population is living in the Amman-Zarqa Basin where considerable high rainfall rates occur, dams to collect surface water and wastewater treatment plants (WWTP) have been built in this basin.

Four WWTP (As-Samra, Baq'a, Jarash and Abu Nuseir) are distributed in Amman-Zarqa Basin as shown in Fig. 6.1. As-Samra WWTP is the largest one and serves about one third of the inhabitants of Jordan.

Six dams exist in Amman-Zarqa Basin (King Talal, Khaldiyeh, Wadi Rajil, Al Lahfi, Abu Sowwaneh and Wadi Al Esh). All of them are earthfill dams since materials were available on site at the time of construction. King Talal Reservoir (KTR) is the largest one in Jordan which is located in the western part of Amman-Zarqa Basin. The others are located in the northeastern part of the basin (Fig. 6.1).

6.2 Wastewater treatment plants

The first sanitary sewers were constructed in Jordan in 1964 to serve about half million residents. In 1968 the first WWTP was constructed in the northeast of Amman at Ain Ghazal as activated sludge facility. As a result of increased population and new developments in Amman-Zarqa Basin, Ain Ghazal WWTP became overloaded and could not treat the sewage in a proper way. In 1982 the Master Plan for wastewater disposal recommended the expansion for the existing activated sludge plant at Ain Ghazal and the construction of new plant (As-Samra WWTP). In order to eliminate the pumping costs, As-Samra WWTP was located at an elevation of 101 m below the Ain Ghazal WWTP.

6.2.1 As-Samra

Amman about 35 km in the northeast of the As-Samra WWTP is located (Fig. 6.1) to serve more than one third of total population of Jordan (most of the greater Amman municipality and most of Zarqa governorate). However, some of houses are not served by As-Samra WWTP and they still use septic tanks or cesspits and the sewage tankers discharge their liquid at Ain Ghazal WWTP (with pretreatment and odour control). In 1985 As-Samra WWTP (stabilization ponds) has been operated on an area of about 300 ha (ha=10,000 m^2) with a treatment capacity about 68,000 m^3/day. It composed of three types of ponds: two anaerobic and four facultative ponds, which empty into four maturation ponds.

Nowadays, As-Samra WWTP is hydraulically and organically overloaded with an average daily influent 170,000 m^3/day. Consequently, the effluent quality has been degraded and exceeds the Jordanian Standards. Loadings of biological oxygen demand (BOD_5) were 92,889 kg/day, 107,555 kg/day and 111,993 kg/day in the years of 2000, 2001 and 2002,

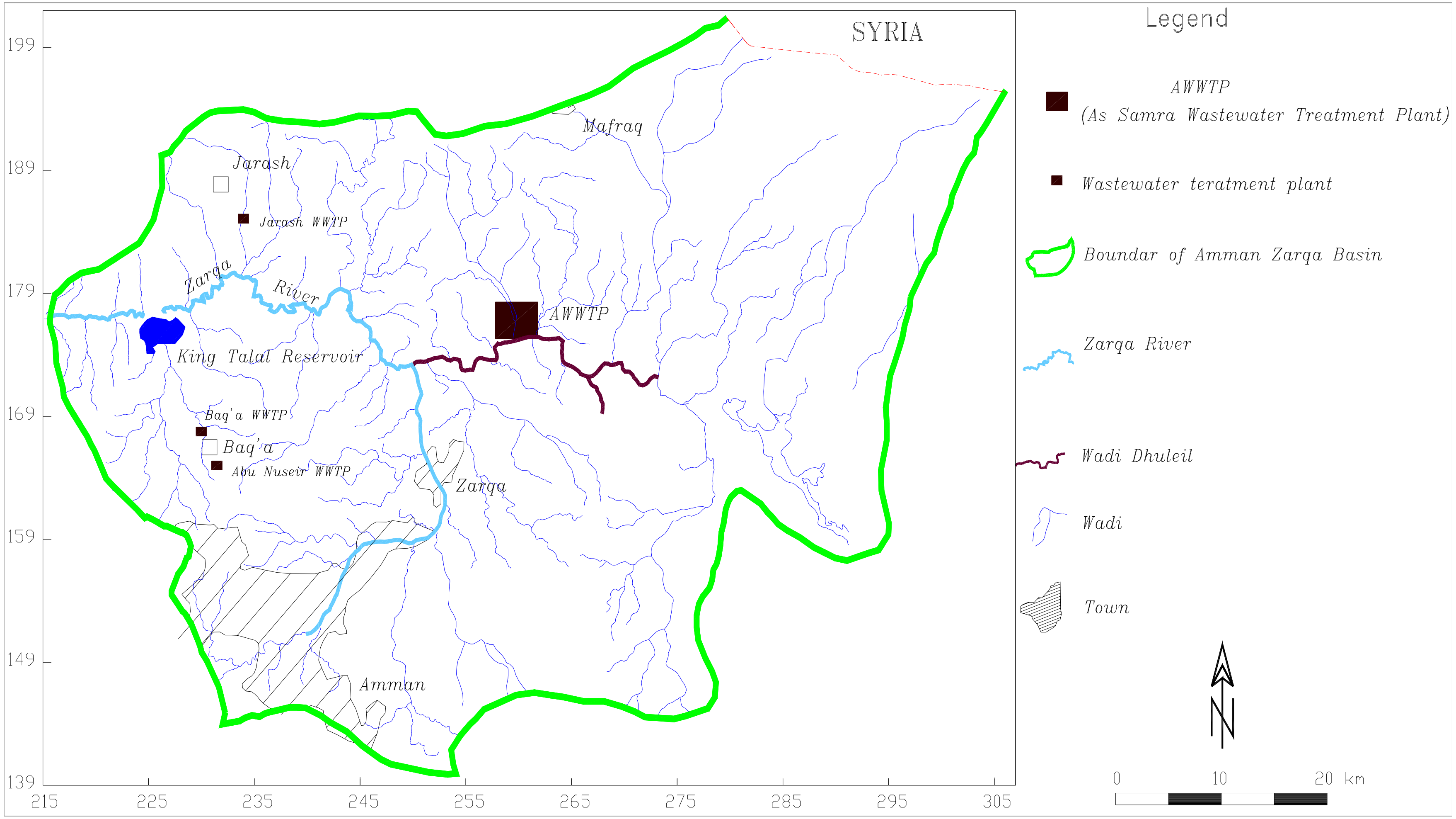

Fig. 6.1: Location map of wastewater treatment plants and King Talal Reservoir in Amman-Zarqa Basin.

respectively while the design capacity load of BOD_5 is 35,768 kg/day and the influent concentration of BOD_5 also exceeded the design level (526 mg/L) to more than 544 mg/L, 578 mg/L and 626 mg/L in the years of 2000, 2001 and 2002, respectively (RSS 2002-2003). Effluent BOD_5 levels have been measured in 2000, 2001 and 2002 with an average concentration of 107 mg/L, 105 mg/L and 117 mg/L, respectively. Comparison these concentration with Jordanian Standards for reclaimed domestic wastewater (Table 6.1), the BOD5 exceeds the allowable limits twofold (60 mg/L). In addition, total suspended solids (TSS) were 83,327 kg/day, 98,437 and 108,415 kg/day in the years of 2000, 2001 and 2002, respectively while the design capacity load of TSS is 42,024 kg/day, however, the influent concentration is still within the design criteria (618 mg/L). Effluent of TSS levels has been measured in 2000, 2001 and 2002 with an average concentration of about 111 mg/L, 118 mg/L and 100 mg/L, respectively (RSS 2002-2003). Comparison of these concentrations with Jordanian Standards for reclaimed domestic wastewater (Table 6.1), the TSS exceeds the allowable limits twofold (60 mg/L). However, the effluent of As-Samra WWTP is used for tree irrigation of 250 ha (acacia eucalyptus) around the treatment plant and some pilot projects (2 ha) for irrigation of beans and wheat with sprinkler irrigation.

USAID/ARD 2001 conducted a study entitled "characterization of wastewater effluent in the Amman-Zarqa Basin" and the projections of effluent generated from all WWTP in Amman-Zarqa Basin until 2025 have been expected based on per capita water supply rising by 29 percent in the next five to ten years and meeting the needs of an expanding population as shown in Fig. 6.2. It is found that the levels of trace elements and metals are much lower than the concentrations specified by the Jordanian Standards (Table 6.1). However, the other parameters: BOD_5, COD, TSS, FOG (fats, oils & greases), NH_4^+-N, Total Nitrogen, PO_4^--P, Cl^-, $HCO_3^-$and fecal coliforms are not in compliance with Jordanian Standards. For PO_4-P, the planned improvements at As Samra WWTP are expected to reduce the concentration in order to match the Jordanian Standards or even less. For BOD_5 and TSS, will be more improvements and stringent to much lower than those specified by the standards to reach about 30 mg/L during the new development and improvements facility at As-Samra WWTP. The comparison between the Jordanian Standards, historical average and maximum, and projected (anticipated) values of water quality parameters in As-Samra effluent is shown in Table (6.1). Thus, the average total dissolved solids (TDS) in the effluent of As-Samra WWTP is in the range of 1200 mg/L which complies with Jordanian Standards (JICA and MWI 2001).

Since the water table at As-Samra WWTP is closed to the surface (about 50 m) and the aquifer is unconfined (B2/A7 aquifer), three wells have been drilled (As-Samra observation wells No. 1, 3 and 4) around the As-Samra WWTP to control the groundwater quantity and quality. Well No. 1 and 3 (2.5 km and 250 m, respectively) are located downstream of As-Samra WWTP but well No. 4 (7 km) is located upstream.

Table 6.1: Jordanian Standards (893/2002) for treated domestic wastewater to be discharged to wadis and water bodies.

Parameter	**Max. limit allowed [mg/L]**	**As-Samra effluent (modified after USAID and MWI 2001)**		
		Average [mg/L]	Maximum [mg/L]	Projected [mg/L]
BOD5*	60	80.6	289	30
COD**	150	425.6	734	200
DO	>1	4.65	0.87***	4.7
TSS	60	123.9	215	30
pH	6-9	7.9	8.3	8
NO_3^-	45	6.64	51	7
Total-N	70	108.5	278	50
Fecal Coliforms [MPN/100 ml]	1000	1.32E+6	7.00E+7	1000
Intestinal Helminthes Eggs	< or 1	0	0	0
FOG	8	9.04	18	8
Phenol	<0.002	0.09	-	0.002
MBAS	25	20.1	35	20
TDS	1500	1218.5	1438	1220
Total-$PO4^-$	15	15.9	24.1	15
Cl^-	350	355.3	434	350
SO_4^{2-}	300	25.57	54	26
HCO_3^-	400	833.7	960	520
Na^+	200	263.3	308	230
Mg^{2+}	60	-	-	60
Ca^{2+}	200	95	117	95
SAR	6	6.05	18	6
Al	2	0.3	0.9	0.3
As	0.05	0.004	0.005	0.004
Be	0.1	0.01	0.01	0.01
Cu	0.2	0.083	0.27	0.08
F	1.5	-	-	-
Fe	5	0.19	0.38	0.19
Li	2.5	0.024	0.025	0.024
Mn	0.2	0.09	0.12	0.09
Mo	0.01	<0.01	<0.02	0.01
Ni	0.2	0.02	0.03	0.02
Pb	0.2	0.01	0.02	0.01
Se	0.05	0.009	0.014	0.009
Cd	0.01	0.004	0.005	0.004
Zn	5	0.06	0.08	0.06
Cr	0.02	0.033	0.043	0.033
Hg	0.002	<0.0009	0.001	0.0009
V	0.1	<0.1	<0.1	0.1
Co	0.05	0.04	0.05	0.04
B	1	-	-	-
CN	0.1	0.03	0.04	0.03

- Not recorded/determined/specified *** minimum value MPN most probable number

* Filtered - waste stabilization ponds, not filtered - mechanical treatment plant

** Allowable for double value in natural treatment plant or sealed pool

Values of trace elements and heavy metals are calculated based on an average water quality of 1000 m^3/1000 m^2/year.

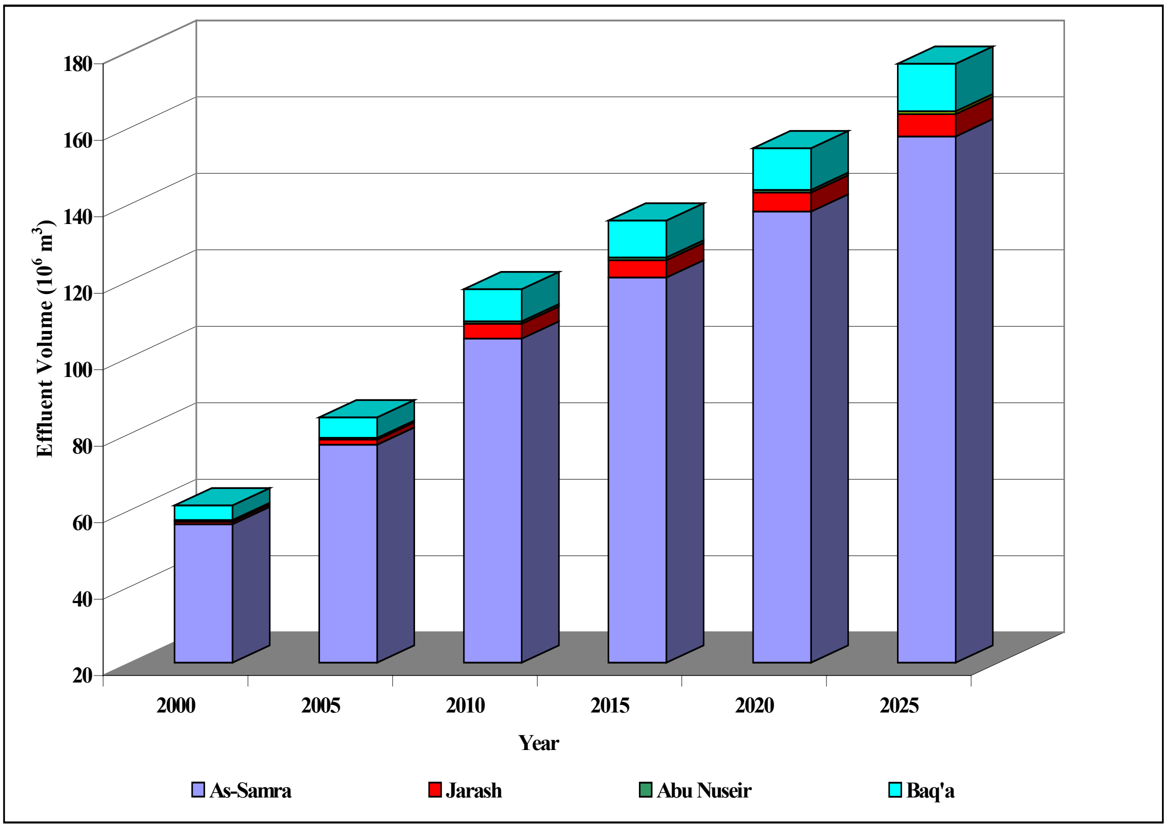

Fig. 6.2: Present and projection of total effluent (10^6 m^3) to be discharged to Amman-Zarqa Basin (modified after USAID and MWI 2001).

It was concluded that the water levels of downstream wells have been raising considerably as shown in Figs. 6.3 and 6.4 with highly deteriorating effects on the water quality as shown in Table 6.2. However, the water level at well No. 4 has a considerable decreased trend of water level with time as shown in Fig. 6.5. Also, a comparison of the groundwater composition in the upstream and downstream before and after the operation of As-Samra WWTP is shown in Table 6.3. There are drastic increases in the chemical composition of groundwater bodies at the downstream sites as a result of As-Samra effluents whereas moderate increases in the chemical composition at the upstream sites of As-Samra WWTP as a result of irrigation return flow. It was concluded that all downstream wells of As-Samra WWTP are deteriorated and became not potable water resources as well as for irrigation purposes (restricted irrigation) in some wells.

The chemical compositions of soil water in different depths have been measured by means of suction cups (Table 6.4). The electrical conductivity of the soil water increased from 5800 µS/cm at 30 cm depth to more than 35,000 µS/cm at 140 cm depth (Al-Kharabsheh 1999). Also, cations and anions have been increased more than 10 times of original values which mean that the soil contains minerals and solids, $CaCl_2$ and $MgCl_2$. Therefore, the soil water s highly affected by treated water of As-Samra WWTP.

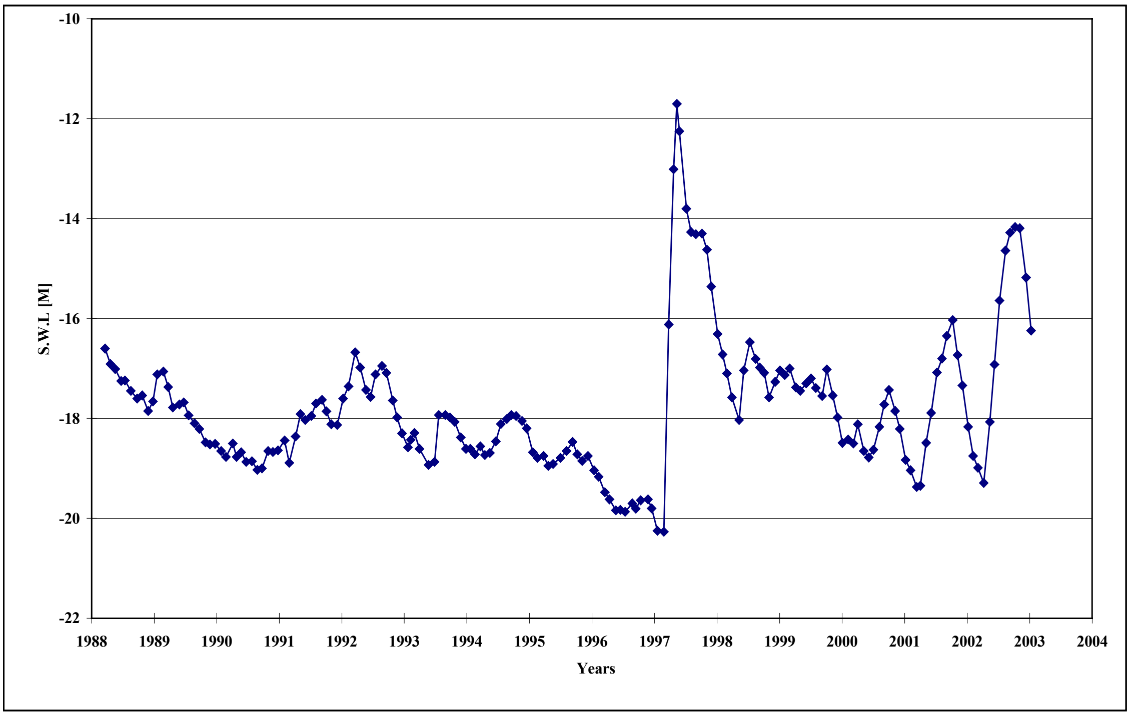

Fig. 6.3: Fluctuation of water level at As-Samra WWTP monitoring well No. 1 (AL2700).

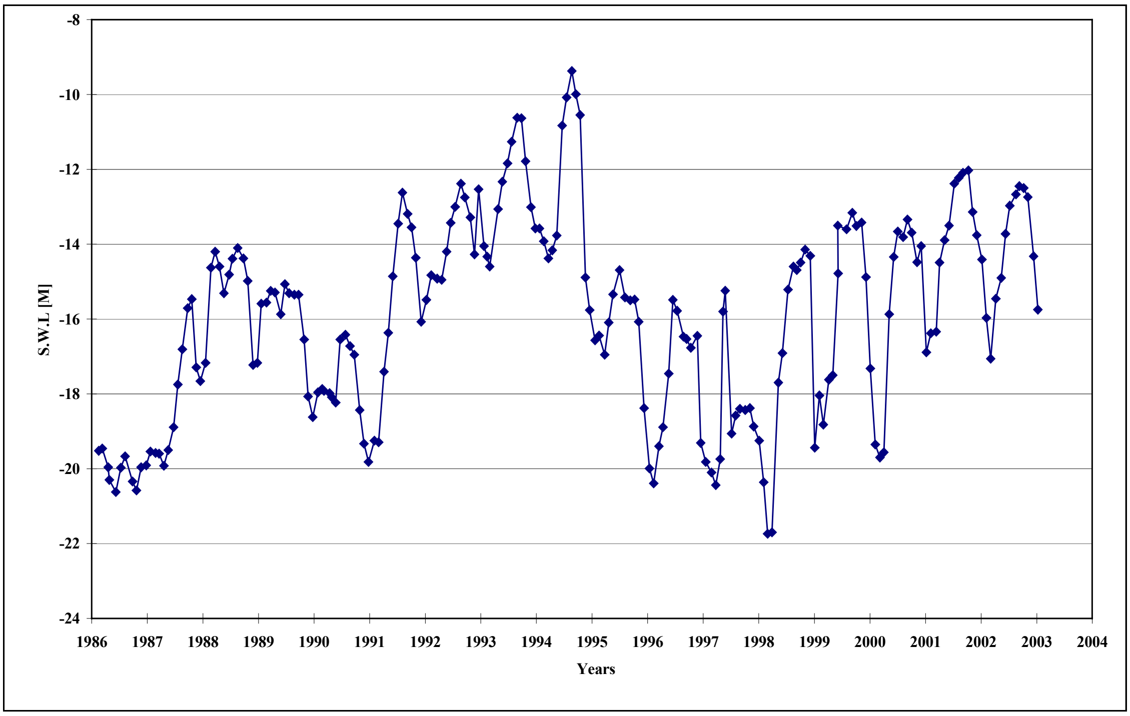

Fig. 6.4: Fluctuation of water level at As-Samra WWTP monitoring well No. 3 (AL2702).

Table 6.2: The effect of As-Samra WWTP on groundwater quality at As-Samra observation Wells No. 1 & 3 (Al 2700 & Al 2702, respectively).

Well Idn.	**Parameters (mg/L)**										
	pH	Ca	Cl	CO_3	SO_4	Mg	K	HCO_3	Na	TDS	NO_3
As-Samra No. 1	7.3	449	1524	0	1264	239	31	219	819	4307	37
As-Samra No. 3	8.8	197	1308	23	217	110	28	96	553	2835	6

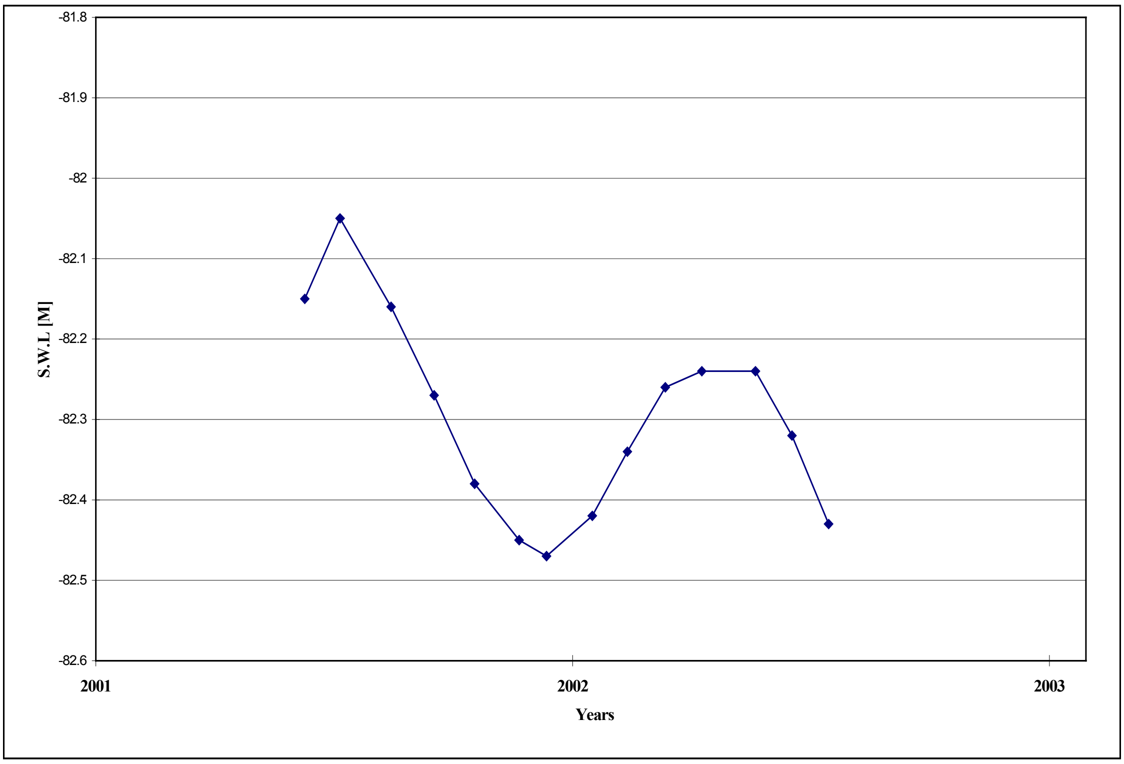

Fig. 6.5: Fluctuation of water level at As-Samra WWTP monitoring well No. 4 (AL3387).

Table 6.3: Comparison of the groundwater composition between the upstream and the downstream before and after 18 years of As-Samra WWTP operation.

Jordanian Standards (JS 86/2001)	**Parameters [mg/L]**	**Moasher Elias well (AL1060)**			**DP17 Well (AL1023)**			**Jordan Pipes well (AL2335)**			**Jordan Paper well (AL1323)**		
		1984	**1995**	**2003**	**1984**	**1995**	**2001**	**1984**	**1995**	**2003**	**1984**	**1995**	**2003**
	EC (µS/cm)	1008	1289	1163	3000	4200	4370	1110	5890	6337	1260	3938	3537
6.5-8.5	pH	7.7	8	7.8	8	7.8	7.7	7.8	7.3	7.34	7.3	7.63	7.15
200	Ca	42	55.5	45	172.9	235.3	226.5	61.9	433.1	390	91	306	252
150	Mg	30	31.1	30	136.1	200.6	222.9	37.9	248.1	185	31	182	135
200-400	Na	131	146.7	112	218	310.5	342.7	97.1	559	741	117.1	358	245
12	K	7.4	9	10	15.6	22.7	22.3	3.5	22.3	20	7.6	20	20
200-500	SO_4	85	109.9	78	225.6	353.3	448.3	53.8	877.9	1067	51.8	507	523
200-500	Cl	234	269.4	239	809	1136.7	1158	236.1	1505.9	1215	234.3	1046	716
500	HCO_3	99	107.4	77	61.6	70.15	74.4	136.6	184.2	343	252.5	223	203
50-70	NO_3	25	24.4	3.6	85	99.8	107	26	244.5	78.4	35	120	21.3
500-1500	TDS		700	604					4100	4238		1800	2286
	SAR		4	3.2					5	7.9		2.9	3
<1.1	TCC (MPN/100 ml)			48						10			15
<1.1	TTCC (MPN/100 ml)			3						2			3

Table 6.4: Chemical analysis of soil water at different depths at As-Samra WWTP (Al-Kharabsheh 1999).

Parameters [mg/L]	Depths [cm]			
	30	70	100	140
EC (µS/cm)	5810	6880	10280	35200
Dry residue 104 °C (g/l)	2.6	3.4	5.3	20.9
pH	8.2	8.9	8.3	8.4
Ca	186	68.1	235.5	3529
Mg	67.4	37.5	247.2	852.7
Na	601.2	1152.3	1169	2703.6
K	115.4	72.4	75.1	143.5
Cl	1108.5	843.2	1284.7	10291.7
HCO_3	361.9	832.3	2036.9	238
CO_3	11.7	189.4	17.4	6.9
SO_4	220.7	530.7	2021.6	2689.7
NO_3	86.8	111.6	130.2	142.6
NH_4	529.7	244.8	154.4	112.6
PO_4	33.6	21.1	9.21	6.3
COD	278.1	108.3	67.2	42.6

In addition, the total losses between the annual inflow and outflow reached about 15.4% based on the current situation (stabilization ponds) but in the case of mechanical plant the total loss will be expected to be about 5.6%. The method of wastewater treatment facility at As-Samra (stabilization method) is not recognized as suitable for dry, arid or semi-arid regions due to its high organic, hydraulic loading a sludge accumulation at the bottom of ponds (Salameh 1996). Fig. 6.6 shows general view of stabilization ponds at As-Samra WWTP.

Therefore, the current influent of As-Samra WWTP exceeds the design capacity flow by two times which leads to less efficiency operation and high organic load and other pollutants (ammonia, detergent, etc.) reaching the KTR and deteriorates its water quality. Thus, the second Master Plan recommends to expand As-Samra WWTP by new construction of WWTP at As-Samra site with a capacity of 267,000 m^3/day as the first stage until 2010 and another WWTP below Zarqa to take the loads from Zarqa, Ruseifa and some parts of Amman until the expansion of As-Samra WWTP in 2015. The development of the improvement facility at As Samra WWTP will have better effluent quality and will either match or lead to concentration less than the Jordanian Standards.

6.2.2 Jarash

Jarash WWTP is located at about 45 km to the north of Amman (Fig. 6.1). It was constructed in 1983 and expanded in 1990 to serve about 27,600 inhabitants with 54% coverage of the total population living in the sewered zone. The method of wastewater treatment at Jarash WWTP is a combination between extended aeration and aerated ponds.

The total inflow into the plant is about 1,600 m^3/day (design capacity 3,500 m^3/day) with a yearly average of about 0.6 $*10^6$ m^3/yr.

The concentrations of NO_3, N, NH_4-N, PO_4-P, B and TFCC, Cl, SO_4 and HCO_3 are not recorded regularly and non of those parameters are in compliance with the Jordanian Standards. Metals were monitored once in September in 1999 for Cu, Fe, Mn, Cd and Zn. All metals investigated were within the range of Jordanian Standards except Cu. Also, BOD_5, COD, DO, TDS, TSS and pH were all in compliance with the Jordanian Standards (USAID and MWI 2001). Thus, most of the effluent flow is being used for irrigated agriculture.

Fig. 6.6: General view of stabilization ponds at As-Samra WWTP.

6.2.3 Abu Nuseir

Abu Nuseir WWTP belongs to the capital municipality of Amman (15 km north of central of Amman). It was constructed in 1988 to serve about 13,800 inhabitants with 64% coverage of the total population living in the sewered zone. The method of wastewater treatment at Abu Nuseir WWTP is a combination between activated sludge process and rotating biological contactor. The total inflow into the plant is about 1,400 m^3/day (design capacity 4,000 m^3/day) with a yearly average of about 0.52 $*10^6$ m^3/yr.

BOD_5, COD, DO, TDS, TSS and pH are regularly monitored by the Water Authority of Jordan (WAJ). It was noticed that all of the above parameters were in compliance with the Jordanian Standards.

Since the influent rate will expect to be relatively low, the quality parameters will not deteriorate. Thus, the effluent quality is suitable for all irrigation agriculture types while the quality of effluents are in compliance with the Jordanian Standards. However, the groundwater quality is endangered and might become unsuitable for domestic purposes in the future.

6.2.4 Baq'a

Baq'a WWTP is located about 15 km to the north of Amman (Fig. 6.1). It was constructed in 1988 and expanded in 1990 to serve about 164,000 inhabitants (refugee camp) with 94% coverage of the total population living in the sewered zone. The method of wastewater treatment at Baq'a WWTP is a combination between trickling filter and maturation pond. The total inflow into the plant is about 10,284 m^3/day (design capacity 15,000 m^3/day) with a yearly average of about 3.75 $*10^6$ m^3/yr.

BOD_5, COD, TDS and TSS are regularly recorded by WAJ. Despite the Baq'a facility being relatively effective at lowering the values of the monitored parameters in the influent, only the TDS in the effluent is within the range of the Jordanian Standards (USAID and MWI 2001). The Baq'a WWTP is hydraulically and organically overloaded. The new development and improvements at Baq'a WWTP will have a conservative assumption in the near future to match the Jordanian Standards or less.

Therefore, the method of wastewater treatment is quite efficient except the odour which is possibly attributed to the sludge thickness or the concentration of the influent sewage. Other problems in this plant are chlorine dosage at the end of the treatment process which produces large amounts of trihalomethanes which affect later on the water quality and assists in the hypertrophication processes in KTR (Salameh 1996). Thus, the effluent flow can be used only for restricted irrigation cropping.

6.3 Dams

There are six dams distributed over Amman-Zarqa Basin. The capacity of these dams ranges from 0.065 $*10^6$ m^3 (as in Wadi El'sh) to 89 $*10^6$ m^3 (as in KTR). However, the total capacity of dams decreases with time as a result of accumulated sediments. From the total storage point of view, the most important dam in Amman-Zarqa Basin as well as in Jordan is KTR.

6.3.1 King Talal Reservoir (KTR)

King Talal Reservoir (KTR) is located 40 km to the north of Amman. It was constructed in 1977 with a total capacity of 56 $*10^6$ m^3 and expanded in 1988 to reach the total capacity of 89 $*10^6$ m^3. The KTR covers more than 94% of the total drainage area of Amma-Zarqa Basin (Seil el Zarqa). In addition, the whole effluents from the above mentioned WWTP discharge into KTR since it is needed in the Jordan Valley (JV) for irrigation purposes. The main purpose of KTD in the beginning was designed for a potable water supply but many harmful substances are discharged into the KTR from point and non-point sources. Nowadays, the main purposes of KTR become only to provide irrigation needs (more than 82000 dunums in Jordan Valley), flood control and artificial recharge.

The long-term average (1970/71-2001/02) of surface runoff measured at KTR is about 70 $*10^6$ m^3 (43.4 $*10^6$ m^3 and 26.6 $*10^6$ m^3 for base flow and flood flow, respectively). The total flow into KTR includes large volume of wastewater effluent from As-Samra, Abu Nuseir, Jarash and Baq'a WWTP. It was concluded that the wastewater flow contributed about 50% or more to the total capacity of KTR as shown in Table 6.5.

Table 6.5: Contribution of As-Samra WWTP effluent on the total percentage inflow to KTR (modified after RSS 2002).

Year	Total inflow to KRT [10^6 m^3]	As-Samra effluent [10^6 m^3]	Contribution of As-Samra to KTR [%]
1989	73	20	27
1990	60	22	37
1991	61	24	39
1992	210	27	13
1993	124	34	27
1994	94	33	35
1995	109	38	35
1996	84	39	46
1997	95	38	40
1998	89	46	52
1999	67	45	67
2000	71	44.1	62
2001	69	45	65
2002	89	42	47

The water quality of KTR (recipient water body of As-Samra effluent) is dramatically changing between acceptable quality in winter when mainly drainage flow from Amman-Zarqa Basin occurs and bad quality during the summer when domestic and industrial wastewater are contributing to fill the KTR. Table 6.6 shows the long-term average of water quality at KTR with respect to As-Samra wastewater quality. It is concluded that BO_5, COD, TP, NH_4-N, T-PO_4 and TN (TDS is not the objective of treatment by biological process) will have less concentration at KTR in comparison with the concentration at As-Samra WWTP as a result of dilution with other flows and self-purification in the stream. The flow time from As-Samra WWTP into KTR has been estimated about 18 hours (Harza 1996). RSS 2003 (annual report of water quality monitoring for inflow and outflow of As-Samra WWT and Seil el Zarqa) showed that at different locations of KTR, the concentration of BOD_5, TP, TN, PO_4-P, NH_4-N and NO_3-N have significant decreases in their concentration which contribute to dilution of pollutants at KTR except the inflow from Zarqa River (As-Samra WWTP) which does not meet the Jordanian Standards.

Table 6.6: Long-term average (1995-2002) of water quality along the course of the Zarqa River (modified after MWI & JICA 2000).

Location	**Parameter [mg/L]**							
	TDS	**BOD_5**	**COD**	**NH_4-N**	**TTCC**	**$T\text{-}PO_4$**	**T-N**	**B**
As-Samra inflow	1228	567	1255	78	1.8E+7	15.5	103	-
As-Samra outflow	1196	127	394	84	3E+4	20	107	0.87
KTR inflow	1318	48	155	42	6.4E+3	9	59.4	0.57
KTR outflow	1143	10	38			4.8	26.8	0.46

Thus, the water quality of KTR has gradually deteriorated up to a level which is no longer suitable for unrestricted irrigation. It is concluded that the pollution parameters after As-Samra WWTP operation are increased drastically in comparison with the past (Table 6.7). This organic load changed the KTR water body from mesotropic to eutrophic from 1977 to 1984/85 and to hypertrophic in the 90's (Salameh 1996). The salinity of KTR was around 2900 µS/cm in the early of nineties with heavily loaded with organic matter, high concentrations of trace elements and depletion of oxygen which leaded to the damage of six thousands hectares with an estimated loss of 43-86 million Dollars (Salameh 1996). The dam storage is subjected to an annual sediment loads in the stream flow. The annual average of sediment entering the KTR is about $0.63 * 10^6$ m^3 carrying with it nutrients such as phosphorus, nitrogen and to some degree metals (Numayr 2004).

Therefore, nowadays the quality of outflow from KTR is acceptable for downstream irrigation (restricted irrigation) with slightly increases in TDS, BOD_5, TSS and NO_3 because most of the biodegradable pollutants have been already removed and additional pollutants entered the water body through the agricultural and pastoral activities (JICA and MWI 2000). Fig. 6.7 gives a general view of the upstream of KTR.

Table 6.7: Average pollution and salinity parameters in the Zarqa River inflows into KTR before and after As-Samra WWTP operation (Salameh 1996).

Parameter [mg/L]	**Years**			
	1984	**1988**	**1991**	**1994**
BOD_5	8	24	25	45
COD	57	77	97	114
Phosphorous	1.5	4.2	7.6	10
NO_3	9.5	27	31	45
EC (µS/cm)	1060	1499	1910	1950
Na	175	245	226	205
SO_4	62	111	118	135
Cl	205	290	361	355

Fig. 6.7: General view of the upstream of King Talal Reservoir.

7 MODELING

7.1 Background

A model is any simplification and abstraction of a complex natural field situation. It can be used in an interpretive sense to get insight into the controlling parameters in a site-specific setting or as a framework for assembling and organizing field data and formulating ideas about system dynamics (Anderson and Woessner 1992). It is a simplified version of the real (here groundwater) system that is approximately simulating the excitation–response relations of the latter (Bear and Verruijt 1992). The simplification is introduced in the form of a set of assumption that expresses our understanding of the nature system and its behavior.

These assumption will relate, among other factors, to the geometry of the investigated domain, to the way the effect of various heterogeneities will be smoothed out, to the nature of the porous medium (e.g., its homogeneity, isotropy), to the nature of the fluid involved and to the kind of flow regime that takes place (Bear and Verruijt 1992). Because of the model is a simplified version of the real system, there is no unique model for a given groundwater system. Different sets of simplifying assumptions will result in different models, each approximating the investigated groundwater system in a different way.

A mathematical model simulation of groundwater flow means a governing equation thought to represent the physical process that occur in the system, together with equations that describe heads or flows along the boundaries of the model (Anderson and Woessner 1992).

Therefore, the main benefit of the model is to increase the understanding of the interaction of simultaneous processes and influences, formulate the current problems to minimize and give alternative solutions of these problems. Generally, when it has been determined that a numerical model (e.g. Modflow) is necessary and the purpose of the modeling clearly defined, the task of model design and application begins. A protocol for any modeling includes conceptual model, code selection, model design, calibration, verification, sensitivity analysis and prediction (Appendix. 7 .1).

7.2 Conceptual model

A conceptual groundwater model is a pictorial representation of the groundwater flow system, frequently in the form of block diagram or cross section to simplify the field problem and organize the associated field data in order to determine the dimensions of the numerical model and the design of the grid (Anderson and Woessner 1992). It consists of a set of assumptions that reduce the complicated real system to simplified view to reach the model objectives.

Based on the data compilation and interpretation of topographic, geological and hydrogeological situation (chapters 2-4), the develop of conceptual model of Amman-Zarqa Basin has been set up (Fig. 7.1). It contains the hydrostratigraphic units, water budget, flow system and data needed to assign values. According to the conceptual model, there are two resources of recharge into the aquifer: direct recharge from the excess rainfall (north-western and western parts) and underflow (north-eastern parts). On the other hand, there are three types of outflow from the aquifer: natural spring discharge, underflow (south-eastern and northern parts), wells pumping and leakage from the upper aquifer into the lower aquifer. However, the amount of underflow and leakage need to be assigned later by mathematical calculations.

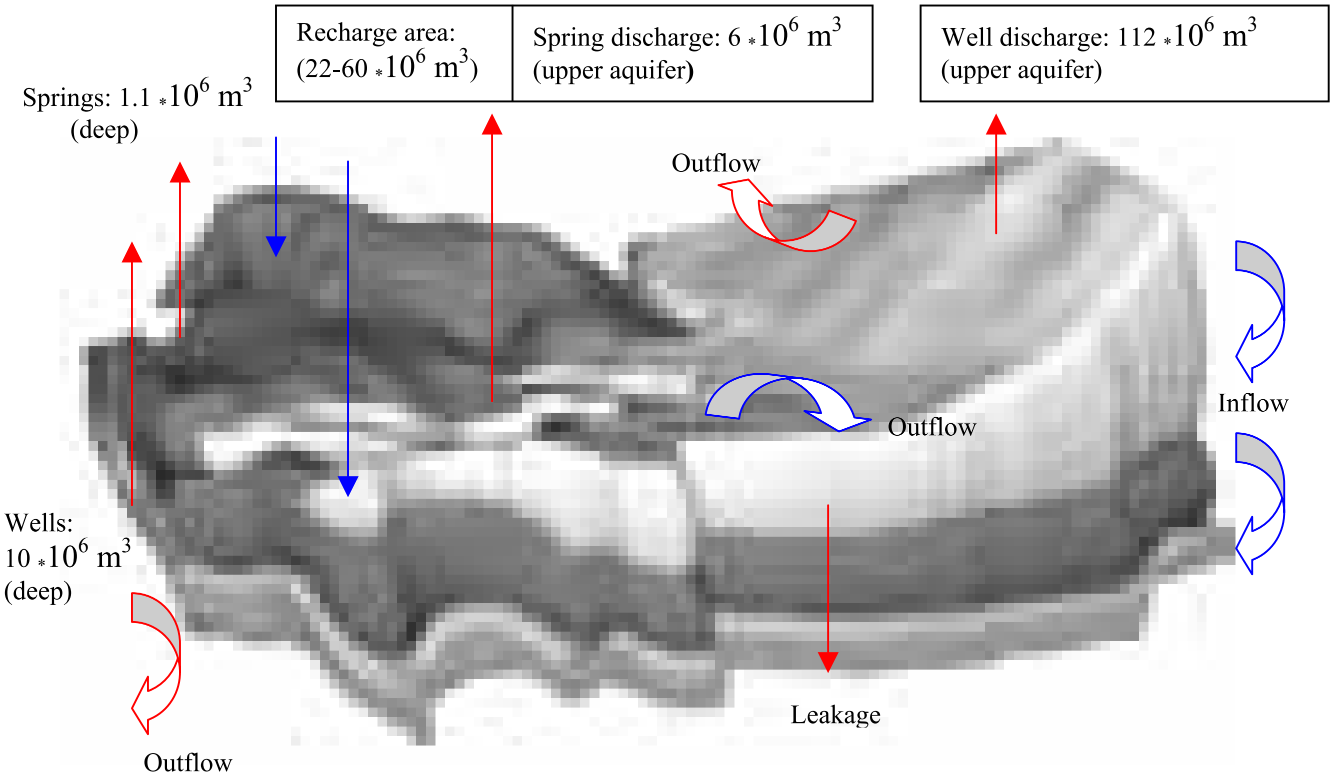

Fig. 7.1: Conceptual model of the study area.

7.3 Computer program (modeling software)

The second step in the procedure of modeling protocol is selecting the governing equation and a computer code (computer program).

The applications of MODFLOW-88 (McDonald and Harbaugh 1988), a modular three-dimensional finite-difference groundwater flow model of the U. S. Geological Survey, to describe and predict the behavior of groundwater flow systems have increased significantly over the last years. MODFLOW-88 and the later MODFLOW-96 (Harbaugh and McDonald 1996) were originally designed to simulate three-dimensional groundwater-flow through a porous medium. MODFLOW- 2000 (Harbaugh et al. 2000) is the most recent version of MODFLOW which was designed to incorporate the solution of multiple related equations into a single code. The single code is divided into entities called processes which deals with a specific equation. For example, the Groundwater Flow Process (GWF) deals with the groundwater-flow equation and replaces the original MODFLOW. The parameter estimation capability of MODFLOW-2000 is implemented by Hill and others (Hill et al. 2000) using three processes in addition to the GWF process. The Observation Process (OBS) calculates simulated values that are to be compared to measurements, calculates the sum of squared, weighted differences between model values and observations and calculates sensitivities related to the observations. The Sensitivity Process (SEN) solves the sensitivity equation for hydraulic heads throughout the grid, and the Parameter-Estimation (PES) Process solves the modified Gauss-Newton equation to minimize an objective function to find optimal parameter values (Chiang and Kinzelbach 2003).

Processing Modflow was originally developed for a remedial project of a landfill site in the coastal region of Northern Germany in 1989 - one year after the first official release of the groundwater flow model MODFLOW. Chiang and Kinzelbach decided to write their own Code when a suitable pre- and postprocessor for MODFLOW was not available at that time - Processing Modflow (Chiang and Kinzelbach 1993). The first commercial version running under MS-DOS was released in 1991. Although that version only supports MODFLOW-88 and MOD-PATH (Pollock 1994) and the graphical output was limited to hydrographs and contours for hydraulic heads.

In 1995, the first Windows-based version of Processing Modflow was released with the goal of bringing various codes together in a complete simulation system. The program was renamed to Processing Modflow for Windows and a later version has been published in 2001 (Chiang and Kinzelbach 2001).

The Processing Modflow Pro (PMWIN Pro) software version 7.0.13 (Chiang and Kinzelbach 2003) is a three-dimensional groundwater flow software which was used to simulate the groundwater flow system and the effects of groundwater abstraction of the Upper and Lower aquifers in Amman-Zarqa Basin based on finite difference approach. The PMWIN Pro is an enhanced version of Processing Modflow for Windows, supporting MODFLOW-2000 and several codes of useful modeling tools and comes with a professional graphical user-interface.

Geographic Information System (GIS) version 3.3 (ESRI 2002) was used to prepare all needed data for model inputs such as: conversion polyline to vectors (using Vector Trans ver. 1). TNT-mips version 6.8 was used to georeference of all imported Raster Images to convert it later into Vector Images using the system of Universal Mercator Transverse. Aquifer Test version 2.57 (Roehrich 1997) was used to evaluate and calculate the aquifer parameters. AutoCAD 2002 (Autodesk 2002) was used for mapping and graphical outputs in the format of *.DXF or *.PGL.

7.4 Discretization (model design)

There are two types of finite difference grids: the block-centered grid where flux boundaries are located at the edge of the block and the mesh-centered grid where the flux boundaries coincide with a node (Anderson and Woessner 1992).

The Processing Modflow Pro (PMWIN) is based on the block-centered finite difference approach. In the block-centered finite difference approach, an aquifer system is represented by a discretized domain consisting of an array of nodes and associated finite difference blocks (cells) as shown in Fig. 7.2. The nodal grid represents the framework of all numerical model calculations. The hydrostratigraphic units and the thickness of each model cell can be specified in terms of layers, rows and columns.

Based on the conceptual mode and other relevant hydrogeological data, the model design of Amman-Zarqa Basin has been built up in order to cover an area of about 3918 km^2 and to reach the objectives that mentioned in chapter one with the following properties:

- Number of square cells: 27,000
- Number of layers: 3
- Mesh size: 0.5 by 0.5 km
- Model orientation: 43.19°

The mesh size of the model 0.5 by 0.5 km was chosen in order to have each production well in one cell and to eliminate the superposition of drawdown in the same cell as much as possible. The model grid was rotated 43.19° to eliminate the discrepancy of the flux boundary and to ensure the use of no flow boundary. The rotation angle is expressed in degrees and is measured counterclockwise from the positive x-direction. 9756 square cells are active and used for model calculations in the upper aquifer and 16335 active cells in the lower aquifer.

Model parameter values have been assigned by three methods: Cell-by-Cell, Polygon and Vector Trans methods. The first two methods are a part of the model software and the Vector Tans method was applied when the thematic map handled by GIS were imported as matrix file to the model.

7.5 Boundary conditions

A critical step in model design is to select the boundary conditions. They have to be defined carefully because they are of great influence on the model results in every sense. They express the way the considered domain interact with its environment, i.e., they express the conditions, e.g., known water fluxes or known values of state variables, such as piezometric head (Bear and Verruijt 1992). The boundary conditions influence the steady state to reach the initial condition and the transient solution when, e.g., the effects of the cone of depression during the transient stress hits the boundary condition.

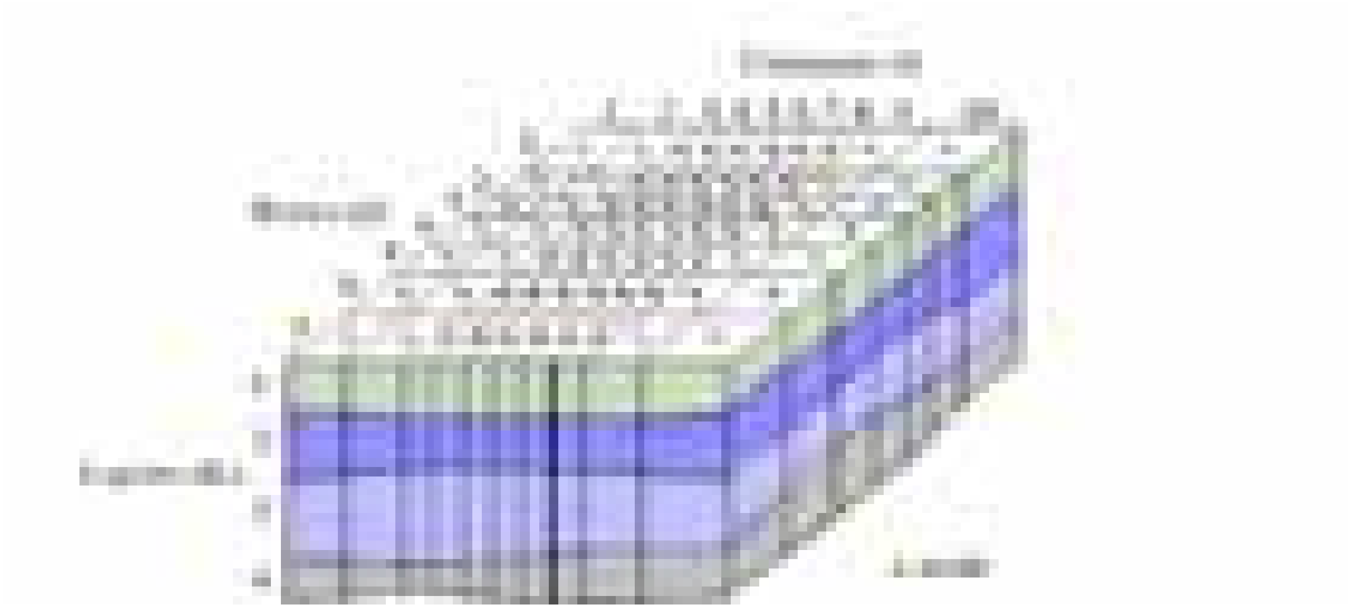

Fig. 7.2: Spatial descretization of an aquifer system and the cell insides (Chiang and Kinzelbach 2003).

There are two types of boundary conditions dominated in the groundwater flow system. Physical boundaries that formed as impermeable body or rock (such as: Fault) or a large water body (such as: lake). Hydraulic boundaries that form as a result of hydrologic conditions (such as: groundwater divides or streamlines). Thus, the hydrogeological boundaries are represented by three types of mathematical conditions (Anderson and Woessner 1992):

Type 1: specified head boundaries (Dirichlet conditions)
At least one point in a modeled domain has to be type 1 to insure that there is a uniqueness of the solution.

Type 2: flow boundaries (Neumann conditions)
This type of boundary means the gradient of head (flux) across the boundary is given. A special case of this boundary is the impervious boundary where the flux is zero (no flow boundary).

Type 3: head-dependent flow boundaries (Cauchy or mixed boundary conditions)
This type of boundary is a linear combination of head and flux at boundary where the flux across the boundary is calculated from given a boundary head value.

Based on the conceptual model (Fig. 7.1) and the groundwater flow pattern of the upper and lower aquifers (Figs. 4.8 and 4.10, respectively), the boundary conditions of the current study have been built up carefully. For the upper aquifer (Basalt and B2/A7), between Amman-Syncline and Zarqa Fault there is no flow into the aquifer (no flow boundary). On the other side, the 535 m water level contour is being used as a constant head boundary in the north-eastern part of the model area. The 520 m water level contour is assumed to be a constant head in the south-eastern parts in order to control the flow towards Azraq Basin. Also, at the northern and central-north parts of the study area constant head has been assigned in order to control the flow towards the Yarmouk Basin and Zarqa River, respectively. In addition, the rest of the model area has been left as specified head boundary. Fig. 7.3 shows the flow model boundaries of the upper aquifer (Basalt and B2/A7) of Amman-Zarqa Basin.

For the lower aquifer (Kurnub), the northern border (close to Mafraq town) has been considered as no flow boundary based on the trend of the direction of flow lines for initial water level. On the other hand, the 525 m water level contour close to Ajlun Dome (north-west) is assumed to be a constant head boundary. Also, the southern border of the study area is assumed as constant head boundary, i.e., the 400 m water level has been taken as a constant head in order to control the flow towards Dead Sea Basin. Moreover, the southwestern borders (Suweileh town) of the study area are considered as constant head boundary to control the flow towards Side Wadis Basin and some flow running into Zarqa River. The rest of the model area has been left as specified head boundary. However, the boundary conditions at the north borders is not yet clearly enough and at the north-east border of the lower aquifer is unknown since no borehole has been drilled yet. Fig. 7.4 illustrates the flow boundaries of the lower aquifer (Kurnub) of Amman-Zarqa Basin.

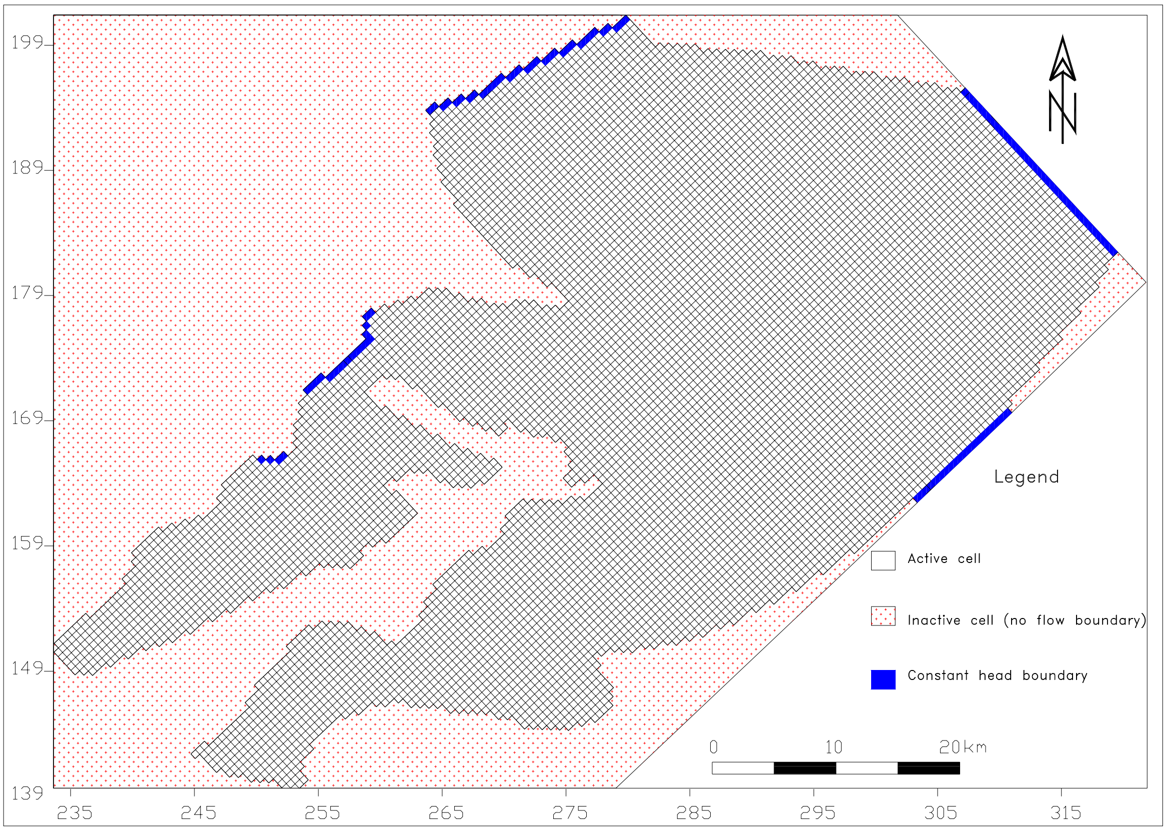

Fig. 7.3: Groundwater flow model boundaries of the upper aquifer.

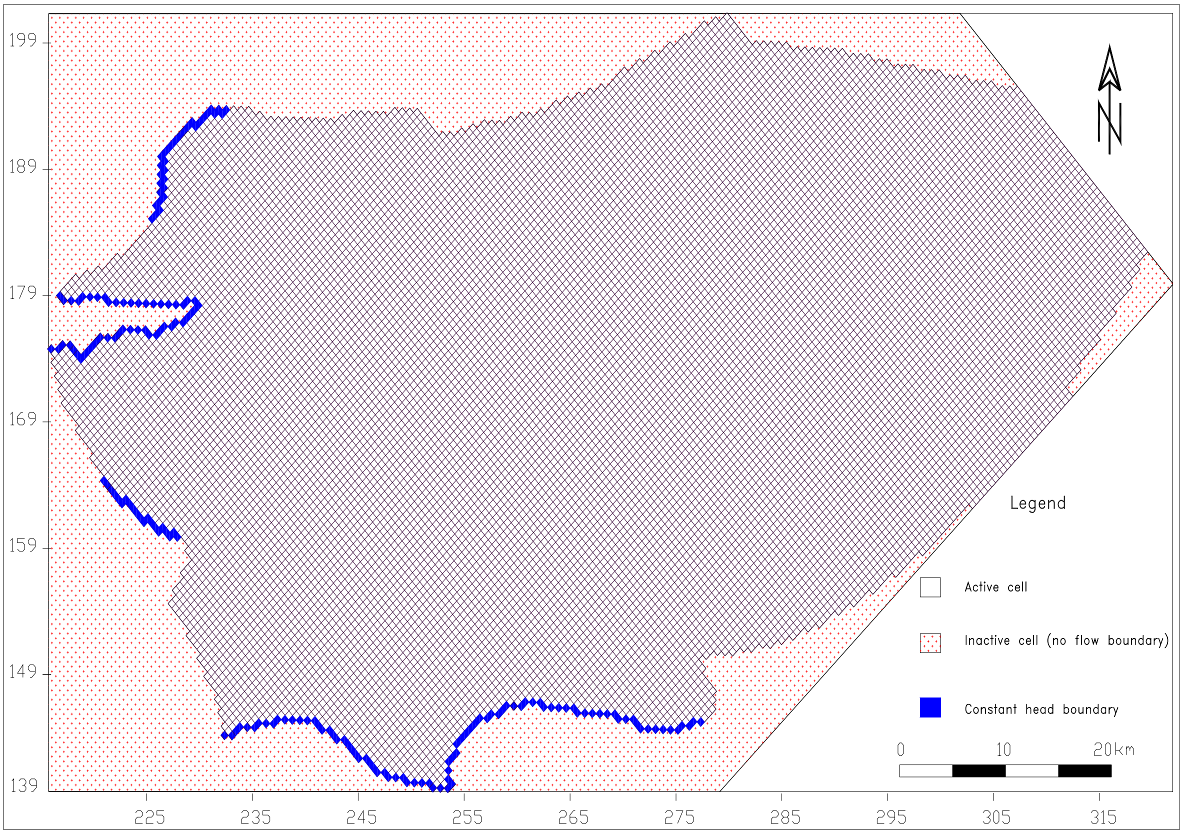

Fig. 7.4: Groundwater flow model boundaries of the lower aquifer.

7.6 Assigning parameter values

Generally, data needed to assign into the model can be grouped into two types: Physical framework, which defines the geometry of the system including the topographic contour lines, structure contour lines of each formation and the areal extent of each hydrostratigraphic unit. On the other hand, hydrogeological parameters including water levels, fluxes, transmissivity, specific yield, etc.

7.6.1 Physical framework

The Structure contour maps of the base of the hydrogeological units are given in chapter four (Figs. 4.1, 4.3 and 4.5) and the topographic map in chapter one (Fig. 1.2). These maps describe the geometry of the aquifer system. The contour lines of these maps have been used for the determination of the relevant values for each model cell.

By using ArcView and TNT-mips, the topographic map and all of structural maps of all layers were prepared for model input by digitizing and transformation polyline to points then assign to the model domain as ASCII file. Also, the thematic maps (vector graphics) were imported into the model by using Cad Reader (DXF format). Some data in some locations has been entered into the model by Data Editor which is used to assign parameter values to the model. The Data Editor provides three methods for specifying parameter values: Cell-by-cell (since the elevation of the base of a hydrogeological unit has a different value in each cell, the data had to be to entered into the model cell by cell), Polygon (when the elevation of the base of a hyrogeological unit is homogeneous) and Polyline method. The first two methods had been applied but the Polyline method was not used because of missing river or drainage system in the study area.

7.6.2 Hydrogeological parameters

7.6.2.1 Hydraulic conductivity

Horizontal and vertical hydraulic conductivities had to be assigned to each model layer. First, the horizontal hydraulic conductivities were assigned in the upper and lower aquifers based on the pumping tests analysis results which was done in chapter four (4.3 aquifer characteristics) and from recompilation of old pumping test data as initial values. Then, by using Field Interpolator (Gridding method by Kriging) all model's cell were addressed. According to the pumping test analysis, the range of hydraulic conductivity of the upper aquifer is between $8.0*10^{-5}$ and $2.0*10^{-4}$ m/s for B2/A7 and Basalt aquifer, respectively. For the lower aquifer, the same methodology was applied to address all cells. The initial value of the hydraulic conductivity of the lower aquifer was ranging between $2.2*10^{-5}$ and $2.7*10^{-5}$ m/s for confined and phreatic conditions, respectively. However, the vertical hydraulic conductivities were kept constant for upper and lower aquifer ($5*10^{-6}$ and $1*10^{-7}$ m/s, respectively) as initial values based on the previous model results (Brunke 1997). During the calibration this value was modified to reach the best fit between the measured and calculated head. Therefore, during the calibration of the model these values were modified cell by cell in some parts of the model. The hydraulic conductivities had to be reduced in some areas where the saturated thickness of the aquifers is very small in order to avoid model cells to fell cell dry that would result in numerical problems. The same approach has been used to interpolate heads where the head is missing or the available data is not enough.

7.6.2.2 Recharge and discharge

Based on the surface water budget (chapter two), the recharge rate was specified in the model as a depth (L/T) using Cad Reader (DXF format). Then, the recharge area cells were interpolated by using the Polygon input method. The initial value of recharge rate in the upper aquifer was between 20 and 45 $*10^6$ m^3 for normal and wet hydrological years, respectively and in the lower aquifer between 10 and 20 $*10^6$ m^3 for normal and wet hydrological years, respectively.

The amount of each pumping well was edited in the model using the cell-by-cell input method. Based on the water budget in 2003, the total abstraction reached about 138 $*10^6$ m^3.

7.7 Theoretical background of the mathematical model

The flow equations for all aquifer types are obtained from two basic principles:
- Continuity
- Darcy's law

while continuity demands the conservation of water mass (outflow-inflow = change in storage), Darcy's law (1856) states that in an isotropic porous medium the specific flow rate (filter velocity) is proportional to the negative head gradient (Kinzelbach 1986). In three-dimensional groundwater flow, the specific rate flow can be written as:

$\nu = -k_f \nabla h$ with $\nu = (v_x, v_y, v_z)$ and $= (\partial/\partial x, \partial/\partial y, \partial/\partial z)$

The proportionality constant k_f is called permeability. In anisotropic aquifers the Darcy law can be written as:

$$\nu = -lk\nabla h \qquad \text{with } lk = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}$$

where lk is the second rank tensor of permeability.

This means in an anisotropic medium the direction of flow is not always heading with the direction of the pressure gradient.

A general form of the governing equation in three-dimension profile is (Anderson and Woessner 1992):

$$\frac{\partial}{\partial x}(K_x \frac{\partial}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) = S_s \frac{\partial h}{\partial t} - R$$

Where K_x, K_y and K_z are components of the hydraulic conductivity tensor. Ss is specific storage which is defined to be the volume of water released from storage per unit change in head per unit volume of aquifer; R is a general sink/source term that is intrinsically positive and defines the volume of inflow to the system per unit volume of aquifer per unit of time. Note that the above equations assume that the density of water is constant.

The vertical leakance (VCONT) between two adjacent layers in quasi three-dimensional models is calculated by the following formula:

$$\text{VCONT} = \frac{2}{\frac{\Delta v_u}{(K_z)_u} + \frac{\Delta v_c}{(K_z)_c} + \frac{\Delta v_L}{(K_z)_L}}$$

Where $(Kz)_u$, $(Kz)_c$ and $(Kz)_L$ are the vertical hydraulic conductivity values of upper layer, semi-confining unit and lower layer, respectively and Δv_u, Δv_c and Δv_L are the thickness of upper layer, semi-confining unit and lower layer, respectively. In addition, the volume of leakage (QL) is calculated by the following equation (Anderson and Woessner 1992):

Q_L = - leakance (h_{source} – h) wl

Where h_{source} is the head in the source reservoir (upper aquifer) and h is the head in lower aquifer. The parameter w and l are the width and length, here the cell size, respectively.

There are different numerical methods to solve the above mentioned equation: finite differences, integrated finite difference, finite elements, analytical elements and the boundary integral equation method. However, finite difference and finite elements are widely used to solve the partial differential equations of flow system. Thus, Finite difference method will be applied in this study since the Processing Modflow Pro (PMWIN Pro) is based on finite difference approach.

7.8 Model calibration

7.8.1 Steady state simulation

Model calibration of steady state was done by comparison observed piezometric heads of the upper and lower aquifers with the calculated hydraulic heads.

Calibration of the upper aquifer (Basalt and B2/A7) was based on the water-table map (Fig. 4.8), which reflects the groundwater situation in the beginning of seventies, and on some spot observations made in 1996. Most of the parameters were considerable changing during the steady state to reach the best fit for the model, particularly the horizontal hydraulic conductivity and the recharge. The vertical hydraulic conductivity of the aquitard layer (A1/A6) was modified on the local scale to reach the optimum fit between the measured and calculated heads. The highest discrepancies were found close to the Khirbit As-Samra (the largest treatment plant in Jordan) where considerable seepage into the upper aquifer occurs and the recharge areas (south-western parts) where the total saturated thickness and transmissivity of the upper aquifer are lower. According to the best matching between the observed heads and model calculated heads (Fig. 7.5), the horizontal conductivity of the upper aquifer was ranging from $2.0*10^{-5}$ m/s at the northern parts (bordered areas with Yarmouk Basin) to about $4.0 * 10^{-4}$ m/s at the south-eastern parts where most of production wells are located (Hallabat area). However, it is concluded that no trends can be distinguished for the distribution of the horizontal conductivity in the study area because of the complexity of the upper aquifer. From the horizontal hydraulic conductivity point of view, Amman-Zarqa Basin can be divided into ten zones as shown in Fig. 7.6. Also, it was found that the hydraulic characteristics of A1/A6 aquitard were ranging from $1.0*10^{-11}$ to $7.0*10^{-9}$ m/s and $1.0*10^{-7}$ m/s of vertical and horizontal conductivities, respectively. The importance of the characteristics of confining unit is to estimate the amount of leakage from the upper aquifer towards into the lower aquifer.

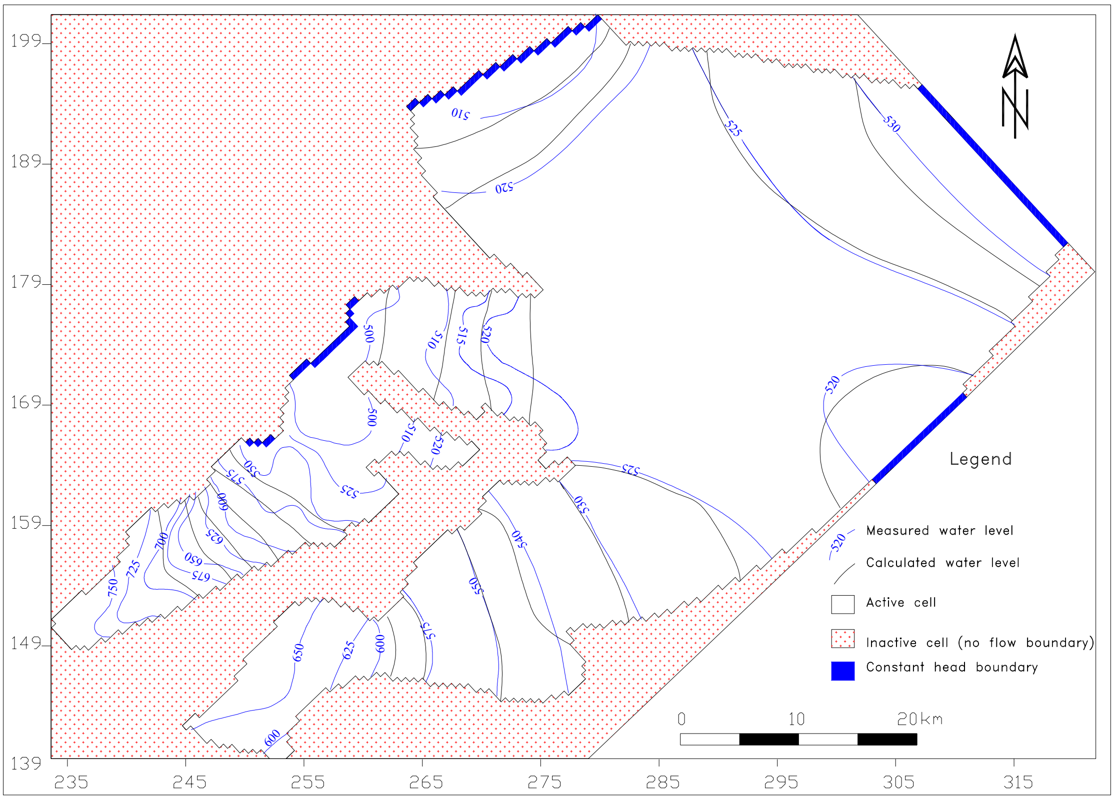

Fig. 7.5: Matching map between measured and calculated water table of the upper aquifer (steady state calibration).

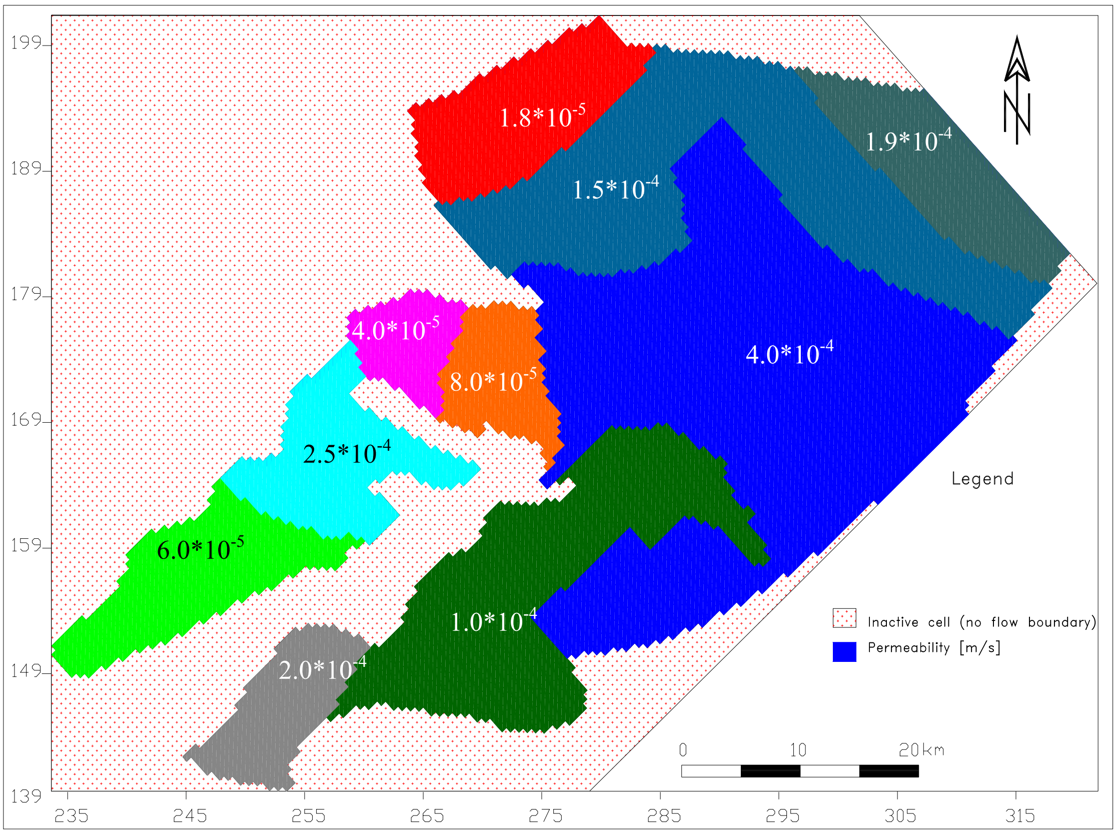

Fig. 7.6: Map of calibrated permeability of the upper aquifer (steady state calibration).

It is concluded that the amount of leakage is in the order of 12 $*10^6$ m^3 which represents about 27% of the total direct recharge of the upper aquifer.

Calibration of the lower aquifer (Kurnub) under steady state calibration was done by comparison with the upper aquifer because of limited number of boreholes and small areas of groundwater exploitation in the lower aquifer.

Based on the initial water level map of the lower aquifer (Fig. 4.10), the model was calibrated and the best match was reached as shown in Fig. 7.7. However, the highest discrepancy of the model was found close to Suweileh town where groundwater recharge is high. This effect is due to the instability of groundwater flux which represents inflow and outflow at the same time.

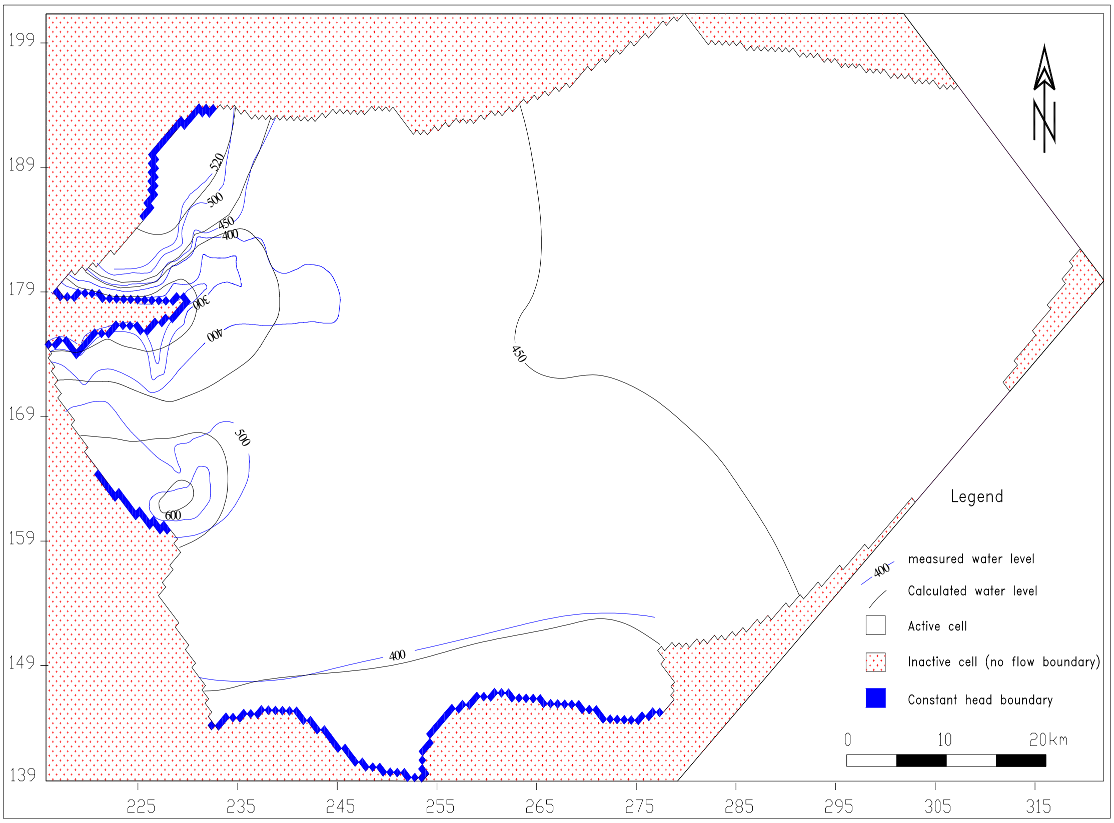

Fig. 7.7: Matching map between measured and calculated water level of the lower aquifer (steady state calibration).

During the calibration it was found that the horizontal hydraulic conductivity was the most sensitive parameter which was considerable changing during the steady state to reach the best match between the observed and calculated heads as shown in Fig. 7.7. However, the amount of recharge has been modified during the calibration, but due to the limited extend of recharge areas its effect was minor. According to the matching between the observed heads and model calculated heads (Fig. 7.7), the horizontal conductivity of the lower aquifer ranges from $1.0*10^{-6}$ m/s at far west of the study area (northern bank of Zarqa River) to about 3.0 $*10^{-5}$ m/s at far north-west (close to Ajloun Dome). However, there is a trend of increasing hydraulic conductivity to the eastern parts of the study area as shown in Fig. 7.8.

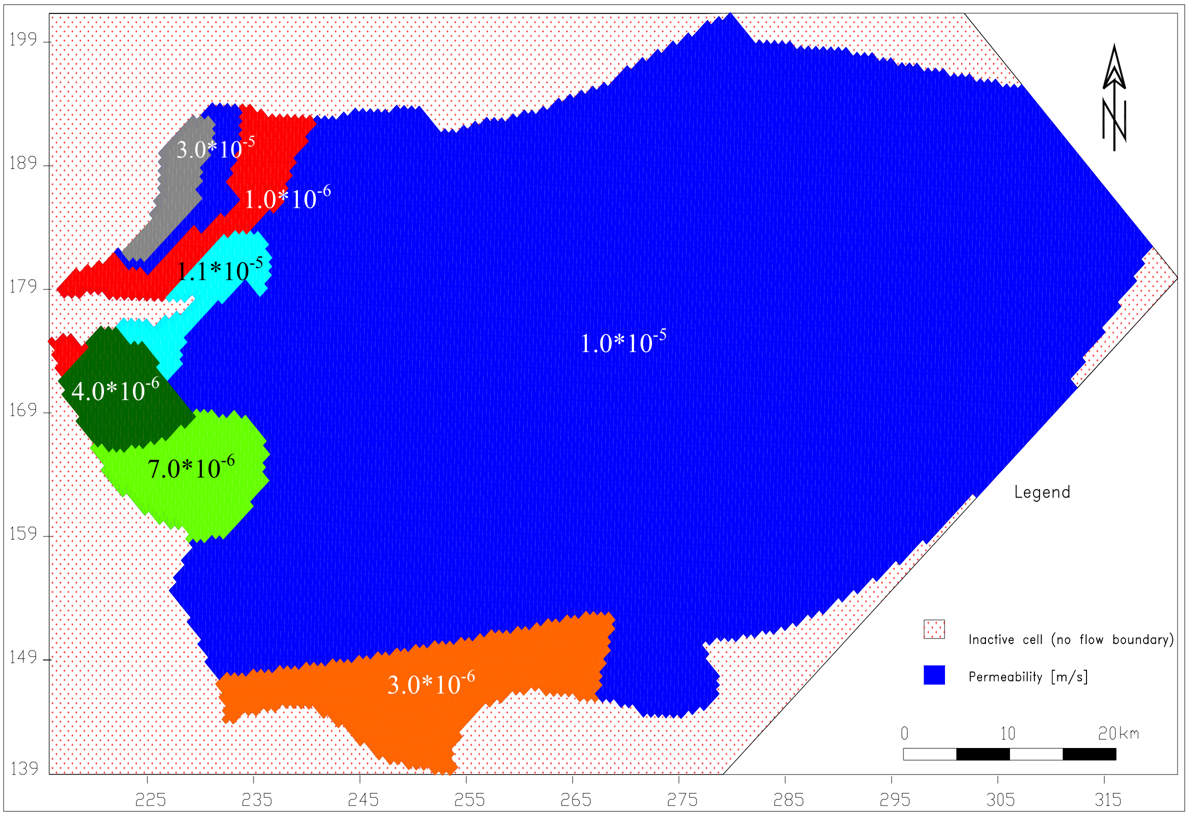

Fig. 7.8: Map of calibrated permeability of the lower aquifer (steady state calibration).

7.8.2 Water budget

The water budget of the study area has been calculated based on the steady state calibration. Tables 7.1 and 7.2 represent the total water budget of the whole model domain in terms of inflows and outflows from or into the groundwater system (upper and lower aquifers).

For the upper aquifer, the biggest amount of inflow into the aquifer is about 61.8 $*10^6$ m^3 as underflow from Jabal Al Arab through the basalt which represents the north-eastern regions and 45.5 $*10^6$ m^3 as renewable recharge from excess rainfall which represents the south-western parts of Amman-Zarqa Basin. On the other side, the biggest amount of outflow from the aquifer is about 66 $*10^6$ m^3 across boundary into Azraq Basin which represents the south-eastern parts, 26.8 $*10^6$ m^3 as underflow towards Zarqa River and natural spring discharge which represents the central-north parts and 3.4 $*10^6$ m^3 as underflow towards into Yarmouk Basin which represents the northern parts of Amman-Zarqa Basin.

For the lower aquifer, the amount of direct recharge (20 $*10^6$ m^3) and leakage (12.3 $*10^6$ m^3) from the upper aquifer represent the majority amount of inflow into the aquifer. Some inflow enters into the aquifer close to Ajlun Dome in the range of 8.7 $*10^6$ m^3 and 3.9 $*10^6$ m^3 close to Suweileh town (south-west). On the other side, there is about 25 $*10^6$ m^3 as outflow towards Zarqa Group and Zarqa River, 14.5 $*10^6$ m^3 as underflow into Dead Sea Basin (southern parts) and small amounts (3.2 $*10^6$ m^3) running into Side Wadis Basin. The difference between the inflow and the outflow is represented by spring discharge in the order of 1.1 $*10^6$ m^3 and 1.1 $*10^6$ m^3 as inflow from the A1/A6 unit.

Therefore, the discrepancy of the water budget of the whole model domain in terms of inflow and outflow was almost 0.0 % either for upper or lower aquifer.

Table 7.1: Water budget of the whole model domain for the upper aquifer (10^6 m^3).

Flow term	**Inflow**	**Outflow**	**Difference (In-Out)**
Constant head	61.8	89.4	-27.6
Spring		6.8	-6.8
Recharge	45.5		45.5
Leakage		11.2	-11.2
Sum	107.3	107.4	0.0007
Discrepancy	0.0		

Table 7.2: Water budget of the whole model domain for the lower aquifer (10^6 m^3).

Flow term	**Inflow**	**Outflow**	**Difference (In-Out)**
Constant head	12.7	42.8	-30.1
Spring	0.0	1.1	-1.1
Recharge	20.0	0.0	20.0
Leakage	12.3	0.0	12.3
Sum	45.0	43.9	1.1
Discrepancy	0.0		

7.8.3 Transient simulation (time dependent simulation)

The calculated initial water levels and the calibrated hydraulic parameters of the steady state calibration were used for the long-term simulation of the transient flow. The transient simulations were carried out to reach the present situation (drawdown levels) and to predict the behavior of the hydraulic system (change of storage and drawdown levels) on a long-term response of the aquifer to groundwater withdrawal. The year of 1970 has been considered as the year in which water production started (21 $*10^6$ m^3) and further development of the transient groundwater flow has been simulated up to the year 2001 (111.5 $*10^6$ m^3). The time period of 32 years was divided into 32 stress periods so that the amount of abstraction for each well could be adjusted on yearly averages. The seasonal variations of the production rates were neglected.

Based on the simulation of long-term (1970-1995) and short-term (1996-2001) drawdown in the observation wells, the calibration of transient state was done. The amount of well abstraction was the only boundary condition to be changed from period to period. All constants head boundaries were changed into flux boundaries so that the maximum drawdown can be distinguished and the effect of the constant head boundaries will be neglected.

For the calibration of the upper aquifer twenty-one observations wells were adopted in the model domain to simulate the transient flow. However, these 21 wells were reduced to eight wells from the starting date of monitoring point of view for long-term calibration. Comparing the calculated drawdown with the observed drawdown close to the observation wells (Table 7.3), the simulation of drawdown could be considered as being representative for the whole model area. Further model results were found based on the short-term calibration (1996-2001) as shown in Table 7.3. Finally, the accumulative drawdown for the long-term calibration (1970-2001) was plotted (Fig. 7.9). The maximum drawdown was about 39 m by the year of 2001 close to the wells AWSA 5 (Nureddeen, AL1813) and Race Club No. 18 (AL2714) representing the southern parts (northern parts of Amman Flexure) of the study area. Also, in the far north-eastern parts (close to Mafraq city) the drawdown was 35 m between the observation wells of Husain Air Force Base (AL1521) and Hussayniat No. 1(AL2697). In contrast, the minimum drawdown over the model area was found at the southern parts of Amman Flexure in the order of 1 m during the long-term simulation. The specific yield of the upper aquifer was found between 0.01 and 0.085. The highest values of the specific yield were found in the limestone unit (B2/A7) whereas the minimum values were found in the Basalt unit.

For the calibration of lower aquifer only three observations wells were taken in the model area to simulate the transient flow. The main reason of the limited numbers of observation wells was the starting date of monitoring and not continuous operation of some wells (such as: Baq'a No. 12, AL2719). However, the drawdown was calibrated based on the short-term period (1996-2001) that may be considered as being representative of the whole model area based on regional scale. Table 7.4 shows the comparison between the calibrated and observed drawdown that was done based on the accumulative drawdown from 1996 until 2001. Thus, the accumulative drawdown for the long-term calibration (1970-2001) is shown in Fig. 7.10. It was found that three cones of depression have been developed due to the increasing of abstraction. The first was found close to Baq'a well field with maximum drawdown reaching about 20 m by the year of 2001. The second is close to Jarash area with maximum drawdown in the order of 10 m by the year of 2001. The third is found close to Dafali well field (Subeihi town) where the maximum drawdown reached about 9 m by the year of 2001. The specific storage of the lower aquifer was between $2.0*10^{-5}$ and $7.0*10^{-3}$ for the best fitting between the calculated and measured drawdown. The highest values of the specific storage were found in western parts of the model area where the Kurnub aquifer (lower aquifer) is outcropping. Also, there is a trend of increasing specific storage from west to east.

Table 7.3: Comparison between the calculated and observed drawdown (DD) of the upper aquifer.

Well Idn.	Cell No.	Calculated DD [m]	Measured DD [m]	Calibration Time (1970-2001)
AL1005	(97,108)	23.0	23.2	Long-term
AL1040	(84,104)	14.4	14.7	Long-term
AL1041	(95,97)	21.8	22.7	Long-term
AL1043	(88,89)	17.7	16.0	Long-term
AL1300	(85,52)	28.2	29.4	Long-term
AL1521	(61,124)	30.0	31.2	Long-term
AL1926	(96,107)	23.2	23.3	Long-term
AL2697	(72,126)	29.2	31.5	Long-term
AL1734	(77,66)	5.0	4.1	short-term
AL1792	(101,50)	0.3	0.3	short-term
AL1022	(91,103)	4.8	6.0	short-term
AL2698	(110,106)	7.0	5.0	short-term
AL2699	(76,74)	4.0	3.4	short-term
AL2714	(83,32)	6.1	7.5	short-term
AL3283	(114,100)	6.5	8.0	short-term
AL3384	(91,120)	6.7	7.8	short-term
AL3390	(94,79)	2.7	3.0	short-term
AL3391	(107,67)	2.3	3.0	short-term
AL3394	(66,108)	5.4	5.8	short-term

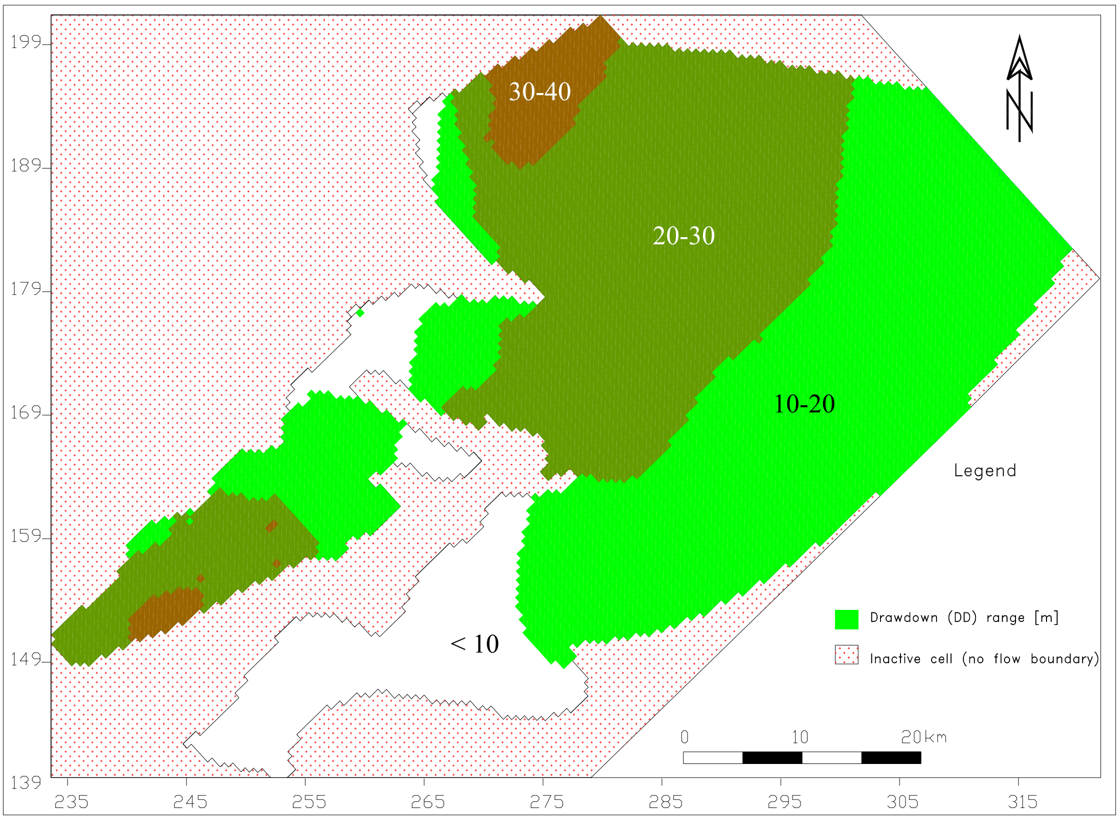

Fig. 7.9: Map of simulated drawdown after 32 years (1970-2001) of groundwater withdrawal (upper aquifer).

Table 7.4: Comparison between the calculated and observed drawdown (DD) of the lower aquifer.

Well Idn.	Cell No.	Calculated DD [m]	Measured DD [m]	Calibration Time (1970-2001)
AL1430	(45,25)	4.6	5.0	short-term
AL1541	(48,27)	6.3	6.3	short-term
AL2360	(27,64)	0.4	0.7	short-term

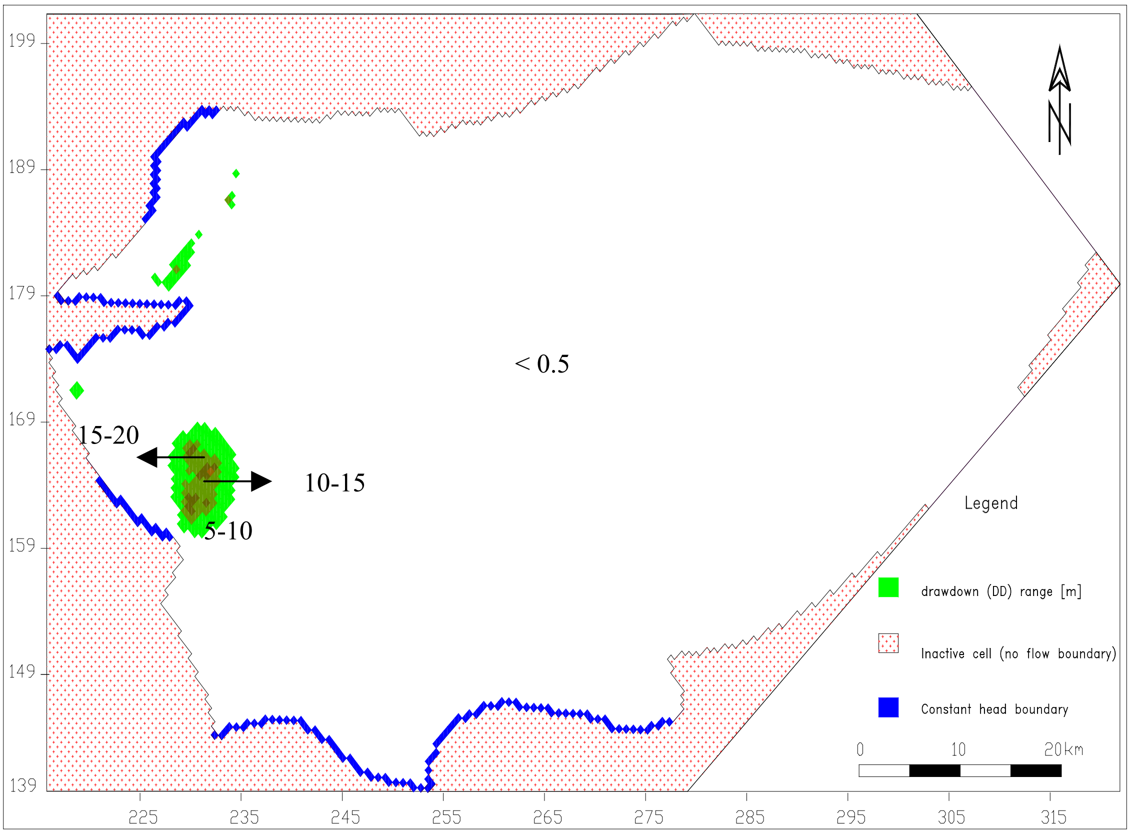

Fig. 7.10: Map of simulated drawdown after 32 years (1970-2001) of groundwater withdrawn (lower aquifer).

However, the drawdowns in or closer to the pumping wells are not determined in the model calculation due to the grid size of 500 m. The actual hydraulic head in the pumping well will be much lower than the ones calculated in the model. The head in the pumping well can be calculated using the Thiem (1906) equation (Kruseman and de Ridder 1991):

$$h_w = h_{i,j} - \frac{Q_{WT}}{2\pi T} \ln\left(\frac{r_e}{r_w}\right)$$

Where Q is the well discharge in m^3/d; T is the transmissivity in the aquifer in m^2/d; h_w is the head in the well; $h_{i,j}$ is the head computed by the model; re is the radial distance of the calculated piezometer ($h_{i,j}$) from the pumping well node and r_w is the well radius. However, based on the regional scale, the calculated annual drawdown rates should reflect the measured mean annual drawdown (a prerequisite for transient calibration).

7.8.4 Inverse model

The process of estimating any unknown parameter is one of the most critical and difficult step during the model calibration. Inverse model is often referred to as automatic calibration. Parameter estimation (PEST) is an external parameter estimation software on the basis of finite parameter differences which was implemented by Hill and others (Hill 2000) and upgraded by Doherty in 2001 (Doherty 2001b).

The purpose of PEST is to assist in data interpretation and searches optimum parameter values for which the sum of squared deviations between model-calculated and observed hydraulic heads or drawdowns at the observation boreholes is reduced to a minimum. The PEST model can adjust parameters and/or excitation data in order that the discrepancies between the pertinent model-generated numbers and the corresponding measurements are reduced to a minimum.

Each parameter has an own identifier that is used to group cells where the parameter values are to be estimated by the PEST program. The parameter number should be unique within a parameter type (e.g., T, Ss). During parameter estimation process, the parameter values of estimation iteration are calculated as the product of the initial parameter cell-values and a parameter multiplier. At the end of each optimization process (when one of the termination criteria having been met), PEST tabulated the optimal values and the 95% confidence intervals pertaining to all adjustable parameter as well as the parameter correlation coefficient matrix. However, during a parameter estimation process, the original model data will not be changed because PEST does not always necessarily lead to a success. This advantage will keep the original data in a greater security.

Based on the sensitivity analyses results, the horizontal hydraulic conductivity and the amount of recharge (the most sensitive parameters) of the upper aquifer have been estimated as well as the specific yield using PEST program. Tables 7.5 and 7.6 illustrate the optimized parameter values of the upper aquifer calculated by PEST. The biggest difference between the current and estimated parameter value was found for the parameter Hk_1 and Hk_9 where the saturated thickness is low. The Hk_1 parameter did not give a better result when its value changed from $6.0*10^{-5}$ to $1.2*10^{-4}$ m/s. On the other side, the Hk_9 gave a better result when its value changed from $2.0*10^{-4}$ to $1.1*10^{-3}$ m/s. According to the generated values of the optimized parameters, the new heads at observation points have been estimated (Table 7.6). Furthermore, the correlation coefficient matrix of the optimized parameters was calculated by PEST (Appendix 7.2). The Hydraulic conductivity and the recharge rate of the upper aquifer are correlated as indicated by the value of the correlation coefficient matrix (Appendix 7.2). This means that these parameters are estimated with a high degree of uncertainty in the parameter estimation process.

The optimized parameter values of the lower aquifer have been found based on PEST calculation (Appendices 7.3 and 7.4). The biggest changed of hydraulic conductivities was found at the western boundary where the Kurnub has contact with Zarqa Group and low transmissivity. The initial value was ranging between $1.0*10^{-6}$ and $1.1*10^{-5}$ m/s, however the calculated values are found ranging between $5.0*10^{-8}$ and $1.5*10^{-5}$ m/s. Also, the hydraulic conductivity between Ajlun Dome and Zarqa River (initial value $1.0*10^{-5}$ m/s) was significantly changed to reach about $1.0*10^{-3}$ m/s. However, this value did not help to improve the model results of the lower aquifer based on the observation head.

Table 7.5: The optimized parameter values of the upper aquifer.

Parameter name	**Current value (calibrated model)**	**Estimated value**	**Lower limit**	**Upper limit**
Hk_1*	$6.0*10^{-5}$	$1.2*10^{-4}$	$6.0*10^{-7}$	$6.0*10^{-3}$
Hk_2	$2.5*10^{-4}$	$3.1*10^{-4}$	$2.5*10^{-6}$	$2.0*10^{-2}$
Hk_3	$4.0*10^{-5}$	$5.7*10^{-5}$	$4.0*10^{-7}$	$4.0*10^{-3}$
Hk_4	$8.0*10^{-5}$	$1.1*10^{-4}$	$8.0*10^{-7}$	$8.0*10^{-3}$
Hk_5	$4.0*10^{-4}$	$2.9*10^{-4}$	$4.0*10^{-6}$	$4.0*10^{-2}$
Hk_6	$1.5*10^{-4}$	$1.5*10^{-4}$	$1.5*10^{-6}$	$1.5*10^{-2}$
Hk_7	$1.8*10^{-5}$	$9.0*10^{-5}$	$1.8*10^{-7}$	$1.8*10^{-3}$
Hk_8	$1.0*10^{-4}$	$1.4*10^{-4}$	$1.0*10^{-6}$	$1.0*10^{-2}$
Hk_9	$2.0*10^{-4}$	$1.1*10^{-3}$	$2.0*10^{-6}$	$2.0*10^{-2}$
Hk_10	$1.9*10^{-4}$	$1.9*10^{-4}$	$1.9*10^{-6}$	$1.9*10^{-2}$
Rch_17**	$1.0*10^{-12}$	$1.6*10^{-12}$	$1.0*10^{-14}$	$1.0*10^{-10}$
Rch_18	$1.0*10^{-12}$	$1.7*10^{-12}$	$1.0*10^{-14}$	$1.0*10^{-10}$
Rch_19	$1.3*10^{-8}$	$2.7*10^{-8}$	$1.3*10^{-10}$	$1.3*10^{-6}$
Rch_20	$6.0*10^{-9}$	$5.0*10^{-9}$	$6.0*10^{-11}$	$6.0*10^{-7}$
Rch_21	$8.0*10^{-9}$	$7.0*10^{-9}$	$8.0*10^{-11}$	$8.0*10^{-7}$
Rch_22	$1.0*10^{-8}$	$1.9*10^{-8}$	$1.0*10^{-10}$	$1.0*10^{-6}$
Sy_1***	$6.6*10^{-2}$	$9.0*10^{-2}$	$6.6*10^{-4}$	0.1
Sy_2	$5.5*10^{-2}$	$1.1*10^{-2}$	$5.5*10^{-4}$	0.1
Sy_3	$2.5*10^{-2}$	$1.0*10^{-1}$	$2.5*10^{-4}$	0.1
Sy_4	$8.5*10^{-2}$	$1.0*10^{-1}$	$8.5*10^{-4}$	0.1
Sy_5	$6.3*10^{-2}$	$1.0*10^{-1}$	$6.3*10^{-4}$	0.1
Sy_6	$6.2*10^{-2}$	$5.2*10^{-2}$	$6.2*10^{-4}$	0.1
Sy_7	$7.1*10^{-2}$	$1.0*10^{-1}$	$7.1*10^{-4}$	0.1
Sy_8	$4.0*10^{-2}$	$4.0*10^{-4}$	$4.0*10^{-4}$	0.1
Sy_9	$1.0*10^{-2}$	$5.6*10^{-2}$	$1.0*10^{-4}$	0.1
Sy_10	$5.5*10^{-2}$	$1.0*10^{-1}$	$5.5*10^{-4}$	0.1
Sy_11	$4.5*10^{-2}$	$1.4*10^{-3}$	$4.5*10^{-4}$	0.1
Sy_12	$3.3*10^{-2}$	$1.0*10^{-1}$	$3.3*10^{-4}$	0.1
Sy_13	$1.7*10^{-2}$	$9.0*10^{-2}$	$1.7*10^{-4}$	0.1
Sy_14	$2.4*10^{-2}$	$2.4*10^{-4}$	$2.4*10^{-4}$	0.1
Sy_15	$2.0*10^{-2}$	$2.0*10^{-4}$	$2.0*10^{-4}$	0.1
Sy_16	$4.5*10^{-2}$	$5.5*10^{-4}$	$4.5*10^{-4}$	0.1
Sy_17	$3.3*10^{-2}$	$5.2*10^{-2}$	$3.3*10^{-4}$	0.1
Sy_18	$2.9*10^{-2}$	$5.7*10^{-2}$	$2.9*10^{-4}$	0.1
Sy_19	$2.5*10^{-2}$	$3.5*10^{-2}$	$2.5*10^{-4}$	0.1
Sy_20	$3.0*10^{-2}$	$9.1*10^{-3}$	$3.0*10^{-4}$	0.1

* Hydraulic conductivity (m/s)_parameter number (Fig. 7.6)

** Recharge rate (m/s)_parameter number (southwestern parts of model area)

*** Specific yield_parameter number

Table 7.6: The estimated heads of observation points based on PEST calculation.

Observation No.	PGE [m]	PGN [m]	Estimated head [m]	Measured head [m]	Residual [m]
1	272602.4	197071.2	506.1	505	-1.1
2	276672.6	189965.1	516.1	520	3.9
3	294265.2	187896.7	523.7	525	1.3
4	299733.5	171067.5	520.7	520	-0.7
5	273802.6	171576.6	519.2	520	0.8
6	265870.8	174209.3	509.8	510	0.2
7	252389.8	160163.8	576.6	575	-1.6
8	282925.5	163531.6	525.7	525	-0.7
9	248590.7	156913.1	624.3	625	0.7
10	275110.5	153533.9	540.7	540	-0.7
11	268848.3	156486.0	551.8	550	-1.8
12	279244.6	197899.3	512.8	510	-2.8
13	314052.6	176175.1	524.6	525	0.4
14	317442.2	180038.0	530.4	530	-0.4
15	301570.4	196119.1	528.1	530	1.9
16	271365.9	147976.2	553.2	550	-3.2
17	269688.0	171682.4	515.1	515	-0.1
18	278837.2	159724.1	532.3	530	-2.2
19	278642.9	164342.7	525.4	525	-0.4
20	308039.3	178942.4	524.4	525	0.6
21	312193.9	184132.2	530.7	530	-0.7
22	283208.0	196738.9	518.2	520	1.8

7.8.5 Sensitivity analysis

The main purpose of a sensitivity analysis is to quantify the effect of uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters (Anderson and Woessner 1992).

Sensitivity analysis was carried out in this study to test the effects on the model (head) if one parameter is changed whereas all other parameters are kept constant. During the steady state calibration, it was found that the horizontal hydraulic conductivity and recharge rate were very sensitive in comparison with respect to other parameters as shown in Table 7.7. The sensitivity analysis was based on the calculation of composite sensitivity of a parameter that means the sensitivity of all observations with respect to a relative change in the value of that parameter. According to the contents of the Jacobian matrix (the matrix of derivatives of observations with respect to parameters), PEST calculates a figure related to the sensitivity of each parameter with respect to all observations. The composite sensitivity of parameter I is calculated as:

$$S_i = (J^t QJ)_{ii}^{\ 1/2} /n$$

Where J is the Jacobian matrix and Q is the "cofactor matrix" which, in the present context, is a diagonal matrix whose elements are comprised of the square weights pertaining to observations; n is the number of observations with non-zero weights. Therefore, the composite sensitivity of the i'th parameter is the normalized (with respect to the number of observations) magnitude of the column of the Jacobian matrix pertaining to that parameter, with each element of that column multiplied by the weight pertaining to the respective observation. Recall that each column of the Jacobian matrix lists the derivatives of all (model-generated observations) with respect to a particular parameter. Immediately after calculating the Jacobian matrix, PEST writes composite parameter sensitivities to a "parameter sensitivity file" called "case.SEN" (Doherty 2000).

A high value of composite parameter sensitivity normally indicates that a parameter is particularly crucial to the model domain. It was concluded that the parameter named Hk_1 was the most sensitive parameter with respect to other parameters. This is due to lower values of total saturated thickness and transmissivity. The parameter named Hk_5 and Hk_8 have moderate sensitive with respect to other parameters. The parameter Hk_5 represents the transitional area where the contact interface of Basalt and B2/A7 is found. The parameter Hk_8 is less sensitive related to the above parameters and its sensitivity generated as a result of the lower saturated thickness. On the other side, the recharge amount of the parameter Rech_19 is very sensitive over the model domain. This is due to the low hydraulic conductivity and the limited saturated thickness. The Rech_20 is a moderate sensitive parameter that was affected by the limited saturated thickness. However, results of transient sensitivity analysis showed that the specific yield parameter related to other parameters in the model domain. Furthermore, the kind of the boundary (fixed head, flow boundary) was highly sensitive.

In addition, a sensitivity analysis for the lower aquifer was carried out. It was noticed that the hydraulic conductivity has a high value of composite parameter sensitivity with respect to other parameters. It is found that the parameters Hk_4, Hk_6 and Hk_8 were more sensitive parameters than others. The Hk_6 ($7.0*10^{-6}$ m/s) was a highly sensitive parameter due to the highest gradient of the water level and represents the recharge region. The Hk_4 was a highly sensitive parameter due to the lower saturated thickness and if represents the contact boundary with Zarqa Group. However, Hk_8 that represents the dominated value of the hydraulic conductivity over the model area has moderate sensitive parameter related to other parameters.

7.8.6 Model prediction (alternative model runs)

Further model scenarios were run based on the current abstraction of the year 2003 until the year 2025. The time period of 23 years was divided into 4 stress periods and 23 time steps so that the model results can be generated at the end of each year.

Table 7.7: Sensitivity analysis of the calibrated model parameters.

Parameter name	Current value (Calibrated model)	Sensitivity
Hk_1*	$6.0*10^{-5}$	High
Hk_2	$2.5*10^{-4}$	Moderate
Hk_3	$4.0*10^{-5}$	Low
Hk_4	$8.0*10^{-5}$	Low
Hk_5	$4.0*10^{-4}$	Moderate
Hk_6	$1.5*10^{-4}$	Low
Hk_7	$1.8*10^{-5}$	Low
Hk_8	$1.0*10^{-4}$	Moderate
Hk_9	$2.0*10^{-4}$	Low
Hk_10	$1.9*10^{-4}$	Low
Rch_17**	$1.0*10^{-12}$	Low
Rch_18	$1.0*10^{-12}$	Low
Rch_19	$1.3*10^{-8}$	High
Rch_20	$6.0*10^{-9}$	Moderate
Rch_21	$8.0*10^{-9}$	Low
Rch_22	$1.0*10^{-8}$	Low

* Hydraulic conductivity (m/s)_parameter number (Fig. 7.6)

** Recharge rate (m/s)_parameter number (southwestern parts of model area)

- First scenario (assuming fixed pumping rate based on the abstraction year 2003)

It is assumed that the abstraction from the whole model area will keep constant and undiminished until the year of 2025 based on the current abstraction of year 2003 ($113 *10^6$ m^3) for the upper aquifer. The predicted drawdown by the years of 2010 and 2025 is shown in Figs. 7.11 and 7.12, respectively. The maximum drawdown will reach 50 and 79 m by the year of 2010 and 2025 in the far north-eastern parts of the study area (south-east of Mafraq governorate, Um El-Jumal town). Furthermore, six pumping wells will completely stop supply water by the year of 2010 based on the assumption of continue pumping as in the same year of 2003. These wells are: Al2596 (Shihadeh Twal), AL3138 (Ghazi El Qaddoumi), AL3005 (Suleiman El Barbki), AL3426 (Central Intelligence 2), AL2454 (Barakat El Khreisha) and AL3334 (Hadram El Khraisha). In addition, 27 pumping wells will completely stop tapping water by the year 2025 as shown in Fig. 7.12. All of these wells are located close to Khaldiya town (between Khaldiya and Um El-Jumal towns). In addition, some dry cells have been developed as a result of continuous abstraction. However, the drawdown will not reach more than 5 m by the year 2025 at the southern parts of Amman Flexure and about 30 and 50 m as an average value (majority value) over the model area by the year 2010 and 2025, respectively. One of the most interesting results is that groundwater abstraction affects the amount of leakage from the upper aquifer to the lower aquifer.

Further model run was done in order to predict the accumulative drawdown for the lower aquifer. Based on the current abstraction of 2003 ($7.4 *10^6$ m^3), the model ran until the year

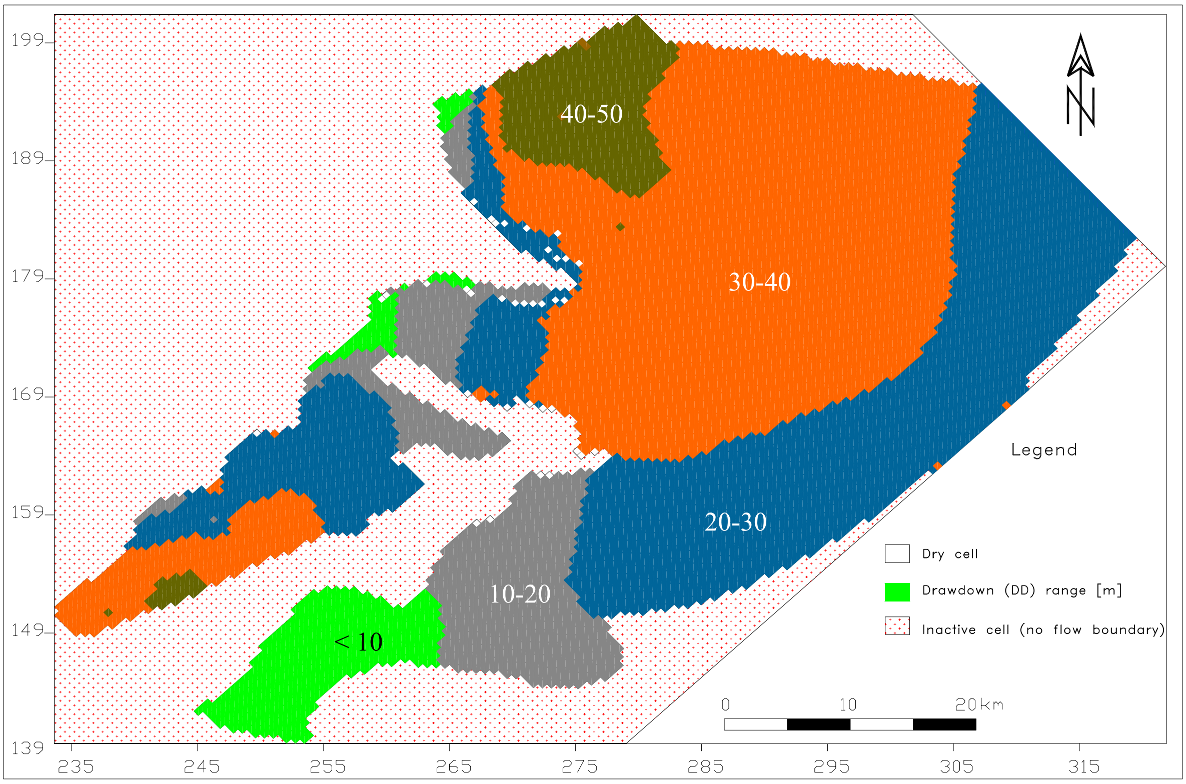

Fig. 7.11: Map of predicted drawdown by the year 2010 for undiminished groundwater withdrawal.

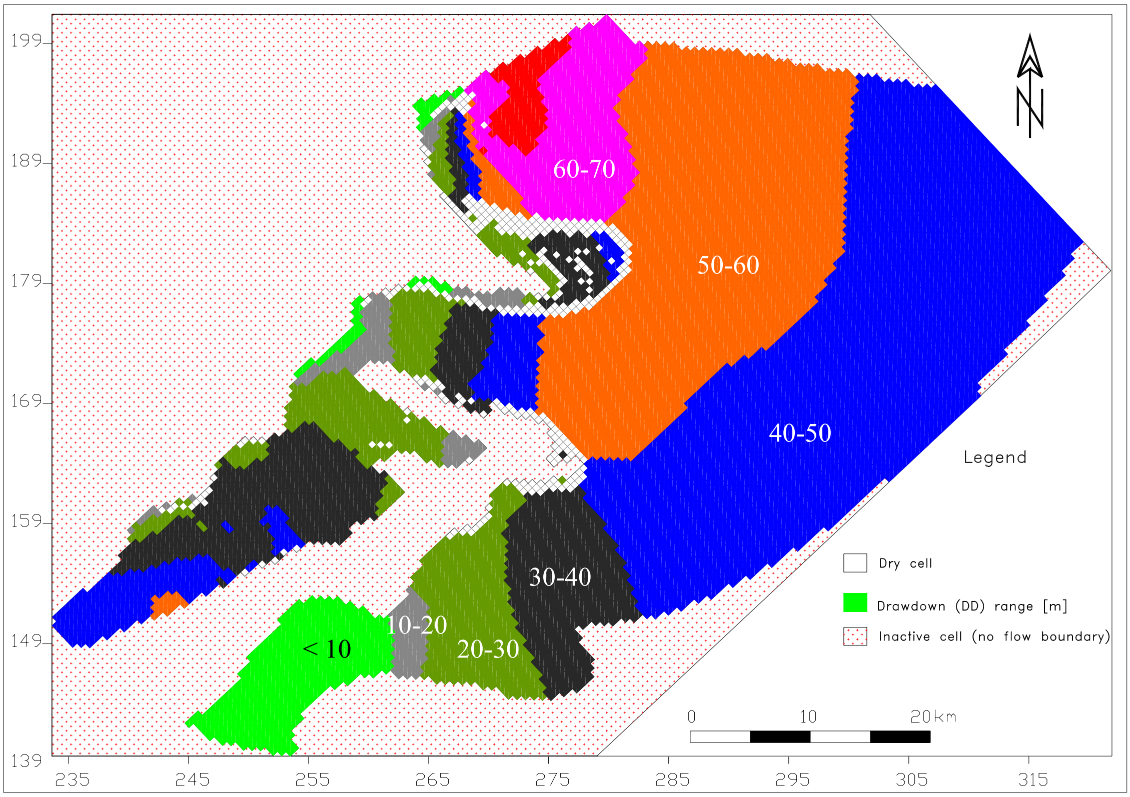

Fig. 7.12: Map of predicted drawdown by the year 2025 for undiminished groundwater withdrawal.

of 2025. The maximum predicted drawdown was found about 19 and 23 at Baq'a well field by the years of 2010 and 2025, respectively. This means that the fluctuation of drawdown in the lower aquifer is relatively constant. Also, the number of cones of depression has been reduced from three (Baq'a, Jerash and Dafali well fields) to two (Baq'a and Dafali well fields) based on the continuous abstraction of the year of 2003. The average value of drawdown in the lower aquifer excluding the area of cones of depression is less than 5 m by the year of 2025.

- Second scenario (assumed reduced pumping rate by one half based on the abstraction year 2003)

It is assumed that the current abstraction from the whole model area will be reduced to the half until the year 2005, i.e., the amount of abstraction will be 56.5 $*10^6$ m^3. The predicted accumulative drawdown by the years of 2010 and 2025 is shown in Figs. 7.13 and 7.14, respectively. The maximum accumulative drawdown will reach 42.6 and 50 m by the years of 2010 and 2025 in the far north-eastern parts of the study area (south-east of Mafraq governorate, Um El-Jumal town). Thus, the drawdown in that area will continue increasing in the order of less than 0.5 m per year. However, at the southern parts (northern parts of Amman Flexure) of the study area the maximum accumulative drawdown will reach 37.5 and 34.7 m by the years of 2010 and 2025, respectively. This means that the water level at this area will recover some meters in the next years. In comparison between the maximum accumulative drawdown at the year of 2005 (45.4 m) and by the year 2025 (50 m), it is concluded that the yearly average of drawdown will be about less than 0.25 m/yr. Therefore, from the regional scale and long-term drawdown points of view, the effects of drawdown in the study area will be relatively small. It means that the sustainable use of groundwater resources (upper aquifer) of the study area will be in the range of 60 $*10^6$ m^3 /yr.

- Third scenario (assumed reduced of pumping rate by three quarters based on the abstraction year 2003)

In this scenario, the total current abstraction will decrease from 113 $*10^6$ m^3 to about 85 $*10^6$ m^3. This scenario has been chosen because most of the previous studies considered that 85 $*10^6$ m^3 is the allowable use of the upper aquifer in the study area. The model results show that the drawdown will continue increasing in the range of more than 1.1 m per year. Also, no water level recovery can be seen in this scenario based on the long-term model prediction.

In addition, the maximum accumulative drawdown will reach 46 and 62.5 m by the years of 2010 and 2025, respectively. The maximum drawdown has been found at the far north-eastern parts (south-east of Mafraq governorate, Um El-Jumal town) and at the southern parts (northern parts of Amman Flexure) of the study area.

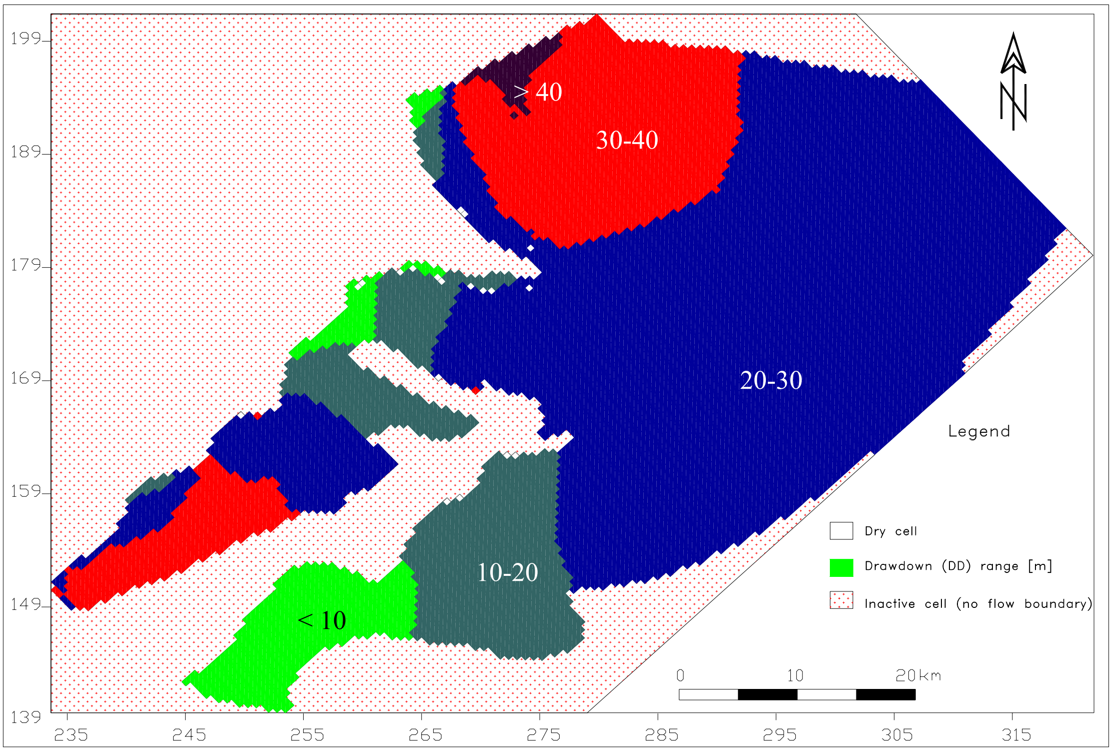

Fig. 7.13: Map of predicted drawdown by the year 2010 for continuous groundwater withdrawal (assumed reduction of pumping by 50%).

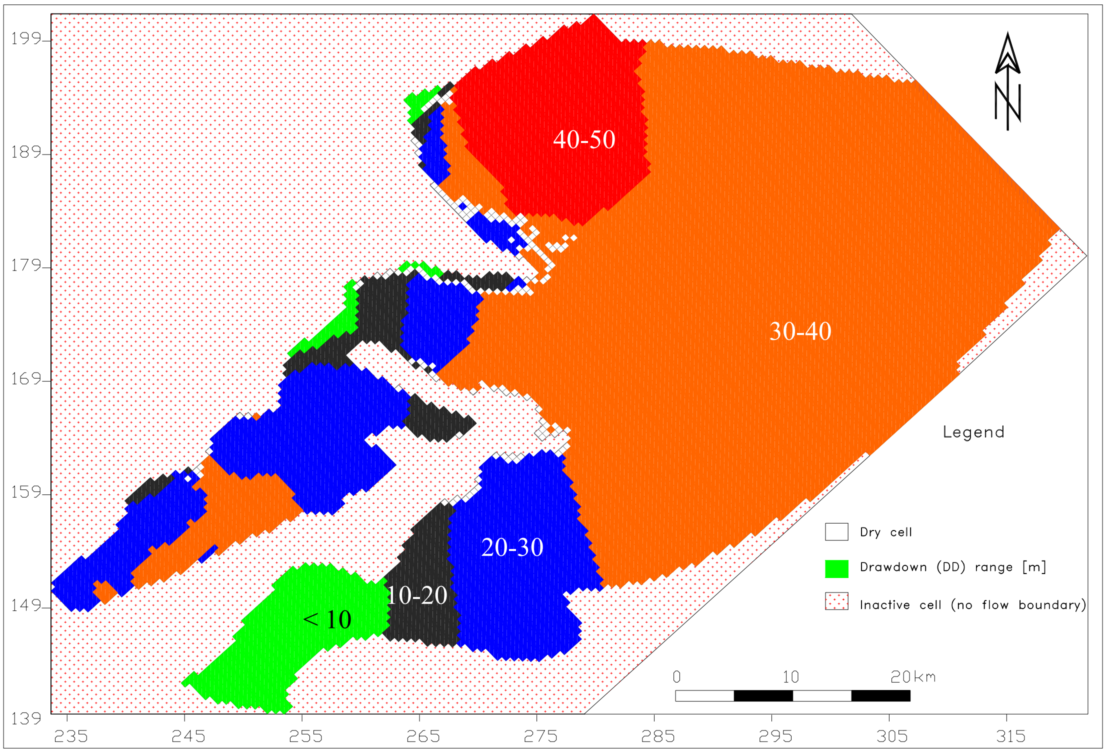

Fig. 7.14: Map of predicted drawdown by the year 2025 for continuous groundwater withdrawal (assumed reduction of pumping by 50%).

Thus, for sustainable development of water resources (upper aquifer) in Amman-Zarqa Basin groundwater abstraction should not exceed the amount of 60 $*10^6$ m^3 /yr. Also, the amount of abstraction at the far north-eastern parts (south-east of Mafraq governorate, Um El-Jumal town) must be reduced to the half of current amount in order to reach a sustainability development of water use.

8 SUMMARY AND CONCLUSIONS

Amman-Zarqa Basin is one of the most important basins in Jordan because this basin is located in the transitional zone between high lands in the west and the desert in the east. Also, more than 60% of the population of Jordan is living inside this basin. Amman-Zarqa Basin comprises an area of about 3918 km^2, where 89% is located in Jordan and 11% inside the Syrian territory. According to Palestine Grids coordinates, this basin lies between 215-306 East and 140-201 North.

The outcropping formations of the study area are extending from Lower Cretaceous (except wadi fill deposits) to recent age. Kurnub and Zarqa groups are exposed in the south-western (Baq'a Valley) and western parts (surrounding Jarash area) of the study area, respectively. Basalt outcrops in the eastern and northeastern parts of the study area. Belqa and Ajloun groups outcrop in other parts of the study area. Three-dimensional geological model was constructed which shows three main geological structures dominating in Amman-Zarqa Basin: Amman Syncline; Zarqa-Fault and Ramtha-Wadi Sirhan Fault.

The average annual rainfall in the study area ranges between less than 100 mm in the eastern and northeastern parts to more than 500 mm in the western and northwestern parts of the study area. Based on the frequency analysis, the maximum monthly rainfall in the study area corresponding to 50-years return period is about 155 mm. Long-term average (33 years) of the rainfall over the study area shows a continuous decline in rainfall depth within the range between 25 and 30 mm. The maximum monthly annual measured runoff is about $50.6 *10^6$ m^3 which corresponds to 50 years return period. Furthermore, the design flood for 50-years frequency (2% risk) period is expected to occur during November to February. Thus, the recommended flood to be considered in the design of the protection structure in Amman-Zarqa Basin is about $51 *10^6$ m^3. The calculated average annual direct recharge over the study area is ranging from $22.4 *10^6$ m^3 to 60.4 for normal and wet year, respectively.

Three aquifer systems are available in the study area. The upper and lower aquifers are major and the middle aquifer is a minor one. The upper one was studied in detail while the lower one was considered in order to study the hydraulic interaction between them. Basalt and B2/A7 (limestone aquifer) are called the upper aquifer while the Kurnub (sandstone aquifer) is called the lower aquifer. The thickness of Basalt increases from the central parts (about 50 m) towards northeastern parts (about 400 m) of the study area. The average thickness of B2/A7 aquifer is about 200 m. The thickness of Kurnub aquifer increases from southeastern to northeastern parts of the study area, 200-500 m, respectively.

65 pumping tests analysis have been evaluated for the upper aquifer. The transmissivity of Basalt ranges from 4.3 to 29,700 m^2/d with an average of about 7000 m^2/d, corresponding to a mean permeability of 20 m/d. On the other hand, the transmissivity of B2/A7 aquifer varies between 4.7 and 2200 m^2/d with an average of about 467 m^2/d, corresponding to a

mean permeability of 7 m/d. Due to the complexity of the upper aquifer, there was no transmissivity trend distinguished. However, there is a trend in transmissivity for the lower aquifer. The transmissivity of the lower aquifer increases from west to east direction to reach the maximum value of about 1000 m^2/d.

Groundwater in the upper aquifer is unconfined (phreatic condition) over the most parts of the study area. The dominant direction of the groundwater flow in the upper aquifer is from southwest and northeast to the far northwest, east and central parts (Seil el Zarqa) of the study area. On contrast, the type of groundwater in the Kurnub aquifer is confined except the Baq'a Valley (water-table).

Two major environmental aspects have been evaluated in this study; i.e., dams and wastewater treatment plants (WWTP). The water levels of downstream wells at As-Samra WWTP (the largest WWTP in Jordan) have been rising considerably and the groundwater quality is highly deteriorated. Also, all downstream wells of As-Samra WWTP turned to become not potable water resources as well as for irrigation purposes (restricted irrigation) in some wells. The water quality of King Talal dam (the largest water body in Jordan) is acceptable only for restricted irrigation purposes with slightly increases in TDS, BOD_5, and NO_3.

Groundwater samples were collected from representative wells (87 samples) in the study area being investigated hydrochemical parameters. According to statistical analysis (cluster analysis) three groups have been distinguished. Group-1 represents the well fields between Amman and Ruseifa regions. This group shows low salinity and high concentration of NO_3. Group-2 shows moderate salinity and low concentration of NO_3. This group includes the well fields between Ruseifa and Zarqa regions as well as the far northeast well fields in the study area. Group-3 shows high salinity and moderate value of NO_3. This group represents most of the well fields close to Khaldiya and Dhuleil regions. Three factors were distinguished in this study based on Varimax rotation method. These factors are: salinity factor, pollution factor and carbonate factor.

A three-dimensional groundwater flow model for upper and lower aquifers was built and calibrated for steady and transient states. The groundwater budget of the whole model domain was calculated. 61.8 $*10^6$ m^3/yr flows into the upper aquifer as underflow from Jabal Al Arab through the Basalt and 45.5 $*10^6$ m^3as renewable recharge from excess rainfall. On the other hand, 66 $*10^6$ m^3/yr and 3.4 $*10^6$ m^3/yr flow out as cross boundary from the upper aquifer into Azraq and Yarmouk Basins, respectively. In addition, there is 26.8 $*10^6$ m^3/yr as underflow towards Zarqa River and natural spring discharge. The total amount of leakage into the lower aquifer is about 12.2 $*10^6$ m^3/yr.

Three scenarios have been taken into account to predict the aquifer response and managing the groundwater resources in sustainable way. The **first scenario** assumed fixed pumping rate based on the abstraction year 2003. The maximum accumulative drawdown by the years of 2010 and 2025 will reach 50 and 79 m, respectively. The maximum drawdown will be in the far northeastern parts of the study area (southeast of Mafraq governorate, Um El Jumal town). In addition, six wells will completely stop tap water by the year of 2010 and 27 wells will completely stop tapping water by the year of 2025. These wells are located between Khaldiya and Um El Jumal towns). A **second scenario** assumed reducing of pumping rate by one half based on the abstraction year 2003. The maximum accumulative drawdown will reach 42.6 and 50 m by the years of 2010 and 2025, respectively. The maximum drawdown will be again in the far northeastern parts of the study area (southeast of Mafraq governorate, Um El Jumal town). On the other hand, the water level will rise up at the southern parts of the study area. It is concluded that the yearly average drawdown will be about less than 0.25 m/yr. Thus, from the regional scale and long-term drawdown point of view, the optimal use of groundwater resources (upper aquifer) of the study area will be in the range of $60 * 10^6$ m^3/yr. A **third scenario** assumed reducing of pumping rate by three quarters based on the abstraction year 2003. The modeled results show that the drawdown will continue increasing in the range of more than 1.1 m/yr. Also, water level recovery will not occur in this scenario based on the long-term model prediction.

Therefore, it is recommended to consider the following items for now and further investigations:

1. The total groundwater withdrawal in Amman-Zarqa Basin (upper aquifer) should not exceed $60 * 10^6$ m^3in order to reach a sustainable use of the basin.

2. The total groundwater withdrawal in Baq'a Valley (lower aquifer) should not exceed $7 * 10^6$ m^3per year.

3. It is strongly recommended to drill new boreholes to reach the lower aquifer (Kurnub aquifer), in particular in the northeastern and eastern parts of the study area. This will improve the knowledge about the water level and provide more information about the hydraulic parameters and will improve the estimation of the leakage rates.

4. It is highly recommended to reduce the current amount of groundwater abstraction of the well fields between Khaldiya and Um El-Jumal towns in order to avoid over pumping and drying up of the well field.

5. It is recommended to construct a new local model surrounding As-Samra WWTP. This model will give better estimations concerning the amount of seepage into the aquifer.

6. The model boundaries need to be modified for upper and lower aquifers on the long-term effects of groundwater withdrawal.

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10 APPENDICES

Appendix 1.1: Description of soil units of Amman-Zarqa Basin (modified after MOA 1994)

Soil Unit	Description	Soil association	Description
Abyad (ABY)	Gently undulating depositional plains of Quaterbary alluvium and loess overlying Al Hisa Phophorite and Muwaqqar Chalk and Marl formations. Gradients <10%; altitude 750-950 m: relative relief <10m: steppe grassland.	Xerochreptic Camborthid and Calciorthid	**70%**: deep (>80cm) silty clay loam on silty clay: very highly calcareous: weakly to moderately saline: gradients mainly <5%.
Ajlun (AJL)	Deeply dissected limestone plateau with colluvial filled valleys and long, steep rocky slopes to valleys: undulating plateau edge and crests with rock outcrops and colluvial mantled landslip zones with limestone boulders: altitude 500-1200 m: relative relief 250m.	Typic Xerochrept Lithic Xerochrept Rock	**30%**: deep and moderately deep (>50cm) stony silty clay and clay: non to moderately calcareous and non-saline: occurs on colluvial material on sleep middle, upper slopes and on plateau deposits and lower valley slope mantels: gradients 1-60%. **20%**: shallow (25-50cm) stony and very stony silty clay and clay: moderately calcareous and non-saline: occurs on rounded hill crests in complex with Typic Xerochrepts, and in colluvium of steep upper and middle slopes: gradients 1-60%. **25%**.
Abu Salih (ALI)	Finely dissected limestone uplands and slopes: moderately dense dendritic drainage: gradients in range 5-35% with some valley sides to 70%: altitude 500-1000m: relative relief 100-150m.	Typic and Calcixerollic Xerochrept Rock	**40%**: deep (>80cm) silty clay: highly calcareous and non-saline: occurs in colluvium of middle and lower slopes and in valley bottom alluvium: gradients 2-35%. **20%**
Tell Alluba (ALL)	Deeply dissected upper part of escarpment on limestones, marls and cherts of the Ajlun and Belqa Groups: includes rock faces, landslip zones, colluvium and fans: altitude 300 to 1200m: relative relief 250-300m.	Calcixerollic Xerochrept Typic Xerochrept Rock	**25%**: moderately deep and deep (>50cm) silty clay and clay: highly calcareous and non-saline:: occurs on moderately sloping colluvial fans and on local benches cut in Pleistocene alluvial fill: gradients 2-23%. **15%**: moderately deep (50-80cm) very stony sandy clay loam, clay loam and clay: highly calcareous and non-saline: occurs on sections of upper escarpment in colluvium and landslips: gradients 5-80%. **25%.**
Anjara (ANJ)	Deeply dissected uplands and gorges on Ajlun Group limestones, chalks and marls: very steep slopes and narrow convex crests: altitude 0 to 800m: relative relief 400m.	Typic Xerochrept Lithic Xerochrept Rock	**25%**: deep and moderately (>50cm) silty clay and clay on sleep colluvial slopes and in valleys (10-30% stones): weakly to moderately calcareous and non-saline: gradients 8-50%. **15%**: shallow (25-50cm) stony-very stony clay loam: occurs on sleep colluvial slopes: moderately calcareous and non-saline: gradients 10-50%. **15%**.

Appendix 1.1 (continue)

Soil Unit	Description	Soil association	Description
Attarat (ATT)	Undulating pediments and alluvial fans derived from Umm Rijam and Muwaqqar Chalk and Marl Formations: includes old and active fans: gradients 1-20%: altitude 600-1000m: relative relief 25m.	Typic Camborthid and Cambic Gypsiorthid	**35%**: moderately deep to deep (>50cm) gravelly and very gravelly silty clay loam to clay: very high calcareous and saline and sometimes gypsiferous: occurs mainly on pediments on higher part of unit and depressions and on active fans: gradients <5%.
		Typic Calciorthid	**15%**: shallow and deep (25-80cm) gravelly and very gravelly silty clay loam to clay loam usually on paralithic limestone: very high calcareous and saline and sometimes gypsiferous: occurs on pediments association with Typic Camborthids and Cambic Gypsiorthids: gradients <5%.
		Lithic Torriorthent and Gypsiorthid	**15%**: very shallow to shallow (<50cm) gravelly to very gravelly silty clay loam: very high calcareous, often gypsiferous and very saline: occurs on eroded pediments: gradients 1-20%.
Aydoun (AYD)	Finely dissected uplands on Belqa limestone producing narrow convex crests and steep slides with banded rock outcrops: altitude 700-900m: relative relief 50-100m: xeric moisture regime and Mediterranean-steppe transition bioclimatic zone.	Calcixerollic and Typic Xerochrept	**30%**: deep (>80cm) silty clay loam and silty clay: very highly calcareous and non-saline: occurs in colluvium, in gently sloping colluvial and loess of mid and lower slopes: gradients 1-20%.
		Lithic Xerorthent and Xerochrept	**30%**: predominantly very shallow (<25cm) very stony silty clay loam and silty clay: Xerorthents predominate: occurs on steep hill sides: gradients 5-30%.
		Vertic Xerochrept	**15%**: deep (>80cm) silty clay and clay: well developed cracks in summer and moderately vertic properties: occurs on bottom slopes and plateau remnants: gradients <8%.
Hisban (BAN)	Rolling hills on Belqa limestone along upper edge of the escarpment to Dead Sea: broad infilled valleys and moderately long slopes in range 5-25%: altitude 750-950m: relative relief 50-100m.	Typic Xerochrept	**30%**: moderately deep and deep (>50cm) silty clay or clay with up to 20% stone content: occurs on mid-slopes: moderately calcareous: gradients 5-15%.
		Calcixerollic Xerochrept	**25%**: deep and moderately deep (>50cm) silty clay on clay with up to 15% stone content: occurs on gently sloping plateau remnants and mid-slopes: strongly calcareous: gradients 5-15%.
		Lithic Xerorthent	**15%**: very shallow (<25cm) very stony silty clay on limestone: occurs on crests, upper slopes and valley sides: very stony surface: strongly calcareous: gradients 5-25%.

Appendix 1.1 (continue)

Soil Unit	Description	Soil association	Description
Baqa'a (BAQ)	Enclosed depression in eroded anticline on Ajlun Group Limestone and Kurnup Sandstone at base: very steep rocky upper slopes in limestone, steep upper slope: landslips and deep colluvial mantle in valley floor: altitude 650-1000m: relative relief<50m: xeric moisture regime and Mediterranean-steppe transition bioclimatic zone.	Entic Chromoxeret Calcixerollic Xerochrept Typic and lithic Xerochrept	**35%**: deep (>80cm) clay and silty clay: moderately well cracked with develop vertic properties: highly calcareous and non-saline: occurs in deep colluvial /loessic mantle at low levels within basin: gradients <8%. **25%**: deep and moderately deep (>50cm) clay and clay loam: weakly cracked: moderately calcareous and non-saline: occurs in colluvial /loessic mantle of lower slopes within basin: gradients <10%. **25%**: shallow to moderately deep (25-80cm) stony and very stony clay loam and silty clay loam: moderately calcareous and non-saline: occurs on steep landslip colluvium and upper slopes: gradients 10-47%.
Jabir (BIR)	Similar to the Bureiqa unit, but lies downslope of the hilly Buaydah and Aydun units and lies within the xeric-aridic transition moisture regime and the steppe grassland zone: altitude 600-700m: relative relief 25-50cm.	Xerochreptic Camborthid and Calciorthid Lithic Xeric Torriorthent	**65%**: deep (>80cm) silty clay loam: Calciorthids predominate: very highly calcareous and weakly to moderately saline: occurs in loessic mantle overlying alluvial fans: gradients mainly <5%. **20%**: very shallow (<25cm) silty clay loam: highly calcareous and weakly saline: occurs on upper slopes of unit where it merges into the Buraydah and Aydun units: gradients 0-15%.
Bureiqa (BUQ)	Extensive alluvial fans derived from limestone with loessic influence: lies to the east of the Irbid Plains unit: long gentle slopes with wadis slightly incised into the plains: xeric moisture regime and Mediterranean-steppe transitional bioclimatic zone: altitude 550-650m: relative relief <25m.	Calcixerollic and Typic Xerochrept Lithic (Xerochreptic) Camborthid	**75%**: deep (>80cm) silty clay loam on silty clay: typic subsidiary: very highly calcareous and non-saline: occurs in old alluvial fan parent material with deep surface loess mantle: gradients <5%. **10%**: shallow (25-50cm) stony and very stony silty clay: highly calcareous and non-saline: occurs on low limestone outcrops with thin loess cover: gradients 0-18%.
Mudeisis (DEI)	Finely dissected limestone and chert plateau on Umm Rijam Chert and Limestone and Muwaqqar Chalk producing undulating to rolling terrain with steep slopes, narrow crests and broad valley floors, colluvial mantles on hill slopes, alluvium in valley floors and loess influence: altitude 600-900m: relative relief 50-100m.	Xerochreptic Camborthid and Calciorthid Lithic Xeric Torriorthent Rock	**40%**: deep (>80cm) clay loam and silty clay loam occurring in colluvium of hill slopes and in valley alluvium: highly calcareous and weakly saline: gradients <10%. **15%**: very shallow (<25cm) stony silty clay loam on limestone of upper slopes, hill crests and scarp slopes: highly calcareous and weakly saline: gradients 2-20%. **10%**.

Appendix 1.1 (continue)

Soil Unit	Description	Soil association	Description
Dhuleil (DHU)	Wadi alluvium and depositional basins with alluvium derived largely from basalt, but with some admixture from limestone: xeric-aridic transitional moisture regime: altitude 600-750m: relative relief <10m.	Xerochreptic Camborthid and Calciorthid Xerertic Camborthid	**70%**: deep (>80cm) silty clay loam, occasionally silty clay: highly calcareous and weakly to non-saline, but very saline after irrigation: gradients <2%. **15%**: deep (>80cm) silty clay: moderately cracked but vew vertic properties: occurs on wadi terraces: highly calcareous and weakly saline: gradients <2%.
Fuluq (FUL)	Highly dissected limestones, cherts and marls of the Umm Rijam and Muwaqqar Chalk and Marl Formations: steeply sloping crests and ridges with colluvial mantels on mid slopes and infilling of valleys: desert bioclimatic zone: altitude 550-800m: relative relief 50-100m.	Typic Calciorthid Lithic (Xerochreptic) Camborthid Cambic Gypsiorthid	**30%**: moderately deep to deep (>50cm) very gravelly to stony silty to sandy clay loam: very highly calcareous and saline and very saline: occurs on crests and upper slopes: gradients 0-15%. **30%**: shallow to moderately deep (25-50cm) structured stony silty clay loam: very highly calcareous and strongly saline: occurs on colluvial slopes and pediments: gradients 2-15%. **20%**: sometimes redder, moderately deep (50-80cm) stony and very stony silty to sandy clay loam: very highly calcareous, moderately gypsiferous and very saline: occurs on crests and ridges: gradients 2-23%.
Ghabawi (GAB)	Undulating plateau formed by weak dissection of Amman silicified limestone and Umm Gudran Formation: low rounded crests with limestone and chert outcrops, long slopes with colluvial and loessic mantle and alluvial fans: altitude 650-850m: relative relief 25-50m.	Xerochreptic Camborthid and Calciorthid Lithic (Xerochreptic) Camborthid and Lithic Xertic Torriorthent	**60%**: moderately deep to deep (>50cm) clay loam and silty clay loam: very highly calcareous and weakly to moderately saline: formed in colluvium, loessic mantles and alluvial fans: gradients <5%. **25%**: shallow and very shallow (<50cm) occasionally stony, silty clay loam: very highly calcareous and weakly saline: occurs on rounded crests and valley shoulders: gradients <20%.
Rihab (HAB)	Moderately dissected limestone plateau on Ajkun and Belqa Group rocks: deep colluvial mantles with rocky limestone ridges and hills: xeric moisture regime: altitude 800-950m: relative relief <500m.	Typic and Calcixerollic Xerochrept Lithic Xerothents and Xerochrept	**40%**: deep (>80cm) silty clay and clay: calcareous and non-saline: occurs as a complex in deep colluvial mantles: gradients <10%. **30%**: very shallow and shallow (0-50cm) silty clay loam to clay: stone content 10-30%: calcareous and non-saline: occurs as a complex on hillcrests, steep upper slopes and rocky ridges: gradients 2-43%.

Appendix 1.1 (continue)

Soil Unit	Description	Soil association	Description
Hallabat (HAL)	Quaternary alluvial fan system with recent wadi alluvium derived largely from Mesozoic calcareous rocks but with Aeolian additions gentle alluvial/loessic slopes with alluvial depressions: xeric-aridic transitional moisture regime: thermic temperature regime: grassland steppe bioclimatic zone: altitude 550-700m: relative relief <10m.	Xerochreptic Camborthid and Calciorthid Calcixerollic Xerochrept	**60%**: deep (>80cm) silty clay loam: very highly calcareous and weakly saline, but strongly saline after irrigation: occurs in alluvial fans and wadi alluvium: gradients <3%. **25%**: as above but occurs in valley bottoms and Qa'a receiving additional moisture.
Qihat (HAT)	Strongly dissected Amman Silicified Limestone and Muwaqqar chalk producing steep hills with banded outcrops of limestone and chert with angular hill crests broad alluvial valleys and colluvial mantels on hill slopes: altitude 650-850m: relative relief 50-100m.	Xerochreptic Camborthid and Calciorthid Lithic (Xerochreptic) Camborthid Rock	**25%**: moderately deep and deep (>50cm) clay loam and silty clay loam in mid slope colluvium and bottom slope alluvium: highly calcareous and weakly saline: gradients 2-10%. **20%**: shallow (<50cm) stony silty clay: occurs on upper slopes and hillcrests overlying limestone: highly calcareous and weakly saline: gradients 2-15%. **15%**.
Ibbin (IBB)	Undulating to roiling dissected plateau on limestone of the Belqa and Ajlun Groups including Wadi Es Sir Limestone and Amman Silicified Chert and Limestone: consists of undulating plateau with colluvial mantles and limestone pavements, steep valley sides with colluvium and rock bands: altitude 850-1100m: relative relief 250m.	Typic Xerochrept Lithic Xerochrept Lithic Xerochent and Typic Xerorhent Rock	**25%**: deep (>80cm) stony silty clay loam and silty clay: weakly calcareous and non-saline: occurs in colluvium of valley sides in upper and mid-slope positions: gradients 2-25%. **15%**: shallow (25-50cm) silty clay and clay: weakly to moderately calcareous and non-saline: occurs in same positions as Typic Xerochrepts, but on the steepest slopes: gradients 12-45%. **15%**: very shallow to moderately deep (0-80cm) stony and very stony silty clay: moderately calcareous and non-saline: occurs in convex crests and rocky plateau areas: gradients 2-40%. **20%**.
Tel Umeiri (IRI)	Rolling hills formed on Belqa limestone with a high proportion of Amman silicified limestone and Wadi Umm Gudran Formations: dendritic pattern of broad valleys in filled by colluvium: crests and slopes covered by dense angular chert: altitude 750-1000m: relative relief 50-100m.	Typic Xerochrept Rock	**60%**: deep and moderately deep (50-80cm) clay loam with 20-30% stones: overlies siliceous limestone: weakly calcareous: very stony surface occurs on mid and lower slopes: gradients 5-12%. **10%**.

Appendix 1.1 (continue)

Soil Unit	Description	Soil association	Description
Jerash (JER)	Deeply dissected plateau on limestone of the Ajlun Group with very steep slopes in upper catchments and gentler slopes with colluvials mantle in lower part of the catchments: deep, partly dissected colluvial/alluvial fills in major valleys: altitude 350-1000m: relative relief 250m.	Typic Xerochrept Calcixerollic Xerochrept Rock	**30%**: deep and moderately deep (50->80cm) stony and very stony, clay, silty clay and clay loam: moderately to strongly calcareous and non-saline: occurs in deep of middle and lower slopes of colluvium and on steep middle and upper slopes: gradients 1-53%. **20%**: deep (>80cm) clay and clay loam: highly calcareous and non- saline: occurs on moderately sloping upper to lower slopes in colluvium: gradients 8-20%. **15%**.
Nisab (NIS)	Dissected plateau Belqa Grouplimestones producing narrow interfluve crests and long valley slopes: colluvials mantle on upper and middle slopes, alluvial fans on lower slopes: altitude 550-750m: relative relief 100m.	Xerochreptic Camborthid and Calciorthid Lithic (Xerochreptic) Camborthid Rock	**40%**: deep (>80cm) silty clay loam and clay loam: very highly calcareous and weakly to moderately saline: formed in loessic gradients <10%. **40%**: shallow and very shallow (<25-50cm) very stony silty clay loam: formed in thin loess mantle of upper slopes, crests and valley shoulders: very highly calcareous and weakly saline: gradients 0-50%. **5%**.
Sabha (SAB)	Undulating plain on Quaternary basalt dissected by parallel wadis producing broad convex crests and moderately steep slopes with broad valleys:xeric-aridic transitional moisture regime: altitude 800-1150m: relative relief 50m.	Xerochreptic Calciorthid Xerochreptic Paleorthid Rock	**40%**: deep (>80cm) silty and sandy clay loam to silty clay: dense calcic horizon in many soils: very highly calcareous and weakly saline: occurs on most facets in complex with Xerochreptic Paleorthids: gradients 1-6%. **25%**: very shallow to moderately (<80cm) silty clay to silty clay loam: 10-30% stone content: overlies petrocalcic. **10%**.
Sakhra (SAK)	Bouldery calcareous colluvium of landslip zone on steep middle slopes: derived mainly from limestone: lies downslope of plateau and rounded hill crests of Ajlun unit: altitude 600-1100m: relative relief 150-200m.	Typic Xerochrept Lithic Xerochent and Typic Xerorhent Calcixerollic Xerochrept	**40%**: deep (>80cm) stony clay and silty clay: weakly to non-calcareous and non-saline: occurs on all facets of the unit: gradients 9-45%. **25%**: shallow and very shallow (0-50cm) stony and very stony silty clay and clay: moderately calcareous and non-saline: occurs on all facets of the unit gradients 1-33%. **10%**: deep and moderately deep (>50cm) stony silty clay and clay: moderately calcareous and non-saline: occurs in association with Lithic Xerochrepts: gradients 5-35%.

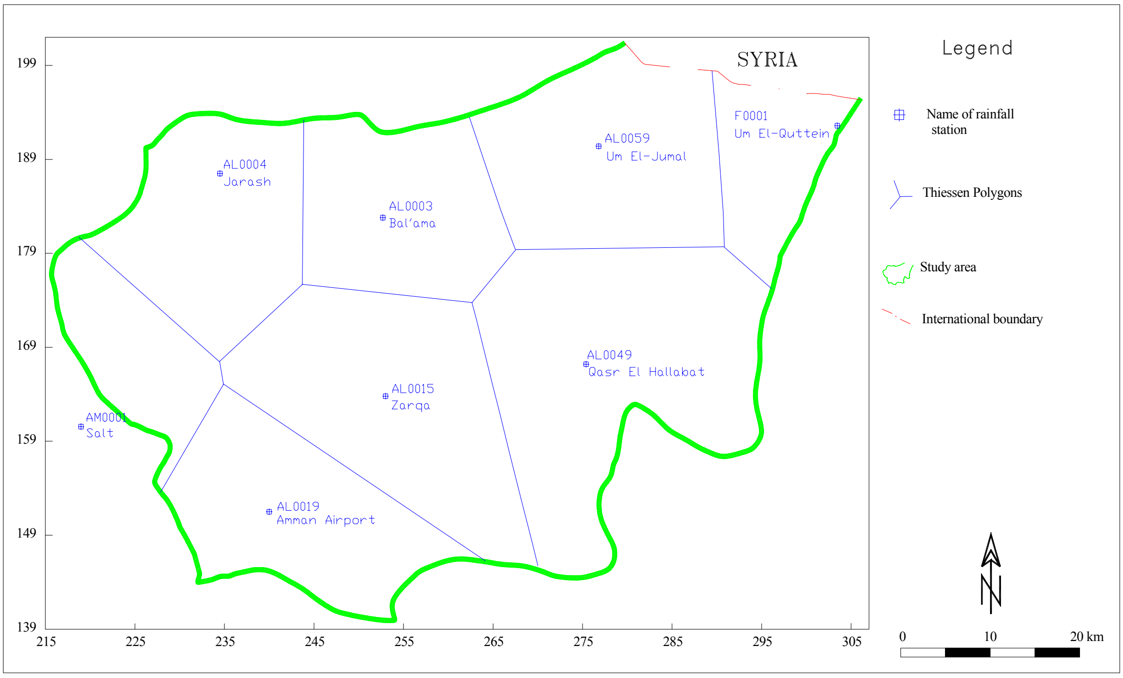
Appendix 1.1 (continue)

Soil Unit	Description	Soil association	Description
Mudeisisat (SIS)	Steeply sloping eroding escarpment on Umm Rijam Chert and Limestone with Muwaqqar Chalk on lower slopes: composed of escarpment, stony talus and pediment with isolated outliers forming steep hills: altitude 750-950m: relative relief 100-150m.	Xerochreptic Calciorthid and Camborthid Lithic (Xerochreptic) Camborthid Rock	**20%**: deep and moderately deep (>50cm) stony silty and loam: formed in stony colluvium and alluvium on mid and lower slopes: highly calcareous and weakly saline: gradients 2-15%. **20%**: very shallow to shallow (25-<50cm) very stony silty clay loam on limestone: occurs on colluvium: highly calcareous and moderately saline: gradients 7-30%. **35%**.
Tarmah (TAR)	Undulating plains on old alluvial/colluvial fan systems on Umm Rijam Chert: isolated low rounded hills and braided wadi systems: altitude 700-800m: relative relief 10m.	Xerochreptic Calciorthid	**75%**: deep (>80cm) silty clay loam on gently sloping colluvial and old alluvial mantels: highly calcareous and moderately saline: gradients <5%.
Ramtha (THA)	Flat to gently sloping lava plateau with coarse sub-parallel drainage formed on Quaternary basalts: deep aeollian mantle with broad convex interfluves occasionally with calcrete outcrops: predominantly in xeric-aridic transitional moisture regime: altitude 500-1000m: relative relief <25m.	Xerochreptic Calciorthid Xerochreptic Paleorthid Rock	**40%**: deep (>80cm) silty clay and silty clay loam: very highly calcareous and weakly to moderately saline: occurs on very gently sloping middle and lower slopes and in broader valley: gradients <4%. **20%**: very shallow to moderately deep (25-80cm) stony and very stony clay loam and silty clay loam on a petrocalcic horizon: bouldery surface and up to 35% stones in soil matrix: occurs on low interfluves and upper and middle slopes: gradients 1-10%. **5%**.
Huwaynit (WAY)	Very gently undulating Quaternary lava plain with coarse sub-parallel drainage: aeolian mantle thins to south and east: low convex interfluves with loess covered slopes, rocky valley sides and small drainage basins: xeric-aridic transitional moisture regime: altitude 500-1000m: relative relief 25-50m.	Xerochreptic Calciorthid and Lithic (Xerochreptic) Camborthid Xerochreptic Camborthid and Paleorthid Rock	**30%**: shallow to moderately deep (25-80cm) silty loam and silty clay loam: very highly calcareous and weakly saline: occurs on crests, upper and mid slopes, occasionally in wadi alluvium: gradients <3%. **30%**: very shallow to moderately (0-80cm) silty clay loam to silty clay with high stone content overlying basalt: highly calcareous and weakly saline: occurs on upper and bottom slopes, wadis and crests: gradients: <5%. **10%**.

Appendix 1.1 (continue)

Yaduda (YAD)	Very gently undulating plain with deep colluvial and loess fill: broad shallow valleys with incised wadis: altitude 700-730m: relative relief <25m.	Calcixerollic Xerochrept Typic Xerochrept	**75%**: deep (>80cm) silty clay and clay: highly calcareous: formed in loess: gradients <5%. **15%**: deep (>80cm) silty clay-clay: highly calcareous: occurs in shallow valleys: alluvial parent materials: gradients <2%.
Soil Unit	**Description**	**Soil association**	**Description**
Zarqa (ZAR)	Very deeply dissected gorge and valley floor of Zarqa River cut into Kurnub sandstone: gentler upper slopes cut in Naur limestone with colluvial mantle: terrace alluvium and mixed colluvium of sandstone and limestone in valley bottom and lower slopes: xeric-aridic moisture regime and thermic and hyperthermic temperature regimes: altitude 500-650m.	Typic and Calcixerollic Xerochrept Ustochreptic Camborthid and Calciorthid Rock	**35%**: moderately deep and deep clay loam and silty clay loam: strongly calcareous and non-saline: formed in colluvium overlying limestone: gradients 6-30%. **20%**: deep (>80cm) fine sandy clay loam and clay loa: highly calcareous and non to weakly saline: occurs on steep lower slopes on mixed sandstone and limestone colluvium below 250m: gradients 20-45%. **10%**.
Uzaymi (ZAY)	Deeply dissected middle section of escarpment in calcareous rocks of the Ajlun Group: very steep, rocky slopes on rock faces, interfluves and wadi sides with associated colluvial fans: xeric-aridic moisture regimes north of Dead Sea: thermic and hyperthermic temperature regime: altitude 100-900m: relative relief 300-400m.	Ustochreptic Calciorthid and Camborthid Typic and Lithic Xerochrept Rock	**35%**: moderately deep and deep (>50cm) stony to very stony clay loam and clay: highly calcareous and weakly saline: found in lower parts of the unit at altitude between 100-600m: gradients 4-70%. **10%**: shallow to moderately deep (25-80cm) very stony clay loam and silty clay loam: moderately calcareous and non-saline: occurs in steep colluvium in higher part above 600m: gradients 4-70%. **25%**.
Zumlat (ZUM)	Undulating, occasionally rolling, plain of Quarter nary lavas with rocky interfluves and alluvial basins: loess mantle on gentle slopes: xeric-aridic transitional moisture regime: altitude 600-1150m: relative relief 25-50m.	Xerochreptic Calciorthid Lithic Torriorthent and Lithic Xeric Torriorthent Xerochreptic Paleorthid and Camborthid Rock	**15**%: deep (>80cm) silty clay-silty clay loam: highly calcareous and non-moderately saline: gradients <5%. **15**%: very shallow (<25cm) stony-very stony silty clay loam: very highly calcareous and moderately saline: founds on crests and valley sides: gradients 2-15%. **22**%: very shallow to deep (25->80cm) silty clay and silty clay loam: highly very highly calcareous and weakly-moderately saline: occurs on middle and lowe slopes: gradients 4-7%. **15%**

Appendix 2.1: Thiessen polygons of representative rainfall stations over Amman-Zarqa Basin.



Appendix 2.2A: Monthly and annual rainfall for Bal'ama station (AL003).

Water Year	Months								Total (mm)
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	
70/71	0.0	5.5	53.9	40.9	42.4	58.2	163.4	0.0	364.3
71/72	0.0	18.0	80.7	11.7	72.4	50.0	12.7	0.0	245.5
72/73	0.0	33.0	0.4	52.6	15.0	49.6	7.9	0.0	158.5
73/74	0.0	54.5	27.0	130.4	65.3	10.0	14.0	0.0	301.2
74/75	0.0	0.0	20.0	2.3	99.7	45.3	0.0	0.0	167.3
75/76	0.0	11.8	32.6	29.3	50.8	69.0	5.5	0.0	199.0
76/77	5.0	20.0	0.0	38.1	17.0	47.5	27.7	0.0	155.3
77/78	19.8	0.0	63.4	15.5	19.2	40.0	0.0	0.0	157.9
78/79	4.8	0.0	34.0	16.3	29.5	40.5	0.0	0.0	125.1
79/80	15.0	62.7	77.6	70.0	82.0	56.9	13.0	0.0	377.2
80/81	0.0	7.0	72.9	25.5	61.4	28.8	7.6	0.0	203.2
81/82	0.0	15.8	2.2	46.0	46.5	30.9	16.0	3.0	160.4
82/83	7.6	23.1	14.1	81.7	97.5	84.5	1.0	0.0	309.5
83/84	0.0	0.0	0.0	30.0	24.0	85.5	7.6	0.0	147.1
84/85	7.0	15.3	19.7	40.0	114.6	13.1	6.6	6.0	222.3
85/86	5.5	4.2	13.8	19.5	70.0	4.0	7.3	8.0	132.3
86/87	7.0	94.5	25.0	61.8	23.0	31.6	0.0	0.0	242.9
87/88	11.0	5.0	62.1	63.6	137.1	37.7	7.5	0.0	324.0
88/89	13.3	7.7	119.0	32.5	12.5	15.0	0.0	0.0	200.0
89/90	0.0	15.3	13.3	70.6	16.9	19.0	5.5	0.0	140.6
90/91	0.0	5.5	0.0	24.3	18.9	35.7	3.0	0.0	87.4
91/92	2.6	5.0	147.3	11.8	65.8	7.0	0.0	0.0	239.5
92/93	0.0	8.5	27.9	86.0	12.5	0.1	0.0	3.0	138.0
93/94	1.0	4.1	4.0	74.5	19.0	26.0	0.0	0.0	128.6
94/95	0.5	58.5	62.6	0.2	41.5	19.5	4.0	0.0	186.8
95/96	0.0	14.0	5.5	54.0	3.5	82.5	3.0	0.0	162.5
96/97	3.9	38.5	22.5	75.9	74.4	49.5	1.5	0.0	266.2
97/98	5.0	8.5	61.0	103.2	15.5	130.5	3.0	0.0	326.7
98/99	0.0	0.0	0.0	28.5	47.0	6.5	0.0	0.0	82.0
99/00	0.0	0.0	7.0	158.0	18.0	30.5	0.0	0.0	213.5
00/01	18.0	0.0	80.0	42.0	42.6	5.6	7.5	4.0	199.7
01/02	0.0	19.5	32.0	98.5	15.0	40.0	5.0	0.8	210.8
Average	**4.0**	**17.4**	**36.9**	**51.1**	**46.0**	**39.1**	**10.3**	**0.8**	**205.5**

Appendix 2.2B: Monthly and annual rainfall for Jarash station (AL004).

Water Year	Months								Total (mm)
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	
70/71	3.2	2.6	54.0	40.0	92.9	120.5	210.6	0.0	523.8
71/72	0.0	36.9	138.3	41.0	65.0	42.7	21.7	12.5	358.1
72/73	0.0	41.0	3.3	80.5	29.3	75.6	0.0	0.0	229.7
73/74	3.3	58.3	33.4	228.7	63.4	33.1	23.6	0.0	443.8
74/75	0.0	24.5	26.2	18.6	166.6	50.1	12.1	0.0	298.1
75/76	0.0	19.0	52.0	29.9	55.4	87.6	10.7	9.0	263.6
76/77	7.5	49.0	1.0	75.1	49.4	49.9	32.9	0.0	264.8
77/78	20.0	2.0	90.0	41.8	14.5	87.8	11.0	0.0	267.1
78/79	8.5	12.0	50.0	28.7	14.5	28.0	3.3	0.0	145.0
79/80	41.8	135.1	123.8	57.0	63.1	139.7	4.2	0.0	564.7
80/81	5.0	10.5	186.9	37.2	47.9	20.4	16.1	0.0	324.0
81/82	0.0	24.3	9.0	76.7	91.6	44.7	10.0	10.0	266.3
82/83	8.5	57.7	32.6	120.2	103.6	92.8	5.0	1.5	421.9
83/84	0.0	4.0	16.0	113.0	31.7	139.2	19.7	0.0	323.6
84/85	18.6	14.0	28.4	21.9	160.5	33.0	6.6	2.0	285.0
85/86	8.0	22.0	22.9	38.3	69.3	5.2	6.3	17.5	189.5
86/87	14.7	141.2	37.5	86.6	20.0	52.2	0.0	0.0	352.2
87/88	40.7	5.0	84.0	94.5	200.7	93.1	8.8	0.0	526.8
88/89	7.5	16.8	146.5	37.2	39.7	49.5	0.0	0.0	297.2
89/90	2.0	37.0	33.8	74.9	48.7	62.0	19.4	0.0	277.8
90/91	3.0	10.5	1.3	110.6	42.7	65.2	5.2	3.0	241.5
91/92	0.0	49.3	216.0	110.5	269.4	22.5	0.0	1.0	668.7
92/93	0.0	46.5	242.1	91.1	49.8	25.5	0.0	7.8	462.8
93/94	5.5	5.0	5.0	115.0	48.0	94.2	7.0	0.0	279.7
94/95	5.2	169.5	121.7	7.2	67.0	34.4	9.2	0.0	414.2
95/96	0.0	36.4	23.0	95.6	4.5	132.0	7.0	0.0	298.5
96/97	17.0	24.5	56.4	72.3	174.0	62.5	10.4	6.0	423.1
97/98	6.0	35.0	100.0	136.5	44.0	134.5	4.0	0.0	460.0
98/99	0.0	0.0	11.0	80.0	67.0	31.3	7.5	0.0	196.8
99/00	0.0	1.0	7.5	223.5	54.7	40.5	0.0	0.0	327.2
00/01	29.0	15.0	122.2	59.5	51.8	9.2	2.5	8.5	297.7
01/02	3.0	22.5	72.5	162.5	38.0	87.0	27.2	3.5	416.2
Average	**8.1**	**35.3**	**67.1**	**81.4**	**73.1**	**63.9**	**15.7**	**2.6**	**347.2**

Appendix 2.2C: Monthly and annual rainfall for Zarqa station (AL0015).

Water Year	Months								Total (mm)
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	
70/71	0.0	0.0	7.3	21.0	13.0	10.7	55.0	0.0	107.0
71/72	0.0	10.3	52.8	11.0	36.2	28.5	9.2	0.0	148.0
72/73	0.0	34.6	0.5	29.4	20.2	11.4	0.0	0.0	96.1
73/74	5.5	21.5	1.8	161.1	28.4	8.4	12.2	0.0	238.9
74/75	6.1	22.8	11.5	7.0	74.6	16.5	0.0	0.0	138.4
75/76	6.1	15.3	10.3	10.5	28.5	39.7	0.0	0.0	110.4
76/77	6.1	0.7	3.5	22.6	12.8	23.2	11.5	0.0	80.4
77/78	12.3	0.0	31.0	12.7	4.3	24.5	1.0	1.5	87.4
78/79	6.3	0.0	17.2	11.0	4.3	14.0	0.0	0.0	52.7
79/80	12.9	90.8	35.0	58.0	59.9	49.2	4.5	0.0	310.2
80/81	0.0	2.7	53.5	22.1	15.9	8.8	2.9	0.0	105.9
81/82	0.0	12.4	0.0	39.5	21.6	20.2	15.1	10.7	119.5
82/83	9.2	15.7	12.0	50.7	62.1	40.3	0.6	3.1	193.7
83/84	0.0	0.0	0.0	26.6	6.3	53.4	0.0	0.0	86.3
84/85	3.3	9.5	0.0	0.0	91.5	0.0	0.0	0.0	104.3
85/86	3.0	0.0	34.1	2.0	32.0	2.8	4.8	6.0	84.7
86/87	26.4	74.8	8.5	27.4	11.2	24.4	0.0	0.0	172.7
87/88	32.6	2.0	34.3	36.0	103.4	35.6	6.2	0.0	250.1
88/89	6.0	5.3	78.1	32.9	12.1	15.4	0.0	0.0	149.8
89/90	0.0	11.8	22.3	29.8	20.4	34.8	11.2	0.0	130.3
90/91	0.0	5.4	0.3	43.2	17.1	18.3	3.6	0.2	88.1
91/92	1.1	14.0	71.8	40.9	114.8	13.6	1.3	0.7	258.2
92/93	0.0	26.8	25.6	18.2	14.7	9.0	0.0	3.6	97.9
93/94	13.5	6.2	9.0	50.2	7.3	21.5	0.0	0.0	107.7
94/95	10.6	69.1	50.4	1.6	10.8	3.3	0.5	0.0	146.3
95/96	0.0	3.5	11.0	48.4	6.0	24.7	2.5	0.0	96.1
96/97	1.5	26.5	15.5	38.0	18.1	22.3	0.0	2.0	123.9
97/98	15.0	17.8	30.5	36.3	17.2	25.8	1.3	0.0	143.9
98/99	0.0	0.0	1.5	12.0	29.0	4.0	1.5	0.0	48.0
99/00	0.0	0.0	1.5	36.0	7.5	18.5	0.0	0.0	63.5
00/01	12.5	0.0	35.1	19.7	17.5	4.7	4.5	6.6	100.6
01/02	3.5	17.6	29.0	57.7	20.0	24.5	4.2	0.5	157.0
Average	**6.0**	**16.2**	**21.7**	**31.7**	**29.3**	**20.4**	**4.8**	**1.1**	**131.2**

Appendix 2.2D: Monthly and annual rainfall for Amman Airport station (AL0019).

Water Year	Months								Total (mm)
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	
70/71	1.5	5.2	37.4	18.4	34.7	51.1	145.6	0.0	293.9
71/72	0.0	13.9	122.5	32.7	53.7	38.5	43.7	6.6	311.6
72/73	0.0	31.1	6.0	107.5	17.9	31.4	1.2	0.0	195.1
73/74	0.4	49.9	31.7	235.2	98.9	12.3	19.5	0.0	447.9
74/75	0.0	34.1	24.7	17.5	125.7	33.2	2.1	0.0	237.3
75/76	0.0	21.3	23.7	29.2	42.9	68.6	9.3	0.0	195.0
76/77	1.1	10.5	1.0	43.4	24.3	52.5	57.6	0.0	190.4
77/78	28.2	6.4	73.3	41.3	27.2	66.7	5.5	0.0	248.6
78/79	1.9	1.4	42.6	42.0	7.1	35.3	0.6	3.3	134.2
79/80	35.0	133.2	87.9	77.3	76.4	77.8	16.2	0.2	504.0
80/81	2.0	7.3	175.0	48.2	37.0	20.5	11.1	0.0	301.1
81/82	0.0	23.9	0.8	57.9	56.4	43.3	12.6	0.0	194.9
82/83	10.2	23.6	18.6	118.6	200.6	46.1	3.1	1.2	422.0
83/84	0.0	23.8	3.7	62.0	25.8	78.5	6.4	0.0	200.2
84/85	15.5	15.1	30.5	25.3	148.4	42.3	2.4	0.0	279.5
85/86	0.0	5.1	27.3	0.0	62.6	6.2	0.0	7.7	108.9
86/87	38.8	102.3	20.9	46.4	16.4	39.4	0.0	0.0	264.2
87/88	33.2	4.0	69.2	50.1	126.3	63.4	13.1	0.0	359.3
88/89	8.0	14.6	123.6	43.7	22.0	31.8	0.0	0.0	243.7
89/90	0.0	0.0	13.9	0.0	55.2	65.9	21.2	0.0	156.2
90/91	1.8	3.7	2.5	90.9	47.2	43.5	6.2	2.1	197.9
91/92	4.7	35.0	166.4	112.1	200.0	15.7	0.0	6.0	539.9
92/93	0.0	39.6	71.5	67.5	49.5	17.1	0.0	11.6	256.8
93/94	0.0	22.1	16.8	74.3	17.6	29.0	0.7	0.0	160.5
94/95	12.6	97.3	99.5	1.7	36.2	27.3	4.2	0.0	278.8
95/96	0.0	1.8	0.0	81.3	18.4	66.9	9.8	0.0	178.2
96/97	0.7	32.1	28.1	66.1	82.4	54.8	3.6	0.8	268.6
97/98	16.5	10.7	59.4	60.8	34.0	75.0	1.9	0.3	258.6
98/99	0.4	0.7	3.6	29.2	57.7	11.7	3.9	0.0	107.2
99/00	0.0	0.5	3.3	117.4	20.8	30.1	0.0	0.0	172.1
00/01	10.9	2.2	51.8	40.7	37.0	9.6	11.0	13.3	176.5
01/02	1.2	20.6	56.7	109.8	29.3	38.4	21.2	0.5	277.7
Average	**7.0**	**24.8**	**46.7**	**60.9**	**59.1**	**41.4**	**13.6**	**1.7**	**255.0**

Appendix 2.2E: Monthly and annual rainfall for Qasr El-Hallabat station (AL0049).

Water Year	Months								Total (mm)
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	
70/71	0.0	0.0	0.0	28.6	3.0	8.0	71.0	0.0	110.6
71/72	0.0	9.5	58.5	0.0	40.7	30.2	33.6	2.3	174.8
72/73	5.7	13.3	0.0	26.9	0.0	15.9	5.0	4.3	71.0
73/74	6.6	10.8	0.0	60.6	54.8	8.1	6.4	0.0	147.3
74/75	4.5	7.7	9.7	14.1	72.0	12.9	5.3	0.0	126.1
75/76	12.3	9.2	5.8	18.9	18.1	19.2	4.7	2.8	90.9
76/77	4.5	4.2	0.0	24.2	5.0	12.6	8.0	0.0	58.4
77/78	14.2	3.5	33.6	17.0	0.0	12.5	1.8	0.0	82.6
78/79	3.9	0.0	18.1	13.1	13.8	2.9	4.2	0.0	56.0
79/80	3.0	36.0	44.0	23.2	26.5	64.0	3.8	0.0	200.5
80/81	0.7	4.0	89.0	2.8	30.4	23.0	0.4	0.0	150.3
81/82	0.0	8.5	1.2	26.3	27.2	12.0	14.0	15.2	104.4
82/83	18.0	0.0	0.0	31.0	9.0	12.0	0.0	0.0	70.0
83/84	4.5	8.5	0.0	26.1	0.1	26.9	2.2	1.8	70.0
84/85	7.5	11.0	2.0	6.0	64.0	17.8	0.4	0.0	108.7
85/86	0.0	0.0	21.5	2.5	2.6	0.8	29.8	3.6	60.8
86/87	7.8	38.8	9.4	21.7	4.2	25.2	0.0	0.0	107.1
87/88	40.0	7.0	22.5	33.2	49.6	31.5	5.6	0.0	189.4
88/89	6.0	3.8	118.0	37.0	4.0	7.8	0.0	0.0	176.6
89/90	0.0	6.0	8.8	28.6	19.4	23.5	13.5	0.0	99.8
90/91	5.1	8.5	2.9	46.6	14.0	5.5	0.0	0.0	82.6
91/92	3.5	0.0	59.5	51.1	83.5	7.5	0.0	0.0	205.1
92/93	4.5	6.6	18.2	23.2	9.8	10.9	1.8	4.8	79.7
93/94	4.5	3.0	0.0	26.1	0.0	10.3	1.8	1.5	47.2
94/95	2.2	34.6	18.4	0.0	6.4	4.4	0.0	0.0	66.0
95/96	0.0	1.3	12.5	43.8	7.0	32.0	0.0	0.0	96.6
96/97	11.5	9.4	8.4	27.5	3.6	7.3	1.8	2.8	72.2
97/98	12.0	15.2	19.0	49.8	0.0	10.0	0.0	0.0	106.0
98/99	0.0	0.0	9.9	0.5	8.6	1.4	0.6	0.0	21.0
99/00	0.0	0.0	13.2	38.2	0.4	18.4	0.0	0.0	70.2
00/01	16.8	0.0	42.4	3.4	0.2	0.0	7.0	0.6	70.4
01/02	0.2	4.6	38.0	22.3	19.4	11.9	14.4	0.0	110.8
Average	**6.2**	**8.3**	**21.4**	**24.2**	**18.7**	**15.2**	**7.4**	**1.2**	**102.6**

Appendix 2.2F: Monthly and annual rainfall for Um El Jumal station (AL0059).

Water Year	Months								Total (mm)
	Oct.	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	
70/71	0.0	6.1	25.3	32.3	17.3	19.4	42.8	0.0	143.2
71/72	0.0	21.8	50.1	29.0	36.4	33.5	39.5	1.0	211.3
72/73	1.1	24.8	0.6	31.9	8.3	25.4	7.2	3.4	102.7
73/74	2.0	19.1	6.4	97.9	56.1	8.6	10.3	0.0	200.4
74/75	0.0	12.0	15.6	6.8	70.9	19.1	7.8	0.0	132.2
75/76	7.3	15.5	12.3	16.3	24.5	32.6	6.4	1.6	116.5
76/77	0.0	4.1	0.0	26.7	13.2	18.3	13.7	0.0	76.0
77/78	9.0	2.5	35.6	12.6	5.5	18.2	0.0	0.0	83.4
78/79	3.4	3.0	20.7	16.8	15.7	5.4	5.7	0.0	70.7
79/80	0.0	60.7	53.0	29.8	31.0	35.8	5.8	0.0	216.1
80/81	0.7	1.6	65.6	5.8	26.3	13.9	4.6	0.0	118.5
81/82	0.0	14.0	1.1	28.6	32.7	9.2	16.7	16.4	118.7
82/83	16.0	22.1	10.6	18.4	39.2	24.1	0.9	13.5	144.8
83/84	0.0	13.9	1.4	30.3	9.0	49.2	1.0	0.0	104.8
84/85	8.5	32.2	19.5	11.5	55.2	31.5	2.3	1.0	161.7
85/86	0.0	0.6	18.7	4.1	23.5	0.0	0.0	0.0	46.9
86/87	5.4	85.5	6.8	11.4	6.9	32.2	0.0	0.0	148.2
87/88	5.2	7.5	29.9	70.6	52.5	39.5	14.5	0.0	219.7
88/89	0.0	12.8	41.8	22.4	8.5	16.0	0.0	0.0	101.5
89/90	3.9	8.3	22.5	31.1	25.6	19.5	7.0	0.0	117.9
90/91	2.5	6.0	2.8	51.5	12.4	37.3	0.0	2.2	114.7
91/92	2.7	11.8	68.6	36.1	63.1	8.6	0.0	0.5	191.4
92/93	0.0	9.5	22.7	24.7	17.4	14.6	0.0	4.0	92.9
93/94	0.0	1.5	0.5	30.3	7.6	13.5	0.0	0.0	53.4
94/95	2.0	63.2	29.2	0.0	39.6	7.0	0.0	0.0	141.0
95/96	0.0	6.3	6.8	27.0	4.8	21.7	1.4	0.0	68.0
96/97	6.5	16.0	14.5	33.0	12.0	7.0	0.0	2.3	91.3
97/98	5.5	21.7	22.5	18.2	11.0	29.3	0.0	0.0	108.2
98/99	0.0	0.0	1.5	8.5	4.8	2.2	0.0	0.0	17.0
99/00	0.0	0.0	3.8	34.7	0.0	7.9	0.0	0.0	46.4
00/01	15.0	0.0	34.5	22.0	36.7	10.0	11.2	0.0	129.4
01/02	0.0	13.5	29.0	67.0	16.0	24.0	11.0	0.0	160.5
Average	**3.0**	**16.2**	**21.1**	**27.7**	**24.5**	**19.8**	**6.6**	**1.4**	**120.3**

Appendix 2.2G: Monthly and annual rainfall for Salt station (AM0001).

Water Year	Months								Total (mm)
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	
70/71	6.5	10.8	137.8	77.1	125.2	74.2	286.4	0.0	718.0
71/72	0.0	53.0	249.8	96.5	85.5	86.1	38.5	10.5	619.9
72/73	0.0	53.0	11.0	156.5	24.0	99.0	0.0	6.0	349.5
73/74	0.0	96.0	44.5	367.0	186.0	45.5	54.0	0.0	793.0
74/75	0.0	53.2	90.0	60.5	194.5	91.5	14.5	0.0	504.2
75/76	0.0	30.0	91.1	72.5	121.0	131.0	25.0	2.0	472.6
76/77	16.5	91.0	13.0	106.0	24.5	104.0	62.3	0.0	417.3
77/78	108.8	5.0	193.0	77.0	47.5	105.8	24.0	0.0	561.1
78/79	11.0	22.3	122.0	125.0	18.5	116.9	5.1	0.0	420.8
79/80	62.5	187.0	237.0	154.9	140.0	120.2	12.6	0.0	914.2
80/81	2.2	17.1	243.1	148.9	145.2	69.1	14.7	0.0	640.3
81/82	0.0	70.5	18.2	135.1	111.2	152.6	6.5	0.0	494.1
82/83	0.1	101.1	60.0	256.0	212.0	174.0	20.0	6.0	829.2
83/84	1.7	55.5	8.0	162.0	32.0	171.0	52.1	0.0	482.3
84/85	34.7	17.6	50.2	36.4	343.0	32.8	27.9	0.0	542.6
85/86	14.0	14.9	38.9	92.9	170.2	17.5	14.0	34.2	396.6
86/87	50.5	229.3	83.9	120.4	40.0	75.1	0.0	0.0	599.2
87/88	43.7	4.2	215.3	105.1	233.9	91.3	13.2	0.0	706.7
88/89	9.2	36.0	200.5	138.0	54.5	130.5	0.0	0.0	568.7
89/90	2.0	54.5	88.5	190.0	76.5	79.0	22.0	0.0	512.5
90/91	5.8	26.0	2.0	210.0	75.4	185.0	16.0	15.5	535.7
91/92	15.8	116.8	379.5	152.5	464.6	59.4	2.6	9.5	1200.7
92/93	0.0	77.5	263.0	167.9	99.2	37.1	0.0	21.8	666.5
93/94	5.0	18.3	32.8	194.8	89.9	92.6	9.3	0.0	442.7
94/95	46.0	224.7	189.1	31.0	55.1	34.7	17.8	0.0	598.4
95/96	0.0	21.0	26.5	216.2	23.9	194.0	11.0	0.0	492.6
96/97	15.2	8.0	80.0	152.3	204.9	126.0	0.6	13.4	600.4
97/98	19.8	35.7	113.4	156.6	66.4	125.3	1.1	0.0	518.3
98/99	2.8	2.2	8.7	109.2	54.1	35.5	10.9	0.0	223.4
99/00	2.5	5.0	19.4	115.4	106.2	78.8	3.0	0.0	330.3
00/01	19.9	0.0	148.6	111.6	101.3	7.0	6.2	17.0	411.6
01/02	8.0	19.3	130.3	282.5	91.7	98.5	36.8	4.9	672.0
Average	**15.8**	**54.9**	**112.2**	**143.1**	**119.3**	**95.0**	**25.3**	**4.4**	**569.9**

Appendix 2.2H: Monthly and annual rainfall for Um El-Quttein station (F0001).

Water	Months								Total (mm)
Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	
70/71	0.0	16.0	67.5	52.0	43.0	22.0	58.0	0.0	258.5
71/72	0.0	11.0	60.0	14.0	34.0	53.0	40.0	0.0	212.0
72/73	0.0	12.5	0.0	37.0	6.5	26.0	3.5	0.0	85.5
73/74	0.0	25.0	13.5	109.5	93.0	25.0	11.0	0.0	277.0
74/75	0.0	0.0	11.0	26.0	99.3	48.0	5.0	0.0	189.3
75/76	11.4	11.0	17.9	26.4	27.8	33.8	6.8	2.3	137.4
76/77	8.0	3.0	6.8	29.8	22.7	20.3	12.4	1.4	104.4
77/78	4.0	1.5	10.1	25.0	14.0	40.5	0.0	0.0	95.1
78/79	9.6	9.4	17.7	15.9	15.4	10.5	10.7	8.0	97.1
79/80	8.5	50.0	48.0	38.0	65.7	35.5	9.5	0.0	255.2
80/81	3.0	0.0	82.7	13.9	38.0	17.0	4.0	0.0	158.6
81/82	0.0	14.0	3.5	24.5	21.0	20.5	0.0	9.2	92.7
82/83	0.0	14.0	11.0	32.0	28.0	23.0	0.0	0.0	108.0
83/84	0.0	12.3	5.7	39.6	9.0	39.2	1.2	0.0	107.0
84/85	15.5	26.5	24.0	20.0	52.5	38.8	3.0	2.0	182.3
85/86	2.0	7.0	39.0	15.6	40.4	1.0	10.5	9.4	124.9
86/87	15.8	64.0	9.5	17.8	9.0	13.5	0.0	0.0	129.6
87/88	14.4	3.6	60.4	37.5	20.0	45.1	9.0	0.6	190.6
88/89	0.0	4.0	61.1	19.0	5.5	8.0	0.0	0.0	97.6
89/90	0.2	9.0	24.5	41.0	57.5	28.5	7.5	0.0	168.2
90/91	0.0	9.0	14.0	35.0	42.0	45.5	2.5	0.0	148.0
91/92	1.0	0.0	58.0	44.5	54.0	5.0	0.0	0.0	162.5
92/93	0.0	10.0	30.0	30.0	11.0	13.0	0.0	33.0	127.0
93/94	0.0	2.0	5.0	34.0	24.0	18.5	0.0	0.0	83.5
94/95	10.5	39.0	18.0	0.0	24.0	5.0	0.0	0.0	96.5
95/96	0.0	7.0	2.0	30.0	3.5	28.0	0.0	0.0	70.5
96/97	1.0	13.0	21.0	22.1	31.0	13.0	0.5	0.0	101.6
97/98	40.5	11.6	44.3	50.8	18.1	26.5	12.6	0.0	204.4
98/99	0.0	0.0	0.0	9.0	5.0	1.0	1.0	0.0	16.0
99/00	0.0	0.0	2.5	47.0	7.0	8.0	0.0	0.0	64.5
00/01	12.0	0.0	35.5	21.0	17.5	5.0	16.0	3.0	110.0
01/02	0.0	10.0	29.8	48.0	14.5	19.0	10.0	0.1	131.4
Average	**4.9**	**12.4**	**26.1**	**31.4**	**29.8**	**23.0**	**7.3**	**2.2**	**137.1**

Appendix 2.3A: The average monthly and annual pan evaporation (EP) of Amman Airport station (AL0019).

Water Year	Months												Total (mm)
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	
70/71	187	131	91	114	128	150	160	285	332	338	336	264	2515
71/72	230	153	67	88	96	146	190	267	212	341	373	292	2454
72/73	272	118	85	135	141	217	255	376	402	413	312	256	2982
73/74	214	116	76	48	100	105	175	298	324	394	305	284	2439
74/75	264	132	71	81	76	171	252	288	324	360	276	237	2532
75/76	186	111	68	78	61	109	171	288	319	339	316	268	2314
76/77	226	157	85	87	96	122	196	265	398	410	392	278	2712
77/78	172	136	79	84	84	149	213	387	368	446	303	234	2655
78/79	285	136	66	60	109	158	282	280	324	294	304	204	2502
79/80	167	177	90	84	81	143	153	353	392	405	343	235	2624
80/81	237	139	59	89	64	146	220	281	343	357	388	320	2643
81/82	254	104	127	90	76	112	204	214	342	335	319	243	2421
82/83	197	83	71	69	51	74	142	242	315	328	320	287	2179
83/84	228	174	102	86	156	188	249	393	354	387	339	331	2987
84/85	280	121	86	120	113	170	233	282	348	372	367	336	2828
85/86	205	140	94	76	96	154	178	254	340	361	331	257	2486
86/87	179	120	73	75	92	132	194	331	346	360	329	257	2488
87/88	197	134	72	75	80	126	199	320	276	308	262	224	2273
88/89	138	102	64	37	79	110	269	321	309	338	336	254	2356
89/90	204	129	93	80	97	156	234	358	398	330	311	200	2590
90/91	206	164	151	94	92	160	218	294	322	258	241	245	2445
91/92	180	147	84	59	45	87	164	203	283	287	314	230	2082
92/93	242	60	54	72	78	141	214	255	393	397	382	272	2560
93/94	196	99	74	72	72	106	237	293	333	353	327	233	2394
94/95	163	80	65	53	69	127	188	292	353	349	363	294	2394
95/96	193	115	54	62	95	103	173	311	323	372	361	231	2393
96/97	151	90	78	60	70	93	151	271	332	368	348	348	2359
97/98	177	87	70	57	75	115	187	258	300	364	334	282	2305
98/99	201	121	78	55	63	124	176	274	304	340	336	233	2303
99/00	163	117	84	53	66	96	177	249	323	370	304	232	2234
00/01	144	84	62	57	61	150	189	272	347	367	466	227	2424
01/02	205	124	59	58	86	121	144	269	312	382	312	225	2298
Average	**204**	**122**	**79**	**75**	**86**	**133**	**200**	**291**	**334**	**357**	**333**	**260**	**2474**

Appendix 2.3B: The average monthly and annual pan evaporation (EP) of King Hussein Nursery (Baq'a) station (AL0035).

Water Year	Months												Total (mm)
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	
70/71	211	130	81	84	120	146	241	261	336	331	331	259	2531
71/72	230	140	59	70	107	125	198	266	347	373	362	304	2581
72/73	244	127	82	98	124	160	242	337	384	406	339	280	2823
73/74	245	133	77	50	93	112	191	287	354	403	332	294	2571
74/75	166	83	56	53	66	99	170	175	192	240	197	165	1662
75/76	149	106	83	82	75	130	178	278	205	350	318	258	2212
76/77	206	179	83	62	118	127	182	297	395	408	388	289	2734
77/78	208	161	75	88	132	162	236	369	385	436	357	274	2883
78/79	232	130	73	71	111	148	276	291	391	391	379	290	2781
79/80	206	205	65	64	59	129	209	330	381	359	326	272	2605
80/81	228	149	101	83	65	146	208	293	357	377	350	294	2651
81/82	229	111	93	74	77	116	192	248	347	328	327	255	2397
82/83	208	90	56	50	58	117	166	259	336	359	342	261	2301
83/84	202	121	84	80	124	135	173	314	343	381	344	295	2595
84/85	240	103	66	85	108	149	218	310	362	407	381	308	2735
85/86	219	143	88	73	99	145	206	308	358	401	354	288	2682
86/87	217	134	84	72	96	140	210	313	361	401	353	288	2669
87/88	218	140	84	72	90	139	211	312	332	377	303	279	2557
88/89	215	125	82	62	89	136	226	312	346	391	358	287	2628
89/90	219	138	88	74	99	146	218	314	382	387	339	273	2677
90/91	219	155	100	77	97	146	215	310	351	354	287	284	2595
91/92	217	146	86	68	70	131	203	305	335	368	342	281	2552
92/93	220	106	80	72	89	142	214	308	380	418	393	292	2713
93/94	218	124	84	71	85	135	219	310	356	398	351	281	2632
94/95	216	115	82	66	84	139	208	310	364	396	378	297	2656
95/96	218	84	83	45	69	104	124	158	171	300	298	238	1892
96/97	202	139	89	98	108	118	199	380	436	510	438	343	3060
97/98	256	117	100	55	73	139	235	351	360	399	476	352	2912
98/99	248	187	148	92	98	192	272	456	406	437	427	419	3382
99/00	261	182	157	76	97	156	252	518	547	617	380	319	3563
00/01	225	167	67	75	80	215	259	372	492	665	466	270	3352
01/02	201	127	83	77	114	180	199	246	277	412	344	314	2575
Average	**219**	**134**	**85**	**72**	**93**	**141**	**211**	**309**	**355**	**399**	**355**	**288**	**2661**

Appendix 2.3C: The average monthly and annual pan evaporation (EP) of king Talal Dam station (AL0053).

Water	Months												Total (mm)
Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	
70/71	221	146	92	99	105	139	209	279	333	346	343	288	2600
71/72	238	160	93	91	100	128	193	280	337	364	367	293	2643
72/73	250	78	92	179	100	156	202	266	332	380	340	302	2677
73/74	264	150	102	99	112	121	169	269	308	351	298	185	2428
74/75	183	79	94	81	98	171	240	233	219	231	232	298	2158
75/76	157	117	119	84	74	121	175	267	321	342	333	288	2398
76/77	318	238	92	86	105	129	187	286	354	378	387	291	2851
77/78	219	190	93	102	110	148	207	300	350	390	363	290	2761
78/79	230	142	70	62	88	171	244	289	370	373	376	323	2738
79/80	221	289	93	87	86	138	201	298	352	355	342	274	2735
80/81	224	182	74	73	55	139		304	418	402	370	322	2563
81/82	246	122	119	112	91	132	202	305	378	394	368	282	2750
82/83	237	149	91	74	61	101	173	263	343	349	319	273	2430
83/84	211	127	119	86	124	176	195	330	360	399	343	293	2762
84/85	236	122	98	100	94	157	211	295	355	397	370	319	2753
85/86	227	95	73	80	97	139	196	288	341	376	361	291	2563
86/87	220	196	66	67	135	110	217	317	256	440	406	347	2776
87/88	208	143	82	92	78	87	145	307	348	372	358	288	2507
88/89	191	140	92	86	94	134	203	289	336	371	364	291	2590
89/90	228	158	92	93	98	139	200	289	349	370	349	289	2654
90/91	228	181	91	95	97	139	199	289	338	356	309	291	2612
91/92	227	169	92	89	87	131	195	288	332	361	351	290	2613
92/93	229	111	92	92	94	137	199	288	348	383	390	291	2655
93/94	227	138	92	92	92	133	201	289	340	374	358	290	2626
94/95	226	125	92	89	92	136	197	289	343	373	379	292	2631
95/96	227	80	102	103	129	100	166	262	268	314	310	257	2318
96/97	185	133	88	96	74	87	163	265	315	332	425	296	2458
97/98	259	128	91	81	88	135	206	297	341	374	455	297	2753
98/99	253	228	88	104	97	163	220	318	358	390	417	304	2939
99/00	264	220	88	94	97	144	213	330	409	466	381	294	3000
00/01	233	198	93	94	90	175	215	301	389	486	447	289	3011
01/02	213	142	92	95	103	157	193	276	311	380	353	294	2610
Average	**228**	**152**	**92**	**92**	**95**	**137**	**198**	**289**	**339**	**374**	**361**	**291**	**2643**

Appendix 2.3D: The average monthly and annual pan evaporation (EP) for Um El Jumal station (AL0059).

Water Year	Months												Total (mm)
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	
70/71	228	147	68	133	110	235	194	386	446	481	421	382	3231
71/72	332	188	74	72	135	184	290	390	419	424	481	411	3400
72/73	331	136	104	103	200	243	327	457	497	541	460	394	3793
73/74	322	184	104	58	112	179	250	313	410	517	430	324	3203
74/75	301	174	80	87	67	176	259	318	449	550	460	304	3225
75/76	193	151	71	76	57	163	253	296	427	525	430	354	2996
76/77	248	227	149	108	185	165	263	387	451	480	456	375	3494
77/78	203	161	83	88	142	231	417	465	432	545	402	346	3515
78/79	346	281	161	91	149	130	320	448	253	485	439	373	3476
79/80	275	205	104	67	45	163	295	437	591	551	485	365	3583
80/81	244	196	107	86	55	146	282	343	407	420	338	373	2997
81/82	263	125	115	69	72	129	300	359	376	384	313	153	2658
82/83	197	112	79	35	62	151	213	311	372	394	358	308	2592
83/84	254	187	150	128	218	193	310	401	385	413	382	353	3374
84/85	273	166	138	171	104	196	235	315	277	305	317	275	2771
85/86	247	233	175	166	146	242	166	245	444	500	422	361	3346
86/87	178	165	88	122	134	177	245	494	488	483	445	347	3366
87/88	224	211	83	102	100	162	268	458	389	539	352	304	3191
88/89	225	179	97	79	143	209	414	551	561	528	461	345	3791
89/90	269	175	117	76	86	163	268	477	431	541	448	312	3361
90/91	309	274	209	117	184	212	398	414	392	365	340	285	3499
91/92	257	188	247	377	144	177	432	443	387	435	229	326	3641
92/93	346	164	80	57	91	180	227	258	392	342	330	259	2727
93/94	265	184	44	104	111	124	246	306	309	381	299	269	2642
94/95	251	120	84	108	96	162	230	289	315	321	318	180	2473
95/96	218	173	96	92	142	146	211	344	337	341	325	266	2691
96/97	221	183	115	112	100	151	228	359	349	294	251	202	2565
97/98	180	126	99	72	88	138	231	314	335	323	297	238	2440
98/99	235	168	139	97	119	178	238	357	304	281	321	253	2689
99/00	207	146	143	93	117	122	222	264	305	357	293	255	2523
00/01	207	194	101	117	120	258	403	365	370	379	295	245	3053
01/02	247	180	112	84	160	282	233	273	336	353	387	366	3013
Average	**253**	**178**	**113**	**105**	**118**	**180**	**277**	**370**	**395**	**431**	**375**	**309**	**3104**

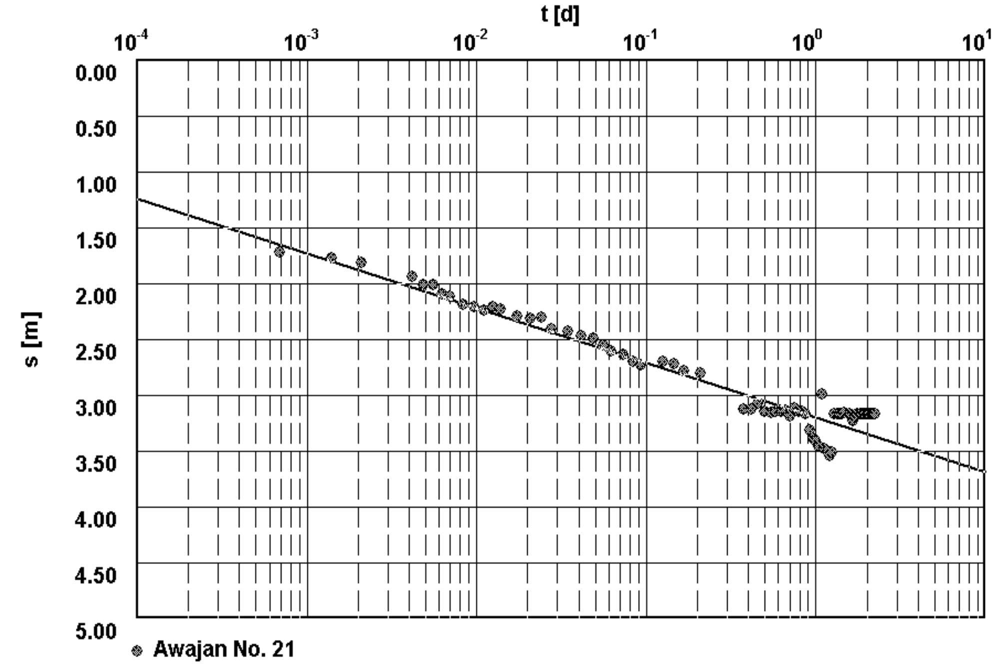
Appendix 2.3E: The average monthly and annual pan evaporation (EP) for Khirbet As-Samra station (AL0066).

Water Year	**Months**												**Total (mm)**
	Oct.	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug:**	**Sep.**	
85/86	148	90	55	34	45	116	126	223	445	447	409	436	2573
86/87	230	140	119	63	108	170	231	372	354	364	326	274	2748
87/88	146	110	69	50	73	112	179	272	324	361	317	262	2275
88/89	146	88	52	132	54	55	225	343	374	236	272	218	2193
89/90	155	79	38	30	42	116	135	261	312	272	319	216	1974
90/91	186	86	59	40	56	116	131	266	243	303	242	215	1941
91/92	130	83	33	36	28	117	124	271	209	310	286	226	1851
92/93	170	82	40	51	51	93	202	216	295	309	227	183	1919
93/94	132	60	46	53	53	86	167	166	244	228	223	172	1628
94/95	121	51	32	41	43	80	149	168	249	253	213	174	1571
95/96	143	80	45	47	60	83	103	203	260	276	233	185	1715
96/97	119	78	54	43	45	78	136	195	311	297	298	250	1902
97/98	178	83	47	57	51	78	132	311	453	371	329	276	2366
98/99	182	98	50	53	59	124	203	338	346	320	354	377	2503
99/00	186	102	54	42	77	110	190	255	282	292	250	232	2068
00/01	154	89	40	63	62	141	182	259	297	328	248	194	2057
01/02	147	102	47	46	76	136	150	216	303	307	266	230	2026
Average	**157**	**88**	**52**	**52**	**58**	**106**	**162**	**255**	**312**	**310**	**283**	**242**	**2077**

Appendix 2.4: Monthly and annual runoff of New Jarash Bridge gauging station (10^6 m^3).

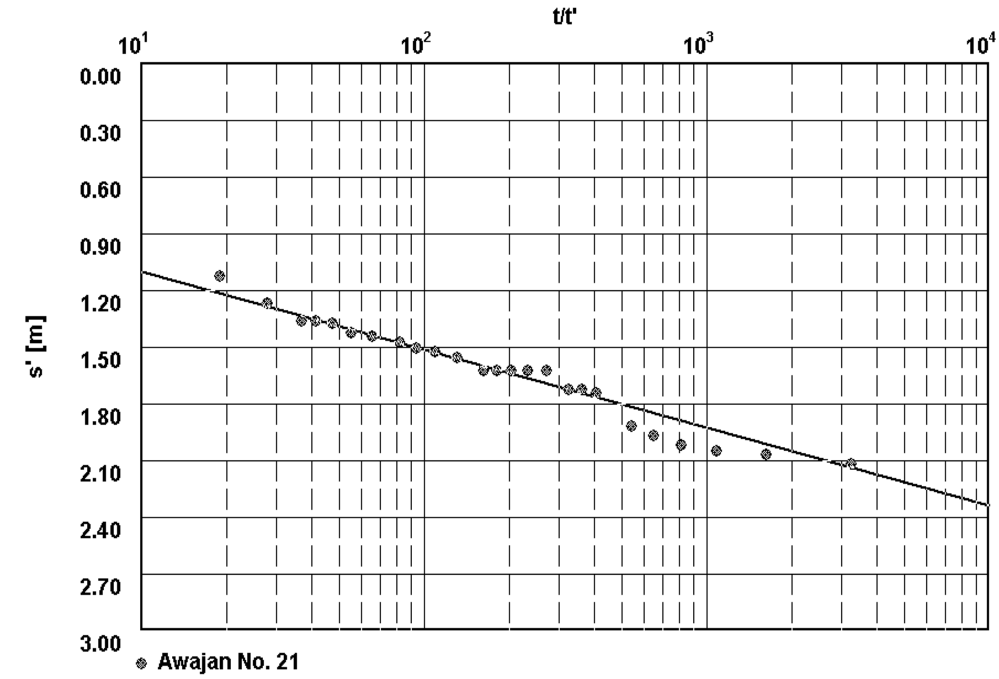
Water Year	Months								Annual
	Oct.	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	
70/71	0.00	0.00	0.02	1.78	0.00	1.04	21.42	0.00	24.3
71/72	0.00	0.00	4.27	0.40	1.12	1.46	2.22	0.00	9.5
72/73	0.00	0.82	0.00	2.26	0.36	1.30	0.00	0.00	4.7
73/74	0.00	1.33	0.32	50.56	20.16	4.33	0.00	0.00	76.7
74/75	0.00	0.22	0.19	0.00	6.65	1.31	5.03	0.00	13.4
75/76	0.13	0.13	0.00	0.27	0.42	8.39	0.00	0.00	9.4
76/77	0.00	0.10	0.01	0.36	0.53	0.51	0.26	0.00	1.8
77/78	1.38	0.17	2.59	2.72	0.26	3.76	0.00	0.00	10.9
78/79	0.00	0.00	1.44	2.01	0.13	0.40	0.00	0.00	4.0
79/80	12.13	38.46	35.09	11.09	3.34	14.82	0.09	0.00	115.0
80/81	0.00	0.00	24.27	0.62	2.67	1.23	0.80	0.00	29.6
81/82	0.00	0.00	0.00	0.00	3.43	0.83	14.11	9.32	27.7
82/83	0.41	0.83	0.00	5.81	11.73	15.77	0.00	0.74	35.3
83/84	0.00	0.04	0.00	1.43	0.88	3.81	0.00	0.00	6.2
84/85	1.52	5.25	5.24	0.00	19.72	2.97	0.00	0.00	34.7
85/86	0.00	0.00	0.22	0.52	3.09	0.00	1.73	0.00	5.6
86/87	1.14	18.91	0.67	3.21	0.07	0.24	0.07	0.00	24.3
87/88	14.64	0.00	1.17	5.27	29.51	11.60	0.22	0.00	62.4
88/89	0.06	0.00	11.85	0.87	0.73	2.04	0.00	0.00	15.5
89/90	0.00	0.00	0.00	2.21	3.50	5.01	1.20	0.00	11.9
90/91	0.05	0.00	0.00	3.08	3.03	7.75	0.00	0.00	13.9
91/92	0.00	0.00	27.52	18.43	30.09	5.01	0.00	0.00	81.1
92/93	0.00	7.37	18.43	10.55	3.00	0.00	0.00	0.00	39.4
93/94	0.00	0.26	0.00	1.05	1.19	1.11	0.00	0.00	3.6
94/95	0.00	29.60	26.32	0.00	2.11	0.00	0.00	0.00	58.0
95/96	0.00	0.00	0.00	6.97	0.24	7.04	0.00	0.00	14.2
96/97	0.00	3.63	1.36	15.30	8.41	3.62	0.00	0.00	32.3
97/98	0.24	0.27	7.15	5.98	0.99	5.33	0.00	0.00	20.0
98/99	0.00	0.00	0.00	1.51	4.68	0.00	0.00	0.00	6.2
99/00	0.00	0.00	0.00	8.31	1.89	2.69	0.00	0.00	12.9
00/01	1.88	0.00	5.62	3.09	0.40	0.23	0.00	0.55	11.8
01/02	0.00	0.00	13.16	15.13	3.04	3.09	2.19	0.00	36.6
Average	**1.0**	**3.4**	**5.8**	**5.6**	**5.2**	**3.6**	**1.5**	**0.3**	**26.6**

Appendix 4.1A: Pumping test evaluation of the Awajan well No. 21-Constant yield (upper aquifer).



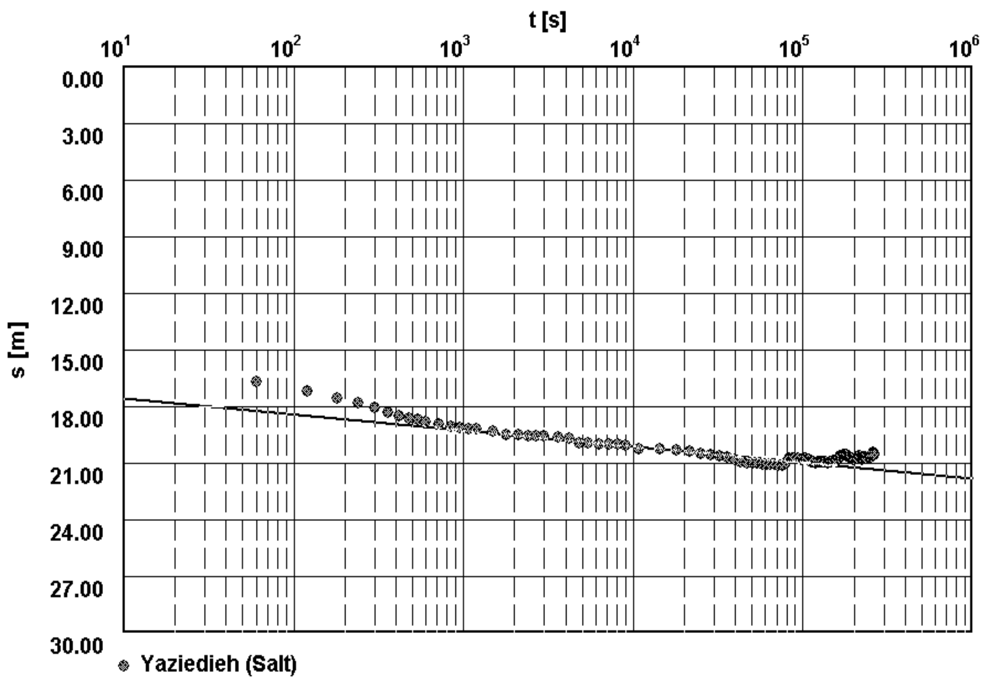
T [m²/d]: 1700 K [m/d]: 13.6 Analysis after COOPER & JACOB I-Unconfined

Appendix 4.1B: Pumping test evaluation of the Awajan well No. 21-Recovery (upper aquifer).



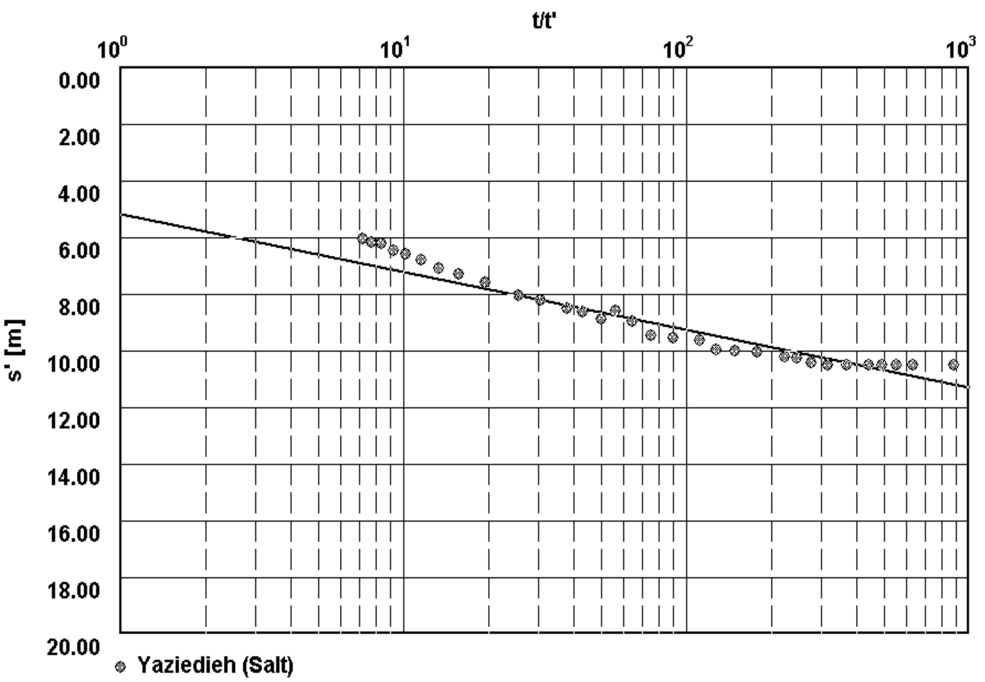
T [m²/d]: 2020 K [m/d]: 10.1 Recovery method after THEIS & JACOB I-Unconfined

Appendix 4.1C: Pumping test evaluation of the Yaziedieh well No. 3-Constant yield (middle aquifer).



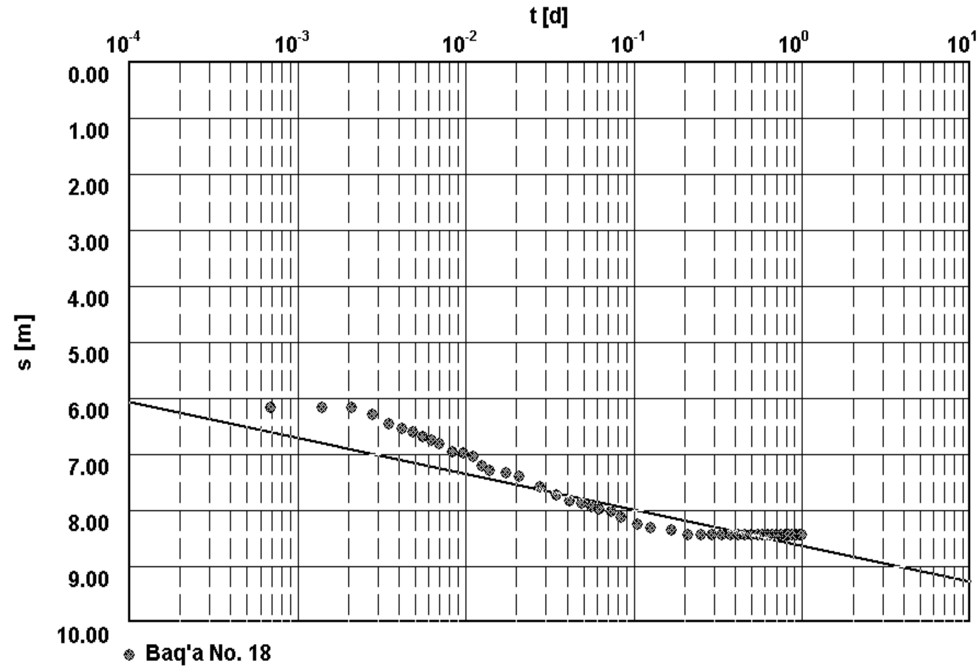
T [m²/d]: 93.5 K [m/d]: 1.9 Analysis after COOPER & JACOB I-Unconfined

Appendix 4.1D: Pumping test evaluation of the Yaziedieh well No. 3-Recovery (middle aquifer).



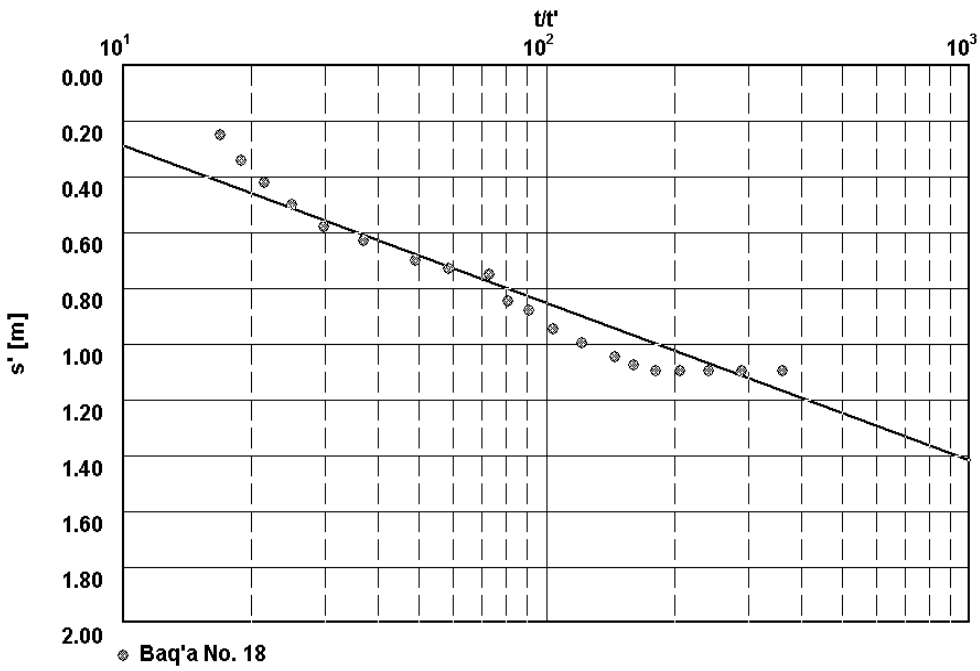
T [m²/d]: 38.7 K [m/d]: 0.5 Recovery method after THEIS & JACOB I-Unconfined

Appendix 4.1E: Pumping test evaluation of the Baq'a well No. 18-Constant yield (lower aquifer).



T [m^2/d]: 364 K [m/d]: 2.4 Analysis after COOPER & JACOB I-Unconfined

Appendix 4.1F: Pumping test evaluation of the Baq'a well No. 18-Recovery (lower aquifer).



T [m^2/d]: 414 K [m/d]: 2.8 Recovery method after THEIS & JACOB I-Unconfined

Appendix 4.2: Pumping tests analysis of selected wells in Amman-Zarqa Basin.

Well Idn.	Well Name	PGN [km]	PGE [km]	Transmissivity (T) [m^2/s]	Saturation Thickness (St) [m]	Permeability (k_f) [m/s]	Aquifer type	Type of Test
AL1006	DP No.5	177.25	263.68	2.50E-03	120	2.10E-05	B2/A7	Constant Yield
AL1006	DP No.5	177.25	263.68	1.20E-03	120	9.60E-06	B2/A7	Recovery
AL1037	DP. 30A	173.65	275.73	5.80E-04	115	5.10E-06	Basalt & B2/A7	Recovery
AL1118	Khirbit El Samra No. 2	174.90	258.40	1.78E-03	85	2.10E-05	B2/A7	Constant Yield
AL1118	Khirbit El Samra No. 2	174.90	258.40	1.00E-02	85	1.22E-04	B2/A7	Recovery
AL1225	KM 104	184.16	294.63	0.052	284	1.80E-04	Basalt & B2/A7	Constant Yield
AL1241	KM 95 (Baghdad No.6)	186.94	285.30	5.20E-02	190	2.70E-04	Basalt & B2/A7	Constant Yield
AL1241	KM 95 (Baghdad No.6)	186.94	285.30	4.50E-02	190	2.40E-04	Basalt & B2/A7	Recovery
AL1265	KM 102 (Baghdad No.8)	185.35	291.35	2.00E-01	255	7.90E-04	Basalt & B2/A7	Constant Yield
AL1274	KM 105.5	183.85	295.60	0.128	294	4.30E-04	Basalt & B2/A7	Constant Yield
AL1295	Ain Ruseifa No. 9	158.66	248.71	5.65E-02	125	4.52E-04	B2/A7	Constant Yield
AL1295	Ain Ruseifa No. 9	158.66	248.71	8.80E-02	125	7.00E-04	B2/A7	Recovery
AL1319	Awajan No. 21	160.41	252.49	2.00E-02	125	1.60E-04	B2/A7	Constant Yield
AL1319	Awajan No. 21	160.41	252.49	2.30E-02	125	1.20E-04	B2/A7	Recovery
AL1352	Ruseifa Municipality No. 2	158.81	248.23	4.20E-02	125	3.30E-04	B2/A7	Constant Yield
AL1352	Ruseifa Municipality No. 2	158.81	248.23	2.30E-01	125	1.80E-03	B2/A7	Recovery
AL1359	Polytechnique No. 2	155.60	246.21	1.00E-04	150	6.60E-07	B2/A7	Recovery
AL1360	Polytechnique No. 1	155.84	246.54	1.13E-02	160	7.00E-05	B2/A7	Constant Yield
AL1360	Polytechnique No. 1	155.84	246.54	1.00E-03	160	6.50E-06	B2/A7	Recovery
AL1393	Abu Nseir No. 1	165.25	231.94	6.70E-03	137	4.89E-05	K	Constant Yield
AL1393	Abu Nseir No. 1	165.25	231.94	8.26E-03	137	6.00E-05	K	Recovery
AL1428	Baq'a No. 1	164.30	230.54	8.20E-03	125	6.60E-05	K	Constant Yield
AL1428	Baq'a No. 1	164.30	230.54	4.30E-03	125	3.40E-05	K	Recovery
AL1432	Baq'a No. 5	162.08	229.68	9.80E-03	150	6.57E-05	K	Recovery
AL1432	Baq'a No. 5	162.08	229.68	1.40E-02	150	9.10E-05	K	Constant Yield
AL1444	Ain Ruseifa No. 8	158.32	245.97	2.17E-03	150	1.44E-05	B2/A7	Constant Yield
AL1495	KM 103	184.38	293.83	0.065	269	4.00E-04	Basalt & B2/A7	Constant Yield
AL1539	Baq'a No. 11	162.55	230.26	5.90E-04	150	4.00E-06	K	Constant Yield
AL1539	Baq'a No. 11	162.55	230.26	4.00E-04	150	2.70E-06	K	Recovery
AL1551	Ruseifa Municipality No. 4	158.70	248.85	7.67E-02	125	6.13E-04	B2/A7	Constant Yield
AL1558	KM 90	188.83	281.34	2.20E-02	200	1.10E-04	Basalt & B2/A7	Constant Yield
AL1778	Race Club No. 4	152.86	243.26	1.80E-05	105	1.80E-07	B2/A7	Constant Yield
AL1778	Race Club No. 4	152.86	243.26	1.80E-05	105	1.80E-07	B2/A7	Recovery
AL1779	Race Club No. 5	151.99	242.99	1.10E-05	107	1.00E-07	B2/A7	Constant Yield
AL1779	Race Club No. 5	151.99	242.99	5.40E-05	107	5.10E-07	B2/A7	Recovery
AL1780	Race Club No. 7	152.08	243.18	1.34E-02	104	1.29E-04	B2/A7	Constant Yield
AL1781	Race Club No. 12	154.00	245.84	1.07E-03	85	1.26E-04	B2/A7	Constant Yield
AL1781	Race Club No. 12	154.00	245.84	1.59E-04	85	1.89E-06	B2/A7	Recovery
AL1791	Madone No. 3	150.30	255.20	0.0025	20	1.00E-04	B2/A7	Constant Yield
AL1791	Madone No. 3	150.30	255.20	1.58E-02	20	7.90E-04	B2/A7	Recovery
AL1849	Mercury No. 3	154.35	244.40	4.88E-03	112	4.36E-05	B2/A7	Constant Yield
AL1849	Mercury No. 3	154.35	244.40	8.85E-04	112	7.91E-06	B2/A7	Recovery
AL2691	Awajan No. 23	160.00	251.98	2.55E-02	125	2.00E-04	B2/A7	Constant Yield
AL2691	Awajan No. 23	160.00	251.98	1.90E-03	125	1.53E-05	B2/A7	Recovery
AL2708	Baq'a No. 18	162.80	231.25	6.70E-03	150	4.50E-05	K	Constant Yield
AL2708	Baq'a No. 18	162.80	231.25	4.80E-03	150	3.20E-05	K	Recovery

Appendix 4.2 (continue)

Well Idn.	Well Name	PGN [km]	PGE [km]	Transmissivity (T) [m²/s]	Saturation Thickness (St) [m]	Permeability (k_f) [m/s]	Aquifer type	Type of Test
AL3027	Um El Jimal	193.50	281.20	5.10E-04	280	1.80E-06	B2/A7	Recovery
AL3181	Rumaimeen No. 1	168.12	226.00	2.30E-03	200	1.20E-05	K	Constant Yield
AL3287	Ruseifa Deep No. 1	158.50	248.50	1.50E-03	130	1.20E-05	B2/A7	Constant Yield
AL3308	Mouhajerin No. 2	150.50	235.50	3.10E-03	75	4.20E-05	B2/A7	Recovery
AL3314	Baq'a No. 13	165.73	228.20	2.40E-04	125	1.90E-06	K	Constant Yield
AL3375	Za'tari No. 7	188.64	273.19	1.60E-03	130	1.20E-05	Basalt & B2/A7	Constant Yield
AL3375	Za'tari No. 7	188.64	273.19	2.70E-03	130	2.10E-06	Basalt & B2/A7	Recovery
AL3376	Za'tari No. 9	187.63	273.39	1.30E-03	110	1.10E-05	Basalt & B2/A7	Constant Yield
AL3376	Za'tari No. 9	187.63	273.39	5.40E-05	110	5.00E-07	Basalt & B2/A7	Recovery
AL3422	KM 103.5	184.50	293.25	0.108	269	1.80E-04	Basalt & B2/A7	Constant Yield
AL3437	Wadi Al Sahan No. 2	168.00	214.50	6.47E-04	150	4.30E-06	K	Constant Yield
AL3437	Wadi Al Sahan No. 2	168.00	214.50	1.50E-04	150	1.00E-06	K	Recovery
AL3439	Wadi Al Sahan No. 4	166.50	215.20	9.47E-04	150	6.30E-06	K	Constant Yield
AL3439	Wadi Al Sahan No. 4	166.50	215.20	2.60E-04	150	1.70E-06	K	Recovery
AL3449	Corodoor No. 7	176.59	291.69	0.037	248	1.50E-04	Basalt & B2/A7	Constant Yield
AL3450	Corodoor No. 8	175.61	291.64	0.07	257	2.70E-04	Basalt & B2/A7	Constant Yield
AL3453	Baq'a No. 5A	162.20	229.80	3.70E-03	150	2.45E-05	K	Constant Yield
AL3453	Baq'a No. 5A	162.20	229.80	1.24E-03	150	8.30E-06	K	Recovery
AL3499	Baq'a No. 25	163.25	230.30	1.00E-03	150	9.00E-06	K	Constant Yield
AL3464	Za'tari No. 8	187.06	274.05	1.60E-03	100	1.60E-05	Basalt & B2/A7	Constant Yield
AL3464	Za'tari No. 8	187.06	274.05	6.20E-05	100	6.20E-07	Basalt & B2/A7	Recovery
AL3475	Corodoor No. 1	183.47	294.46	0.344	279	1.20E-03	Basalt & B2/A7	Constant Yield
AL3476	Corodoor No. 2	179.58	293.68	0.075	259	2.90E-04	Basalt & B2/A7	Constant Yield
AL3477	Corodoor No. 3	178.51	293.63	0.105	253	4.10E-04	Basalt & B2/A7	Constant Yield
AL3478	Corodoor No. 4	177.51	293.59	0.113	263	4.30E-04	Basalt & B2/A7	Constant Yield
AL3479	Corodoor No. 5	181.51	293.66	0.019	263	7.00E-05	Basalt & B2/A7	Constant Yield
AL3495	Hallabat No. 12	165.65	281.80	2.21E-02	165	1.30E-04	B2/A7	Constant Yield
AL3497	Hallabat No. 14	165.20	282.10	6.20E-04	160	3.90E-06	B2/A7	Constant Yield
AL3497	Hallabat No. 11	166.00	281.50	1.70E-02	165	1.00E-04	B2/A7	Constant Yield
AL3500	Baq'a No. 26	161.85	229.80	9.00E-04	150	6.20E-06	K	Constant Yield
AL3505	Dafali No. 3 (Subehi)	172.00	218.60	1.20E-02	100	1.20E-04	Z	Recovery
AL3515	KM 94A	186.54	282.62	5.70E-03	155	3.70E-05	Basalt & B2/A7	Constant Yield
AL3516	Fawa'reh No. 1A	192.57	272.74	1.80E-04	140	1.40E-06	B2/A7	Constant Yield
AL3516	Fawa'reh No. 1A	192.57	272.74	2.10E-04	140	1.50E-06	B2/A7	Recovery
AL3559	Sukhneh Deep No. 2	172.95	250.07	7.10E-04	400	1.80E-06	K	Constant Yield
AL3559	Sukhneh Deep No. 2	172.95	250.07	6.80E-04	400	1.70E-06	K	Recovery
AN1000	Wadi El Shita No. 1	147.00	235.00	7.72E-04	80	9.65E-06	B2/A7	Constant Yield
AN1000	Wadi El Shita No. 1	147.00	235.00	6.65E-04	80	8.31E-06	B2/A7	Constant Yield
AN1012	Wadi El Shita No. 4	146.00	234.00	4.63E-04	85	5.45E-06	B2/A7	Constant Yield
AL1190	Zarqa (S13)	166.87	254.89	1.60E-02	350	4.70E-05	K	Recovery
AL1190	Zarqa (S13)	166.87	254.89	1.30E-02	350	3.60E-05	K	Constant Yield
AN1015	Bahath No. 3	146.00	226.30	2.81E-03	30	9.40E-05	A1/A2	Constant Yield
AN1015	Bahath No. 3	146.00	226.30	3.30E-03	30	1.10E-04	A1/A2	Recovery
AL1162	Ein Ghazal (Seil el Ruseifa)	173.04	249.32	1.17E-03	45	2.60E-05	A4	Recovery
AL1162	Ein Ghazal (Seil el Ruseifa)	173.04	249.32	3.60E-03	45	8.00E-05	A4	Constant Yield
AL3583	Yazidiyyah No.4	166.31	231.35	2.80E-02	40	5.70E-04	A4	Constant Yield
AL3561	Yajouz No. 3	182.35	244.30	1.00E-03	45	2.20E-05	A4	Constant Yield
AL3578	Yazidiyyah No.3 (Salt)	158.13	254.30	1.10E-03	50	2.20E-05	A4	Constant Yield
AL3578	Yazidiyyah No.3 (Salt)	158.13	254.30	4.50E-04	50	5.40E-06	A4	Recovery

Appendix 4.3: List of all groundwater abstraction based on aquifer type in Amman-Zarqa Basin (10^6 m^3).

Years	Aquifer type					Total
	All	Basalt & B2/A7	A4	A1/2	K	
1995	3.1	114.4	10.9	3.1	10.3	141.8
1996	2.9	123	12.9	3.4	9.3	151.5
1997	2.6	110	13.6	2.9	8.2	137.3
1998	2.5	111	13.3	2.9	9.1	138.8
1999	2.1	107	13.5	5.1	9.4	137.1
2000	2.1	101.7	12.9	3.7	9.3	129.7
2001	1.5	102.2	12.6	3.1	9.4	128.8
2002	2.0	111.5	12.4	3.2	8.2	137.3
2003	2.1	113.1	12.6	3.3	7.5	138.6

Appendix 4.4: List of observation wells and yearly average drawdown in Amman-Zarqa Basin.

Well ID	Well Name	PGE [m]	PGN [m]	Aquifer	Yearly average drawdown [m]	Time interval [year]	W.L measured	Type of Recording
AL1005	DP 4 - Farouq H. Shlaif (PP 144)	277160	174440	BS+B2/A7	0.8	1974-2002	DWL	Manual
AL1022	DP 16 NRA (PP 315)	273377	175329	BS+B2/A7	1	1998-2003	SWL	Manual
AL1040	Wadi Dhulail Well No.TW-5	271278	177834	B2/A7	0.5	1968-2003	SWL	Recorder
AL1041	Wadi Dhulail Well No.TW-6	272484	171392	B2/A7	1	1980-2003	SWL	Recorder
AL1043	Wadi Dhulail Well No.TW-15	266987	171506	B2/A7	0.5	1968-2003	SWL	Recorder
AL1179	Refinery No. 6	256000	170127	A4	0.07	2000-2003	SWL	Recorder
AL1230	Hashimiya No.3	256690	170130	B2/A7	0.4	1999-2000	DWL	Manual
AL1300	Awajan Observation	252800	160020	B2/A7	1	1972-2003	SWL	Recorder
AL1351	Ruseifa Municipality No. 1	248468	158753	ALL	2.5	1999-2002	DWL	Manual
AL1371	Jamal Flour Mill Well	240415	151821	B2/A7	1.4	2000-2001	DWL	Manual
AL1428	Baq'a Well No. 1 (W.S.C)	230543	164303	K		1999-2002	DWL	Manual
AL1429	Souf Municipality Well No. 1	227585	192013	A1/A2	0.3	2002	DWL	Manual
AL1430	Baq'a Well No. 3 (W.S.C)	229021	165035	K	0.8	1985-2002	SWL	Recorder
AL1444	Ruseifa Spring Obs. Well No. M-8	245970	158550	B2/A7	0.06	1985-2002	SWL	Recorder
AL1521	Husain Air Force Base (BA'IJ)	270660	193480	B2/A7	1.2	1986-2002	SWL	Recorder
AL1541	Baq'a No. 9 (W.S.C)	230940	164465	K	1.05	1992-2002	DWL	Manual
AL1548	Awsa Seil el Rusaifa No.3	244350	158050	A4	7.7	1999-2002	DWL	Manual
AL1551	Ruseifa Municipality No. 4	248850	158700	B2/A7	1.1	1998-1999	SWL	Manual
AL1637	Yajuz Well No. 1	240060	159140	A4	0.4	1999-2002	DWL	Manual
AL1641	Yajuz Well No. 6	236000	160400	A4	0.1	2000-2002	DWL	Manual
AL1689	Ain Ghazal (Seil El Rusaifa No. 2A)	243890	156850	A4	9.3	1999-2002	DWL	Manual
AL1720	Shawahed East (Souf Camp) Well	234332	190145	A1/A2	-	2001-2002	DWL	Manual
AL1734	Zarqa Observation Well	255050	167460	B2/A7	< 0.05	1988-2002	SWL	Recorder
AL1782	Nadi Es-Sebaq (RC) Observation Well N	243750	152500	A4	0.5	1989-2003	SWL	Recorder
AL1792	Al Madona Well No. 4	256800	149350	B2/A7	< 0.05	1997-2002	SWL	Recorder
AL1813	Nur-Eddin Well	241006	152556	B2/A7	1.1	1997-2002	SWL	Recorder
AL1851	Mercury Well No. 5	246750	156050	B2/A7	-0.5	1999-2002	SWL	Manual
AL1859	Awsa Well No.1 (Ras El Ain No. 1)	237375	150370	B2/A7	0.4	1999-2001	SWL	Manual
AL1892	Baq'a Experimental Well No. 6A	230135	163020	B2/A7	< 0.05	1992-1993	SWL	Manual
AL1926	A'qib Dam Well No. 1- Khaldiyeh	276624	174655	B2/A7	1.1	1986-2003	SWL	Recorder
AL2360	Riyashi Well No. 2 / Jerash	237200	184750	K	0.12	2001-2002	DWL	Manual

W.L: water level SWL: static water level DWL: dynamic water level

Appendix 4.4 (continue)

Well ID	Well Name	PGE [m]	PGN [m]	Aquifer	Yearly average drawdown [m]	Time interval [year]	W.L measured	Type of Recording
AL2413	Hallabat Well No. 5	279866	165899	B2/A7	2.8	1998-2002	SWL	Manual
AL2690	Ain Ghazal Station Well No. 2 (New)	242100	154225	B2/A7	15	2000-2002	DWL	Manual
AL2695	Al Ba'ej Well 2	279750	199820	B2/A7	1.1	1986-1991	SWL	Manual
AL2697	Hussayniat Well No. 1	275200	189940	B2/A7	1.5	1986-2002	SWL	Manual
AL2698	Hallabat Well No. 1	281000	169120	B2/A7	0.8	1988-2002	SWL	Recorder
AL2699	Hashimiya Well No. 6	257800	170600	B2/A7	0.3	1988-2003	SWL	Recorder
AL2700	Samra Well No. 1	257920	173100	B2/A7	< - 0.05	1988-2003	SWL	Recorder
AL2702	Samra Well No. 3	255550	172120	B2/A7	-0.25	1986-2002	SWL	Recorder
AL2704	North Badiya No. 1 (Salhiyeh)	295000	180000	B2/A7	0.15	1989-1991	SWL	Manual
AL2714	Race Club Well No. 18	244750	153700	B2/A7	1.25	1998-2002	DWL	Manual
AL2719	Baq'a Well No. 12	230060	165490	K	0.6	1992-1994	SWL	Manual
AL3283	Hallabat Well No. 6	279866	165596	B2/A7	1.7	1997-2002	SWL	Recorder
AL3324	Ain Ghazal Deep Well No. 4	244500	158200	A1/A2	6	1999-2002	DWL	Manual
AL3343	Wadi El Qattar Well No. 1	248260	150450	A4	0.1	1998-2002	DWL	Manual
AL3349	Wadi El Qattar Well No. 7	249180	147160	A4	-0.14	1998-2002	SWL	Recorder
AL3355	Baq'a Well No. 17	229100	163625	K	0.35	2001-2002	SWL	Recorder
AL3361	A'qib Well No. 3 (KM 97.5)	287650	186500	BS	1	1988-1993	SWL	Manual
AL3384	Hallabat Well No. 2	279653	180987	B2/A7	1.3	1997-2002	SWL	Recorder
AL3386	Ruseifa Landfill Well No. 3	249998	157873	B2/A7	0.3	1998-2002	SWL	Manual
AL3387	Samra Well No. 4	264768	174833	B2/A7	0.3	2001-2002	SWL	Recorder
AL3389	Zarqa Industrial Monitoring Well No. 2	254100	171709	B2/A7	0.8	2001-2002	SWL	Manual
AL3390	Tafeh East Monitoring Well No. 1	265822	165814	B2/A7	0.5	1998-2003	SWL	Recorder
AL3391	Tafeh South Monitoring Well No. 2	265619	157188	B2/A7	0.6	1998-2002	SWL	Recorder
AL3392	Wadi I'shash Monitoring Well No. 1	252937	159420	B2/A7	-	2001-2002	SWL	Manual
AL3394	Thaghret Al Job Monitoring Well No. 1	265652	184790	B2/A7	0.7	1997-2002	SWL	Recorder
AL3396	Hussayniyat Monitoring Well No. 2	279185	187112	B2/A7	1.8	2001-2002	SWL	Recorder
AL3430	Maqarr Investigation 148 Well	239800	151500	A4	1	1999-2002	SWL	Recorder
AL3482	Corodor Well No. 11	292678	174092	BS	1.4	2001-2002	SWL	Recorder
AL3519	Sukhneh Monitoring Well	245000	172000	A4	-1	2000-2002	SWL	Recorder
AL3520	Yajouz Well No. 1 (Mon)	234950	158200	A4	-1.2	2000-2002	SWL	Recorder
AL3522	Za'tari Well Monitoring	270500	185720	A4	-6	2000-2002	SWL	Recorder
AL3523	Ruseifa Monitoring Well No. 1	245000	150030	A4	2	2000-2002	SWL	Recorder
AL3530	Baq'a Deep Well No. 13A	228100	165900	Z	0.4	2001-2002	SWL	Recorder
AL3572	Yazidiyyeh Well No. 6	221000	163750	A4	-	2002	SWL	Recorder

W.L: water level SWL: static water level DWL: dynamic water level

Appendix 5.1: The chemical and physical analysis of the groundwater sampled in Amman-Zarqa Basin.

Well Id.	Well Name	PGE [m]	PGN [m]	Aquifer	Sample date	EC [uS/cm]	pH	Ca^{2+} [mg/L]	Mg^{2+} [mg/L]	Na^{+} [mg/L]	K^{+} [mg/L]	Cl^{-} [mg/L]	SO_4^{2-} [mg/L]	HCO_3^{-} [mg/L]	NO_3^{-} [mg/L]
AL1356	Pepsi Cola No. 5	246449	156355	B2/A7	2003	956	7.6	100.0	31.1	49.9	3.9	91.2	27.8	335.5	53.0
		246449	156355	B2/A7	2004	983	7.2	97.2	29.4	46.9	4.7	113.6	27.8	301.3	
AL3352	Jarash No. 3 (Wadi El Dair-East)	234596	189051	A1/A2	2003	820	7.7	94.6	28.3	27.8	2.0	65.3	26.9	320.3	58.0
AL2341	Yousef & Ali Elfare'a	230548	167047	K	2003	967	7.7	72.5	36.8	68.8	8.6	113.6	50.4	256.8	64.5
		230548	167047	K	2004	961	7.5	72.5	26.8	77.7	9.4	109.3	55.2	253.8	80.0
AL1479	Nawaf Qadi	275043	191114	Bs	2003	1226	8.0	70.9	31.9	115.0	4.3	269.8	52.8	139.7	23.6
		275043	191114	Bs	2004	1091	7.8	39.3	45.0	125.1	5.1	291.1		140.3	27.7
AL2716	Shawahed East No. 3A	234235	190276	A4	2003	792	7.8	77.6	41.5	25.3	2.0	52.2	65.3	311.1	24.3
AL1522	KM-81(Fawaareh)	272922	192532	Bs	2003	901	7.9	50.1	39.6	61.2	2.7	149.1	49.0	228.1	21.1
AL2801	Qasem El A'bsi	276486	196199	Bs	2003	1636	8.0	60.1	68.0	148.6	11.0	403.3	74.9	102.5	32.3
AL1608	Faleh Gharaybeh	237146	185073	A1/A2	2003	988	7.7	82.4	44.9	53.1	2.7	125.0	35.0	281.2	66.9
		237146	185073	A1/A2	2004	967	7.91	87.98	37.09	48.3	4.3	127.8	30.72	372	
AL3328	Ismail Jaghoob	265942	184778	B2/A7	2003	1097	7.8	58.3	48.0	67.9	2.0	156.2	44.2	244.6	37.8
AL1627	Yazidiyya No. 2	224604	163220	K	2003	650	7.8	41.7	44.5	22.8	1.6	42.6	24.5	311.1	6.8
		224604	163220	K	2004	672	7.6	83.4	40.5	20.5	3.1	42.6		321.5	6.8
AL1393	Abu Nusair Well	231560	165074	K	2003	703	7.7	69.1	27.9	41.2	3.1	73.8	51.4	254.4	6.8
		231560	165074	K	2004	658	7.1	75.0	25.1	43.2	4.7	71.0	54.2	277.6	7.3
AL2114	Race Club No. 14	244348	153156	B2/A7	2003	1020	7.8	83.4	26.8	60.0	5.1	132.4	17.8	276.9	40.8
		244348	153156	B2/A7	2004	1053	7.6	103.8	23.5	65.3	6.3	149.1	20.64	330.0	40.3
AL1831	Race Club No. 22	241857	152698	B2/A7	2003	1175	7.6	121.6	24.6	74.5	9.4	147.3	20.6	324.5	88.5
		241857	152698	B2/A7	2004	1167	7.1	117.0	12.7	75.7	10.2	157.6	24.96	327.6	98.3
AL1360	Polytechnique No. 1	246070	155756	B2/A7	2003	725	7.8	30.1	20.7	83.0	5.9	129.9	53.3	131.8	10.5
AL3343	Wadi El Qattar No. 1	248384	150241	A4	2003	806	7.9	62.1	33.1	51.5	2.0	89.5	34.6	256.2	26.9
		248384	150241	A4	2004	816	7.69	62.73	40.74	50.6	3.52	113.6	31.2	248.9	
AL2690	Ain Ghazal Station No. 2	242056	154293	B2/A7	2003	1100	7.4	103.0	21.5	78.7	7.4	132.4	43.2	305.0	54.8
		242056	154293	B2/A7	2004	1051	7.1	100.0	21.3	75.2	7.4	130.6		306.8	107.2
AL1637	Yajouz No. 1	239829	159027	A4	2003	708	7.8	71.7	27.2	30.1	2.4	56.8	21.6	268.4	33.5
		239829	159027	A4	2004	648	7.71	62.52	26.02	28.52	3.91	63.19	18.72	282.43	
AL1548	Seil El Ruseifa No.3 A	244945	157979	A4	2003	603	7.8	57.5	32.8	20.9	1.6	42.6	18.7	280.6	11.9
		244945	157979	A4	2004	536	7.69	54.11	34.41	19.32	2.74	28.76	15.36	294.63	
AL1860	Ruseifa No. 17 /Ain Ghazal 1A	244044	157246	A4	2003	588	7.7	59.1	23.8	20.7	1.6	35.5	16.3	270.8	10.9
		244044	157246	A4	2004	948	7.42	89.98	22.5	72.91	7.43	119.99	35.52	265.96	
AL1830	Awsa 21 Jesr Al Hamam	238109	150520	B2/A7	2003	1070	7.4	116.6	20.8	59.6	5.1	115.0	20.2	300.1	92.7
		238109	150520	B2/A7	2004	1053	7.14	115.43	19.21	64.63	6.26	120.7	20.2	284.87	104.20
AL3305	Hallabat No. 3A (East)	278896	166516	B2/A7	2003	838	7.9	35.5	28.1	77.5	5.5	180.3	40.8	107.4	13.8
AL2566	Hlayyel Khalaf	276748	165698	B2/A7	2003	2140	7.9	69.9	58.7	280.6	7.8	564.5	102.7	96.4	25.7
		276748	165698	B2/A7	2004	2750	8.05	89.18	77.46	320.85	15.64	700.06	145.92	96.38	
AL1351	Ruseifa No. 1	248221	158908	ALL	2003	1383	7.6	112.6	32.8	110.2	7.4	202.4	42.7	366.0	56.3
		248221	158908	ALL	2004	1698	7.4	121.4	39.3	125.1	8.6	234.3	48.5	402.0	
AL1307	Jordan Dairy	251251	159266	B2/A7	2003	1380	7.5	118.4	31.9	104.0	8.2	195.3	59.0	356.2	32.5
		251251	159266	B2/A7	2004	1333	7.2	114.2	31.9	92.5	8.2	182.5	57.1	366.0	
AL1075	Sa'eed Qteishat Well	268748	171031	B2/A7	2003	3220	7.8	127.5	98.3	407.1	11.7	706.5	495.4	109.8	78.5
AL2715	Hashimiya No.2	256944	169795	B2/A7	2003	3300	7.7	157.7	88.9	400.2	7.8	706.5	339.8	306.2	56.3
		256944	169795	B2/A7	2004	3450	7.35	157.92	85.97	388.7	11.73	639	337.92	314.15	
AL1319	Awajan No. 21	252452	160435	B2/A7	2003	1904	7.4	128.5	38.9	174.6	8.6	355.0	74.9	314.8	56.4
		252452	160435	B2/A7	2004	1827	7.1	107.2	54.8	56.1	3.9	355.0		314.8	59.3

Appendix 5.1 (continue)

Well Id.	Well Name	PGE [m]	PGN [m]	Aquifer	Sample date	EC [uS/cm]	pH	Ca^{2+} [mg/L]	Mg^{2+} [mg/L]	Na^{+} [mg/L]	K^{+} [mg/L]	Cl^{-} [mg/L]	SO_4^{2-} [mg/L]	HCO_3^{-} [mg/L]	NO_3^{-} [mg/L]
AL1689	Ain Ghazal Seil El Ruseifa 2A	243890	156850	A4	2003	578	7.6	51.7	31.5	22.3	3.1	27.3	25.9	286.7	7.7
AL1826	Ruseifa 18/Amman Municipality No. 25	247266	158704	A4	2003	618	7.3	60.9	27.8	23.7	2.3	38.7	21.1	294.6	18.9
AL2032	Yeast Industries Co. Ltd. No. 2	246510	158662	B2/A7	2003	691	7.3	62.7	34.3	25.5	2.7	43.3	21.6	317.2	3.5
		246510	158662	B2/A7	2004	760	7.82	60.72	40.49	26.22	4.3	53.25	36	314.15	
AL1618	Sami Hanna Khouri & Partners	255830	175340	B2/A7	2003	884	7.9	43.1	29.5	82.8	6.6	150.9	62.9	145.2	21.5
AL1575	Abdel Kareem Mifleh El Wraikat 3	231080	165795	K	2003	1211	8.0	72.1	36.8	117.1	6.3	204.8	73.0	226.9	60.1
Al1394	Jordan Tiels & Blocks Com.	232905	166205	K	2003	705	7.6	55.1	23.1	60.5	4.3	76.0	37.9	251.3	8.5
		232905	166205	K	2004	790	7.9	64.9	29.9	71.3	3.9	106.5	52.8	284.9	13.7
AL1147	Sa'eed Mo'awad	251620	173335	ALL	2003	777	7.4	70.7	26.8	32.2	3.5	55.0	19.2	266.0	48.4
AL1005	DP 4 (Faroug H.Shlaif)(PP 144)	276840	174440	Bs	2003	2830	6.4	113.0	86.8	342.5	11.7	623.4	378.7	106.8	64.7
		276840	174440	Bs	2004	2030	8.1	97.2	86.0	134.1	12.1	475.7	165.6	103.1	
AL2603	Elias El Moa'sher 1	268800	169200	B2/A7	2003	1900	6.4	74.3	50.0	205.2	11.0	418.2	144.0	101.9	26.0
		268800	169200	B2/A7	2004	2220	7.5	88.0	58.4	223.6	10.6	482.8		99.4	33.3
AL1086	Jack Khayyat 4 (SHARIF M.H.8)	273694	171447	B2/A7	2003	1250	6.4	54.5	36.4	129.3	8.2	267.3	99.8	122.6	15.7
		273694	171447	B2/A7	2004	1690	7.7	64.1	53.1	154.6	8.6	340.8	154.6	253.8	23.4
AL1082	Matar Abdallah Nassar 1	269143	168674	B2/A7	2003	3560	6.2	162.5	96.7	422.1	11.7	913.4	292.3	104.3	50.8
		269143	168674	B2/A7	2004	3650	7.7	145.9	126.5	381.8	11.7	958.5		133.6	50.3
AL2600	Mohammad Abu El Nadi (PP 404)	271800	169380	B2/A7	2003	1900	6.4	73.1	60.6	205.6	11.0	444.1	177.1	100.7	28.3
		271800	169380	B2/A7	2004	2430	7.6	96.4	59.7	250.7	8.6	518.3		94.6	37.1
AL1072	A'rnoos Al U'qail 1	266429	171549	B2/A7	2003	1418	6.5	83.4	50.3	231.2	8.2	376.7	229.9	143.4	38.7
		266429	171549	B2/A7	2004	2440	7.5	100.6	60.9	271.4	9.4	422.5		138.5	58.6
AL1073	A'rnoos Al U'qail 2	266498	171015	B2/A7	2003	1965	6.6	89.6	51.1	231.2	10.6	396.2	250.6	155.6	40.0
AL1392	Yousef Ibraheem Al Nahar	232315	165655	K	2003	864	6.4	61.7	32.3	68.8	2.3	83.8	207.8	133.0	5.8
AL3364	Beerain No.3 (Shafa Badran 3)	239500	166750	A1/A2	2003	1116	7.6	69.9	46.1	76.4	1.2	156.6	56.2	287.9	44.5
		239500	166750	A1/A2	2004	1096	7.53	86.77	44.75	66.47	3.52	142	43.68	311.71	
AL3179	Beerain No.2 (Shafa Badran 2)	238250	167100	A4	2003	1176	7.6	81.0	42.0	79.6	0.0	162.6	57.1	291.6	47.0
		238250	167100	A4	2004	1145	7.78	88.38	44.02	75.67	3.91	163.3	49.44	299.51	
AL1079	Hazeem Husain Saleem & Parts.	267486	169746	B2/A7	2003	1412	6.3	64.7	36.5	149.5	8.6	319.5	96.5	104.3	21.0
		267486	169746	B2/A7	2004	1884	7.6	79.6	48.3	190.7	9.4	369.2		112.9	34.6
AL2569	Mohammad Ahmad Shar'ab	284900	163350	B2/A7	2004	1221	8.06	69.54	14.84	117.3	6.65	220.1		163.48	
AL1843	Awsa 33 (Race Club 2)	243200	152130	B2/A7	2003	1087	6.4	107.0	25.3	63.3	8.2	136.3	17.3	309.3	81.0
AL2691	Awajan 23	251980	160000	B2/A7	2003	1520	6.5	112.0	37.1	123.7	8.6	264.5	28.8	328.8	46.6
		251980	160000	B2/A7	2004	1598	7.68	120.84	47.06	137.77	8.21	319.5	39.84	362.3	61.8
AL1088	Shihadeh Tawal 2	267536	167536	B2/A7	2003	2170	6.4	98.0	55.3	245.4	9.8	521.5	171.4	114.1	28.9
		267536	167536	B2/A7	2004	3680	7.4	150.1	129.0	388.7	10.6	923.0	148.3	181.2	47.6
AL2333	Race Club No. 29	242700	152150	B2/A7	2003	1017	6.4	66.1	46.0	62.8	6.3	128.9	25.0	322.7	55.2
AL1318	Awajan 22 Zarqa Municipality A	252468	160340	B2/A7	2003	1791	6.5	123.0	40.3	161.0	9.0	340.1	64.8	318.4	49.6
		252468	160340	B2/A7	2004	1858	7.40	120.04	55.33	190.44	8.99	383.4	48.48	357.46	
AL2597	Hammad Salem El Saheem 1	281860	172715	Bs	2003	2270	7.7	115.6	110.4	131.3	14.9	647.5	37.9	66.5	79.1
AL1864	Shoqi Hamam Well	290380	187740	Bs	2004	952	8.50	24.25	22.13	119.6	9.78	167.92	63.84	105.53	
AL2573	Ahmad Khaleel El Sutari	286000	163000	Bs	2004	500	8.22	24.45	7.54	52.9	5.08	49.7		99.43	

Appendix 5.2: Jordanian standards and World Health Organization (WHO) guidelines for drinking water (after JISM 2001 and WHO 1996).

Parameters	**Jordanian**	**Standards**	**WHO Guidelines**
	permissible	Max. Permissible*	
Temp. ^oC	25		25
pH-value	6.5-8.5		8
Colour	10 Unit	15 Unit	15 Unit
Turbidity	1 Unit	5 Unit	5 Unit
Na (mg/L)	200	400	200
Ca (mg/L)		200	
Mg (mg/L)		150	
K (mg/L)		12	12
HCO3 (mg/L)		500	350
Cl (mg/L)	200	500	250
SO4 (mg/L)	200	500	250
NO3 (mg/L)	50	70	50
TDS (mg/L)	500	1500	1000
TH (mg/L)	300	500	500
As (mg/L)	0.01		0.01
Se (mg/L)	0.05		0.01
Fe (mg/L)	0.3	1	0.3
Mn (mg/L)	0.1	0.2	0.1
Cr (mg/L)	0.05		0.05
Cd (mg/L)	0.003		0.003
Ni (mg/L)	0.07		0.02
Pb (mg/L)	0.01		0.01
Cu (mg/L)	1	1.5	1
Zn (mg/L)	3	5	3
Al (mg/L)	0.1	0.2	0.1

* Since good water quality resources are not available.

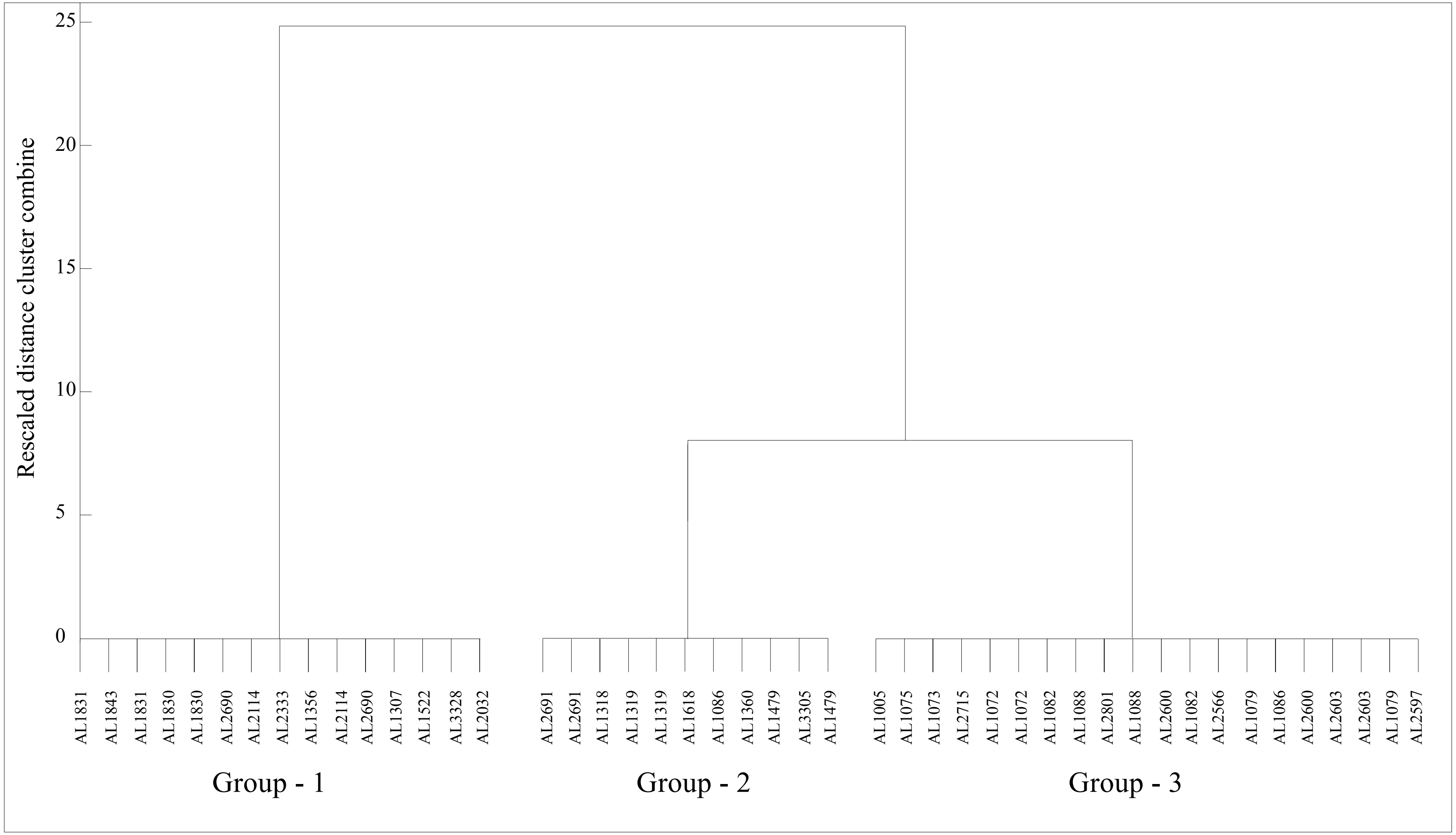
Appendix 5.3: The correlation coefficients and significance levels between the chemical parameters.

		CA	MG	NA	K	HCO3	SO4	CL	NO3	EC	SAR	HARDNESS
CA	Pearson Correlation	1										
	Sig. (2-tailed)	.										
	N	56										
MG	Pearson Correlation	.506**	1									
	Sig. (2-tailed)	.000	.									
	N	56	56									
NA	Pearson Correlation	.517**	.816**	1								
	Sig. (2-tailed)	.000	.000	.								
	N	56	56	56								
K	Pearson Correlation	.388**	.629**	.647**	1							
	Sig. (2-tailed)	.003	.000	.000	.							
	N	56	56	56	56							
HCO3	Pearson Correlation	.389**	-.365**	-.397**	-.415**	1						
	Sig. (2-tailed)	.003	.006	.002	.001	.						
	N	56	56	56	56	56						
SO4	Pearson Correlation	.366**	.653**	.859**	.523**	-.402**	1					
	Sig. (2-tailed)	.006	.000	.000	.000	.002	.					
	N	56	56	56	56	56	56					
CL	Pearson Correlation	.537**	.926**	.937**	.716**	-.459**	.716**	1				
	Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.				
	N	56	56	56	56	56	56	56				
NO3	Pearson Correlation	.634**	.027	-.010	.235	.410**	.004	.004	1			
	Sig. (2-tailed)	.000	.860	.950	.116	.005	.978	.982	.			
	N	46	46	46	46	46	46	46	46			
EC	Pearson Correlation	.663**	.898**	.955**	.693**	-.301*	.776**	.966**	.117	1		
	Sig. (2-tailed)	.000	.000	.000	.000	.024	.000	.000	.438	.		
	N	56	56	56	56	56	56	56	46	56		
SAR	Pearson Correlation	.292*	.672**	.952**	.632**	-.541**	.835**	.852**	-.160	.842**	1	
	Sig. (2-tailed)	.029	.000	.000	.000	.000	.000	.000	.289	.000	.	
	N	56	56	56	56	56	56	56	46	56	56	
HARDNESS	Pearson Correlation	.810**	.907**	.798**	.622**	-.071	.621**	.876**	.321*	.920**	.594**	1
	Sig. (2-tailed)	.000	.000	.000	.000	.605	.000	.000	.030	.000	.000	.
	N	56	56	56	56	56	56	56	46	56	56	56

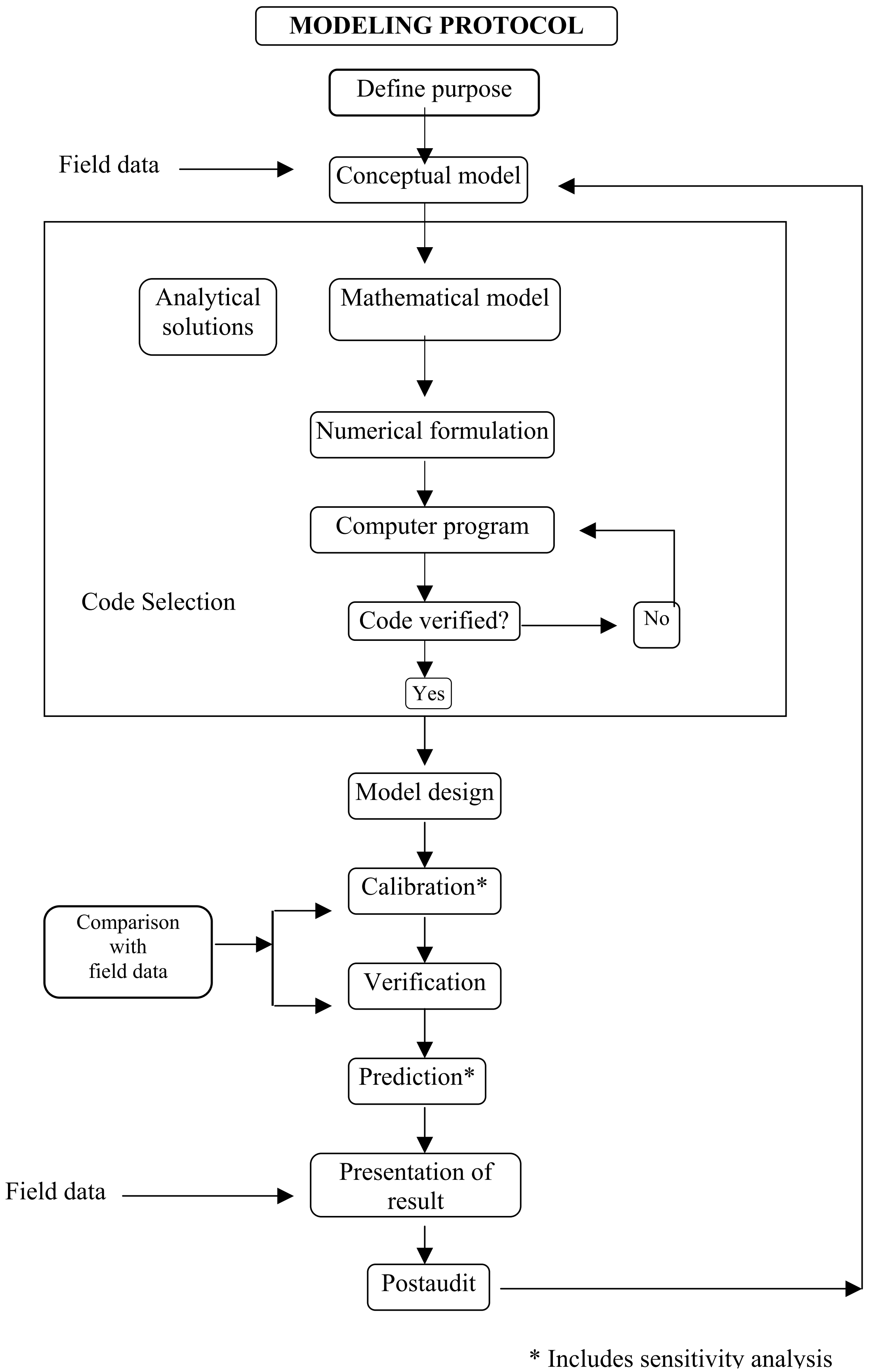
**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Appendix 5.4: Dendrogram of the cluster analysis for water sampled using Ward Method.



Appendix 7.1: Step in a protocol for model application (Anderson and Woessner 1992).



Appendix 7.2: The correlation coefficient matrix of the optimized parameter values in upper aquifer calculated by PEST.

Parameter	**hk_1**	**hk_2**	**hk_3**	**hk_4**	**hk_5**	**hk_6**	**hk_7**	**hk_8**
	hk_9	**hk_10**	**rch_17**	**rch_18**	**rch_19**	**rch_20**	**rch_21**	**rch_22**
hk_1*		1.00	-0.93	-1.00	-0.94	-0.93	-0.90	-0.93
	0.77	-0.95	-0.83	-0.21	1.00	0.13	0.45	-0.49
hk_2	1.00		-0.93	-1.00	-0.94	-0.93	-0.90	-0.93
	0.77	-0.95	-0.83	-0.21	1.00	0.13	0.45	-0.49
hk_3	-0.93	-0.93		0.95	0.99	0.98	0.97	0.99
	-0.64	0.99	0.81	0.36	-0.93	0.16	-0.61	0.20
hk_4	-1.00	-1.00	0.95		0.96	0.94	0.91	0.94
	-0.76	0.96	0.83	0.24	-1.00	-0.09	-0.48	0.45
hk_5	-0.94	-0.94	0.99	0.96		1.00	0.99	0.99
	-0.66	1.00	0.82	0.37	-0.94	0.17	-0.66	0.23
hk_6	-0.93	-0.93	0.98	0.94	1.00		0.99	0.99
	-0.64	0.99	0.81	0.40	-0.93	0.22	-0.71	0.19
hk_7	-0.90	-0.90	0.97	0.91	0.99	0.99		0.98
	-0.60	0.99	0.82	0.38	-0.90	0.26	-0.72	0.13
hk_8	-0.93	-0.93	0.99	0.94	0.99	0.99	0.98	
	-0.63	0.99	0.83	0.38	-0.93	0.20	-0.64	0.18
hk_9	0.77	0.77	-0.64	-0.76	-0.66	-0.64	-0.60	-0.63
		-0.67	-0.71	-0.01	0.77	0.40	0.20	-0.67
hk_10	-0.95	-0.95	0.99	0.96	1.00	0.99	0.99	0.99
	-0.67		0.83	0.36	-0.95	0.14	-0.64	0.25
rch_17**	-0.83	-0.83	0.81	0.83	0.82	0.81	0.82	0.83
	-0.71	0.83		-0.13	-0.83	-0.06	-0.46	0.39
rch_18	-0.21	-0.21	0.36	0.24	0.37	0.40	0.38	0.38
	-0.01	0.36	-0.13		-0.21	0.59	-0.59	-0.40
rch_19	1.00	1.00	-0.93	-1.00	-0.94	-0.93	-0.90	-0.93
	0.77	-0.95	-0.83	-0.21		0.13	0.45	-0.49
rch_20	0.13	0.13	0.16	-0.09	0.17	0.22	0.26	0.20
	0.40	0.14	-0.06	0.59	0.13		-0.69	-0.89
rch_21	0.45	0.45	-0.61	-0.48	-0.66	-0.71	-0.72	-0.64
	0.20	-0.64	-0.46	-0.59	0.45	-0.69		0.28
rch_22	-0.49	-0.49	0.20	0.45	0.23	0.19	0.13	0.18
	-0.67	0.25	0.39	-0.40	-0.49	-0.89	0.28	

* Hydraulic conductivity(m/s)_parameter number

** Recharge rate (m/s)_parameter number

Appendix 7.3: The optimized parameter values of the lower aquifer.

Parameter Name	Current value (calibrated model)	Estimated value	Lower limit	Upper limit
Hk_1*	$3.0*10^{-5}$	$1.4*10^{-4}$	$3.0*10^{-7}$	$3.0*10^{-3}$
Hk_2	$1.0*10^{-5}$	$1.0*10^{-3}$	$1.0*10^{-7}$	$1.0*10^{-3}$
Hk_3	$1.0*10^{-6}$	$5.0*10^{-8}$	$1.0*10^{-8}$	$1.0*10^{-4}$
Hk_4	$1.1*10^{-5}$	$1.5*10^{-5}$	$1.1*10^{-7}$	$1.1*10^{-3}$
Hk_5	$4.0*10^{-6}$	$6.7*10^{-7}$	$4.0*10^{-8}$	$4.0*10^{-4}$
Hk_6	$7.0*10^{-6}$	$4.4*10^{-6}$	$7.0*10^{-8}$	$7.0*10^{-4}$
Hk_7	$3.0*10^{-6}$	$3.5*10^{-6}$	$3.0*10^{-8}$	$3.0*10^{-4}$
Hk_8	$1.0*10^{-5}$	$9.5*10^{-6}$	$1.0*10^{-7}$	$1.0*10^{-3}$

* Hydraulic conductivity(m/s)_parameter number

Appendix 7.4: The estimated heads of observation points based on PEST calculation (lower aquifer).

Observation No.	PGE [m]	PGN [m]	Estimated head [m]	Measured head [m]	Residual [m]
1	224336.3	179123.0	389.1	400	10.9
2	226252.6	172677.3	293.4	300	6.6
3	217093.3	174435.3	286.8	300	13.2
4	232846.1	181727.4	322.7	300	-22.7
5	228104.0	176421.1	214.9	200	-14.9
6	256340.7	150938.1	395.3	400	4.7
7	230376.1	160893.5	592.3	600	7.7
8	231393.0	159661.0	514.9	500	-14.9
9	244758.0	179743.5	396.3	400	3.7
10	222095.6	172783.5	373.2	400	26.8
11	229358.4	192775.0	525.0	525	0.0
12	229320.1	185337.3	523.3	520	-3.3