Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley, JORDAN

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DEDICATION

To my lovely & safe country Jordan
To the king

To my Parents, Sisters & Brothers
For their love, encouragement & endless support which lights up my life…

To my real friends & to everyone supporting my success

& more…
To my everlasting love, the light of my eyes & my soul
*My Kids … **Leen, Hiba** & **Michael***
For understanding during my absence, support & unlimited encouragement
Who make me realize that…
"A mother is one who can take place of all others, but whose place no one can take"

For them all … love & respect

Julia

Eidesstattliche Erklärung

Ich erkäre hiermit an Eides statt, dass ich die vorliegende Promotion selbständig und ohne unzulässige fremde Hilfe angefertigt habe.

Die verwendeten Literaturquellen sind im Literaturverzeichins vollständig zitiert.

Karlsruhe, den 30.03.2011

Julia Sahawneh

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ABSTRACT

The work was accomplished as part of an interdisciplinary "Integrated Water Resources Management" project (SMART) in the Lower Jordan Valley. The aim of this study was to work out the relationship and dependencies of the hydrogeological characteristics and circumstances of the NW part of Jordan from a structural geological view and to classify their significance for the groundwater flow patterns. The study area extends from the Dead Sea to the Jordanian-Syrian border in the north. It includes the Jordan Valley to the west, the rise of the mountain with the ridges to the east, and it gradually merges towards the east into the East Jordanian Plateau. The longitudinal extent is 150 km with a width 70 km. The altitude ranges from the northeast corner of the Dead Sea at -420 m below sea level to an altitude of 1240 m.

The spatial information is based on comprehensive research and data provided from the national authorities, particularly the Natural Resources Authority (NRA) and the Ministry of Water and Irrigation (MWI) as well as on data from oil and water wells. A total of 1,500 wells were evaluated both in terms of lithological and hydraulic properties. A first key task was to develop a data management structure. The compilation of data was based on local topographic and geologic maps at 1:50,000 and on the analysis of aerial photographs. To overlay this basic information with the geological structures and hydrogeological data in a GIS, digital versions of the maps were created. It was therefore an objective of the GIS processing to integrate the different 3D data sets and make them accessible for improved interpretation.

Another objective of the basic data collection was to first assess the large-scale structural elements in the narrower surroundings, as well as to cover the wider area and set it in a chronological order. This showed that many of the older time definitions were based on wrong time assignments and thus by the juxtaposition of different tectonic processes resulted in a false picture of the deformation phases. From a re-evaluation of the various structural elements a superior 3-phase model could be derived. In connection with the Upper Cretaceous narrowing and the closure of the Mesozoic Tethys E-W trending troughs and sills were created already in the sedimentary phase, which later were deformed to the WSW-ENE Syrian fold belt. The sedimentary troughs and sills are still noticeable in the different aquifer thicknesses. The second major deformation phase appeared in the Eocene to lower Miocene and was characterized by extensional rift formation in NW-SE direction (Red Sea, Wadi Sirhan Graben). The third phase, from the Upper Miocene till Recent, is the left lateral strike-slip displacement along the N-S trending Dead Sea - Levant structure with the accompanying groups of faults and fractures. This deformation still determines the Landscape and morphology of the study area.

By integrating the lithological profiles from oil wells with the thickness data for each layer complex, a three-dimensional image of the structural conditions was created that found clear expression in 6 transverse or oblique sections and one longitudinal profile. The superposition of this three-dimensional geological database with the hydrogeological data resulted in the evaluation of the hydrogeological dependence on changes over time on the dynamically acting

structural elements. On the basis of the structural maps of the base and top of the aquifers and in relation to the hydraulic potential distribution, the spatial groundwater flow behavior could be clarified. As essential structural elements dominating the flow patterns of sub-sectors from north to south, are the following elements: the Ajlun structure (Domal Zone) with the south bounding E-W fault systems, the NNE fracture zone of the Zarqa River and Belqa, as well as in the south the WSW-ENE folds and reverse fault structures of the Deir Allah anticline forming a watershed, the parallel synclines, e.g. of Shueib and Kafrain (water collection troughs) and finally in the very south of the study area, the Amman-Suweimeh Halabat flexure, acting both as a preferred watershed, as well as effective groundwater flow paths. To the west of the study area there are numerous nearly N-S striking faults associated to the main strike slip fault. However, these were activated only as transversal movement paths of low water conductivity. Their often observed reactivation as normal faults makes them, however, preferred water pathways of high permeability.

This study also showed that not only the dynamics of groundwater flow was influenced or determined by structural geology, but also the hydro-chemical characteristics of the water. This is primarily determined by the direct recharge of near-surface infiltration and by the mean residence time in the underground which enhances chemical reactions, but these two processes are actually dependent on the structural geology of the subsurface.

KURZFASSUNG

Die Arbeit wurde im Rahmen eines interdisziplinären “Integrated Water resources Managment“ Projektes (SMART) über das Untere Jordan Tal erstellt. Ziel dieser Arbeit war es die Beziehung und Abhängigkeiten der hydrogeologischen Eigenschaften und Verhältnisse NW Jordaniens von den strukturgeologischen Gegebenheiten herauszuarbeiten und deren Bedeutung für die unterirdischen Abstrombedingungen zu erfassen und zu klassifizieren. Das Untersuchungsgebiet erstreckt sich vom Toten Meer bis an die jordanisch-syrische Grenze im Norden. Es schließt damit das linksufrige Jordantal, den Anstieg des Gebirges, die Kammlagen sowie den Übergang zur jordanischen Sedimenttafel nach Osten mit ein. Die Längserstreckung beträgt 150 km die erfasste Breite 70 km. Die Höhenlage reicht von der Nordostecke des Toten Meeres bei -420 m unter dem Meeresspiegel bis auf eine Höhe von 1240 m.

Die räumlichen Informationen stützen sich auf eine umfassende Recherche und die zur Verfügungstellung der bei den nationalen Behörden, insbesondere der Natural Resources Authority sowie des Ministeriums für Wasser und Bewässerung aber auch auf Daten der Ölindustrie wie auch der Wasserwirtschaftsverwaltung vorhandenen Daten. Insgesamt wurden über 1500 Bohrungen sowohl hinsichtlich der lithologischen wie hydraulischen Befunde ausgewertet. Eine erste zentrale Aufgabe war es ein Datenmanagement- Struktur zu entwickeln. Die Kompilation der Daten basierte auf regionalen topographischen und geologischen Karten im Maßstab 1:50,000 und Luftbildauswertungen. Um diese Basisinformationen mit den strukturgeologischen und hydrogeologischen Daten in einem GIS überlagern zu können, wurden digitale Fassungen der Karten erstellt. Es war deshalb ein Ziel der GIS Bearbeitung die unterschiedlichen 3D-Daten zu integrieren und für eine verbesserte Interpretation zugänglich zu machen.

Eine weitere Aufgabe der Basisdatenerfassung war es zunächst die großräumigen strukturgeologischen Gegebenheiten des engeren Untersuchungsgebietes, wie auch der weiteren Umgebung zu erfassen und sie einer zeitlichen Einordnung zu zuführen. Hier zeigte sich das viele der älteren Einordnungen von falschen zeitlichen Zuordnungen ausgehen und dadurch die Aneinanderreihung der unterschiedlichen tektonischen Prozesse ein falsches Bild der Deformationsphasen ergaben. In einer Neubewertung der verschiedenen Strukturelemente konnte eine übergeordnete 3-Phasigkeit abgeleitet werden. Im Zusammenhang mit der oberkretazischen Einengung und Schließung der Mesozoischen Tethys entstanden bereits in der sedimentären Phase annähernd W-E streichende Tröge und Schwellen, die sich noch in den unterschiedlichen Aquifer-Mächtigkeiten bemerkbar machen und später zu dem WSW-ENE streichen Syrischen Falten gürtel deformiert wurden. Die zweite maßgebliche Deformationsphase wirkte im Eozän bis unteres Miozän und war durch extensionale Riftbildung in NW-SE Richtung (Rotes Meer, Wadi Sirhan Graben) gekennzeichnet. Als dritte s heute vor allem auch die Morphologie bestimmendes Element kommt seit dem oberen Miozän, die N-S verlaufende linkshändische transversal Komponente der Toten .-Meer -Levante Struktur mit der begleitenden Schar von Störungen und Klüften hinzu.

Durch Integration der Bohrbefunde mit den Mächtigkeitsangaben für die einzelnen Schichtkomplexe konnte ein dreidimensionales Bild der strukturellen Gegebenheiten erstellt werden, die ihren sichtlichen Ausdruck in 6 Quer- bzw. Schrägprofilen sowie einem Längsprofil

erfahren. Die Überlagerung dieser dreidimensionalen geologischen Datenbasis mit hydrogeologischen Daten führt schließlich zur Bewertung der hydrogeologischen Abhängigkeiten von den zeitlich sich verändernden und damit dynamisch wirkenden Strukturelementen. Ausgehend von den Strukturkarten der Basis und Deckschichten der Grundwasserleiter kann im Zusammenhang mit den hydraulischen Potentialverteilungen das räumliche Abflussverhalten des Grundwassers verdeutlicht werden. Als wesentliche Strukturelemente, die das Abflussverhalten in Teilbereichen dominieren sind von Norden nach Süden folgende Elemente zu benennen: die Ajlun Aufwölbungszone mit den nach Süden begrenzenden W-E Störungen, die NNE streichen Störungszone des Zarqa River und Balqa Störungssystem, sowie nach Süden die WSW-ENE streichen Falten und Aufschiebungsstrukturen der Deir Allah Antiklinale als Wasserscheide und die dazu parallelverlaufenden Synklinalen, z.B. von Shueib und Kafrein, als Wassersammelträge und schließlich im ganz im Süden des Untersuchungsgebietes die Suweime-Amman- Halabat Flexur, die sowohl als Wasserscheide als auch als bevorzugte Grundwasserabflussbahn wirkt. Im Westen des Untersuchungsgebietes sind es die zahlreichen annähernd N-S streichenden die Hauptblattverschiebung begleitenden Störungen. Allerdings sind diese soweit sie nur als transversal Bewegungsbahne aktiviert wurden weniger wasserwegsam, Ihre vielfach zu beobachtende Reaktivierung als Abschiebungen macht sie jedoch zu bevorzugten Wasserwegen hoher Durchlässigkeit.

Mit den Untersuchungen konnte auch gezeigt werden, dass nicht nur die Abflussdynamik des Grundwassers strukturgeologisch beeinflusst bzw. bestimmt wird, sondern auch die hydrochemische Beschaffenheit der Wässer. Diese wird zwar primär von der direkten Grundwasserneubildung über oberflächennahe Infiltration sowie über die mittlere Verweilzeit im Untergrund als chemische Reaktionszeit bestimmt, doch sind diese beiden Vorgänge wieder von den strukturgeologischen Gegebenheiten des Untergrundes abhängig.

تأثير التراكيب الجيولوجية على هيدرولوجية، هيدروجيولوجية وكيميائية المياة على امتداد الحافة الشرقية لمنطقة غور الأردن

الخلاصة

تم هذا العمل كجزء من مشروع "الإدارة المتكاملة للموارد المائية"، مشروع (سمارت) في وادي الاردن الادنى. ويهدف العمل لدراسة العلاقة بين التراكيب الجيولوجية المختلفة في شمال غرب الأردن وتأثيرها على الخصائص الهيدروجيولوجية للخزانات المائية المختلفة وتصنيف أهميتها بالنسبة لحركة المياة الجوفية. تمتد منطقة الدراسة من البحر الميت إلى الحدود الأردنية السورية في الشمال. وتشمل وادي الأردن من جهة الغرب، وتمتد شرقا الى المنطقة الجبلية المنحدرة التي تطل على غور الاردن، الى المرتفعات الشمالية والتى تمتد شرقا الى الهضبة الاردنية الشرقية. بطول 150 كيلومترا، وعرض 70 كيلومترا. ويتراوح الارتفاع في الجهة الشمالية الشرقية للبحر الميت ب -420 متر تحت مستوى سطح البحر الى ارتفاع 1240 متر.

وتعتمد المعلومات المستخدمة في هذة الدراسة على البحث الشامل وعلى المعلومات التي تم التزود بها من السلطات الوطنية، وبشكل خاص سلطة المصادر الطبيعية ووزارة المياه والري، كما وتستند على معلومات آبار البترول والمياه . وقد تم تقريبا تقييم ما مجموعة 1500 بئر على اساس الخصائص الليثولوجية والهيدروليكية. وكان تطوير قاعدة بيانات أساسية للمنطقة هو من اول المهام الرئيسية ، وأعتمد تصنيف البيانات على الخرائط الطبوغرافية والجيولوجية المتوفرة بمقياس 1:50,000 وعلى تحاليل الصور الجوية. وقد أستخدمت قاعدة البيانات الاساسية هذة في انشاء خرائط رقمية تتضمن التكاوين الجيولوجية والمعلومات الهيدروجيولوجية المختلفة باستخدام تقنيات نظم المعلومات الجغرافية (نظام GIS). ومن ثم خضعت جميع البيانات للمعالجة بواسطة الـ GIS وذلك من اجل تكامل مجموعات المعلومات المختلفة بصورة ثلاثية الابعاد لتسهيل الوصول الى التفاسير التي تم تطويرها في هذا العمل.

وهدف جمع المعلومات الاساسية ايضا الى التقييم الاولي للتراكيب الجيولوجية الرئيسية في منطقة الدراسة وفي المناطق المحيطة بها، بهدف تغطية مساحة اوسع ووضع جميع هذة التراكيب حسب ترتيبها الزمني. وقد ساعد ذلك على توضيح ان عدد كبير من هذه التراكيب في دراسات سابقة قد أعتمد تحديد عمر غير صحيح، وكان لهذا التجاوز الزمني للعمليات التكتونية المختلفة أن أعطى صورة خاطئة لمراحل التشوة. وبأعادة التقييم لمختلف العناصر التركيبية كان بالامكان الوصول الى تصور تكتوني ثلاثي الابعاد للاحداث التكتونية المختلفة. ومن اعادة تقيم المعلومات كان بالامكان استنتاج نموذج ثلاثي المراحل لمختلف العناصر التركيبية في المنطقة. حيث وجد ان هذة التراكيب ترتبط مباشرة مع التضيق والاغلاق الذي حدث بالعمر الكريتاسي العلوي من الدهر الوسيط لبحر التيثس (المتوسط حاليا) فان المرتفعات والمنخفضات والتي كانت نتجة شرق-غرب في مرحلة الترسيب، تشوهت (المرحلة الاولى) لتمثل ما يعرف بحزام الطيات السوري والذي يمتد باتجاة غرب جنوب غرب-شرق شمال شرق. وهذة المرتفعات ما يزال بالامكان ملاحظتها في سماكة الخزانات المائية المختلفة. وكان لثاني مراحل التشوة والتي امتدت من عصر الايوسين الى الميوسين السفلي ان تميزت بحدوث صدوغ (rifts) تمتد باتجاة شمال غرب-جنوب شرق (مثل البحرالأحمر ووادي السرحان). أما المرحلة الثالثة والتي أمتدت من عصر الميوسين العلوي وحتى العصر الحديث، والتي تمثلت بالحركة الأفقية اليسارية الأزاحة على إمتداد فالق البحر الميت-شرق المتوسط والممتد بإتجاة شمال جنوب وبتكون جميع الفوالق المصاحبة لة. وهذة المرحلة تُعد المسئولة عن تضاريس ومورفولوجية منطقة الدراسة.

وبدمج المعلومات التي تم الحصول عليها من المقاطع الجيولوجية لآبار البترول، مع معلومات السماكة لكل تكوين صخري، كان بالإمكان توضيح صورة ثلاثية الأبعاد للوضع التكتوني للمنطقة، وتمثل ذلك بإعداد 6 مقاطع جيولوجية بإتجاهات مائلة ومقطع طولي واحد بإتجاة شمال-جنوب. وتعتبر قاعدة المعلومات المعلومات الجيولوجية ثلاثية الأبعاد التي وضحتها المقاطع الجيولوجية المختلفة بالإضافة الى الخصائص الهيدروجيولوجية الأساس في تقييم تأثر الخصائص الهيدروجيولوجية بالتراكيب الجيولوجية الفاعلة أو النشطة في المنطقة وتغيرها أو تطورها مع الزمن. وأعتمادا على الخرائط التكتونية المعدة وعلى تحديد مستوى الحد السفلي والحد العلوي للخزانات المائية المختلفة، وإعتمادا على التوزيع الهيدروليكي للخزانات المائية، فقد كان بالإمكان توضيح حركة المياة الجوفية لكل خزان مائي. وتعتبر أهم التراكيب الجيولوجية السائدة في المنطقة والمؤثرة بشكل مباشر على حركة المياة في الخزانات المختلفة، موزعة من الشمال الى الجنوب كالتالي:تركيب عجلون (Ajlun Dome) الذي يحدة من طرفة الجنوبي فوالق تتجة شرق-غرب (فالق نهر الزرقاء وفالق رميمين)، المنطقة المتشققة (fractured zone) على إمتداد نهر الزرقاء ومنطقة البقعة والممتدة شمال شمال شرق، وللجنوب تركيب دير علا الذي يتكون من طية وفالق عكسي يتجهان غرب جنوب غرب- شرق شمال شرق ويشكل حد مائي فاصل (watershed)، تقعرات شعيب والكفرين الموازية لتحدب دير علا والتي تُعد مناطق تجمع مياة (أحواض مائية) وفي أقصى الجنوب لمنطقة الدراسة يتواجد تركيب عمان – سويمة – الحلابات الذي يشكل منطقة حد مائي فاصل (watershed) ومنطقة تدفق للمياة الجوفية ، وللغرب من منطقة الدراسة يتواجد عدد كبير من الفوالق ذات الأتجاة الشمالي-الجنوبي مصاحبة لفالق البحر الميت اللرئيسي. ولكن هذة التراكيب تُعد نشطة كمسارات عرضية من توصيل المياه المنخفضة. تنشيط تلك الملاحظة في كثير من الأحيان على الصدوع العادية مما يجعل منهم مسارات مياه مفضلة ذات نفاذية عالية.

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LIST OF SYMBOLS AND ABBREVIATIONS

µS/cm	microsiemen per centimetre
A_{1-2}	Na'ur
A_{1-6}	Lower Ajlun Group
A_3	Fuheis
A_4	Hummar
A_{5-6}	Shueib
A_7	Wadi as Sir
AHP	Al Hisa Formation
AJ-1	Ajlun oil well No.1
Al	Alluvial
Alf	Alluvial fans
Alg	Alluvial gravel
ALT	Altitude
ANS	Arabian-Nubian shield
ARG	Abu Ruweis Formation
asl	Above sea level
ASL	Amman Silicified Limestone Formation
AZ	Azab group
B	Basalt
B'T	Tuff volcanoes
B_1	Wadi Ghudran
B_2	Amman Silicified
B_3	Muwaqqar
B_4	Um Rijam
B_5	Shallala
BGR	Federal Institute for Geosciences and Natural Resources
bsl	Below sea level
Ca^{2+}	Calcium (ion)
$CaCO_3$	Calcium Carbonate
Cl^-	Chloride (ion)
cm	centimetre
CO_3^{2-}	Carbonate (ion)
ct	Calcrete
DA	Damya Siltstone Formation
DEM	Digital Elevation Model
DH	Dahab Limestone Formation
DS	Dead Sea
DSB	Dead Sea Basin
DSR	Dead Sea Rift
DSRSW	Dead Sea River Side Wadis
E	East
EC	Electric conductivity
ER-1 A	Er Ramtha oil well No. 1 A
ESRI	Economic and Social Research Institute
F/H/S	Fuheis/Hummar/Shueib
FAO	Food and Agricultural Organization
g/l	gram per liter
GGM	German Geological Mission
GIS	Geographic Information System
GTZ	German Agency for Technical Assistance

H	Hummar Formation
HA	Hamam Formation
HCO_3^-	Bicarbonate (ion)
HI	Hihi Claystone Formation
HL	Hisban Formation
HZ	Hamzeh oil well
IR	Iraq el Amir Formation
IR	Irkheim Formation
JAD	Jabel Arab-Druz
JF-1	Al Jafr oil well No.1
JICA-1	Japan International Cooperation Agency No.1
JISM	Jordanian Institution for Standards and Metrology
JTM	Jordan Traverse Mercator
JV	Jordan Valley
JVR1	Jordan Valley Rift No.1
K^+	Potassium (ion)
KAC	King Abdullah Canal
KH-1	Khalidiya oil well No.1
km	Kilometer
Km^2	Squared kilometer
Km^3	Cubic kilometer
km^3/yr	Cubic kilometer per year
KS	Kurnub Sandstone
KS	Kurnub Aquifer System
LL	Lisan Lake
LM	Lisan Marl Formation
LMb	Beach rock
LMg	Gravel
m	Meter
m/s	Meter per second
m^3/capital/year	Millimetre per capital per year
m^3/yr	Cubic meter per year
Ma	Million year
MCM	Muwaqqar Chalk Marl
MCM/yr	Million cubic Meter per year
mg/l	milligram per liter
Mg^{2+}	Magnesium (ion)
MK	Mukheris Formation
mm/a	Millimetre per annual
mm/yr	Millimetre per year
mmol/l	millimoles/liter
MOA	Ministry of Agriculture, Jordan
MUG	Mughanniyya Limestone Formation
MWI	Ministry of Water and Irrigation, Jordan
N	North
Na^+	Sodium (ion)
NACSN	North American Commission on Stratigraphic Nomenclature
NH-1	Northern High Lands oil well No.1
NL	Na'ur Limestone Formation
NO_3^-	Nitrate (ion)
NR	Nimr Limestone Formation

NRA	Natural Resource Authority, Jordan
NRSW	North River Side Wadis
NWMP	National Water Master Plan
Pl	Pleistocene sediment
Plg	Pleistocene gravels
QA-1	Qitar el Abd oil well No.1
RCC	Roller Compacted Concrete
RH-19	Risha oil well No.19
RJGC	Royal Jordanian Geographic Center
RM	Ramla Sandstone Formation
S	South
s	Soil
SA-1	Safra oil well No.1
Sh	Shueib Formation
SHC	Shagur Formation
SL	Silal Sandstone Formation
SM-1	Smeica oil well No.1
SMART	Sustainable Management of Available Water Resources with Innovative Technologies
SO_4^{2-}	Sulfate (ion)
SQ-1	Siwaqa oil well No.1
SRSW	South River Side Wadis
SSL	Suwayma Formation
STL	Static water level
SW-1	Suweileh Oil well No.1
TD	Total Depth
TDS	total dissolved solids
Th	Thickness
TIN	Triangular Irregular Network
TL	Tayyiba Limestone Formation
TP	Treatment Plant
Tr	Travertine
Tr	Triassic
TSL	Top from mean sea level
UM	Um Tina Formation
URC	Um Rijam Chert Limestone Formation
USDA	United States Department of Agriculture
USGS	United States Geological Survey
W	West
WAF	Wadi ‘Araba Fault
WAJ	Water Authority of Jordan
WC	Waqqas Conglomerate Formation
WG	Wadi Um Ghudran Formation
WG-1	Wadi Ghadaf oil well No.1
WHO	Water Health Organization
WIS	Water Information System
WR-4	Wadi Rijal oil well No.4
WRB	World Reference Base
WS-2	Wadi Sirhan oil well No.2
WSC	Wadi Shallala Chert Formation
WSL	Wadi as Sir Limestone Formation
ZM	Zarqa Ma’in

1. INTRODUCTION

1.1 Location

The northwestern part of Jordan has been selected to carry out this integrated study (Figure 1.1). It is formed in the western part by the uplifted, step-faulted margin of the Dead Sea Transform and followed towards the west by the down-faulting Jordan Valley. Towards the east it merges gradually into the East Jordanian Plateau. To the north it is bordered by the Yarmouk River and to the south; mainly to the southwest by the Dead Sea Basin.

The study area is covering an area of about 5280 km^2 and bounded by the following coordinates: 32°0′21.244″-32°42′47.437″ Latitude and 35°29′37.843″-35°59′20.178″ Longitude respectively between 127577.913-2399504.421 N and 198340.11-244427.496 E referenced on the Palestine Grid; 1128545.968-1239621.335 N and 199499.072-243832.186 E referenced on the Palestine Belt and respectively between 514021.751-624968.042 N and 357527.676-406329.874 E referenced on the Jordan Traverse Mercator (JTM) (Figure 1.2). Maps used in this study are digitized and/ or drawn by using Geographic Information System (GIS), ESRI-ArcMap 9.3. These maps are georefrenced by using the Jordan Traverse Mercator (JTM) coordinate system. Other coordinate systems, Latitude Longitude and Palestine Belt coordinate systems are also displayed in all maps.

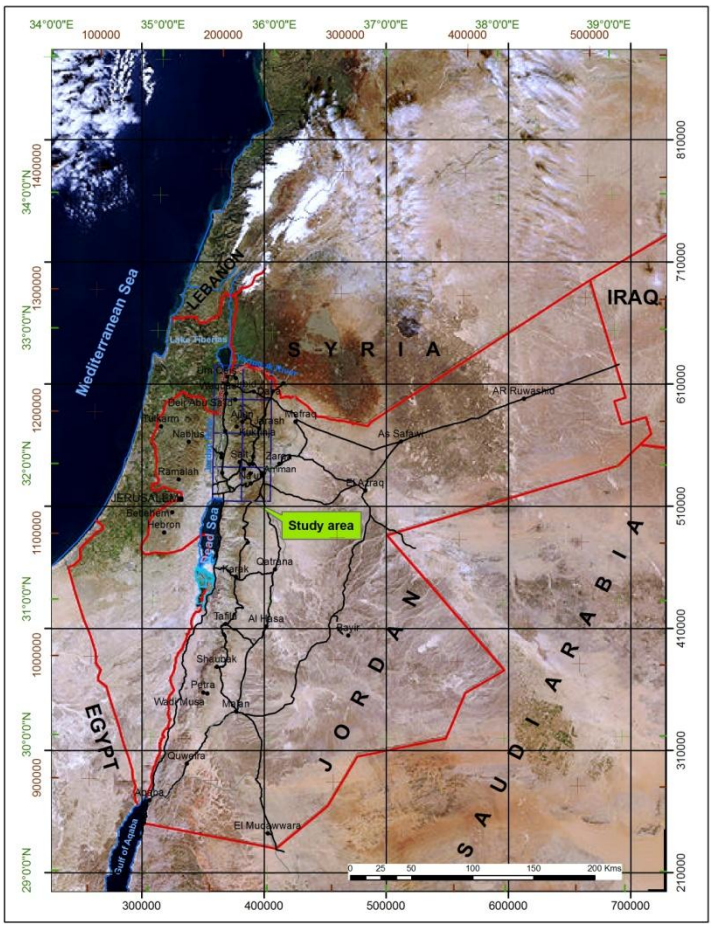


Figure 1.1: Regional location map of the study area.
(Source: http://commons.wikimedia.org/wiki/Atlas_of_Jordan)

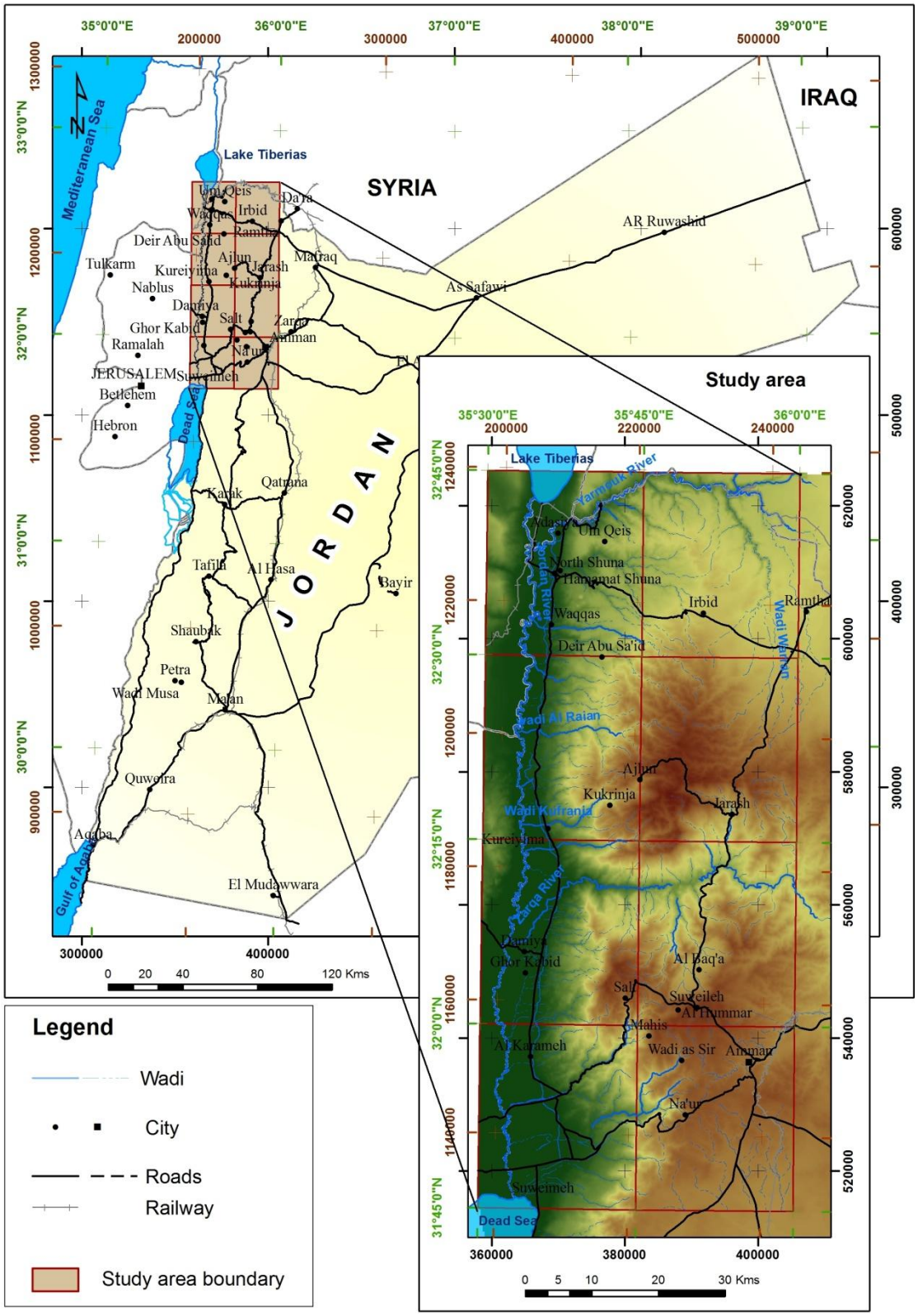


Figure 1.2: Detailed location map of the study area.
(For more details see Plates 1, 2 &3).

1.2 Country Profile

The following represents a brief description of the Hashemite Kingdom of Jordan:

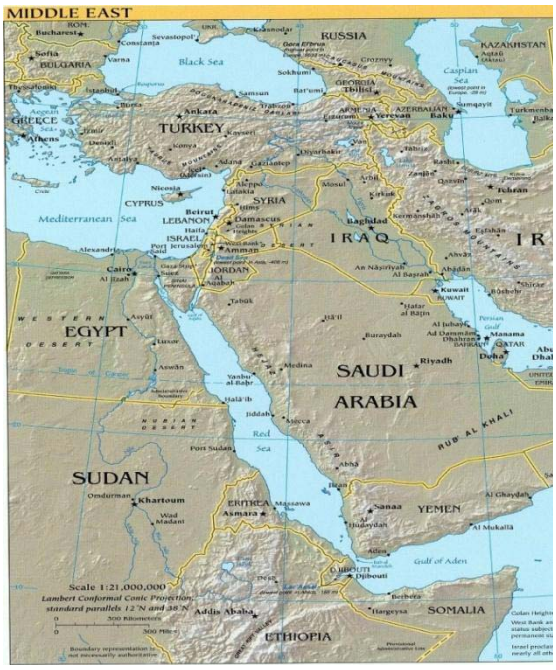


Figure 1.3: Reference map of the Middle East.

Location: Middle East, northwest of Saudi Arabia (Figure 1.3).

Geographic coordinates:
31° 00′ N, 36° 00′ E

Area
Total: 89,455 km^2;
Land: 88,915 km^2
Water: 540 km^2

Country name
Conventional long name: Hashemite Kingdom of Jordan
Conventional short form: Jordan
Local long form: Al Mamlakah al Urduniyah al Hashimiyah
Local short form: Al Urdun
Former: Transjordan

Capital name: Amman

Independence: 25 May 1946

Land boundary
Total: 1,635 km
Border countries: Iraq 181 km, Israel 238 km, Saudi Arabia 744 km, Syria 375 km, West Bank 97 km

Administrative divisions: 12 governorates (muhafazat, singular-muhafazah): Ajlun, Al ‘Aqaba, Al Belqa’, Al Karak, Al Mafraq, ‘Amman, At Tafilah, Az Zarqa, Irbid, Jarash, Ma’an, Madaba

Population: 6,342,948 (July 2009 estimated)

Population growth rate: 2.264% per year (2009 estimated)

Languages: Arabic (official),
English widely understood among upper and middle classes

Religions: Sunni Muslim 92%, Christian 6% (majority Greek Orthodox, but some Greek and Roman Catholics, Syrian Orthodox, Coptic Orthodox, Armenian Orthodox, and Protestant denominations), other 2% (several small Shia Muslim and Druz populations) (2001 est.)

Literacy

Definition: age 15 and over can read and write
Total population: 89.9%
Male: 95.1%
Female: 84.7% (2003 estimates)

Elevated extremes

Lowest point: Dead Sea -422 m bsl
Highest point: Jabel Um Ad-Damy 1854 m asl (This mountain was part of Saudi Arabia before the alteration of the borders with Jordan. Previously, the hieghest point in Jordan was the 1754 m of Jabal Rum on the sandstone massif of Ram area.)

Natural Resources: Phosphates, Potash, Oil Shale

Land use: Arable land: 3.32%; Permanent crops: 1.18%; Other: 95.5% (2005)

Irrigated land: 750 km^2 (2003)

Total renewable water resources: 0.9 km^3 (1997)

Freshwater withdrawal (domestic/ industrial/ agricultural)

Total: 1.01 km^3/yr (21%/ 4%/ 75%)
Per capita: 177 m^3/yr (2000)

Environment – current issues: Limited natural fresh water resources; deforestation; overgrazing; soil erosion; desertification

Natural hazards: droughts; periodic earthquakes

Labor force – by occupation

Agriculture ≈ 2.7%;
Industry ≈ 20%;
Services ≈ 77.4% (2001 estimated)
and the **food production** in Jordan covers around 50% of the country's needs.

Exports: clothing, fertilizers, potash, phosphates, pharmaceuticals, manpower, vegetables and fruits.

Imports: crude oil, machinery, transport equipment, iron, cereals, wood, paper…..etc.

Energy: Only very limited gas fields, large oil shale deposits that are not yet mined. Nowadays the Natural Resources Authority of Jordan participated with some International Research Organizations to extract liquid fuel from Jordanian oil shale.

1.3 Topography

The study area shows considerable topographic variations (Figure 1.4). Elevations vary from 422 m bsl; the Dead Sea level 2009, to a maximum altitude of 1240 m asl, northeast of Umm al Julud village (Jarash sheet), in the central eastern part of the study area (Plate1).

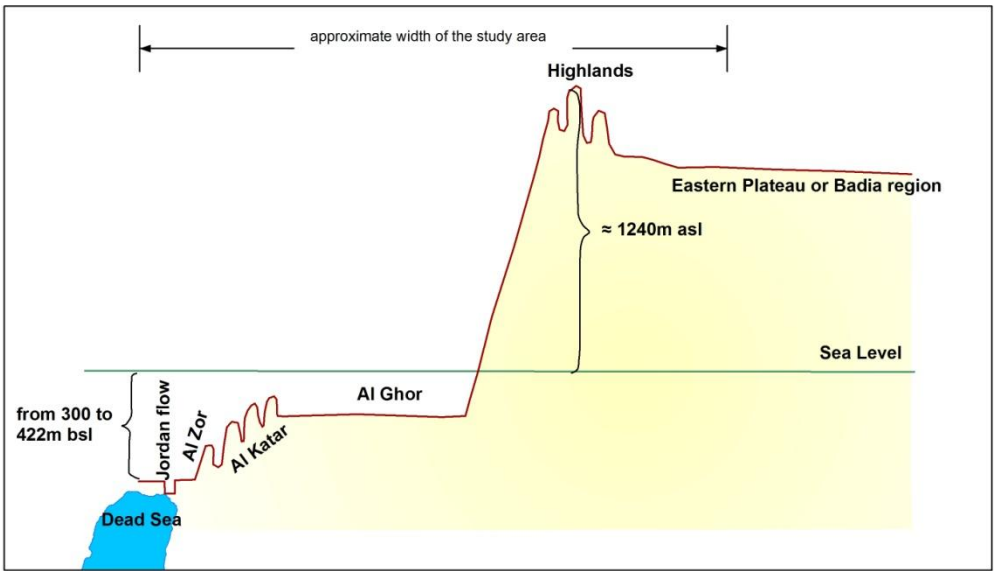


Figure 1.4: Topography profile of the study area.

1.4 Geomorphology

Generally, four terrain categories can be identified in the area under consideration (Figure 1.5) (see BENDER, 1968b; 1974a; QUENNELL, 1956b and BURDON, 1959b):

1.4.1 The Dead Sea Depression

This part forms the southwestern sub-area of the study area. It is located at the lowest point on the earth, forming a base level for all the surroundings surface and groundwater.

1.4.2 The Jordan Valley area

This is a flat area within the tectonic depression of the Jordan Rift Valley, with elevations varying from -210 m bsl (Lake Tiberias) to -422 m bsl (Dead Sea); and a width, E-W extension of 30 km just to the north of the Dead Sea, narrowing to 4-5 km south of Lake Tiberias. In the most northern part of the study area the lowland zone (including all areas; less than 400 m asl) of the Yarmouk River, Shallala and other wadis are also be included within this terrain. The Jordan Valley is filled by Upper Tertiary and Quaternary sediments (such as the lacustrine Lisan Marl, the alluvial fan sediments of Pleistocene age, and the Recent fluvial sediments. The Jordan Valley is drained by the southward-flowing Jordan River and its western and eastern tributaries draining the surrounding mountain range. Two terraces are found in the valley; the low-lying flood plain of the Jordan River (Zor), and the Jordan Valley proper area (Ghor). These two zones are separated by a transition zone (Katar) along most of the

length of the valley. The Katar zone shows a dense drainage system within the Lisan Marl sediments, which indicates the role of rare rainfall and erosional processes in this arid area.

1.4.3 Escarpment slopes

This consists of the slopes overlooking the Jordan Valley from its eastern side. It is the western part for the mountain range. Its elevations go up from the Jordan Valley plain to about 1000 m asl; with an E-W extension of some 15-20 km. This escarpment formed as a result of step faulting and flexture formations initiated during rifting and modified later by fluvial erosion during the fluvial periods of upper Miocene to Recent time (BENDER, 1974a). Most of the study area lies within this zone of the escarpment. It is characterized by the presence of the mountainous zone (550-1000 m) which consists of high rugged and steep areas dominating the majority of the western part.

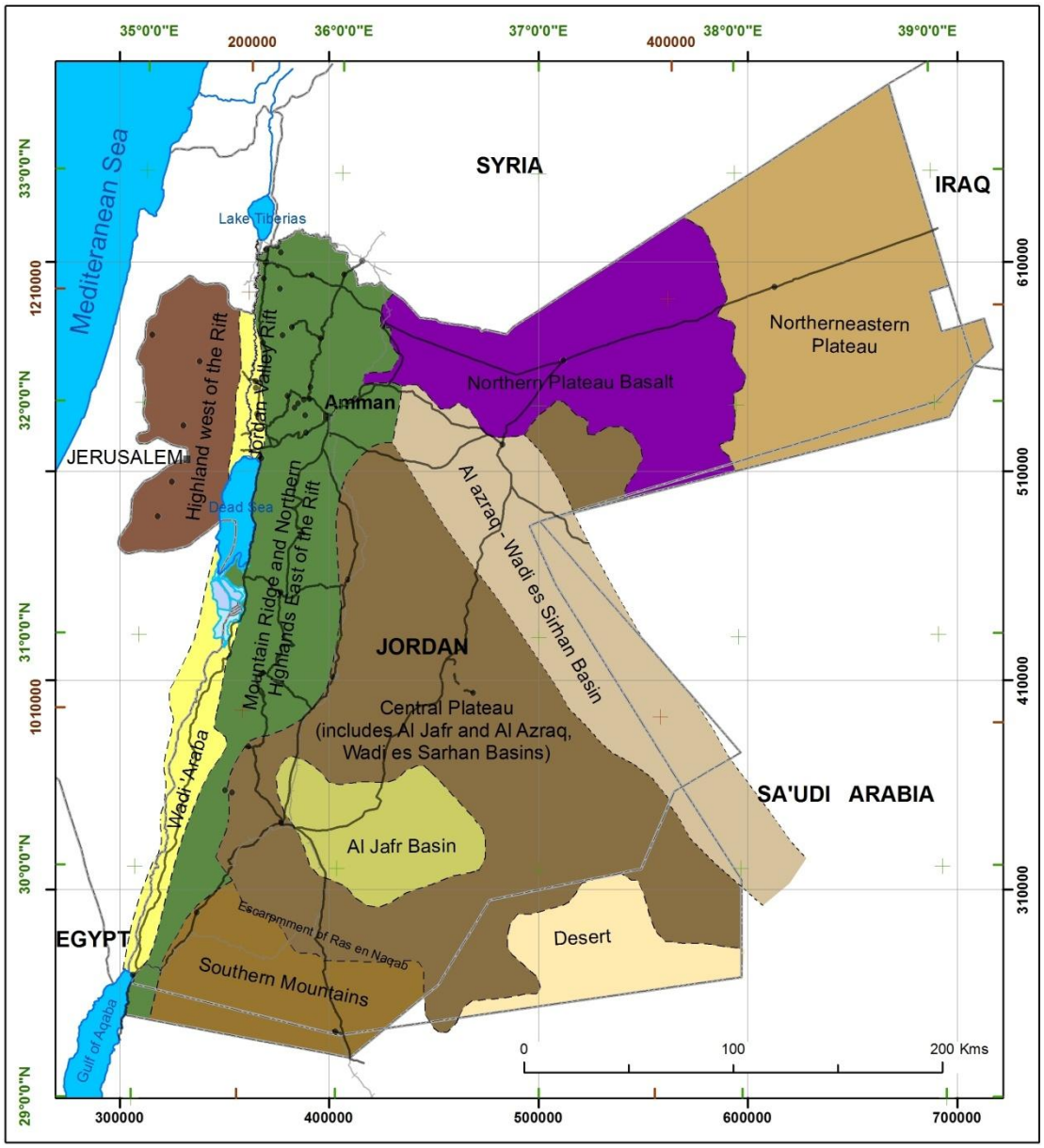


Figure 1.5: Geomorphological Provinces of Jordan (modified after BENDER, 1974a).

1.4.4 The Northern Highlands

These are the flat to hilly highlands lying east of the escarpment, ranging in elevation from 550 m to more than 1000 m. The highlands are characterized by folded and faulting strata. Outcrops are mainly composed of limestone, marl, shales, clays and sandstones.

The topography reflects the Neogene regional upwarping, folding and eastward tilting of the area, accompanied by relative uplift in relation to block faulting. The difference in altitudes is a reflection of the westward-directed dissection of the wadis. The drainage has rejuvenated during the tectonic phases, and a rapid incision into the main wadis has given rise to high relief with deep valleys and slopes where mass movement took place as landslides and debris flow (BENDER, 1974a). The highlands drain both to the west, the Jordan Valley and to the east to desert playas or to wadis which are later captured by westward flowing wadi courses.

1.5 Climate

Climate in Jordan which has an area of 89,342 km^2 is the result of its geographical position in the Eastern Mediterranean region, its geological structures and its relief, which ranges from -422 m at the Dead Sea to 1800 m in the Southern Highlands. Generally, Jordan can be classified as a semi-arid to arid area.

In the study area, three different climatic zones can be distinguished:

- *Mediterranean climate zone:* Only the Mountain Ridges and the Northern Highlands areas with a width of 30 km and a length of some 300 km prevails this type of climate. It is characterized by hot, dry summers which extend from late April until early October; August is the hottest month with a mean daily range of 24 to 28 °C, and cool rainy winters from October until April; January is the coldest month with a mean daily range of 8 to 10 °C. The most favored areas around Ajlun receive more than 600 mm/yr of rainfall in average years. In winter, snowfall is not uncommon.

- *Arid climate zone:* This type of climate prevails in the Jordan Valley (Ghor areas). Where summers are very hot especially in July with a mean daily range from 24 to 45 °C, and winters are mild, but in January the temperature in this area reaches a few degrees above zero. The northern part receives fairly good rainfall during the rainy season (October - May). Average rainfall ranges between 350 mm/a in the north, 200 mm/a around the Dead Sea and less than 50 mm/a in the South towards the Red Sea.

- *Semi-arid to Mediterranean climate zone:* This type of climate is transitional zone prevails along the slopes extending from the Mountain Ridges and the Northern Highlands areas to the Jordan Valley.

1.6 Aim of the study

Jordan, like most arid and semi arid areas suffers from water shortage problems, due to the regional hydrogeological situation characterized by low amount of precipitation and high intensity of evaporation. It is considered among the region's water poorest countries as it is dependent on water from the Jordan and Yarmouk Rivers, limited rainfall and groundwater resources. Rainfall water are varies in quality, intensity and distribution from year to year. In addition to that about 40% of its recourses are shared with neighboring countries, Israel and Syria. Other factors influencing this shortage are the high rate of population, miss-use of available water and continuous demand for industrial, agricultural and domestic needs. The annual water per capita in Jordan is the lowest among Arab countries, ranging between 100-200 m^3/capita/year.

Jordan is situated in a very active tectonic region. Therefore, the structural set up of Jordan is affecting the hydrology, hydrogeology and groundwater salinity in general. In Jordan, the prevailing climatic conditions affected the amount and distribution of precipitation as well as the potential evaporation. Groundwater movement (direction and quantity) in Jordan is highly governed by several factors among which geological structures mainly faults and folds are considered very important. Extensional faults acts as prevailed water paths, while they can form also barriers or semi-barrier to the groundwater movements due to the fact that the permeable rocks in the uplift of the fault are facing impermeable rocks of the downthrown. Fold axes acts as water divides while synclines act as water collectors and recharge areas. The water in Jordan is of good quality near the recharge areas, whereas towards the discharge areas the salinity of water increases.

This integrated study aims to achieve a better understanding of how much does the structural complexity affected and complicating the recharge flow, discharge mechanism of the groundwater system and hydrochemistry in the northwestern part of Jordan. In order to reach this aims the Geographic Information System (GIS) mainly; ESRI-ArcMap 9.3 software was used (for more details see section 1.7) and the next working steps were followed:

1. Preparing digital topographic and geological maps at a scale 1:50,000 in addition to preparing Triangular Irregular Network (TIN) and Digital Elevation at a scale of 1:75,000 for the study area.

2. Developing a 3-dimensional structural model of the study area based on surface and subsurface information and by using aerial photographs. In addition geologic cross sections (E-W) at least 7, and one N-S along the highlands were constructed.

3. Distribution and extents of hydrogeological units and groundwater flow systems in the study area were evaluated and documented in detailed maps.

4. Groundwater chemistry with special reference to salinities in the different aquifers and aquifer parts were investigated and trends deviated.

5. Working out the relationship between the structural set-up and the groundwater and surface water flows, in addition to interflows between aquifers along geologic structures or as caused by such structures.

6. Impacts of structural set-up on the water salinity.

As a result of the previous mentioned steps, this study includes

1. detailed description of different lithological units,

2. description and aging of different structural features,

3. delineation and analysis of joints in the area parallel to the eastern Jordan River from aerial photographs,

4. characteristics, depth, thickness and lateral extends of different geological formations and groups forming aquifers and aquicludes,

5. description of surface water resources, the long term average rainfall distribution as isohyets for normal, dry and wet water years,

6. potential evaporation, spatial distribution of runoff in normal, dry and wet years,

7. runoff volumes in normal, dry and wet years,

8. the groundwater recharge, level and flow direction for different aquifers,

9. the effect of major structures on groundwater movement and

10. the groundwater salinity in different aquifers in the study area.

1.7 Data compilation and preparation by GIS

Scanned topographic and geologic maps, in addition to tabulated data from different sources were used to create different thematic layers in this study, by using Geographic Information System (GIS) mainly, ESRI-ArcMap 9.3 software. The digital maps and the different GIS tools were useful in eases the correlation between different layers of geology, hydrology, hydrogeology and hydrochemistry. Figure 1.6 and Figure 1.7 show the flow charts of thematic layers created from scanned maps and tabulated data, respectively. Some digital data sources related to each chapter will be described within the different chapters.

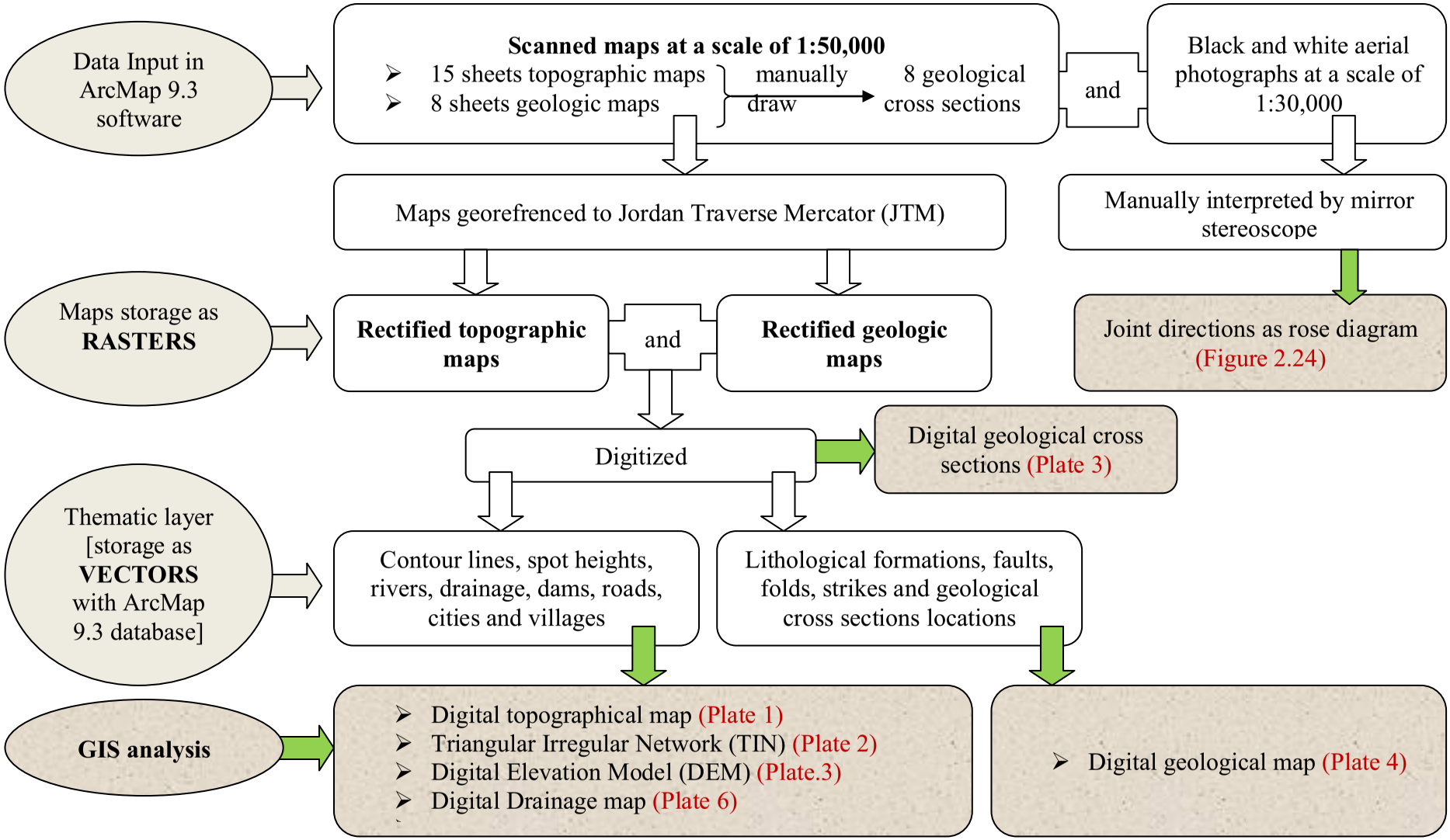


Figure 1.6: Schematic diagram of thematic layer creation from scanned maps.

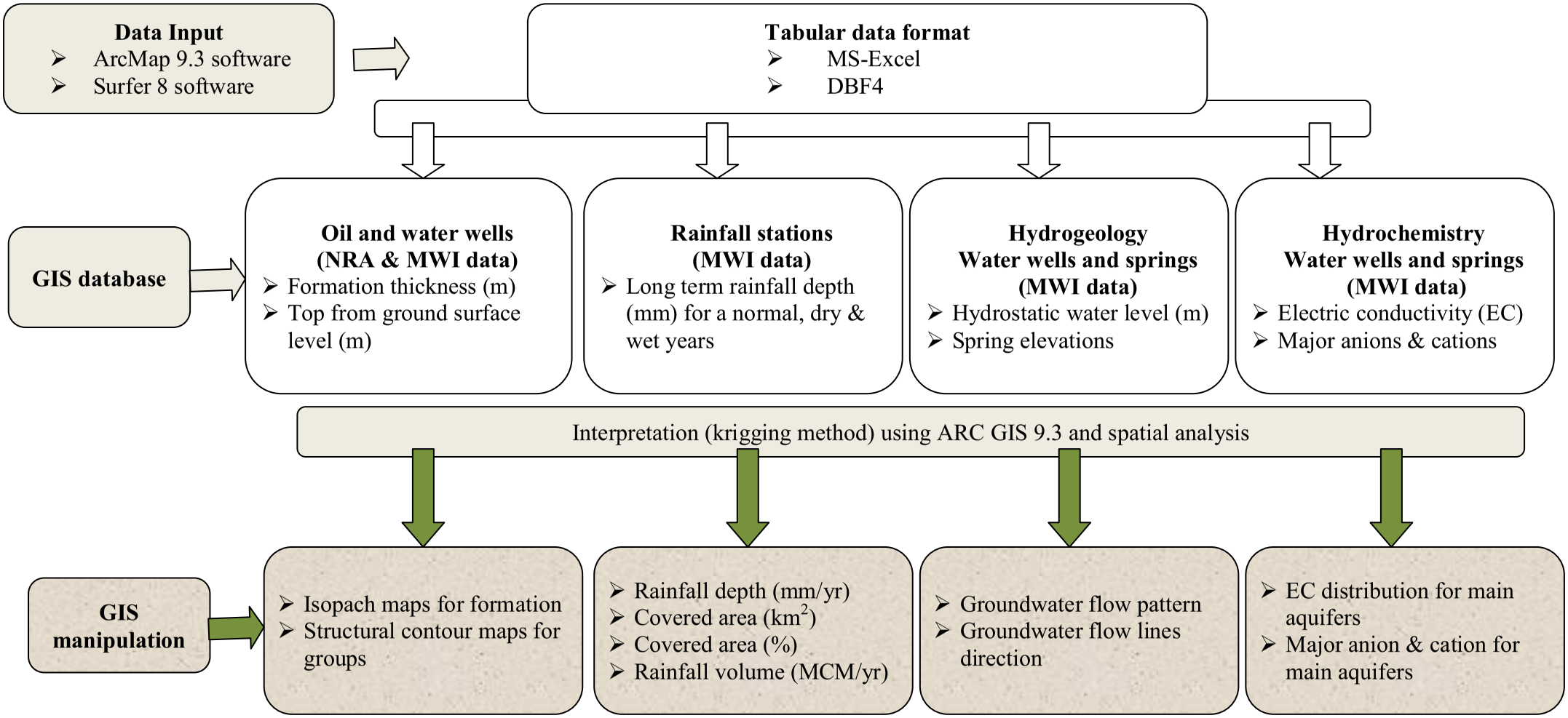


Figure 1.7: Schematic diagram of thematic layer creation from tabulated data.

1.7.1 Scanned topographic and geologic maps (Raster Maps)

1.7.1.1 Topographic maps

Fifteen topographic maps at a scale of 1:50,000 produced by Royal Jordanian Geographic Center (RJGC, 1963) (Figure 1.8) were used to prepare a digital contour map for the study area and surroundings with 20 m contour interval and 10 m supplementary contour interval. Only six topographic maps cover the study area. These are: **Amman** (Official No. 3153-I; No. on Figure 1.8: 58); **El Karama** (3153-IV; 57); **Suweileh** (31542; 42); **Es Salt** (3154-III; 41); **Jarash** (3154-I; 26) **Deir Abu Sa'id** (3155-III; 25); **Irbid** (3155-II; 14) and **Ash Shuna Ash Shamaliyya (Waqqas)** (3155-IV; 13). The other seven additional topographic maps cover the eastern and southern parts of the study area. These are: **Er Ramtha** (3255-III; 15); **El Mafraq** (3254-IV; 27); **Al Zarqa** (3254-III; 43); **Sahab** (3253-IV; 59); **Ma'in** (3153 III; 71); **Madaba** (3153-II; 72) and **Khan ez Zabib** (3253-III; 73) (Figure 1.9). In addition to contour lines, main cities, villages, drainage system, dam's locations, roads and spot height were digitized.

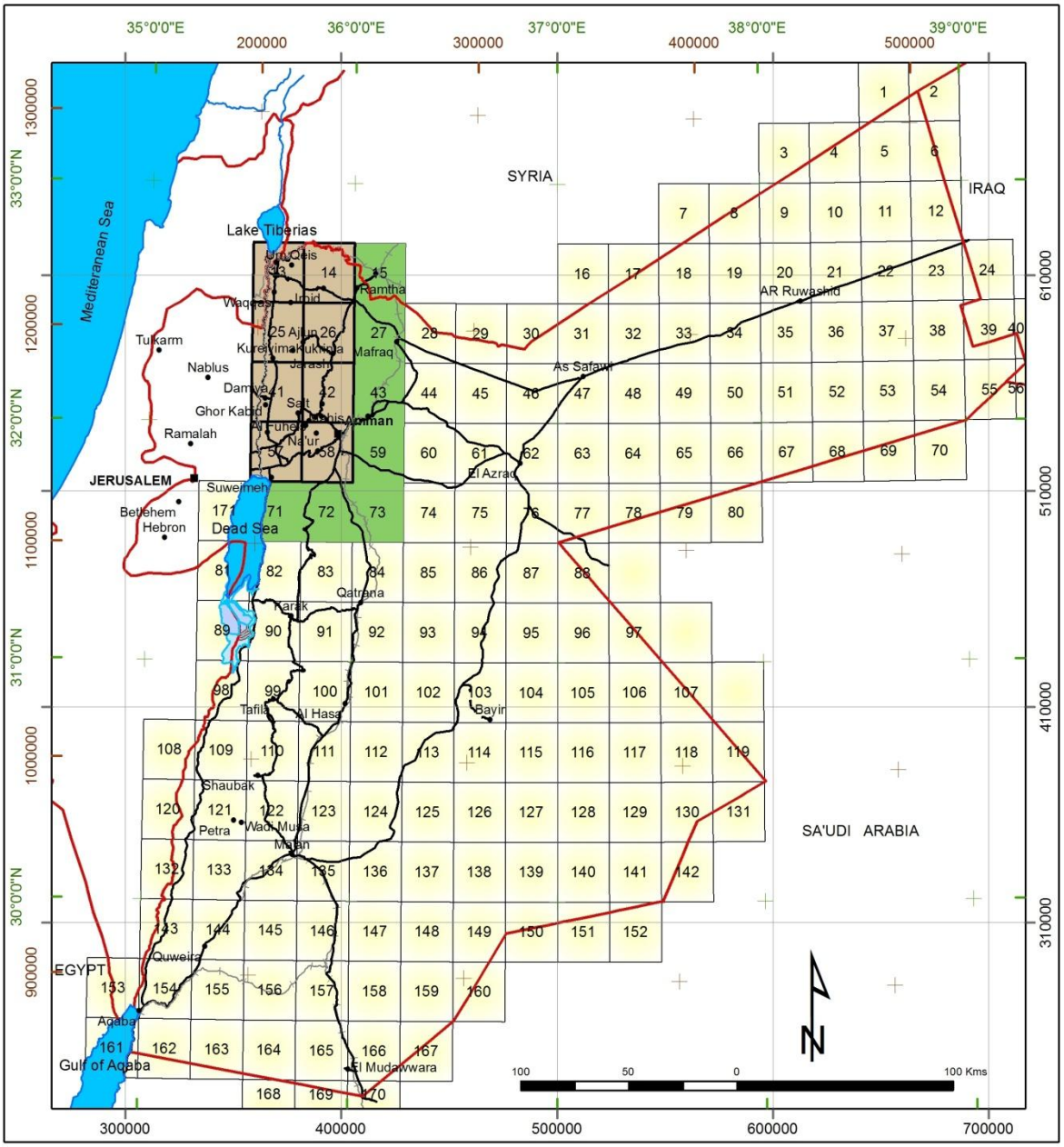
Based on the digital contour map and other thematic layers: a digital topographic map, a Triangular Irregular Network (TIN) and a Digital Elevation Model (DEM) at a scale of 1:50,000 were created (Plates 1, 2 & 3, respectively). The digital topographic map and the TIN and the DEM show that the area under consideration is topographically complex region due its location at the slopes to the Jordan Rift System. The study area consists of mountainous region on the eastern side (Jordan Highlands), trending north-south parallel to the Jordan Rift Valley. Bordering the Jordan Valley to the east is an escarpment which quickly rises to the Eastern Highlands. The area is drained via different rivers and wadis into the Jordan River which pours into the Dead Sea.

The digital topographic map (Plate 1) shows that, along the highlands different cities, villages and settlement have developed such as Amman, es Salt and Irbid and numerous towns along the escarpment margin and the Jordan Valley such as Na'ur, Wadi as Sir, Fuheis, Deir 'Alla, Ash Shuna, El Karama…..etc. The drainage system in the study area drains mainly westwards to the Jordan River, and to the Yarmouk River where it ends ultimately in the Dead Sea (Plate 6).

1.7.1.2 Geologic maps

Eight paper geological maps at a scale of 1:50,000 produced by the Natural Resources Authority, National Mapping Project (NRA, 1993 - 2004), were used to create a digital geological map at the same scale (For details see chapter 2) (Plate 4).

In order to produce an isopach maps (thickness distribution maps) for different groups and different formations in the study area (in chapter 2), the lithological distribution of different rock formations were prepared from the digital geological map with relevant attributes contain: symbol, name, group, stage, period and era for each formation.



Legend

43 **Index of topgraphic maps at a scale of 1:50,000 (RJGC, 1963).**

Limits of digital contour (with 10m contour interval).

This digital data were used to produc at a scale of 1:50,000:

- -- The Triangular irrigular Network (TIN) (Plate 2) &
- -- The Digital Elevation Model (DEM) (Plate 3)

Study area and the limits of different digital data (Geology, drainage, towns, roads, spot heighs....etc).

This digital data were used to produce at a scale of 1:50,000:

- -- The Digital Topographic Maps (Plate 1),
- -- The Digital Geological Map (Plate 4),
- -- Eight Geological Cross Sections (Plate 5) &
- -- The Digital Drainage System Map (Plate 6).

Figure 1.8: Topographic index map of Jordan at a scale of 1:50,000 (showing the limits of the digital data used to produce different maps for the study area at the same scale).

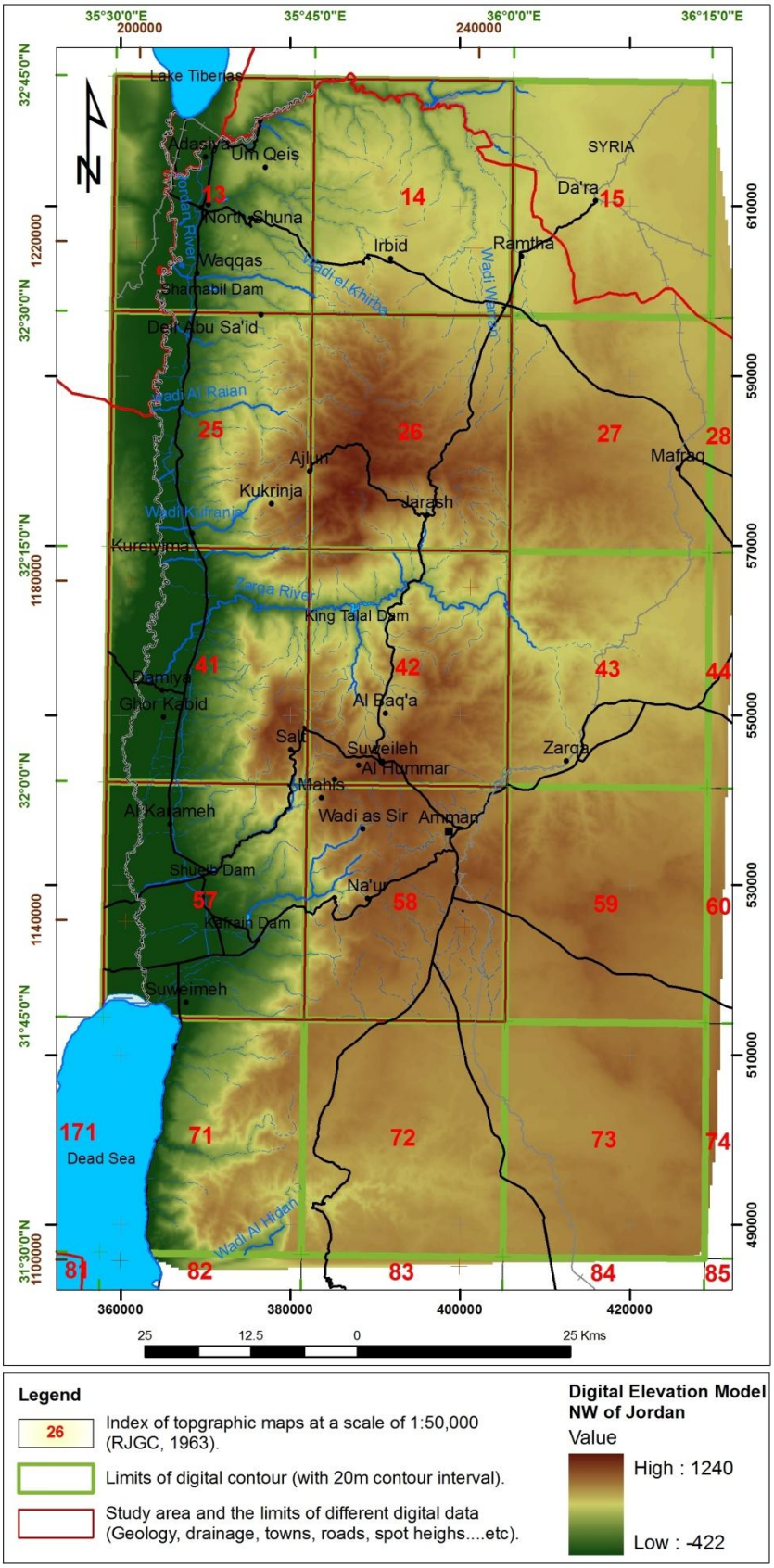


Figure 1.9: Digital data index map for the study area (For more details see Plate 1 and Plate 4: the Topographic and the Geological Map of the study area at a scale of 1:50,000; respectively).

1.7.1.3 Geological cross sections

All topographic and geologic maps at a scale of 1:50,000 that cover the study area were used to construct manually eight geological cross sections at the same scale (chapter 2, Figure 2.3). Then the geological cross sections were digitized as shown in Plate 5 (AA′, BB′, CC′, DD′, EE′, FF′, GG′ & HH′).

1.7.2 Tabulated data

Data from oil wells, water wells and springs was mainly in MS-Excel format. Therefore, these data were recorded as locations in Jordan Traverse Mercator (JTM), then converted into the database format and finally integrated into ESRI-ArcMap 9.3 software as a shapefile (shp) format with attributes, in order to overlay other formally created layers (shapefiles), such as TIN, DEM, surface basins extends, geology, structures……etc. Such layers include: location of wells and springs in the study area, in order to construct:

- Structural contour maps for the top of different groups, in addition to the structural contour maps for the top of B_2/A_7 aquifer system in the study area (chapter 3).
- Location of rainfall stations in the study area, with relevant attributes of the long term depth of rainfall, in order to construct long term depth of rainfall as isohyets for normal, dry and wet years (chapter 4).
- Distribution of the hydrostatic water level (chapter 4).
- Distribution of major cation, anion and electric conductivity (EC) (chapter 4).

1.7.3 Aerial photographs

Manual interpretation of black and white aerial photographs at a scale of 1:30,000 was beneficial in delineating the joint direction along the Jordan Rift Valley.

2. GEOLOGICAL AND STRUCTURAL SETTING

Jordan's location in the Middle East entails it to share some of the Middle East geological and tectonic history. The importance of the study area is its location at the eastern rim of the Dead Sea-Jordan Valley Rift system (DSR), which branches off the Red Sea (SUESS, 1909; GREOGORY, 1921) and extends to Lake Tiberias and further northwards to the edge of Taurus Mountain (Figure 2.1). Due to that it has a complex tectonics controlled by the formation and the movement of the Arabian Plate away from the African Plate towards the north since Mid Tertiary times (GARFUNKEL, 1981 1997; BAYER et al., 1988).

In order to better understand the recent geology and how does it affect directly and indirectly the complexity of the hydrogeology of the study area, a review is carried out of the earliest regional geological studies related to the development and evolution of the DSR regarding the tectonic and structural conditions that existed in the region prior, during and after the formation of the DSR. Most concept of the tectonic evolution of the DSR and the sedimentary sequence which fills its depression was obtained by surface geological studies over many decades, borehole data and interpretation of the seismic reflection data. In addition to that gravity, magnetic and seismic refraction data provide important information on the deeper structures.

Jordan's tectonic history is divided into three phases according to DEWEY et al. (1973): Gondwana, Syrian Arc and Rift phases. The formation of the DSR occurred in the last phase, and since that time, Mid Miocene, the tectonics of Jordan has been controlled by its formation and the sinistral movement along it.

The DSR is located at the northwestern edge of the Arabian–Nubian shield (ANS), which is part of the East African Orogen that developed during the so called Pan–Africa Orogenic Cycle (~ 950-650 Ma) by suturing of juvenile arc terrains (STOESER & CAMP, 1985; JARRAR et al., 2003; STEIN, 2003). In Jordan, parts of the shield are unconformably overlain by platform sediments (STOESER & FROST, 2006).

The DSR crosses a continental area with a normal crust, ~32–35 km thick (GINZBURG et al., 1979; EL-ISA et al., 1986, 1987; AL-ZOUBI & BEN-AVRAHAM, 2002), which was part of a Craton, stabilized after the Late **Pre-Cambrian** Pan African Orogeny. The stabilization of the region was marked by the development of an extensive continental-scale flat erosion surface (Peneplain). Afterwards the region behaved as a rather stable platform mainly in areas bordering the southern Dead Sea Rift. Due to that several depositional cycles of a shallow marine sedimentary cover accumulated almost from Early Cambrian to Late Eocene times (PICARD, 1943; BENDER, 1968b, 1974a; GARFUNKEL, 1981; 1997; BEN-AVRAHAM, 1996). While the platform history further north was punctuated by a few episodes of volcanic and tectonic activities (GARFUNKEL, 1988, 1989). This tectonic activity was expressed in the form of high angle faulting and folding. These faults resulted from the extensional wrenching tectonic regime. The seismic data (NRA files) marked some active faults such as Wadi Rajil and Fuluq in the Azraq Basin which were active from **Cambrian to Ordovician** and are still active up-to-date.

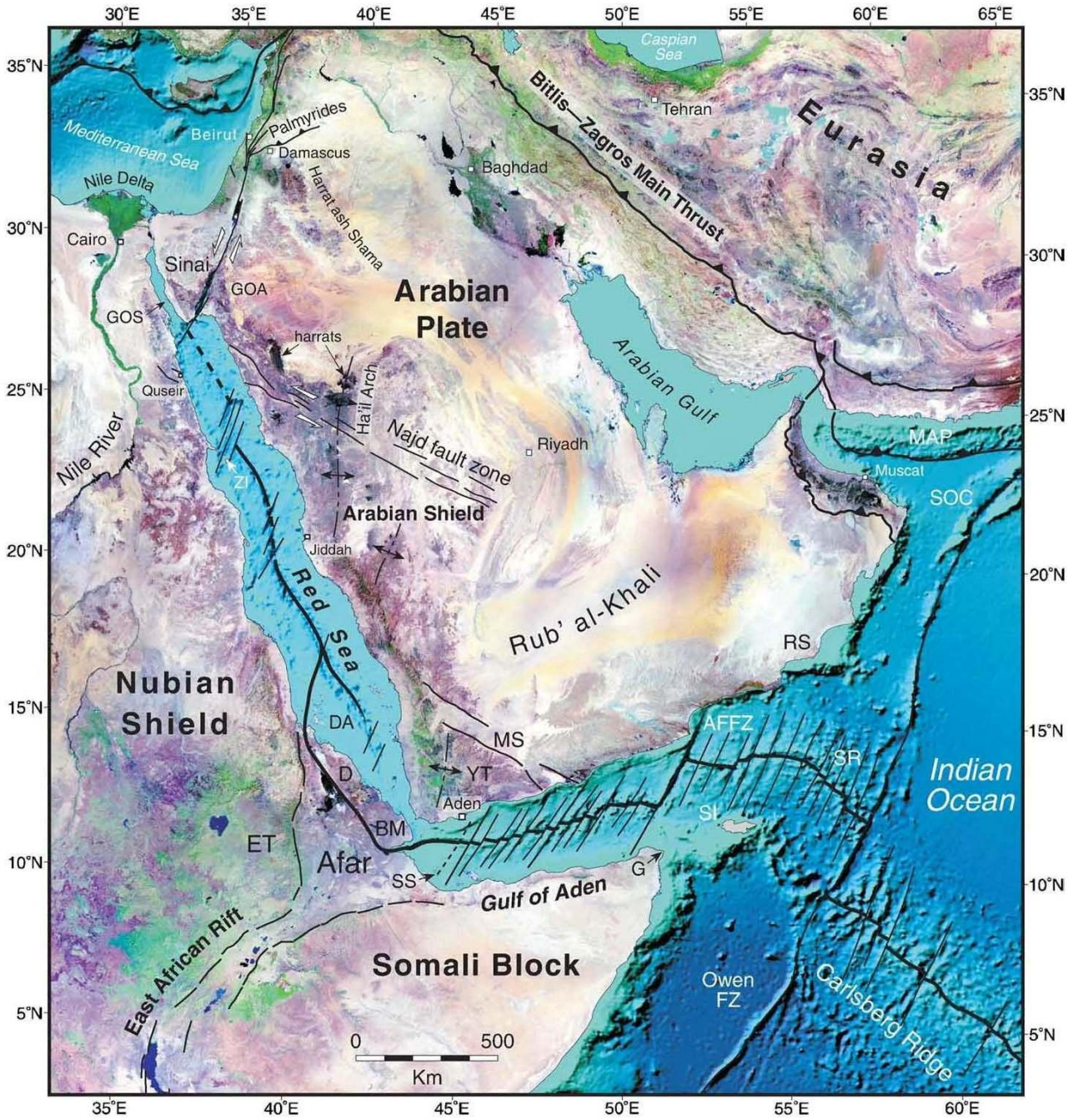


Figure 2.1: Regional setting of the study area, on Landsat imagery (onshore) and Seasat-derived bathymetry (offshore) of the Red Sea–Gulf of Aden rift system and environs. Individual Landsat 5 scenes were color-matched and mosaiced by the Stennis Space Center of NASA. Seasat bathymetric interpretation is from SMITH & SANDWELL, 1997. Major elements of the Neoproterozoic Pan-African Najd fault system, the Aqaba–Levant intra-continental transform boundary, the Mediterranean–Bitlis–Zagros convergence zone, and East African rift are highlighted. Albers conical equal area projection (after BOSWORTH, et al., 2005).

Abbreviations: AFFZ = Alula-Fartaq fracture zone; BM = Bab al Mandeb; D = Danakil horst; DA = Dahlak archipelago; ET = Ethiopian trap series; G = Cape Gwardafuy; GOA = Gulf of Aqaba; GOS = Gulf of Suez; MAP = Makran accretionary prism; MER = main Ethiopian rift; MS = Mesozoic Marib-Shabwa (Sab_atayn) Basin; SI = Socotra Island; SOC = Semail oceanic crust; SR = Sheba Ridge; SS = Shukra al Sheik discontinuity; RS = Ras Sharbithat; YT = Yemen trap series; ZI = Zabargad Island.

The most important tectonic phases were the **Permian** (?), **Triassic** and **Jurassic** rifting phases which were responsible for shaping the eastern Mediterranean passive continental margin. From the end of Silurian to the Triassic; almost all Jordan was covered by a widespread hiatus. Jordan and Saudi Arabia were part of the major Afro-Arabian plate (DEWEY et al., 1973). The most known event in Jordan is the Hercynian unconformity which has been identified from oil wells data and seismic lines in the northern parts of Jordan. In **Early Jurassic** the first geosuture appeared as a triple-junction at the intersection point of Afro-Arabian-Turkish plates. Due to that separation grabens and mountains started to be formed in the developed plates.

During **Early Cretaceous** (Aptian age) the Afro-Arabian plate moved northwards towards the subduction zone at the south margin of the Turkish plate (DEWEY et al., 1973). In **Late Cretaceous** times, deformation structures collectively known as the Syrian Arc fold belt (KRENKEL, 1924; PICARD, 1943) started developing as a response to the closing of the Tethys Ocean (Mediterranean Sea) (FLEXER, et al., 1970). The Syrian Arc fold belt essentially predates the rifting (GARFUNKEL, 1981). It stretches from western Sinai in the southwest to the Palmyrides in the northeast. The Syrian Arc includes a bundle of NNE-SSW to ENE-WSW trending folds and a group of roughly E-W trending lineaments of aligned folds and faults, along which some dextral-lateral shear was produced. BARTOV (1974) referred to this shear as "the Central Negev-Sinai shear belt" which extends across Sinai and the central Negev to about 200 km east of the Dead Sea. Extension within the Afro-Arabian Plate during the **Late Cretaceous** caused a series of NW tending grabens and uplifts such as: Al Jafr, Sirhan-Azraq, Bayir (BENDER, 1974b; LOVELOCK, 1984).

Prior to Eocene, the region was part of a continental shelf. The latest major transgressive cycles (BRAUN et al., 1987; HAQ et al., 1987) **of Mid-Cretaceous** to **Late Eocene** accumulated mainly carbonate sediments. These carbonates, with minor contributions from older sandstones, still cover most of the area flanking the Rift. However, recent erosion in the southernmost part of the rift has exposed older parts of the sediments cover as well as the Crystalline Basement (GARFUNKEL & BEN-AVRAHAM, 1996; HOROWITZ, 2001). At the end of the Eocene a flat erosional plain was developed (GARFUNKEL, 1988) due to global sea regression, which extended to early Miocene (PICARD, 1943; GARFUNKEL, 1970). The shield remained stable for most of its history until the opening of the Red Sea Rift (BOHANNON et al., 1989).

The young continental breakup phase of the Arabian - Nubian Shield, began in the **Late Eocene-Oligocene** (at about 35 Ma) accompanied by igneous activity (COLEMAN et al., 1977; BLANK, 1977; CIVETTA et al., 1978; BARBERI et al., 1975; MENEISY & KREUZER, 1974; STEINITZ et al., 1978; GARFUNKEL, 1981). Radiometric dating of the Cenozoic volcanic of Jordan (BARBERI et al., 1979) indicates also that the activity began in Oligocene and has continued to recent times. The breakup resulted in the detachment of Africa from Arabia, which became two distinct plates. Due to that the Red Sea was initiated by a low angel simple shear fault forming the NNW-SSE trending intercontinental Red Sea-Gulf of Suez stage of the Red Sea-Late Eocene and Lower Miocene (VOGGENREITER & HÖTZL, 1989; PURSER & HÖTZL, 1988; BAYER et al., 1988).

Major rifting and faulting followed in the **Miocene** around ~15-12 Ma due to the E-W oriented opening of the Gulf of Aden and connected seafloor spreading (Carlsberg

Ridge) which pushed the Arabian Plate to the north. This caused on one hand the further opening of the Red Sea south of Sinai together with the initiation of the Sinai triple junction and on the other hand caused the sinistral strike-slip displacement of the Aqaba-Red Sea transform fault (Red Sea-Gulf of Aqaba stage) with the formation of the DSR between the Arabian and the Sinai Sub-Plates (MCKENZIE et al., 1970; GARFUNKEL, 1981; COURTILLOT et al., 1987; JOFFE & GARFUNKEL, 1987; BAYER et al., 1988). This plate motion which was the reason in originating the Dead Sea Transform fault system is the same which originated the continental collision and the up-thrusting of the Taurus and the Zagrous mountain belt in southeast Turkey and west Iran. Therefore, the rift is considered as a transform boundary forming the western margin of the Arabian sub-plate, which is along a complex system of sinistral strike-slip faults in an accurate manner (KASHAI & CROKER, 1987).

Due to the northward movement of the Arabian Plate it became in contact with the Sinai and Palestine plates (QUENNELL, 1983). This movement in addition to the sinistral movement along the DSR, which has been active from **Middle Miocene** to **recent** time (MARCO et al., 1997), was associated with an oriented compression resulting in the formation of folded areas such as Palmyra Mountains in the northwest (LOVELOCK, 1984) and extended towards the southwest and into the northeast of Jordan (MIKBEL, 1985). Such fold structures have been also described along the eastern side of the southern Gulf of Aqaba by (BAYER, 1986) and in Dhahl area in Wadi ‘Araba (ATALLAH, 1992a).

As the DSR opened (probably during the Late Miocene to Early Pleistocene), the entire system was characterized by the uplift of its margins (HOROWITZ, 1979), and subsidence of depressions in between (MART et al., 2005). The eastern margin was uplifted more than 5 km, while the western margin was uplifted more than 3 km (GARFUNKEL, 1981; KOHN & EYAL, 1981; MART & HOROWITZ, 1981). The uplift of the margins was followed by intensive erosion, where some of its products fill the Rift, and over 3.5 km of evaporites were deposited (BENDER, 1974a). The basin fill has a tremendous thickness of 10 km at Lisan sub-basin (diapir) in the DSB (KASHAI & CROKER, 1987; TEN-BRINK et al., 1990; GARFUNKEL, 1997; HASSOUNEH, 2003). The floor of this depression, the Jordan Valley, is covered with fluviatile deposits, marl and clay of Quaternary age (BENDER, 1968b).

Along the depression alluvial fans of probably late Miocene and Pliocene age are found at mouths of major wadis, which suggest that the structural evolution of basins in the axial zone of the present Jordan Rift started at that time (CALVO & BARTOV, 2001). The alluvial sediments are generally delimited by normal faults (Ben-AVRAHAM, 1985) and mainly by the presence of the major strike-slip faults at the floor of the Rift which are typically arranged en-echelon (QUENNELL, 1956b; ZAK & FREUND, 1966; GARFUNKEL et al., 1981; GARFUNKEL, 1981; BEN-AVRAHAM, 1985). This fault arrangement produced several pull-aparts basins (rhomb-grabens) which form deep basins (BEN-AVRAHAM & GARFUNKEL, 1986; BEN-AVRAHAM & TIBOR, 1993; GARFUNKEL & BEN-AVRAHAM, 1996). The largest are the Dead Sea Basin (DSB) and the basins beneath the Gulf of Aqaba (QUENNELL, 1958; BEN-AVRAHAM et al., 1979, 1981; BEN-AVRAHAM, 1985).

2.1 Geological Setting

The study area is a part of the Arabian Plate. In the south of Jordan Precambrian crystalline and Paleozoic sandstone are outcropping. Rocks of Triassic and Jurassic ages are exposed in the central and in the most southern part of the area; mainly along Zarqa River and further south along the northern shore of the Dead Sea. Cretaceous to Quaternary aged rocks covers most of the study area. No sediments older than Triassic are exposed in the study area.

Geological investigations in Jordan are included in several publications related to the geology of Jordan and Palestine, since the middle of the last century such as (LARTERT, 1869; IONIDES & BLAKE, 1939; DUBERTRET, 1932; PICARD, 1943; QUENNELL, 1948, 1951; BURDON, 1959a; BENDER, 1968a). The first systematic study of Syria-Palestine-East Jordan was made by BLANCKENHORN between 1896 and 1914. More recently extensive descriptions of the geology of Jordan are found in BENDER (1974a) (Figure 2.2), ABED (1982a in Arabic), POWELL (1989a & b) and in the current mapping project of the Natural Resources Authority (since 1984 up to date).

The study area forms part of the first geological map covering the whole of east Jordan produced by IONIDES & BLAKE (1939) at a scale of 1:100,000. In the fifties the area was covered by 1:500,000 geological map of Quennell survey from 1946-1948. Later the QUENNELL's work (1956a) was compiled as three geological sheets (Amman, Karak and Ma'an covering the highland area east of the Jordan Rift Valley at a scale of 1:250,000, to accompany BURDON's (1959b) Handbook of the geology of Jordan. In addition to that, the study of WETZEL & MORON (1959) was an important contribution to the geology and stratigraphy of East Jordan.

The German Geological Mission (GGM) in the sixties (1961-1966) carried out a detailed geological survey in Jordan. Five geological maps at 1:250,000 scale covering whole Jordan (Amman, El Azraq, Aqaba-Ma'an, Bayer and Mahttat Al Jafr-H4) was made in addition to three geological sheet maps at 1:100,000 scale for the Wadi 'Araba area. One of the 1:250,000 sheets namely, Amman sheet covers the study area. The result of this work is compiled by BENDER (1968a) which is one of the most comprehensive works undertaken on Jordanian geology, and in the earlier more complete text in German (BENDER, 1986b). The colored geological maps of Jordan prepared by BGR in cooperation with NRA (BENDER, 1968a) scale 1:250,000 and the publications of BENDER (1968b, 1974a, 1975) and Abu Ajamieh et al., (1989) provided essential general information on the geology of Jordan, including the study area.

An unpublished preliminary report was written on the geology of north Jordan, with a 1:10,000 scale geological map by WIESMANN & ABDULLATIF (1963) within the scope of an engineering project for the constructing a dam there. Later it was followed by a final published report in 1964 by the German Geological Mission. The study of AL-MASRI & KHALIL (1987) summarized the geology and mineral resources in greater Irbid region. An unpublished 1:100,000 geological map covering the northern part of the study area was compiled recently for oil exploration purposes along with exploratory notes (ABDELHAMID et al., 1991, 1995). This map was prepared parallel with the exploration plan of the Northern Highland to evaluate the Hydrocarbon possibilities of the area (ABDELLATIF et al., 1992).

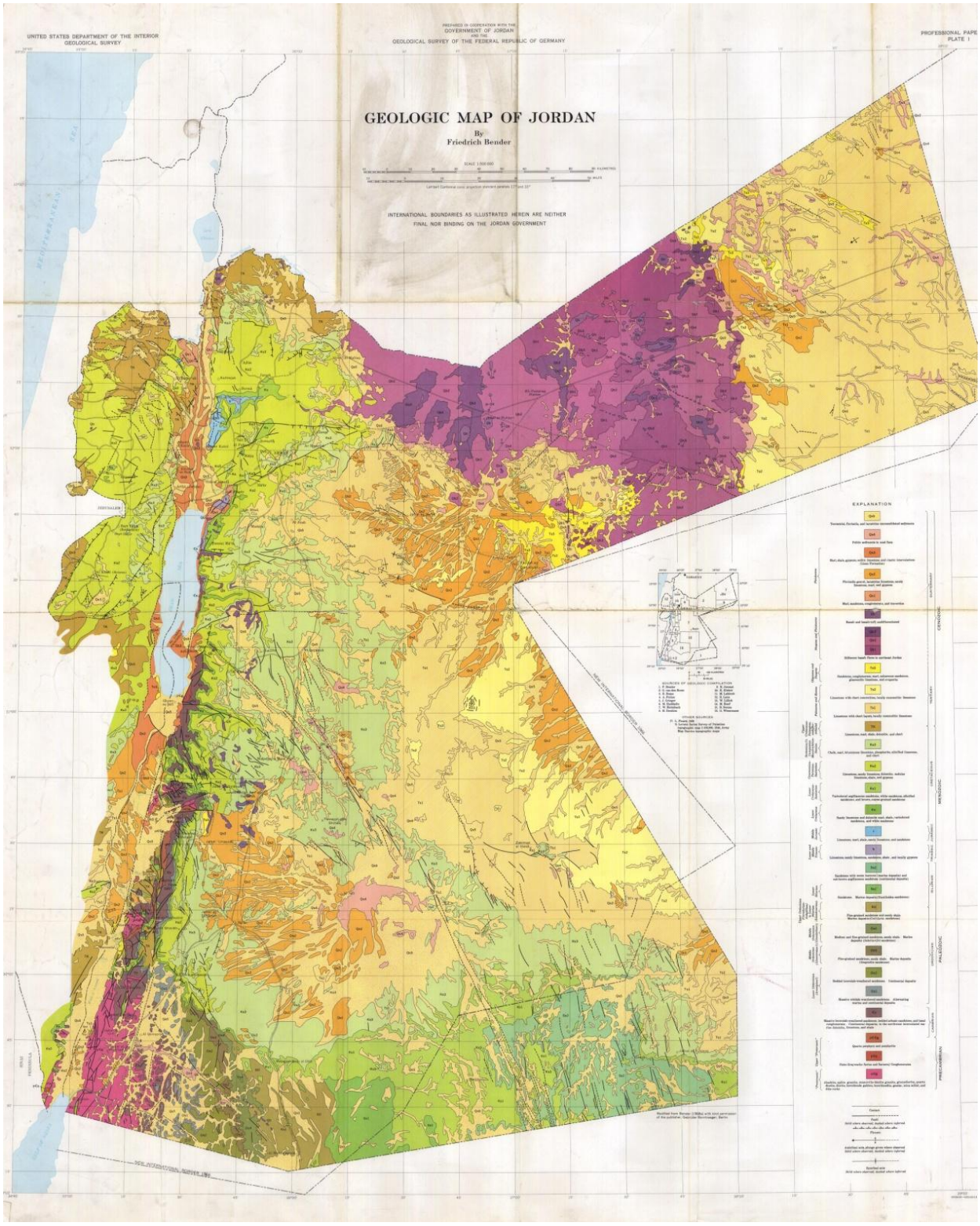


Figure 2.2: Geological map of Jordan at a scale of 1:500 000 (after BENDER, 1974a).

2.1.1 Geology of the study area

The digital geological map of the study area at a scale of 1:50,000 is a modification of eight paper geological maps at a scale of 1:50,000 produced by the Natural Resources Authority, National Mapping Project (NRA, 1993 - 2004) (Plate 4). The mapping sheets involved in this study are Suweileh (sheet 3154-II) (SAWARIEH & BARJOUS, 1993); es Salt (sheet 3154-III) (MUNEIZEL & KHALIL, 1993; KHALIL & MUNEIZEL, 1998); Jarash (sheet 3154-I) (ABDELHAMID, 1993; 1995); Irbid (sheet 3155-II) (KHALIL, 1997; 2000b) ash Shuna ash Shamaliyya (Waqqas) (sheet 3155-IV) (KHALIL, 2000a; 2000b); el Karama (sheet 3153-IV) (SHAWABKEH, 2001); Amman (sheet 3153-I) (DIABAT & ABDELDGHAFOOR, 2004) and Deir abu Sa'id (sheet 3155-III) (ABU QUDAIRA, 2005) (Plate 4).

This study follows the same lithostratigraphical nomenclature of the Jordan National 1:50,000 Geological Mapping Project of the NRA outlined in HOLLAND et al. (1978); HEDBERG (1976) and the North American Commission on Stratigraphic Nomenclature (NACSN, 1983). This has necessitated some changes to previous lithostratigraphical nomenclature (such as QUENNELL, 1951; BURDON, 1959b; BENDER, 1968a; 1968b; 1974a). Formal descriptions are given in POWELL (1989a; 1989b) (Table 2.1). The equivalent of these groups in a former study done by Hunting Technical Services & Sir MACDONALD & Partners (1965a; scale 1: 25,000), the rock types and the thickness of different formations are summarized in (Table 2.2).

The prepared Digital Topographic Map (Plate 1) and Digital Geological Map (Plate 4) at a scale of 1:50,000 for the study area were used to construct eight Geological Cross Sections (Figure 2.3). These geological cross sections mainly trend NW-SE and E-W, and one trends N-S along the highlands (Plate 5).

The sedimentary rocks in the study area according to the NRA 1:50,000 geological mapping are represented by six major geological groups, beside Pleistocene and Holocene to Recent sediments (Table 2.1). These are:

1- Pleistocene and Holocene to Recent Sediments (Quaternary)

2- Jordan Valley Group (Quaternary)

3- Belqa Group (Upper Cretaceous – Tertiary)

4- Ajlun Group (Upper Cretaceous)

5- Kurnub Group (Lower Cretaceous)

6- Azab Group (Jurassic)

7- Ramtha Group (Triassic)

Table 2.1: Chronological sequence of the lithological formations in the study area (compiled from NRA open files and modified after Powell, 1989a & b).

	Era	Period	Age		Group	NRA 1: 50,000 Geological Maps				
							Formation	Symbol	Lithology	Thickness (m)
PHANEROZOIC	CENOZOIC	Quaternary	Recent			Basalt Plateau (B)	Soil cover bedrock, soil	s, s	soil over bedrock, soil	
							Calcrete	ct	calcrete	
			Holocene		Jordan River deposits		Alluvium; Aluvial fan	Al/Alg/Alf	(AL) alluvium andwadi deposits (Alg) alluvial gravel (Alf) Aluvial fan	
			Pleistocene				Travertine	Tr	Travertine	
					Jordan Valley		Pleistocene Gravel	Pl /Plg	gravel, conglomerate	
							Dayma Siltstone	DA	marl, clay, mudstone, gypsun, sand, gravel (evaporites)	
							Lisan Marl Gravel	LM	mudstone, sandstone	from 33 to 40
							Ghour El Katar Basalt	B	basalt dyke	
							Ghour El Katar	GR	conglomerate, sandstone, mudstone	350
		Tertiary	Neogen	Pliocene			Shaghur Conglomerate	SHC	Conglomerate, marl	~25
				Miocene			Saham/ Irkheim (?Miocene-Pleistocene)	SF / IR	(IR) limestone,marly-clay, gravel, chalky limestone; (SF) friable sandstone, chalky-marly, conglomeritic limestone	
							Waqqas Conglomerate	WC	course to fine conglomrates, siltstones, limestones, marls and alluvial fans	200
			Paleogene	Oligocene			Tayyiba	TL	limestone, glauconitic sandstone	from 40 to 65
							Unconformity			
				Eocene	Belqa		Wadi Shallala	WSC	Chalk &chalky limestome with beds of marly limestone	~300
							Umm Rijam	URC	chert, limestone	220
				Paleocene			Muwaqqar	MCM	chalky limestone and marly-chalk, chalk	from 120 to 320
	MESOZOIC	Upper Cretaceous	Maestrichtian			ASL/AHP	Al Hasa	AHP	phosphate	from 10 to 15
			Campanion				Amman	ASL	silicified limestone	60
							Wadi um Ghudran	WG	chalk, chalky marl	40
			Santonian				Khureij Limestone	Kh		
			Coniacian							
			Turonian		Ajlun		Wadi As Sir	WSL	limestone, dolomitic limestone and dolomite	from 80 to 150
			Cenomanian			F/H/Sh	Shu'ieb	Sh	chalky limestone, limestone, dolomitic limestone with marly limestone	80
							Hummar	H	limestone, dolomitic limestone and dolomite	from 40 to 65
							Fuhies	F	Marly limestone, dolomite, clay and shale	from 50 to 80
							Na'ur	NL	Marly limestone	from 20 to 50
			Albian				Wadi Juhra Member		fossiliferous sandstone, clay	from 3 to 40
		Lower Cretaceous	Aptian		Kurnub Sandstone		Undivided (Arda & Subeihi Formations)	KS	white sandstone, dolomite varicolored sandstone, siltstone, clay	350
			Neocomian							
		Jurassic	Upper	Tithonian	Azab		Unconformity			
				Kimmeridgian						
				Oxfordian			Mughanniyya	MUG	limestone	from 110 to 120
			Middle	Callovian			Ramla and Hamman	HA/RM	siliclastic-carbonate (sandstone, clay and limestone)	80 + 76
				Bathonian			Dhahab	DH	fossiliferous limestone, often dolomitised with marl	60
				Bajocian			Silal	SL	limestone, dolomitic limestone, dolomite and dolomitic sandstone	60
				Aalenian						
			Lower	Tovacian			Nimr	NR	limestone, dolomite with thin sandstone beds	from 7 to 20
				Pliensbachian						
				Sinemurian			Hihi	HI	silty mudstone, fossiliferous limestone, shale	40
				Hettangian			Unconformity			
		Triassic	Upper	Rhaetian	Ramtha					
				Norian			Abu Ruweis	ARG	massive gypsum deposits	60
				Carnian		Salit	Iraq al Amir /Umm Tina	IR/UT	carbonate and shale sediments	65 + 50
			Middle	Ladinian			Mukheiris	MK	sandstone, siltstone, claystone shale	70
				Anisian			Hisban	HL	bedded limestone with fossiliferous, marl	35
						Suwayma	Ain Musa	SSL	sandstone, siltstone, marl	80
							Dardur		dolomitic limestone, marl, sandstone, clay	60
			Lower	Scythian			Ma'in		sandstone, siltstone, clay	
		Permian	Upper	Tatarian	Hudayb		Unconformity			
				Kazanian			Buwayda Huwayra Anjara		sandstone, siltstone, shale	
				Ufimian						
			Lower	Kungurian						
				Artinskian						
				Sakmrian						
				Asselian			Major Unconformity			
	PALEOZOIC	Carboniferous Devonian								
		Silurian			Khreim		Khushsha		sandstone, shale	
							Mudawara		sandstone, shale, mud	
		Ordovician					Dubaydib		sandstone, shale	
							Hiswah sandstone		mudstone, sandstone	
					Ram		Umm Sahm		sandstone	
							Disi		sandstone	
		Cambrian					Umm Ishrin		sandstone, siltstone	
							Burj dolomite		siltstone, dolomite, limestone, sandstone	
							Salib		arkosic sandstone, siltstone	
		Pre-Cambrian			Safi		Sarmuj Conglomerate Aqaba Granite Complex		Coglomerates Granite with basic and acidic intrusives	

Does not occur in the study area

Table 2.2: Chronological sequence of the litologial formations and the hydrological classification in the study area (compiled from NRA open files and MACDonald et. al., 1965a).

Era	Period	Age	Group	NRA 1: 50,000 Geological Maps		MacDonald et. al., 1965			Thickness	Hydrogeological classification		Aquifer Potential
				Formation	Symbol			Rock type	(m)			
CENOZOIC	Quaternary	Recent		Soil cover bedrock, soil	s, s			Soil, Sand & Gravels		very good aquifer in Jordan	Shallow Aquifer (Superficial Deposits - Gravels)	
				Calcrete	ct							
		Holocene	Jordan River deposits	Alluvium; Aluvial fan	Al/Alg/Alf		Qal Qalf	Superficial deposits				
		Pleistocene	Jordan Valley	Travartine	Tr			Travartine				
				Pleistocene Gravel	Pl /Plg			Conglomerates with Silicious Cement				
				Dayma Siltstone	DA							
				Lisan Marl Gravel	LM		JV1					
				Ghour El Katar Basalt (Basalt Plateau (B))	B		JV1 a-b	Basalt				
				Ghour El Katar	GR			Sandstone, Mudstone & Gravels	350			
	Tertiary	Neogen: Pliocene		Shaghur Conglomerate	SHC							
		Neogen: Miocene		Saham / Irkheim (? Miocene-Pleistocene)	SF / IR							
				Waqqas Conglomerate	WC				200			
		Paleogene: Oligocene		Tayyiba	TL			Limestone, Chalk & Marly with Glauconite		Aquitard		
				Unconformity								
		Paleogene: Eocene	Belqa	Wadi Shallala	WSC		B5	Chalk &chalky limestome with beds of marly limestone	~300	Aquifer	Middle Aquifer Complex	
		Paleogene: Paleocene		Umm Rijam	URC		B4	Chalk Limestone & Chert	220			
MESOZOIC	Upper Cretaceous	Maestrichtian		Muwaqqar	MCM	Muwaqqar	B3	Chalk, Marly Chalk & Marl	from 120 to 320	Aquitard		
		Campanion		Al Hasa (ASL/AHP)	AHP	Amman	B2	Phosphate	~70	Excellent		
				Amman	ASL			Silicified Limestone		aquifer		
		Santonian		Wadi um Ghudran	WG	Ruseifa	B1	Dolomitic Marl, Chalk, Marl and Marly Limestone	40	Aquitard		
		Coniacian		Khureij Limestone	Kh							
		Turonian	Ajlun	Wadi As Sir	WSL	Wadi As Sir	A7	Limestone. Dolomitic Limestone. some Chert	from 80 to 150	Excellent		
		Cenomanian		Shu'ieb (F/H/Sh)	Sh	Shueib	A3-A6	Limestone, Marly Limestone	80	Aquifer		
				Hummar	H	Hummar		Dolomite, Dolomitic Limestone	from 40 to 65	Aquiclud		
				Fuhies	F	Fuheis		Marl and Marly Limestone	from 50 to 80	Aquifer		
		Albian		Na'ur Wadi Juhra Member	NL	Na'ur	A1-A2	Limestone, Dolomitic Limestone, Marly Limestone, Shale	~90	Aquitard		
	Lower Cretaceous	Aptian	Kurnub Sandstone	Undivided	KS	Kurnub Group	KS	Sand, Shale, Clay and Sandy Limestone	350	Aquifer	Lower aquifer complex (brakish to saline water mostly thermal)	
		Neocomian		(Arda & Subeihi Formations)				sandstone, Marl and Shale				
	Jurassic	Upper: Tithonian	Azab	Unconformity								
		Upper: Kimmeridgian										
		Upper: Oxfordian		Mughanniyya	MUG	Zarqa Group	Z2	Limestone, Marlstone Sandstone and Shale	from 1137 to 1160	Aquiclud		
		Middle: Callovian		Ramla and Hamman	HA/RM							
		Middle: Bathonian		Dhahab	DH							
		Middle: Bajocian		Silal	SL							
		Middle: Aalenian		Nimr	NR							
		Lower: Tovacian		Hihi	HI					Aquifer Aquiclud		
		Lower: Pliensbachian										
		Lower: Sinemurian										
	Triassic	Upper: Hettangian	Rantha	Unconformity								
		Upper: Rhaetian										
		Upper: Norian		Abu Ruweis	ARG		Z1	Limestone, Shale Sandstone and Evaporites	~420	Aquitard		
		Upper: Carnian										
		Middle: Ladinian		Iraq al Amir /Umm Tina (Salit)	IR/UT	T						
		Middle: Anisian		Mukheiris	MK							
				Hisban	HL							
				Ain Musa (Suwayma)	SSL							
		Lower: Scythian		Dardur Ma'in								
	Permian	Upper: Tatarian	Hudayb	Unconformity								
		Upper: Kazanian		Buwayda Huwayra Anjara		P		sandstone, siltstone, shale				
		Upper: Ufimian										
		Lower: Kungurian										
		Lower: Artinskian		Major Unconformity						Aquifer		
		Lower: Sakmarian										
		Lower: Asselian										
PALEOZOIC	Carboniferous Devonian											
	Silurian		Khreim	Khushsha				sandstone, shale				
				Mudawara				sandstone, shale, mud				
	Ordovician			Dubaydib				sandstone, shale				
				Hiswah sandstone				mudstone, sandstone				
			Ram	Umm Sahm				sandstone				
				Disi				sandstone				
	Cambrian			Umm Ishrin				sandstone, siltstone				
				Burj dolomite				siltstone, dolomite, limestone, sandstone				
				Salib				arkosic sandstone, siltstone				
	Pre-Cambrian		Safi	Sarmuj Conglomerate				Coglomerates				
				Aqaba Granite Complex				Granite with basic and acidic intrusives				

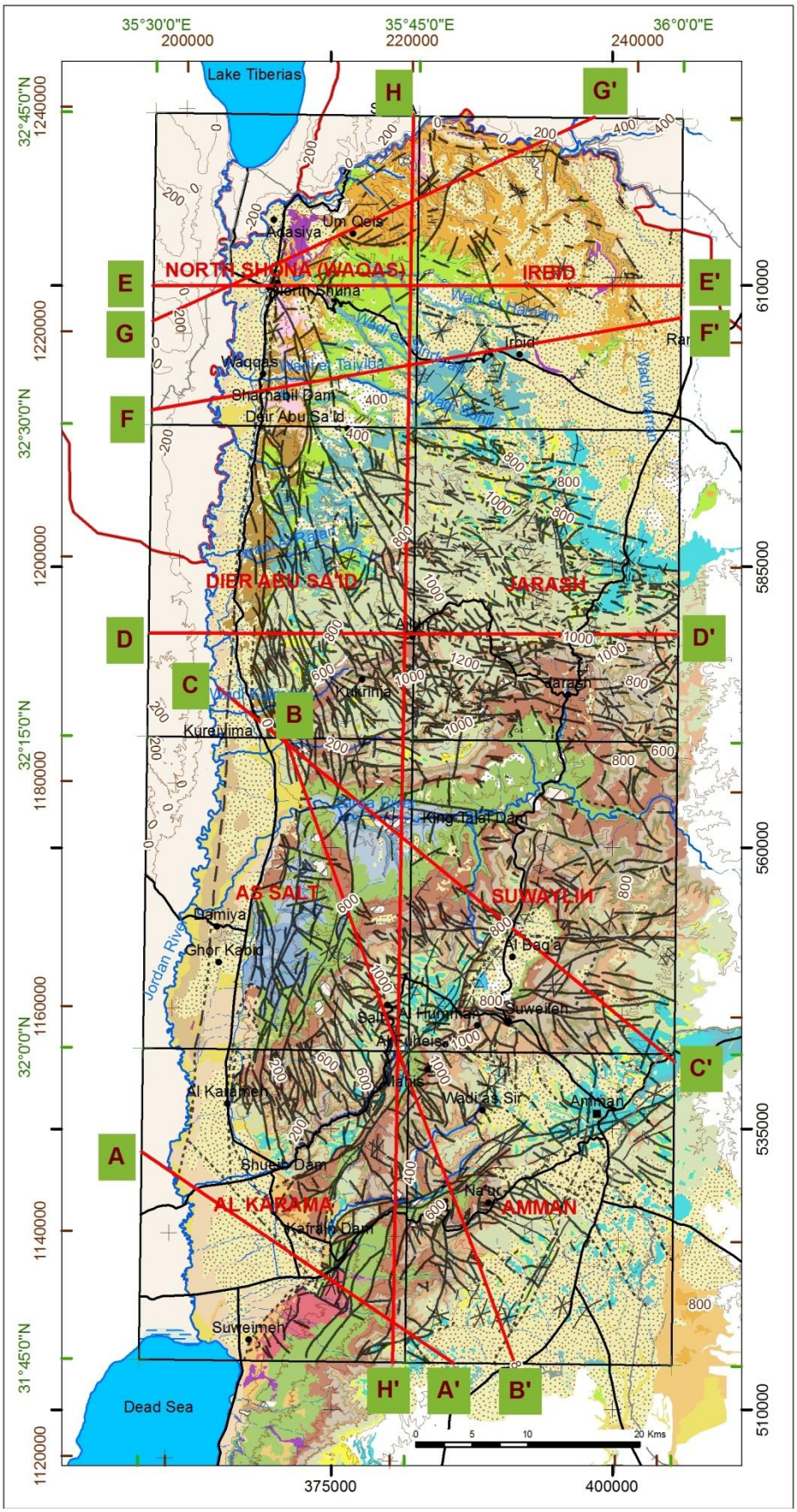


Figure 2.3: Geological Cross Sections Location Map.

2.1.1.1 Ramtha Group (ZM) (Triassic)

The oldest rocks at outcrop in the study area belong to the Ramtha Group of Triassic age. The Jordan 1:50,000 Geological Mapping Project based on BANDEL & KHOURY (1981) subdivided the Triassic group into six formations. These are (in ascending sequence): Suwayma (SSL), Hisban (HL), Mukheris (MK), Iraq el Amir (IR), Um Tina (UT) and Abu Ruweis (ARG) formations (Plate 4 & Table 2.2).

The most important lithofacies are clastic (interbedded shale, siltstones and sandstones) argillaceous, fossiliferous limestone or dolomite, often interbedded with shale and marl, anhydrite and halite.

At outcrop, the base of the Triassic rocks is absent. At the northeastern edge of the Dead Sea Triassic rocks are unconformably overlain by the Lower Cretaceous Kurnub Sandstone Group (Plate 4), and further to the south of the study area (along the shore of the Dead Sea) it is found that the basal formation of Triassic Group (Suwayma formation) overlies the Um Irna Formation (of Permian Group). The top of this Group (in Zarqa River area) is overlain unconformably by Jurassic strata of Azab Group as shown in the geological cross section BB′ (Plate 5).

2.1.1.1.1 Distribution and Thicknesses of Ramtha Group

In northwestern Jordan, the Triassic rocks are exposed in three main areas (Figure 2.4). The geological cross sections AA′, BB′, CC′ & HH′ show the surface and subsurface extents of the Triassic rocks in northern Jordan (Plate 5).

The first outcrop area lies south of the study area, along the shore of the Dead Sea (from Wadi Mujib northward to Wadi Hisban), where a 305 m-thick succession overlying Permian strata was described by BANDEL & KHOURY (1981) (geological cross section AA′, Plate 5).

The second main outcrop area of Triassic rocks is located west of Na'ur (HUNTING & MACDONALD, 1965a) (geological cross section AA′, Plate 5), where a 140 m-thick succession was described along Wadi Na'ur and Wadi Siyala (BANDEL & KHOURY, 1981).

The Third Triassic outcrop area lies in the Middle of the study area, in Zarqa River, where only the uppermost Triassic rocks are poorly exposed (BLACK, 1935). A 150 m maximum thickness for this exposure was estimated by ABU AJAMIEH, et al. (1989) (Plate 4 & geological cross section CC′, Plate 5).

2.1.1.1 Azab Group (AZ) (Jurassic)

The Azab Group sediments (Jurassic) are exposed extensively in the study area along the side wadis of the Jordan Valley. They overlie unconformably the Zarqa–Ma'in Group of Triassic age. The name of Azab was derived from a spring (Azab) and a north-flowing tributary (Wadi el Azab) of Zarqa River. (PARKER, 1970; KHALIL & MUNEIZEL, 1992).

The Azab group was subdivided according to Jordan 1:50,000 Geological Mapping Project of NRA into seven formations. These are (in ascending sequence): Hihi Claystone (HI), Nimr Limestone (NR), Silal Sandstone (SL), Dahab Limestone (DH), Ramla Sandstone (RM), Hamam (HA) and Mughanniyya Limestone (MUG) Formations (Plate 4; Table 2.2).

The predominant lithology of the Azab Group consists mainly of sandstone, limestone and clayey siltstone. Marl is also common in the upper part of the sequence (KHALIL & MUNEIZEL, 1992). Generally a full well differentiated sequence is only found in Jordan along Zarqa River, where the contact between Jurassic and Triassic rocks is exposed east of Tell Ed Dahab (confluence of Wadi Huni and the lower Zarqa River) (Plate 4). In Wadi Mahis and Wadi Safut (1 km west of 'Ain el Bashs town), the Azab Group sediments are undifferentiated and overlie the Zarqa-Ma'in Group sediments with a greater amount of missing section. This group is considered as a week aquifer in the study area containing brackish water (Table 2.2).

In northwestern Jordan, the Abu Ruweis Formation of Triassic Group is unconformably overlain by the lower part of Jurassic sediments (Hihi Claystone Formation). This is clear in the exposure of the Azab Group along the Zarqa River (Plate 4) and as shown in the geological cross section CC′ & HH′ (Plate 5). The upper boundary of Azab Group is unconformably overlain by the Lower Cretaceous Kurnub Sandstone as shown in the geological cross sections BB′, CC′ & HH′ (Plate 5). No subsurface data are available for the Azab Group along the southeast extension of the geological cross section BB′ (Plate 5) in the area between Wadi el Farwa and southeast of Wadi Hisban.

2.1.1.2.1 Distribution and Thicknesses of Azab Group

Geological cross sections BB′, CC′ & HH′ (Plate 5) show the surface and subsurface extents of Jurassic rocks in northwestern Jordan. The major exposure of Azab Group extends from Wadi as Samra (west of es Salt) in the north to Zarqa River (east of Deir 'Alla) in the south (Figure 2.4), where the Jurassic was mapped as a narrow belt along the Zarqa River and its tributaries; notably at the mouth of Wadi el Huni and Wadi el Azab; downstream from King Talal Dam (QUENNELL, 1959; BENDER, 1968b; KHALIL & MUNEIZEL, 1998; SAWARIEH & BARJOUS, 1993). Further to the east, two small outcrops are mapped in the core of an anticlinal structure. The Jurassic rocks in the first core of an anticline located west of 'Ain al Basha town (geological cross section CC′, Plate 5) were reported and described by ABED (1987). The second anticline cores where Jurassic rocks are exposed are located southwest of Mahis village (geological cross section BB′, Plate 5). This outcrop was first reported by IBRAHIM (1965) during the exploration activities of clay in Ghour Kabid area.

The Azab Group thickness has been estimated by BANDEL (1981) and BANDEL & KHOURY (1981) as 430-450 m and 400 m by KHALIL & MUNEIZEL (1992). While the exposed part of this group in Wadi Mahis is 42 m thick only.

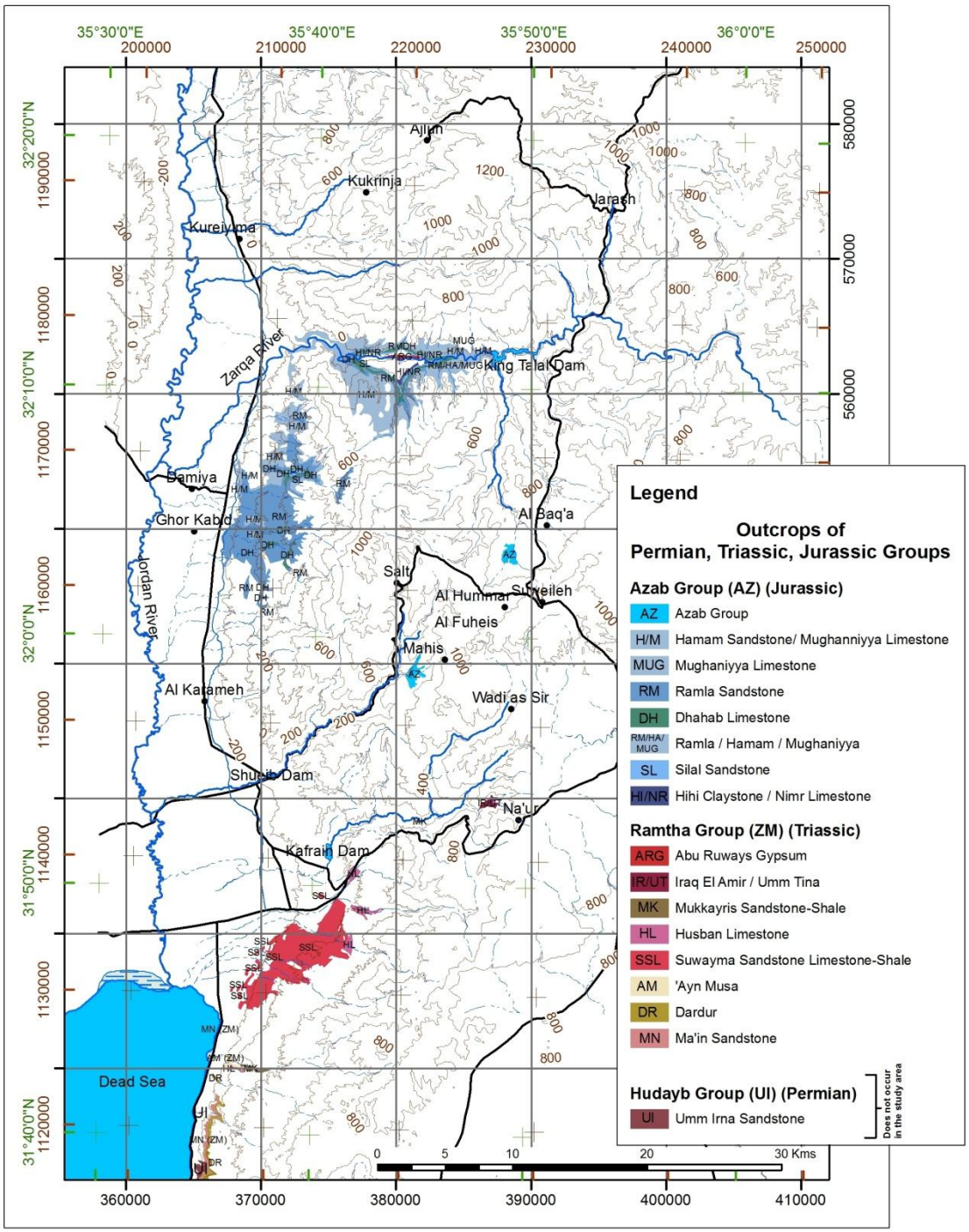


Figure 2.4: Location map of the Zarqa-Ma'in Group (Triassic) and Azab Group (Jurassic) outcrops in NW Jordan (For more details see Plate 4: the Geological Map of the study area at a scale of 1:50,000).

2.1.1.2 **Kurnub Sandstone Group (KS)** (Lower Cretaceous)

The Kurnub Sandstone Group is one of the most important rock groups in Jordan. In general, it is porous and permeable and as such constitute an important aquifer (MASRI, 1963); which along the highland contains fresh water and in the Jordan Valley area brackish water. The Kurnub Sandstone Group is also an important source providing good quality sand for building construction, which locally is known as "Raml Suweileh"; and have proven petroleum reservoir potential in Azraq well field (well HZ-14) (ABU AJAMIEH et al., 1989).

The Kurnub Sandstone Group of predominantly clastic (fluvial medium-to coarse grained sandstone) sediments (BENDER, 1974a; ABED, 1982b) forms the basal deposits of the Cretaceous sedimentary cycle throughout Jordan. This group rest unconformably on the Triassic and Jurassic rocks dominated by carbonate (ANDREWS, 1992). The Kurnub Sandstone was divided into the lower Arda Formation and the upper Subeihi Formation (PARKER, 1970). But in the 1:50,000 Geological Map (Plate 4) Kurnub Sandstone Group is considered as one unit, characterized at outcrops by medium to coarse-grained sandstones with beds of siltstones. But in north Jordan sandy dolomite, dolomitic limestone and claystone are intercalated (PARKER, 1970; BENDER, 1974a; ABED, 1982b; POWELL, 1988; 1989b). At outcrops the top of the Kurnub Sandstone Group is overlain by limestones of the Ajlun Group in most areas of Jordan (Plate 4).

2.1.1.3.1 **Distribution and Thicknesses of Kurnub Sandstone Group**

The Kurnub Sandstone Group is widely distributed in Jordan and neighboring countries. In the study area, it is exposed east of the rift forming the rift escarpment. The exposed Kurnub Sandstone founds mainly in wadi Zarqa and its deeply incised wadis (Figure 2.5). To the south the Kurnub Sandstone reaches Ras en Naqab area and the Saudi border in the south and southeast (POWELL, 1988; 1989b).

Exposures of this group are found in the southern part of the study area, at the northeastern corner of the Dead Sea along major wadis such as Shueib and Kafrain as shown in geological cross sections AA′ & HH′ (Plate 5). They extend to the east to reach Wadi Mahis, Al Baqa' depression south and southeast of King Talal Dam; where it unconformably overlies the Azab Group and west Amman areas as shown in the geological cross sections BB′, CC′ & HH′ (Plate 5). Other major exposures are found:

(1) North and south of the Zarqa River area as shown in geological cross sections CC′ & HH′ (Plate 3);

(2) In Arda area just below and west the level of Kufr Huda-Subeihi triangle-Arda road and

(3) West of it within the deeply incised wadis (KHALIL & MUNEIZEL, 1998), Wadi Jarash, Wadi Haddadeh and Wadi Nahla (ABDELHAMID, 1995) in the central of the study area.

The thickness of Kurnub Sandstone Group at outcrops varies from 150 -200 m. In the area northeast of the Dead Sea (SHAWABKEH, 2001); 200 – 300 m and in Arda area (MUNEIZEL & KHALIL, 1993); 250-300 m, west of Amman (DIABAT & ABDELGHAFOOR, 2004), where it reaches the maximum recorded thickness of 350 m west of Suweileh (SAWARIEH & BARJOUS, 1993).

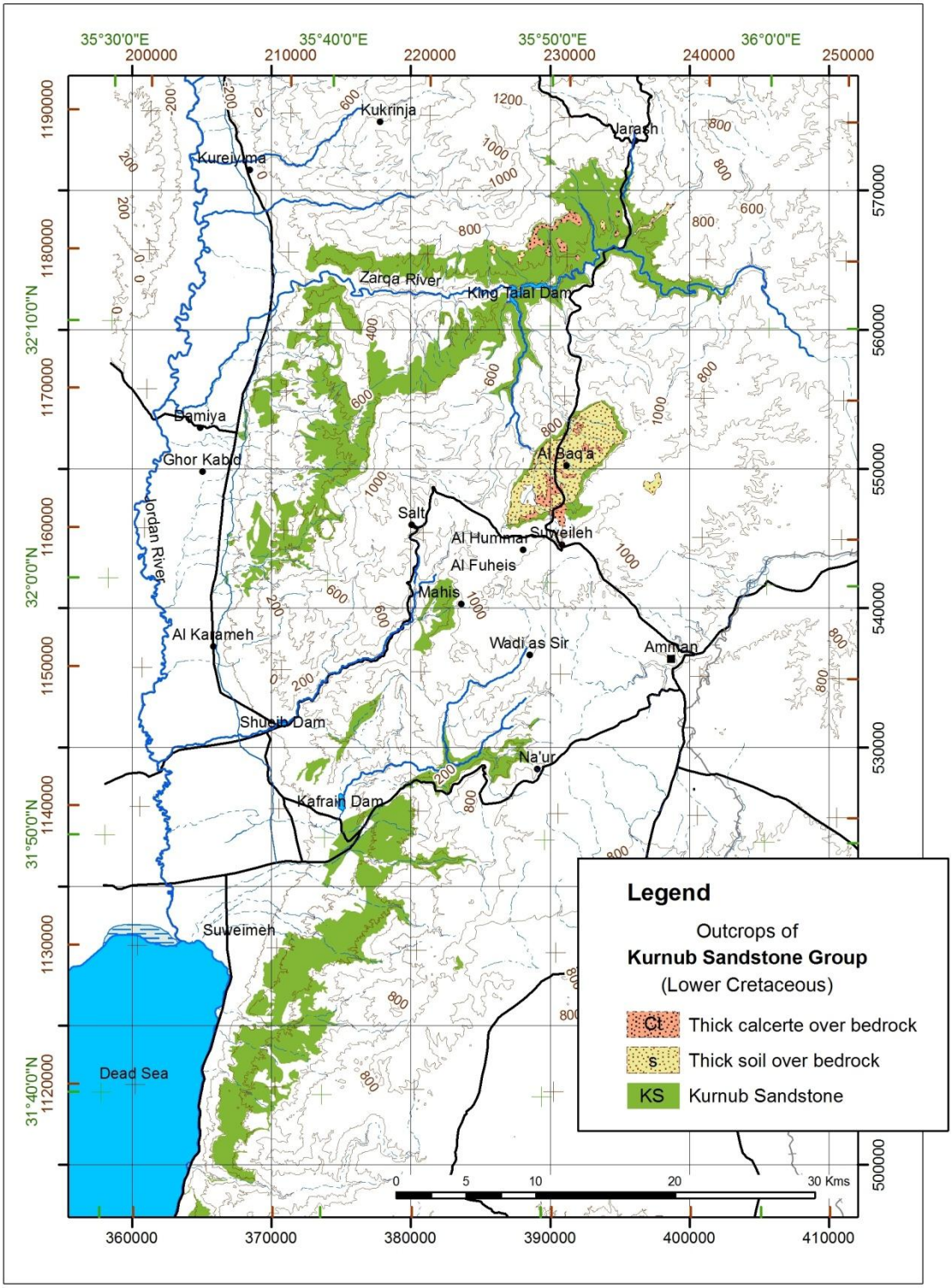


Figure 2.5: Location map of the Kurnub Sandstone Group (Lower Cretaceous) outcrops in NW Jordan (For more details see (Plate 4): the Geological Map of the study area at a scale of 1:50,000).

2.1.1.3 **Ajlun Group** (Upper Cretaceous)

Throughout most of Jordan, the Ajlun Group (Cenomanian - Turonian) overlies unconformably the Kurnub Sandstone (Plate 4 & Table 2.1). In the study area outcrops, the group is divided into **lower** interbedded limestone-shale sequence (Na'ur, Fuheis, Hummar and Shueib Formations) and **upper** uniform limestone sequence (Wadi as Sir Formation) (MASRI, 1963). Whereas, in south Jordan, the so-called 'F/H/S unit' is used for the undivided Ajlun Group along the rift margin (POWELL, 1989b).

The Ajlun Group was first named as the Ajlun Series by QUENNELL (1951) and was subdivided into seven lithostratigraphical subdivisions A_1-A_7 by WOLFART (1959). MASRI (1963) established five formations based on mapping in the Amman-Zarqa area, some of these formations are equivalent to WOLFART's subdivisions. MASRI's subdivision comprises, in ascending order: A_1 and A_2 were combined as Na'ur; A_3 as Fuheis; A_4 as Hummar; A_5 and A_6 as the Shueib and A_7 as Wadi Es Sir Formations. Three mappable units are recognized in north Jordan; these are in upward sequence: the Na'ur Limestone Formation ($A_{1/2}$), undifferentiated Fuheis, Hummar and Shueib Formations (A_{3-6}), and the Wadi Es Sir Limestone Formation (A_7) (Table 2.2). The lower Ajlun Group (A_{3-6}) has been studied in some details due to its importance as a reservoir in the Hamzeh oilfield, near Azraq (CORE LAB, 1987), as an aquifer (MASRI, 1963) and as a source of clay for cement (ABU AJAMIEH et al., 1989).

BENDER (1968a, b & 1974a) did not use the term Ajlun Group, but subdivided the equivalent-marine and continental Upper Cretaceous-beds into three units, in ascending order: the Nodular Limestone Unit, the Echinoidal Limestone Unit and the Sandy and Massive Limestone Unit. These subdivisions correspond in part, to those of previous authors, but the boundaries are often drawn at different levels. MASRI's (1963) scheme was later adopted by PARKER (1970) and the 1:50,000 National Geological Mapping Project. BASHA (1978) differentiated the lower and upper Na'ur Formation according to microfossils assemblages.

The Ajlun Group in northwestern Jordan comprises a thick sequence of predominantly carbonate rocks; limestone, marl and dolomite with subordinate amounts of gypsum, mudstone and chert.

The base of the Ajlun Group (Na'ur Limestone Formation) overlies unconformably the Kurnub Sandstone. The base of the Ajlun Group (Na'ur Formation) in some localities in north Jordan is marked by a transitional zone between the siliclastic Kurnub Sandstone Group and the carbonate dominated Na'ur Formation. This zone is called "Wadi Juhra Member". The top of this group is overlain unconformably by the chalk, limestone, chert and locally phosphates of the Belqa Group (Amman Formation) (Plate 4 & geological cross sections AA´, BB´, CC´, DD´ & HH´, Plate 5).

2.1.1.4.1 **Distribution and Thicknesses of the Ajlun Group**

Exposures of this group can be seen in the study area, mainly the extensive outcrop in the Ajlun mountains (north Jordan), the good exposure along the Rift margins and also the exposures along the deeply incised eroded westward-draining wadis (i.e. into

the Dead Sea Rift) (Figure 2.6). Geological cross sections AA′, BB′, CC′, DD′ & HH′ (Plate 5) show the main locations of these exposures. The thickness of the Ajlun Group ranges from 300 to 400 m for Lower Ajlun Group and 80 to 100 m for Upper Ajlun Group (POWELL, 1989b; ABDELHAMID, et al., 1991).

Due to the importance of the different formations within this group either as an aquifer or an aquitard; the distribution and thicknesses for the different formations are described below:

2.1.1.4.1.1 Lower Ajlun Group

In northern Jordan, the four formations (Na'ur, Fuheis, Hummar and Shueib Formations) of the **Lower Ajlun Group** have a combined outcrop thickness of 300 – 400 m (POWELL, 1989b). The 1:50,000 Geological Map (Plate 4) and the geological cross sections AA′, BB′, CC′, DD′ & HH′ (Plate 5) show the distribution and the main exposures of the Lower Ajlun Group in the study area.

The Lower Ajlun Group reaches its widest surface distribution on the slopes of the Zarqa River valley. From there to the south, the Lower Ajlun Group outcrops are common on the slopes of the escarpment and the side wadis (Figure 2.6).

2.1.1.4.1.1.1 Na'ur Limestone Formation (NL) (Late Albian to Early Cenomanian)

The Na'ur Limestone Formation according to the 1:50,000 Geological Map (Plate 4) comprising a sequence of alternating limestone and marl beds overlain by yellowish – grey, soft to medium-hard marl, interbedded with thin layers of marly limestone in its middle part. The top of the Formation is marked by dolomitic limestone with chert nodules.

At outcrops of the study are, the Na'ur Limestone Formation ranges in thickness from 20 to 50 m; while the basal part (Wadi Juhra Member) ranges from 3 to 40 m (Table 2.1 & geological cross sections AA′, BB′, CC′ & HH′, Plate 5). The Formation thickness reaches 200 m in Na'ur and 86 m in Wadi esh Shita (Figure 2.6).

2.1.1.4.1.1.2 Fuheis Formation (F) (Cenomanian)

The Fuheis Formation according to the 1:50,000 Geological Map (Plate 4) consists of marls intercalated with thin bedded nodular limestone and marly limestone. Shale and carboniferous layers intercalate with the marls of the Formation.

At outcrops the thickness of Fuheis Formation ranges from 50 to 80 m (Figure 2.6). The main exposures of this Formation are shown in the geological cross sections AA′, BB′, CC′ & HH′ (Plate 3). The Formation thickness reaches 80 m in Suweileh and 57 m in Wadi esh Shita.

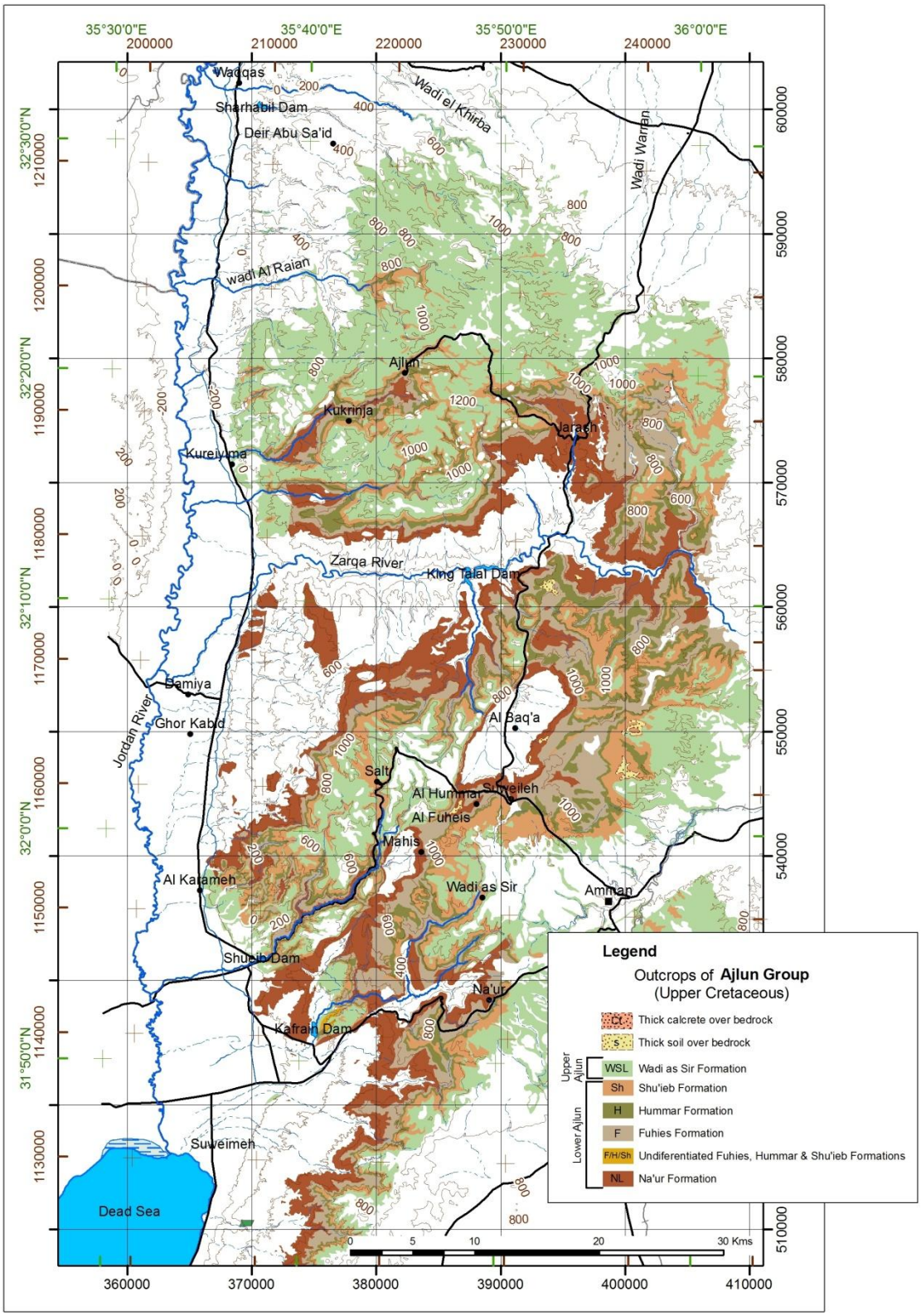


Figure 2.6: Location map of the Ajlun Group (Upper Cretaceous) outcrops in NW Jordan (For more details see Plate 4: the Geological Map of the study area at a scale of 1:50,000).

2.1.1.4.1.1.3 **Hummar Formation (H)** (Late Cenomanian)

The Hummar Formation according to the 1:50,000 Geological Map (Plate 4) comprises grey limestone and dolomitic limestone.

The thickness of the Hummar Formation at outcrops ranges from 40 – 65 m (geological cross sections AA′, BB′, CC′, DD′ & HH′, Plate 5). It seems that the Formation slightly thickens towards the southeast, where the thickness reaches about 65 m in Wadi Shueib, Suweileh and Hummar areas (ABDELHAMID, 1995) (Figure 2.6).

2.1.1.4.1.1.4 **Shueib Formation (Sh)** (Late Cenomanian – Early Turonian)

The Shueib Formation according to the 1:50,000 Geological Map (Plate 4) consists of marl alternating with thin chalky limestone and brown dolomitic limestone.

At outcrops, the thickness of the Shueib Formation reaches a maximum of 80 m in the northwest of Jordan (Ajlun district) up to 50 m in Wadi Shueib and 48 m west and southwest of Amman (geological cross section BB′, Plate 5). The thickness of the Formation is 36 m in Wadi Es Sir and Wadi Esh Shita west of Amman and ~ 72 m in Na'ur area (PARKER, 1970; POWELL, 1989b). The geological cross sections (AA′, BB′, CC′, DD′ & HH′, Plate 5) show the variations of outcrop thicknesses of Shueib Formation in different exposures.

2.1.1.4.1.2 **Upper Ajlun Group**

2.1.1.4.1.2.1 **Wadi as Sir Limestone Formation (WSL)** (Turonian)

At outcrops the Wadi as Sir Formation consists of well-bedded, massive, limestone, dolomitic and dolomite with lesser amounts of limestone, marl, gypsum and chert (POWELL, 1989b).

The Wadi as Sir Formation shows considerable variations in thickness at outcrops; 90 m in the type area (Wadi as Sir) (MASRI, 1963), 215 m in north Jordan (Ajlun district) (MACDONALD et al., 1965a) and 80 m at Qalat et Twail southwest of Maddaba (MACDONALD et al., 1965a). It reaches a maximum in the northwest of Jordan (geological cross sections DD′, EE′, FF′, GG′ & HH′, Plate 5), where it ranges from 80–200 m (POWELL, 1989b; ABDELHAMID et al., 1991; ABU QUDAIRA, 2005). The geological cross sections (AA′, BB′, DD′ & HH′, Plate 5) show the major Wadi as Sir outcrops and their thicknesses within the study area (Figure 2.6).

2.1.1.5 **Belqa Group** (Upper Cretaceous–Tertiary)

The Upper Cretaceous to Paleogene Belqa Group (QUENNELL, 1951; PARKER, 1970) overlies the Ajlun Group and is unconformably overlain by the Waqqas Conglomerate (Oligocene–Miocene) (Table 2.1). The Belqa Group was first introduced by QUENNELL (1951), who with BURDON (1959b) used the term "series". The name was derived from the Belqa district in north Jordan where the Group is well exposed. WOLFART (1959) established five mapping units (B_1/B_5) in Irbid area. MASRI (1963) studied the Amman-Zarqa area and recognized only two formations: Amman Formation ($B_{1/2}$) and Muwaqqar Formation (B_3). MACDONALD et al. (1965a & b) used the group status for the mapped five units and separated Masri's Amman Formation into $B_{1a/b}$ and $B_{2a/b}$. Later PARKER (1970) formalized MacDonald's units as: Wadi Ghudran, Amman, Muwaqqar, Rijam and Wadi Shallala Formations, but did not subdivide the lowest two. Group status was not used by BENDER (1974a) and the GEOLOGICAL MISSION (1961-1966) named the unit (in upward sequence): the "Silicified Limestone Member", "Phosphorite Member", "Chalk-Marl Member" and "Chert-Limestone Member".

According to POWELL (1988) the Belqa Group can be divided into six formations and includes (in ascending sequence); Wadi Um Ghudran (WG), Amman (ASL), Al Hisa (AHP), Muwaqqar MCM), Um Rijam (URC); Wadi Shallala (WSC) and Tayyiba Limestone (TL) Formations. However, due to facies changes, some formations may be lumped together where formational boundaries cannot be recognized such as: Amman and Al Hisa Formations.

The Belqa Group comprises predominantly pelagic sediments (QUENNELL, 1951; PARKER, 1970) including chalk, marl, chert, phosphate, coquina, limestone and siliclastic sand, disconformably overlying the bioclastic platform carbonate of the Ajlun Group. The upper most Tayyiba Limestone Formation (Oligocene) is separated from regressive, alluvial and lacustrine facies by a distinctive regional unconformity (Table 2.1).

At outcrops in northwestern Jordan the base of the Belqa Group is defined by the appearance of chalk of Wadi Um Ghudran Formation overlain by the thick bedded chert of Amman Silicified Formation (Plate 4). The top of the Belqa Group (Wadi Shallala Formation) is overlain by the Oligocene limestones of the Tayyiba Formation (WETZEL & MORTON, 1959).

2.1.1.5.1 **Distribution and Thicknesses of the Belqa Group**

The Belqa Group is not fully exposed in the study area due to late Tertiary-Quaternary erosion at different formation levels (Figure 2.7). A more complete succession is present in Waqqas area in the extreme northwest of the study area. Here it unconformably overlain by the Waqqas conglomerate (Oligocene – Miocene) (Plate 4 & Table 2.1).

The Belqa Group shows variation in thickness throughout Jordan. It is about 600 m thick in the type locality in Irbid area and increases to about 1400 m along the NW-SE trending Azraq Basin (Hamzeh Oil well No. 3) (POWELL, 1988). The thickness

variations and the main exposure location of the Belqa Group are shown in all geological cross sections (AA′, BB′, CC′, DD′, E E′, FF′, GG′ & HH′, Plate 5).

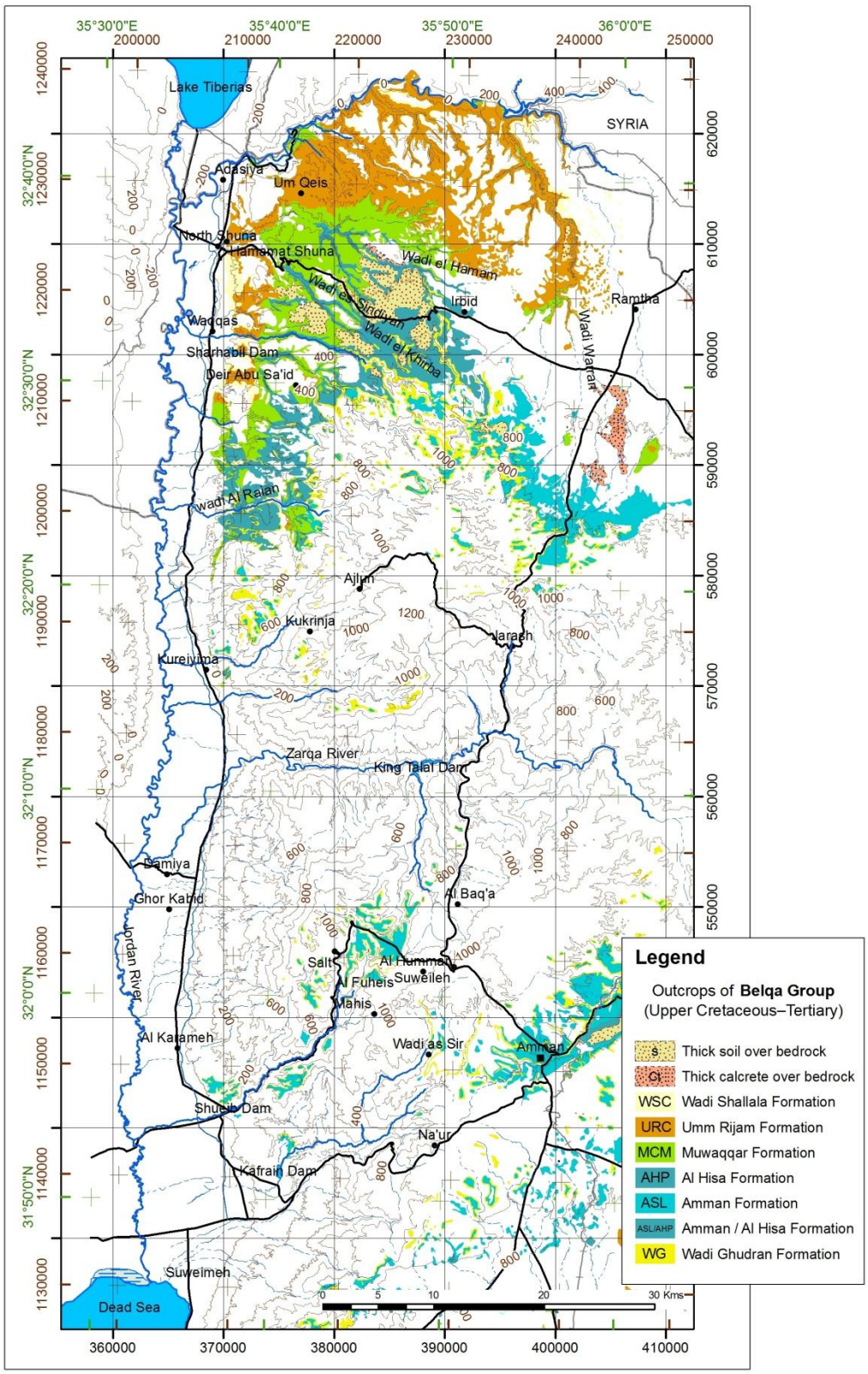


Figure 2.7: Location map of the Belqa Group (Upper Cretaceous – Tertiary) outcrops in NW Jordan (For more details see Plate 4: the Geological Map of the study area at a scale of 1:50,000).

2.1.1.5.2 Distribution and Thicknesses of the Wadi Um Ghudran Formation (WG) (Santonian - Campanian)

The Wadi Umm Ghudran Formation according to the 1:50,000 Geological Map (Plate 4) consists of white-grey massive chalk and marl.

The exposures of the Wadi Um Ghudran Formation are restricted to the highest areas in the study area (Plate 4). These exposures are shown in the geological cross sections (AA´, BB´, CC´, DD´ & HH´, Plate 5), such as the exposures within Amman-Halabat Structure close to mount Nebo (geological cross section AA´), near Al Kafrain Dam as shown in the geological cross section (BB´, Plate 5) or the exposures in the northeastern parts of the study area (geological cross sections CC´, DD´ & HH´, Plate 5).

At outcrops a maximum thickness of 52 m was measured (in Wadi Ghudran Ed Dib southeast of Irbid (MACDONALD et al., 1965a), whereas it is 25-30 m thick around Jarash.

2.1.1.5.3 Distribution and Thicknesses of the Amman Silicified Limestone and Al Hisa Phosphorite Formations (ASL/AHP) (Campanian)

The Amman Silicified Limestone and Al Hisa Phosphorite Formations are widely distributed throughout Jordan, especially along the eastern side of the Dead Sea – Rift and in the central Plateau. Sparse exposures of the Amman Silicified Limestone Formation can be seen in the central part of the study area and in the area southeast of Amman (Plate 4 & geological cross section BB´, Plate 5).

The Amman and Al Hisa Formations are considered as an important unit in northern and central Jordan due to their economic significance both as an aquifer (MASRI, 1963) and as the source of an estimated 1100 million tones of phosphate reserves (ABU AJAMIEH, et al., 1989).

Generally, the thickest outcrop section of Amman – Al Hisa Formations (140–160 m) occur in Wadi Al Mujib, Karak and Siwaqa area with a thinning toward north (88 m in Amman) (geological cross section HH´, Plate 5) and south (40-69 m in Gharandel) (POWELL, 1989b).

2.1.1.5.4 Distribution and Thicknesses of the Muwaqqar Chalk-Marl Formation (MCM) (Maestrichtian - Paleocene)

At outcrop the Muwaqqar Chalk-Marl Formation is characterized by chalky marl, marl and chalky limestone with harder beds and nodules of microcrystalline limestone and brown chert (POWELL, 1989b). Phosphate is occasionally present and the marl is highly bituminous and occurs in lenses ranging in length from 80 to 100 m with few meters thick.

The Muwaqqar Chalk-Marl Formation is widely distributed throughout Jordan, where older rocks are not exposed (Plate 4 & geological cross sections DD′, EE′, FF′ & HH′, Plate 5).

The Formation has the thickest measured outcrop thickness of 332 m in the extreme northwest of Jordan in the vicinity of the Yarmouk River (PARKER, 1970).

In the Yarmouk River area, Bituminous, marly limestone, the so called oil shale, had been known since long and even used for oil retorting at Maqarin during World War I (BEYSCHLAG, 1919). The Formation was later recorded in various localities (CLAPP, 1936; IONIDES & BLAKE, 1939; QUENNELL, 1951; BURDON, 1959b; HEIMBACH, et al., 1962; 1964; among others). Jordanian oil shales are a matter of interest by many companies nowadays in Jordan in order to produce oil from them.

2.1.1.5.5 Distribution and Thicknesses of the Um Rijam Chert Limestone Formation (URC) (Paleocene-Eocene)

The Um Rijam Chert Limestone Formation is widely distributed throughout Jordan (Plate 4 & geological cross sections DD′, EE′, FF′ & HH′, Plate 5).

The Um Rijam Chert Limestone Formation maximum outcrop thickness is 220 m in north Jordan, thinning to 122-145 m in isolated outcrops along the southern Rift margin (POWELL, 1989b).

The Um Rijam Chert Limestone Formation consists of (partly phosphoritic) limestone, chalky limestone, chalk and beds and nodules of brown to black chert.

2.1.1.5.6 Distribution and Thicknesses of the Wadi Shallala Chalk Formation (WSC) (Eocene)

The Wadi Shallala Chalk Formation is the youngest formation of the Belqa Group (Table 2.1) and it crops out in the Yarmouk River area (geological cross section GG′, Plate 5).

At outcrops the Wadi Shallala Formation has a thickness of 130-140 m and about 35 m (incomplete exposure) in Wadi Shallala area (WOLFART, 1959; HUNTING & MACDONALD, 1965a). To the east of the study area (Azraq area), the base of Wadi Shallala is not exposed and only 55 m are recorded (WETZEL & MORTON, 1959).

The Wadi Shallala Formation is exposed at the surface in most areas to the north of the study area. These exposures are shown in the Geological Cross Sections (geological cross sections EE′, FF′ & GG′, Plate 5).

The Wadi Shallala Formation consists of chalk and chalky marl with thin beds of marly limestone. The marls are locally bituminous.

2.1.1.6 **Jordan Valley Group** (Upper Tertiary - Quaternary)

The main exposures locations of the Jordan Valley Group are shown in (Figure 2.8). This Group consists of the following formations:

2.1.1.6.1 **Distribution and Thicknesses of the Tayyiba Limestone Formation (TL)** (Oligocene)

The Wadi Shallala Formation in northwestern Jordan is disconformably overlain by the Tayyiba Limestone Formation of Oligocene age (WETZEL & MORTON, 1959), which consists of glauconitic marl and limestone.

At outcrops, a limited exposure of 40.5 m was described by WETZEL & MORTON (1959) and by BENDER (1974a). However, no other equivalent Oligocene rocks have been found in Jordan so far.

2.1.1.6.2 **Waqqas Conglomerate Formation (WC)** (Oligocene - Miocene)

The Waqqas Conglomerate Formation is well exposed in the northwestern part of the study area, where the easternmost outcrop occurs in Wadi Zahar (Plate 4). The outcrops of this Formation are shown in the geological cross sections CC′, DD′ & EE′ (Plate 5) which shows that this Formation conformably overlies the Tayyiba Limestone Formation and unconformably overlies other rock units such as Muwaqqar Chalk-Marl, Um Rijam Chert-Limestone and Wadi Shallala Chalk Formations.

The Waqqas Formation sequence reaches up to 150 m in thickness, composed of coarse- to -fine grained conglomerates, siltstones, limestone, marl and basalt.

2.1.1.6.3 **Saham Conglomeratic Limestone Formation** (Pliocene-Recent?)

The Saham Formation crops out in the northern and northwestern parts of the study area (Plate 4) and presents an evidence for a lake which covered part of the present day Yarmouk River which separated Jordan from Syria and Golan Heights. The base of this Formation starts with white, friable sandstone bed followed by few meters of chalky – marly porcellanite.

2.1.1.6.4 **Irkheim Formation (IR)** (Late Pleistocene)

The Irkheim Formation is well exposed in the northwestern highlands of the study area, overlooking the Rift. It is characterized by patchy distribution as it fills pre-existing topography and thus of wide thickness variations (<10 m to about 100 m) (Plate 4).

The lower boundary of the Irkheim boundary is marked by younger soil and/or calcretes. The Formation comprises three members; a marly clastic member sandwitched between two massive limestone members.

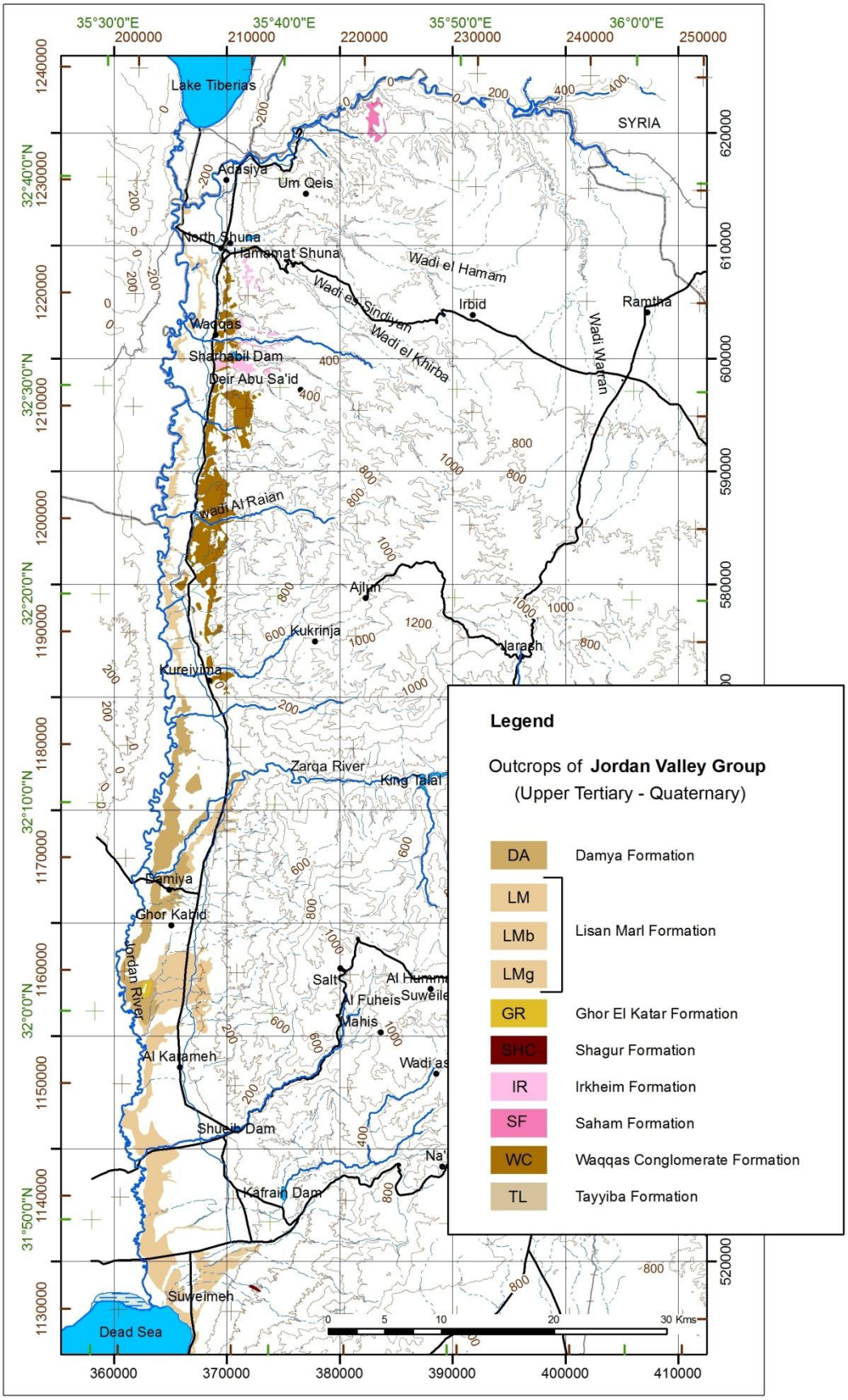


Figure 2.8: Location map of the Jordan Valley Group (Upper Tertiary - Quaternary) outcrops in NW Jordan (For more details see Plate 4: the Geological Map of the study area at a scale of 1:50,000).

2.1.1.6.5 **Shagur Formation (SHC)** (Late Pliocene – Early Pleistocene)

The Shagur Formation (BENDER, 1974a) in the study area is restricted to one outcrop overlying older rocks of Triassic age (Plate 4). It crops out at about 3 km southeast of Al Kafrain (in Wadi Abu Qaraf) (Plate 1).

The Shagur Formation consists of gravels and boulders (up to 1 m in diameter) intercalated with clays and marl, with 25 m thickness in the study area.

2.1.1.6.6 **Ghor El Katar Formation** (Middle Pleistocene)

Ghor El Katar Formation is restricted to one outcrop about 1 km^2 in area, at Grain Sabt 30 km north of the Dead Sea (Plate 4). This is a small domal uplift with an intrusive basalt core (DANIEL, 1963; BENDER, 1968a & b).

This Formation was subdivided by WETZEL & MORTON (1959) and Daniel (1963). It consists of alteration and repetition of conglomerate, sandstone, siltstone and limestone with white-cream, red and grey colors (DANIEL, 1963; ABED, 1985).

The Formation is about 350 m thick (WETZEL & MORTON, 1959). Its base does not cropping out in the study area and the top is marked by an angular and erosional unconformity, conglomerates carrying some basalt bebble; pass up into typical Lisan Marl overlying the unconformity surface of Ghor El Katar.

2.1.1.6.7 **Ghor El Katar Basalt** (Middle Pleistocene)

The Ghor El Katar basalt occurs in the area where Ghor El Katar Conglomerate Formation outcrops. This basalt was assigned a middle Pleistocene age (BENDER, 1968a & b) consisting mainly of alkali olivine basalts derived from the upper mantle (SAFARINI et al., 1989).

2.1.1.6.8 **Lisan Marl Formation (LM)** (Middle to Late Pleistocene)

The Lisan Marl Formation (named by LARTET, 1869) dominates the surface, along both sides of the Jordan River. It is equivalent to the Lisan Series of BURDON (1959b), and Samra facies of the Lisan beds (BENDER, 1974a). The NRA 1:50,000 Geological mapping Project used PICARD (1943) classification and divided the Lisan Marl Formation into three main lithofacies; marl (LM), beach rock (LMb) and gravel (LMg) (Plate 4).

The Lisan Marl Formation rests unconformably on the older Mesozoic and Cenozoic sediments, and in the central Jordan Valley the Formation is overlain by the Damya Siltstone Formation. It consists of laminated and varved lacustrine marls with evaporites residues and some sandstone and mudstone beds. The exposed thickness of this Formation in Central Jordan Valley is about 30 m.

2.1.1.6.9 **Damya Siltstone Formation (DA)** (Upper Pleistocene)

The Damya Siltstone Formation (named by ABED, 1985) crops out in the central Jordan Valley area (Plate 4). It consists of red-brown thin to medium bedded silty limestone to calcareous mudstone (ABED, 1985).

The Formation has a maximum thickness of 14 m in Damya area (Plate 4) where it is well developed (ABED, 1985). From Damya area the thickness decreases to about 9 m southwards and to 1 m northwards until it reaches about 0.5 m near el Mashare (north) and in Sweimeh area (south). The formation also decreases in thickness eastwards to vanish completely near the foot of the eastern mountains.

2.1.1.7 **Superficial Deposits** (Quaternary)

The Superficial Deposits (Pleistocene to Recent Sediments) form a good aquifer containing fresh and brakish water. The main locations of the Superficial Deposits are shown in (Figure 2.9).These deposits are differentiated in the study area into:

2.1.1.7.1 **Fluviatile and Lacustrine Gravels (Pl/Plg)** (Pleistocene)

Pleistocene sediment (Pl) and Pleistocene gravels (Plg) comprise coarse-grained sand and gravels of different lithologies present above the modern day drainage levels in the study area. The gravels are mostly unconsolidated and composed of sub-angular to sub rounded pebbles and cobbles of chert, limestone, dolomite, dolomitic limestone, sandstone and basalt.

2.1.1.7.2 **Alluvial (Al); Alluvial Gravel (Alg); Alluvial Fans (Alf)**

Holocene to Recent alluvium and wadi sediments are being deposited and reworked by the present-day drainage. Extended recent alluvial fans are wide spread at the mouth of the tributary wadis (side wadis) of the margin of the Jordan Valley. They consist of rounded to subrounded, variably sorted clasts in a sandy matrix (Plate 4).

The locations of a few alluvial fans in the study area were delineated in the analyzed aerial photographs at a scale of 1:30,000 (for more details see section 2.3). The locations of these fans are shown in Figure (2.21).

2.1.1.7.3 **Calcrete (ct)**

Superficial Calcrete crusts up to 2 m characterize considerable areas in the highlands of the study area. They are mainly developed on the northeastern part of the study area (Plate 4) as shown in the geological cross section FF´ (Plate 5). They develop as surface cementation of carbonaceous material in the areas of high seasonal rainfall.

Also it is mostly developed on the top of Jurassic and Kurnub rocks south of the Zarqa River as shown in the geological cross sections CC´ (Plate 5). The Calcrete consists mainly of limy material, with chert filling pores (caused by surface evaporation of upward migrating carbonate water).

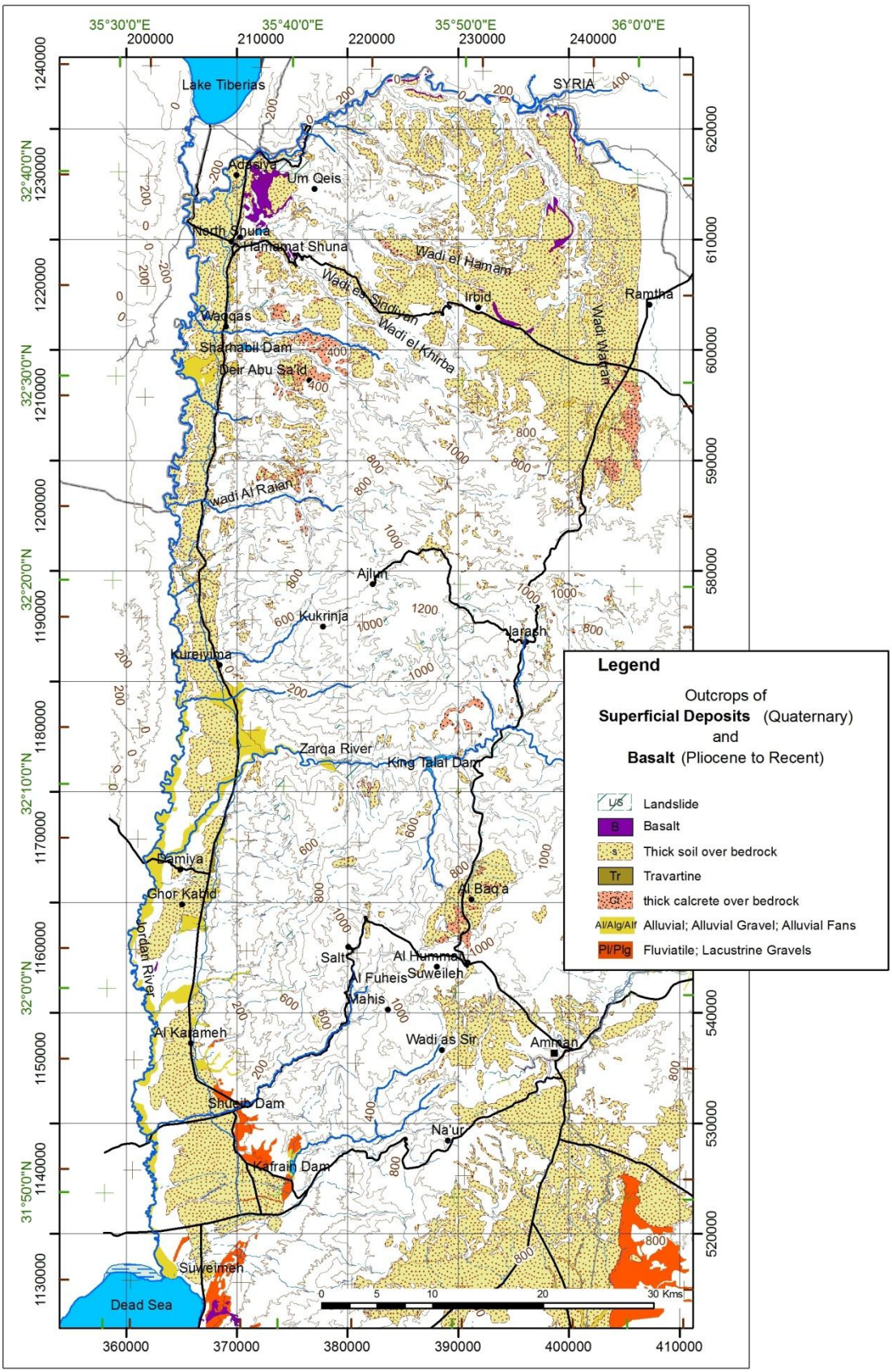


Figure 2.9: Location map of the superficial deposits sediments (Quaternary) and the Basalts (Pliocene to recent) outcrops in NW Jordan (For more details see Plate 4: the Geological Map of the study area at a scale of 1:50,000).

2.1.1.7.4 Travertine (Tr)

Travertine is a rock resulting from the precipitation of carbonate of hot spring water (Plate 4). It forms thick and thin covers in the downstream areas of the hot springs and/or as transported isolated block away from the original location. BENDER (1974a) stated that the Travertine is of Pleistocene age. Mainly, however they are formed also recently.

2.1.1.7.5 Soil (s)

The study area is covered with red, pale brown to yellowish–brown Quaternary soil of various thicknesses. Patches of soil cover the topographic lows and the pediment slopes, in some places together with calcrete (Plate 4). According to BENDER (1974a) four soil groups can be distinguished in Jordan:

1. **Grey desert soils (Siersem)**, formed under arid areas (<150 mm precipitation/yr).

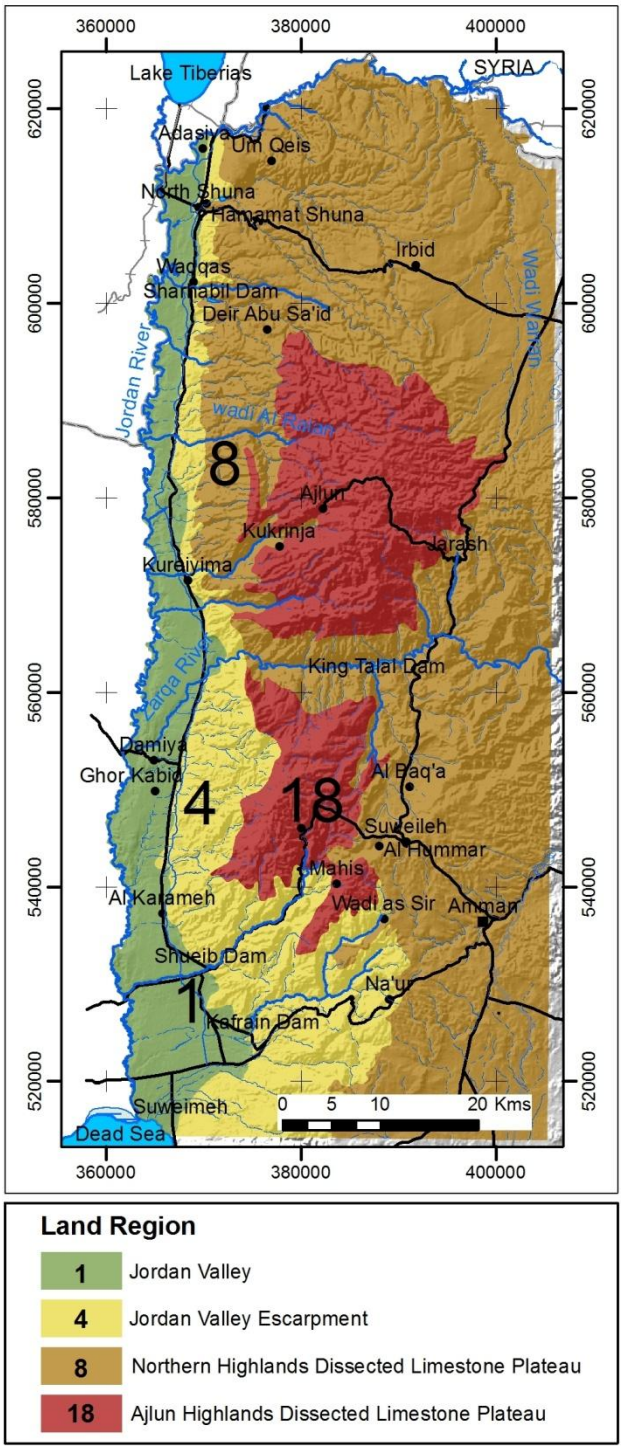
2. **Red Mediterranean soils**, formed under sub humid environment (>600 mm precipitation/ year). and under semi arid conditions (precipitation between 300 mm/yr to 600 mm/ year)

3. **Yellow steppe soils**, formed under semi arid conditions (precipitation between 150 - 300 mm/ year).

4. **Yellow Mediterranean soils** (transitional type of soil between the red Mediterranean soils and the yellow steppe soils), formed under semi arid climate conditions (250 - 350 mm precipitation /year).

An overview of the types of soil present in the study area shall be given here and has been extracted from a Reconnaissance Soil Survey within the National Soil Map and Land Use Project conducted by the Jordan Ministry of Agriculture in 1993-1994 (MOA, 1993). USDA soil classification (USDS, 1975) was used, but the report contains some descriptions which are used here to correlate the soil types to the World Reference Base of soil resources (WRB/ FAO, 1998). Kuntz compiled a 1:50,000 soil map for the Wadi Shueib catchment (KUNTZ, 1993), and reports on the difficulties, due to "great variation over comparatively small distances, due to the high relief in the area". Just the predominating soil types are indicated here for the four main land regions in the study area (Figure 2.10) defined by MOA (1993).

The main relevant drivers for soil development are climate, parent material and morphology (MOA, 1993). In arid climates, shallow soils prevail, occasionally deeper soils develop where favored by morphological position, e.g. on the foot of colluvial deposits. Parent material for the soils in the Jordan Valley is mostly carbonate rich source rock as limestone. Climate makes a difference for example between cambisols or calcisols (KUNTZ, 2003) as it is determines the degree of $CaCO_3$-leaching. Human influence plays a role for the wide distribution of irrigation agriculture which creates an artificial Ap horizon and changes the soil water regime.



Region 1 - Jordan Valley: The predominating soil type is Camborthids (51%), especially present on the extensive alluvial fans. In USDA Soil classification these are part of aridisols (dry conditions, with sufficient age for subsoil weathering, little leaching due to low precipitation, accumulation. of minerals or salt). Cambic means, they have a pedogenic alteration horizon, but no argillic/argic horizon (USDA, 1975) (→Cambisol, WRB). Orthids show little or no textural change with depth. They are highly calcareous but in study region with no reported calcic/gypsic horizon (limited leaching, recent/subrecent alluvium). The **camborthids** on the alluvial fans are described as fine-loamy to fine-silty, depth varying depending on the morphology, and well drained. They have low organic matter, but in large extensions (40% of Region 1) they show a darker anthropic A horizon with higher OM, formed by long periods of irrigation agriculture.

Figure 2.10: Land region in NW of Jordan (MOA, 1993).

Region 4 – Valley Escarpment: The escarpment shows a complex distribution of temperature and moisture regimes, depending on altitude, latitude, slope and exposition (north/ south). Therefore, soil type variations could not be matched by the broad scale of the survey (MOA, 1993). As can be expected from there geomorphologically unstable position on the slopes, shallow, poorly developed soils are reported for this region (Xerochrepts, Xerorthents, Aridisols), but also deep Xerochrepts could be found. The texture is fine-loamy to clayey, calcic layers/concretions are common and erosion increases towards the upper (steeper) part of the escarpment (MOA, 1993).

Region 8 – Northern Highlands Dissected Limestone Plateaus: The plateau is very heavily dissected towards the west the steep wadis and more undulated in the centre and east where the calcareous rocks of the Belqa and Ajlun groups may be buried by Quaternary alluvial material. Therefore, the plateaus contain a wide range of soil types, but Xerochrepts prevail in 61% of the area (MOA, 1993). Soils are calcareous, calcium carbonate content decreases from the east (calcixerollic, calcic horizon > 15 cm thick) to the west, as leaching is increased by rainfall. Lithic soils are present in 22% of the region, mainly on eroded steep slopes and hill tops. Clay content is higher than in the other 2 regions.

Region 18 – Ajlun Highlands Dissected Limestone Plateaus: This is the highest plateau in the area (generally > 1000 m), very deeply dissected by wadis. Rock outcrops (Limestones of Ajlun and Belqa Groups) occur at the crests and ridges, often showing karstic features. Shallow colluvial material is present at the steep slopes; valleys contain colluvium and alluvial deposits. Lithic soils (leptosols, WRB) prevail on the slopes, with stony and silty clays. Together with rock outcrops they comprise around 60% of the whole region. The dominant deeper soil type are Xerochrepts (slight to moderate alteration, no argic horizon, yellowish-red and brown clays), which are weakly to non-calcareous due to annual rainfall exceeding 500 mm. They are the most important soils for agriculture (MOA, 1993).

2.1.1.7.6 Basalt (B)

Basalts and tuff (Pliocene to Recent) of different types form an essential feature in the northern parts of the study area (Plate 4). They either mantle the Plateau or fill wadi courses.

Generally, Basalts are found in various parts of Jordan, especially along the eastern margin of the Dead Sea, at the rims of and on the plateaus facing the Yarmouk Valley and in the lower Wadi el Arab, in the subsurface of the Jordan Valley and in the vast Harrat Ash-Shaam Basaltic province north and east of Azraq. All those basalts are associated with the formation of the Red Sea–Dead Sea Jordan Rift and the relative northward movement of the eastern (Arabian Plate) that governed the area from (?Upper Eocene) to Recent time (MARGANE et al., 2002).

The Tertiary-Quaternary continental basalt flows and tuffs cover approximately 11,414 km^2 in central northeast Jordan. They are considered as part of the North Arabian Plateau Basalt province, which stretches over about 700 km in a NW-SE direction along the eastern margin of Wadi Sirhan tectonic depression (Figure 2.11). They extend from the southern rim of the Damascus Basin in Syria across Jordan into Saudi Arabia covering a total area of about 45.000 km^2. The Hauran - Jabel Arab-Druz - Harrat Ash - Shaam Basaltic Plateau is considered as "the greatest volcanic region in the Near East" (DE VAUMAS, 1961). It follows in a NW–SE direction (330°), the "Erythrean" tectonic trend (SHALEM, 1954) Parallel to the Red Sea and Wadi Sirhan.

VAN DEN BOOM & SAWWAN (1966) studied in detail the Jordanian portion of the Arabian plateau basalts. Their work was part of the German Geological Mission studies of the geology of Jordan. They concluded that six different basalt flows could be distinguished based on field observations and information from shallow boreholes, by using aerial photographs which were available at a scale of 1:60 000. A subdivision of the Jordanian basalts has been made by them as follows: Basalt flow (B6); Tuff volcanoes (B´T); Upper basalt sheet (B5) and Lower basalt sheet (B4).

The investigation of the basalts of Jordan by BARBERI et al. (1980) dated the volcanic activity from early Miocene to Holocene with lulls within the Miocene–Pliocene, although this investigation related all the volcanism to the Dead Sea shear, including even Harrat Ash-Sham Plateau of northeast Jordan.

Recent studies by the Jordan Natural Resources Authority (IBRAHIM, 1993) have classified the exposed basalts as one super-group, named the Harrat Ash-Shaam Basaltic Super - Group. The super - group is classified into five groups; known as the Bishriyya (10.5-9.4 Ma), Rimah (9.3-8.5 Ma), Asfar (3.4-2 Ma), Safawi (2.9-2 Ma) and Wisad less than 2 Ma). Most of the extrusives are flows of olivine basalt with thicknesses of up to around 10 m. Intercalations of tuff scoria and clay beds occur to a minor degree.

In the study area, a small outcrop of basalt is exposed in the eastern part of the Zarqa River (Plate 4) and in the area of the Yarmouk River; a few terraces of basalt remains, 100-200m above the present river. All the basalts extrusions on the eastern margin of the Red Sea–Dead Sea–Jordan Rift according to BENDER (1974a) are possibly of Pleistocene age. The youngest are those associated with the Yarmouk River Valley, and are approximately 60,000 years old.

Figure (2.11a) shows the main tectonic features of the western part of the Arabian Plate (after LUNINA et al., 2005) and Figure (2.11b) shows the Hauran–Jabel Druz–Harrat Ash-Shaam Basaltic Plateau and Regional location (modified from NRA open files) and showing simplified structural features of Jordan (compiled from NRA files; ATALLAH, 1992b; HOROWITZ, 2001).

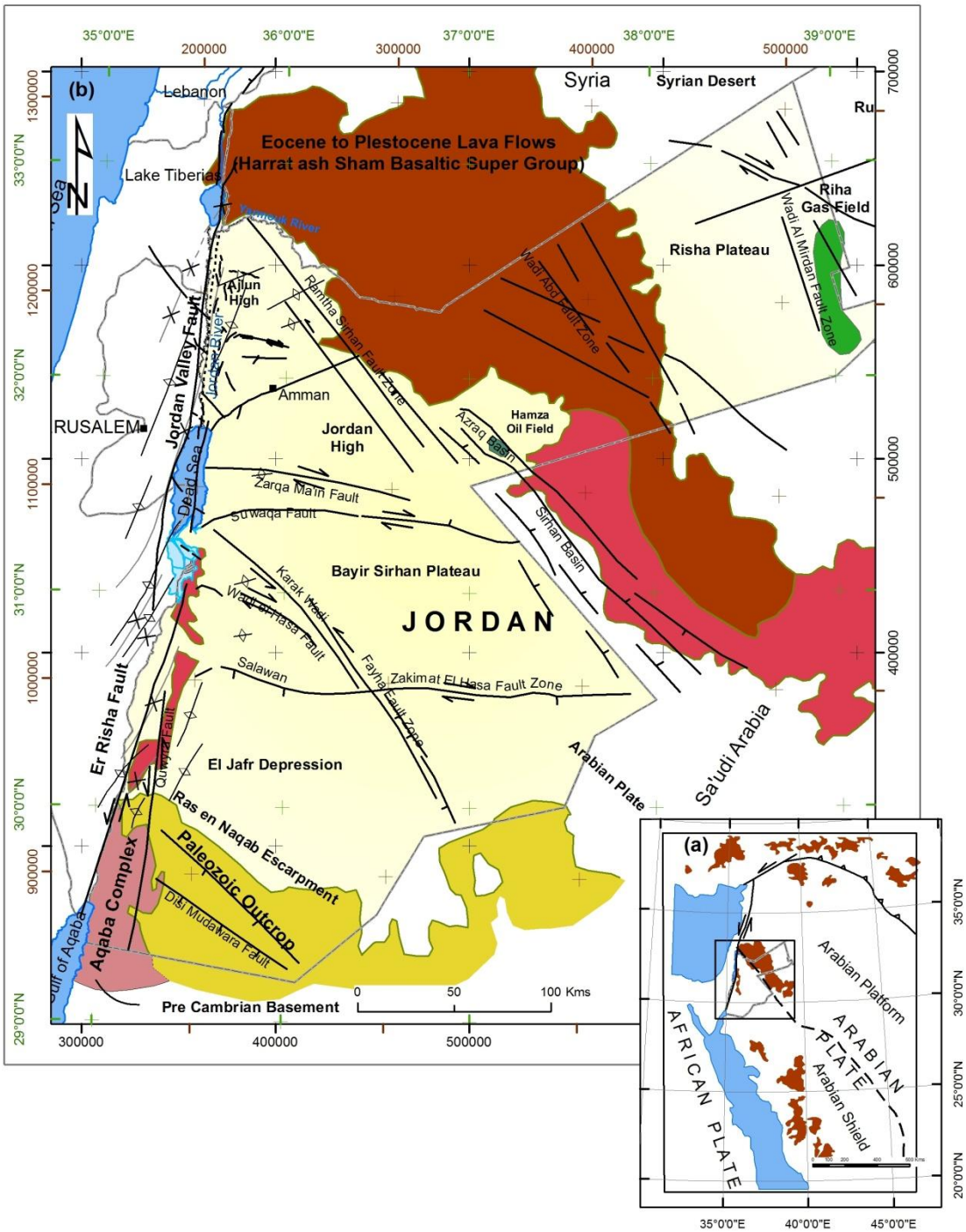


Figure 2.11: (a) A simplified map showing the main tectonic features of the western part of the Arabian Plate (b) The Hauran–Jabel Arab-Druz–Harrat Ash-Shaam Basaltic Plateau and Regional location and showing simplified structural features of Jordan.

2.2 Structural Setting

Jordan is structurally affected by the formation of the Dead Sea Rift (DSR) or also called the Levant[1] Rift, which is the most prominent geological and geomorphological feature in the Middle East (QUENNELL, 1956b; BENDER, 1968b; LOVELOCK, 1984). As part of the Arabian-Nubian Shield the underground of Jordan received its initial structural stamping (character) in connection with the different Precambrian orogenies. Throughout the later geologic history of this area with its characteristic framework of tectonic development various structural features reveal the effect of different phases of deformation since Cambrian (BENDER, 1968b; 1974a). These structural features can be predominantly described as features partly reactivated structures of the Precambrian and traced through the Paleozoic and Mesozoic sequence as well as new deformation patterns according the changing stress field. They are related to the:

1. The opening and closure of the Mesozoic Mediterranean basin formation trending WNW during Triassic till Cretaceous period (FLEXER et al., 1984; HOROWITZ, 2001).

2. The opening of the Red Sea due to an extensional stress pattern with low angle sinistral shear fault trending NNW-SSE (Red Sea-Gulf of Suez stage) causing the separation of the African and Arabian plate in Late Eocene-Lower Miocene (VOGGENREITER & HÖTZL, 1989; BAYER et al., 1988).

3. The formation of the Dead Sea Rift as a left lateral strike slip displacement along the N-S trending transform fault (Upper Miocene-Recent) due to the deformation pattern caused by the ocean rifting in the Gulf of Aden (BAYER, 1988; GARFUNKEL & BEN-AVRAHAM, 1996).

The crustal movements that affected the country have resulted in gentle, regional shifting, tilting, uplifts and subsidences in combination of faulting and folding.

The DSR overall outline was discussed in early regional geology (LARTERT, 1869; HULL, 1886; SUESS, 1909; BLANCKENHORN, 1914; GREGORY, 1921; QUENNELL, 1958, 1984; PICARD, 1965a, 1967; FREUND, 1965; GARFUNKEL, 1981; BAHAT & RABINOVITCH, 1983 among others). Classification and description of most of the structures associated with the Dead Sea are given by QUENNELL (1951; 1959) BURDON (1959b) and BENDER (1968b; 1974a). The geological and structural maps of Hunting Technology Services and Sir MACDONALD & Partners (1965a; 1965b, scale 1:25,000 and 1:100,000) formed the most important source of information on the area of Jordan valley and adjacent eastern area. BEICIP study (1976) concluded that the recent Mio-Pliocene tectonic movements are the most prominent tectonic feature in the NW part of Jordan. The area is criss-crossed by faults and reveals a complex structural history, linked to that of the Dead Sea Depression. BEICIP's (1981) structural study of Jordan shows the major structural features in Jordan. This map provides general information on the structural geology of the study area (Figure 2.12).

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[1] The Levant (eastern Mediterranean) is situated between two major regional tectonic units, the stable Arabo-Nubian Mussif to the south, and the Alpine orogenic belt to the north (FLEXER et al., 1984).

SAHAWNEH (1991) carried out a geological and structural study in the northeast Dead Sea area to produce geological and structural maps at a scale of 1:25,000, and different structural maps for faults, folds, lineaments and drainage basin. The study was based on field work and aerial photographic interpretation. Some of her conclusions were that, Pliocene sediments were not affected by folding, but local stress trending NE-SW. The lineaments and drainage system are structurally controlled, since they are parallel to the major structural elements.

The tectonic activities affecting the area are reflected in its topography, which consist of three distinctive and elongated topographic provinces that trend mainly north-south. The highland with an E-W width of some 20 km followed by the uplifted, step faulted margins of the Dead Sea, and then the Jordan Valley area further west (Figures 2.11 & 2.12).

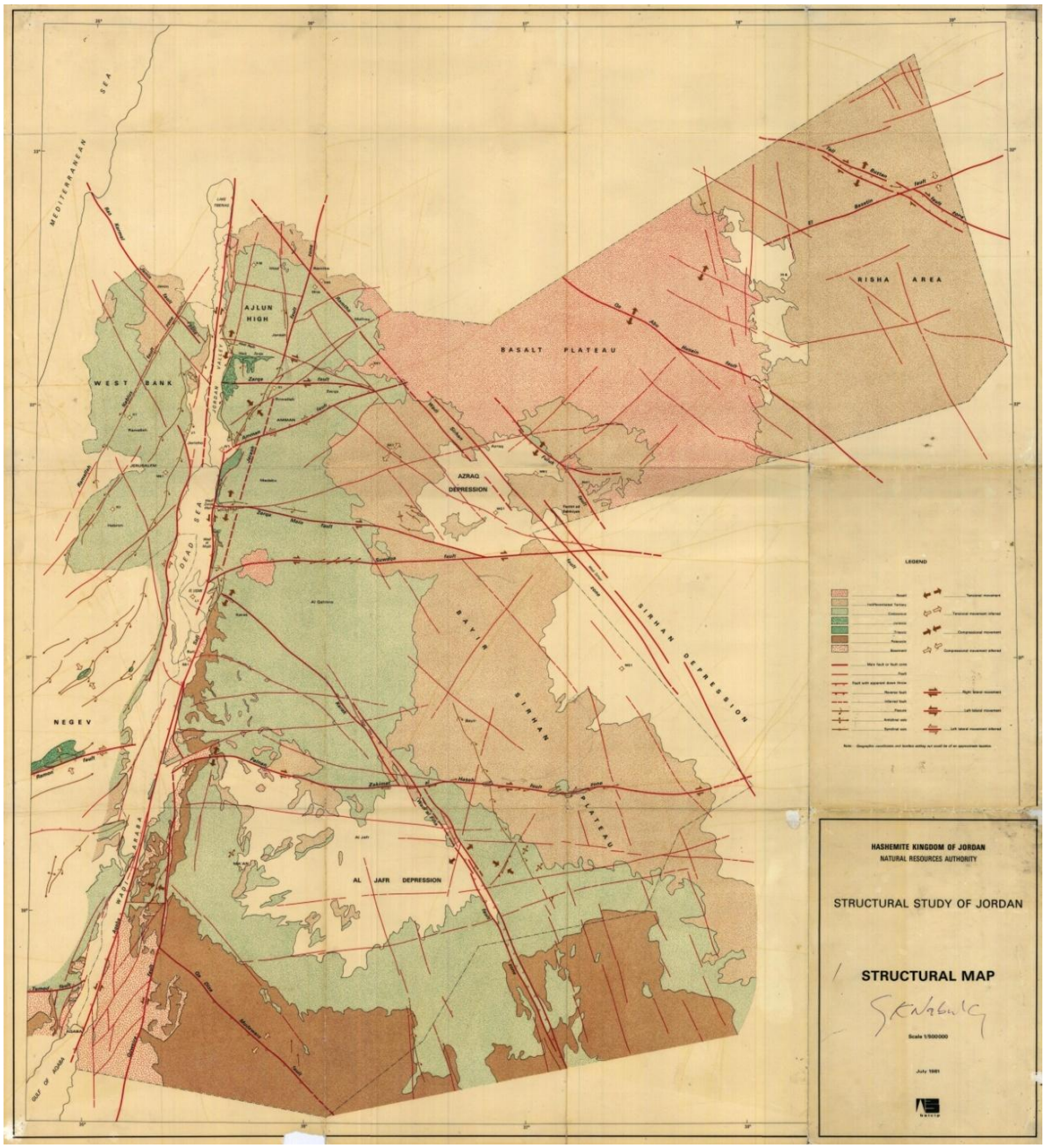


Figure 2.12: Structural map of Jordan (BEICIP, 1981).

The Post-Cambrian tectonic features in Jordan comprise three major deformational phases; namely:

1. ***The Syrian Folded Arc System***:
   The term "Syrian Folded Arc System" was introduced by KRENKEL (1924) and is distinguished by its huge "S" shape belt of folds. Ages of folding range from Turonian to Neogene (Quaternary?) (BENTOR & VROMAN, 1951; 1954; 1960; BARTOV, 1974), whereas the deformation peaks are discerned at the late Turonian-middle Campanian (FLEXER in HOROWITZ, 2001). This fold belt characterized by mainly, northeast trend, asymmetry due to the presence of basement controlled through deep seated reverse faults, and multiphase history of deformation (QUENNELL, 1959; BURDON, 1959b).

2. ***The Dead Sea Rift***:
   The DSR and its uplifted margins started to develop in the middle-late Miocene, and most of the structural development occurred in the Plio-Pleistocene. The interpretation of PICARD (1965a; 1970) concerning a connection between the DSR and the Red Sea was adopted by HOROWITZ (1979) , MART & HOROWITZ (1981) and BAYER et al. (1988) assuming originally that the area was subjected to two tectonic phases:

   2.1 ***Erythean phase:*** The age of this phase is the transition from the Eocene to Miocene. This phase was responsible for the formation of SE-NW and E-W structures in the Middle East. Examples of this tectonic phase are: the Red Sea, Wadi Sirhan depression, and the other E-W faults in East Jordan and Sinai. This phase was attributed according to QUENNELL (1951; 1959) and BURDON (1959b) to three sub phases of a clockwise rotating compressional stress systems directed successively ESE, SE and SSE, which started in the Maestrichtian (Figure 2.13). It dominated the region until Miocene (EYAL & RICHES, 1983; EYAL, 1996).

   2.2 ***Levant phase:*** This phase has been active since the Late Miocene. This phase was responsible in forming the DSR and its uplifted shoulders. In this phase, the change in trend of the northern Red Sea spreading centre from NW-SE to N-S deformed the east shoulder of the southern DSR, so that sinistral strike slip displacement occurred. The 107 km sinistral movement along the DSR which in the area runs close to the Jordan River, was accompanied with anticlockwise rotation of the Arabian plate (FREUND, 1965; FREUND et al., 1968).

Several interpretations were suggested to explain the complex Cenozoic structural development in the area and the mechanism of the DSR in order to understand the transform processes, structural development and associated phenomena related to it. The tectonic deformations along the DSR according to these interpretations were attributed mainly to N-S relative movement along the Rift (QUENNELL, 1959, FREUND, 1965) which may resulted from NE-SW tension (GARFUNKEL, 1981); E-W tension (MART & HOROWITZ, 1981; SAGY & RICHES, 2000; HOROWITZ, 2001); N-S compression (LETOUZEY & TREMOLIERES, 1980) and NNW-SSE compression and ENE-WSW tension (BAYER et al., 1988; EYAL, 1996). Due to this importance the following paragraphs includes a brief description of the DSR system in the region.

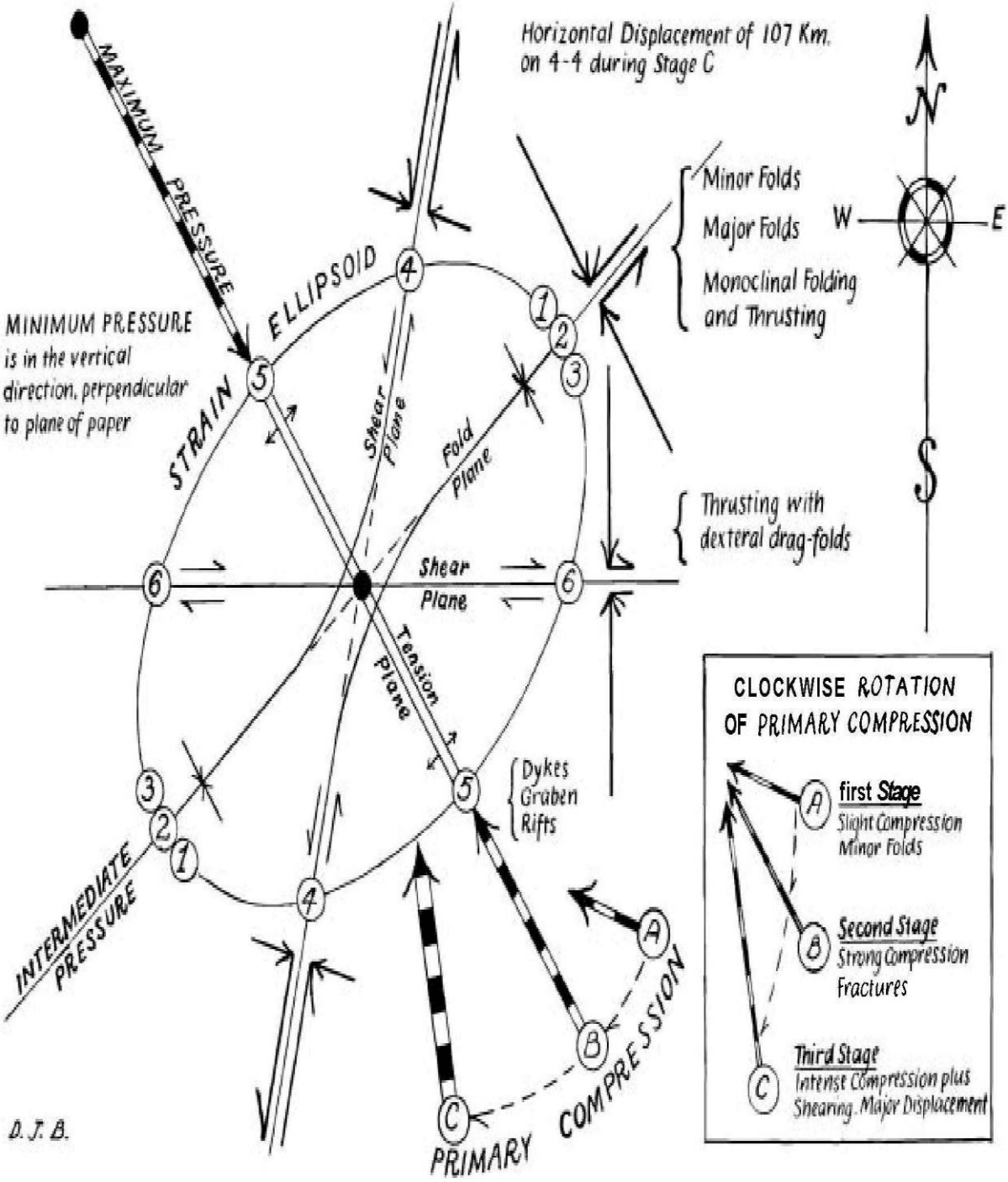


Figure 2.13: Horizontal Section through the Strain Ellipsoid for the Dead Sea Region (after BURDON, 1959b). This diagram shows the directions in which fracturing occurred (by compression on 2-2, by tension on 5-5 and by shear on 6-6) under the second (B) set of compressive forces acting from the south-east; the resultant stresses are shown by thin lines within the ellipse. The rotation of the force system in an anti-clockwise direction into position (C) caused a great intensification of the sinistral shear couple on the 4-4 plane and gave rise to the stresses shown by heavy lines outside the ellipse; these were the stresses which produced the major post-folding deformations.

2.2.1 The Dead Sea Rift system (DSR)

The DSR is the single most important complex structure in Jordan; it ranks among the famous continental transforms (WILSON, 1965; FREUND et al., 1970; GARFUNKEL, 1981) in the world (EHRHEDT et al., 2005). Its tectonic evolution attracted the attention of geo-scientists all over the world for the last 150 years, in order to elucidate its origin and nature of movement along its course, and it remains one of the most continues issues of ongoing study and discussion of the Middle East tectonics.

The DSR is a segment of the major East African–Dead Sea Rift Complex, which has been forming since the Cenozoic. This major rift system occurs as a margin of five plates; the Arabian, the Nubian, the Palestine–Sinai, the Somalian, and the Danakil. It extends from north Syria to central Mozambique, with an overall length of about 6000 km i.e. almost 1/6 of the circumference of the Earth. The northernmost extension runs through south Syria and Lebanon, the Jordan Valley, the Dead Sea, and the Gulf of Aqaba. It continues into the trough of the Red Sea and at the southern end branches into the Gulf of Aden (Afar depression), where it continues as part of the Mid-Oceanic Ridge of the Indian Ocean via the Carlsberg ridge (UEMURA & MIZUTANI, 1984). In Africa the rift continues from the Red Sea southwest across Ethiopia and south across Kenya, Tanzania, and Malawi to the lower Zambezi River valley in Mozambique. The East African–Dead Sea Rift Complex ranges in elevation from 422 m bsl in the Dead Sea to 1830 m asl in south Kenya (Figure 2.1).

The 1200 km long, N20°E direction (GARFUNKEL, 1981; GARFUNKEL et al., 1981) trending Dead Sea–Jordan Valley Rift System (DSR) is the major fault affecting the area. The Jordanian Rift portion called "Aqaba–Dad Sea–Jordan Valley Transform Fault" is a narrow, straight, and elongated feature, extending for 420 km, from the Gulf of Aqaba, via Wadi 'Araba and the Dead Sea northwards through the Jordan Valley, Lake Tiberias, Beqa'a Valley in Lebanon. It is composed of a number of transform faults trending north–northeast (Figure 2.14).

The DSR is a major wrench fault of Tertiary and Quaternary age. The ~107 km proven multi-stages sinistral (left-lateral) strike-slip shears (QUENNELL, 1958; 1959; BURDON, 1959b; FREUND, 1965; FREUND et al., 1970) has taken place since Upper Miocene (PURSER & HÖTZL, 1988; BAYER et al., 1988), minor component of extension (pull-apart basins), transpression and upwarping occur in many localities along it. This shear movement was accompanied also with a large vertical downthrown of 1.5 km towards the west (QUENNELL, 1959). A considerable difference in elevation due to this vertical movement is recognized between the west side and the east side of the rift. The west side is lower than the east side where elevations reach 1250 m asl (highlands) to 1754 m asl.

The internal structure of the transform is dominated by left stepping strike-slip fault (QUENNELL, 1958, 1959; FREUND, 1965; GARFUNKEL et al., 1981), with a deep rhomb-chasm or pull-apart basins (QUENNELL, 1958; 1959; GARFUNKEL, 1981; 1997; GIRDLER, 1990; LAZAR, et al., 2006). These pull-apart basins are result of change of main movement from one major strike faults to further westward strike slip fault if a major strike slip fault turns to the uplift (eastward) this cause transpressional deformation.

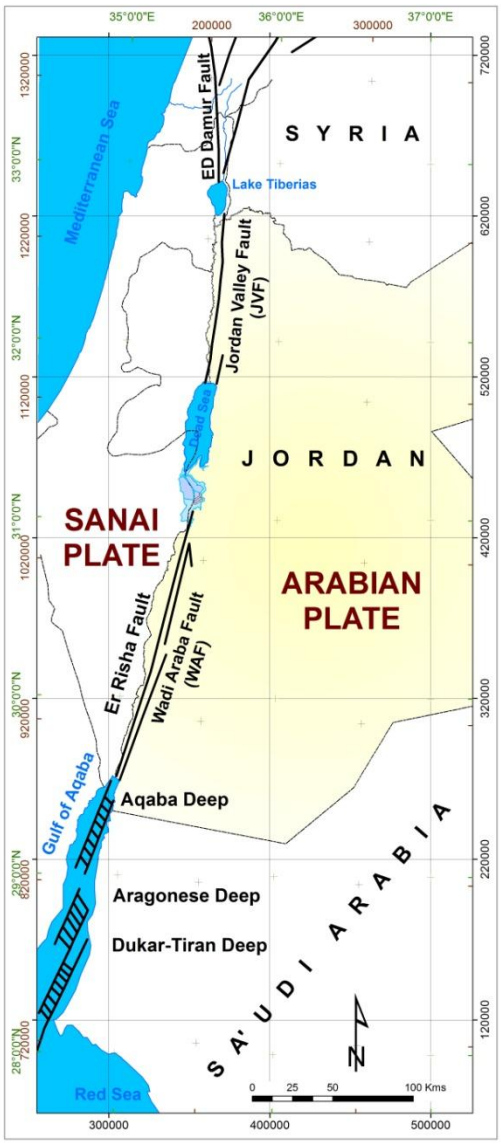


Figure 2.14: The overlapping segments of the Dead Sea Rift (modified after GIRDLER, 1990).

The Dead Sea Basin (DSB) is the lowest point on the earth which stands out by its extreme salinity of 332 g/L total dissolved solids (TDS) (ROSENTHAL et al., 2006). The DSB is divided into two parts, the northern part (the Hypersaline Lake of the Dead Sea depression itself) with a minimum bottom elevation of 720 m bsl, whereas the southern part is the sub area with a minimum elevation of 422 m bsl. (Figure 2.15). It is with the other two lakes along the Rift created suitable local conditions for the drainage of the fluids from areas along both sides of the Rift.

The evaporites are confined to the southern part of the DSB, where two salt diapirs have formed: the Sedom diapir in the southwestern side of the basin, along the Sedom fault, and the large Lisan diapir in the central part of the basin (Lisan Peninsula) (NEEV & EMERY, 1967; ZAK, 1967; BENDER, 1974a; NEEV & HALL, 1979; ABU AJAMIEH et al., 1989) (Figure 2.15 a & c). The Lisan diapir is about 20 km long and dome-shaped, and its base is about 5 km deep (BENDER, 1974a; NEEV & HALL, 1979; ABU AJAMIEH et al., 1989). More details were given concerning these evaporites by GARFUNKEL & BEN-AVRAHAM (1996); AL-ZOUBI & TEN-BRINK (2001) and AL-ZOUBI (2005).They consist mainly of halite, some gypsum, calcites, and minor amounts of potassium salts.

Evidence lines of continuous tectonic activity were described along the trace of the DSR and were proven by various workers, such as:

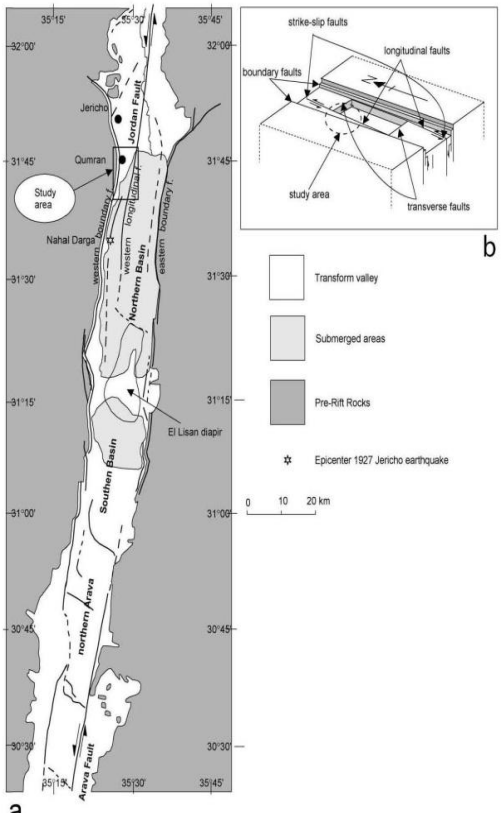
- The clear physiographical expression of faults (BOWMAN, 1994; SHTOBER-ZISU et al., 2008).

- Displacement of Late Quaternary sediments (SHAW, 1947; QUENNELL, 1956b; ZAK & FREUND, 1966; GARFUNKEL, 1970, 1981; GARFUNKEL et al., 1981; FERRY et al., 2007 among others); especially along WAF segment, which comprise the offset of alluvial fans and surface offset of streams coarses.

- Formation of pressure ridges and sag ponds basins, which occurred at various scales (GARFUNKEL et al., 1981; ZHANG, 1998; GALLI, 1999; AL-TAJ, 2000; NIEMI et al., 2001; ATALLAH et al., 2005).

- The historical seismic activity (AMBRASEYS & JAKSON, 1998; AMBRASEYS & BARAZANGI, 1989; BEN-MENAHEM, 1991; AL-TARAZI, 1999; MEGHRAOUI et al., 2003; DAËRON et al., 2005; AKYUZ et al., 2006; HEIDBACH & BEN-AVRAHAM, 2007).

Recent estimated slip rate along the DSR varies between 1 and 10 mm/year following different measurement techniques (field studies, GPS, e.g. QUENNELL, 1958; ZAK & FREUND, 1966; 1981; FREUND et al., 1970; GARFUNKEL et al., 1981; GARDOSH et al., 1990; GINAT et al., 1998; KLINGER et al., 2000; GOMEZ et al., 2003; PE'RI et al., 2002; MEGHRAOUI et al., 2003).



c

Figure 2.15:

(a) The Dead Sea Basin and its sub-basins with the main faults as compiled from different sources (redrawn after GARFUNKEL & BEN-AVRAHAM, 1996).
(b) Highly abstracted version of the internal structure of the Dead Sea Basin and related tectonic depressions along the Dead Sea transform (after LUBBERTS & BEN-AVRAHAM, 2002 redrawn after FREUND & GARFUNKEL, 1976 and GARFUNKEL, 1981).
(c) Landsat image of the Dead Sea (Hypersaline Lake) with the evaporation pans of the potash industry in the south (source: http://upload.wikimedia.org/wikipedia/commons/thumb/b/b1/Dead_Sea_1920px.jpg/260px-Dead_Sea_1920px.jpg).

2.2.2 Structures of the study area

Based on the 1:50,000 geological map of Natural Resources Authority (NRA) and the manual interpretation of aerial photographs with a scale of 1:30,000 a detailed digital structural map for the major structural features such as faults, folds, and flexures was prepared at a scale of 1:50,000 (Plate 4).

The intimate description of the major structural features within the study area is as follows (Plate 4):

2.2.2.1 Folds

Most of the folding system in the study area belongs to the Syrian Folded Arc System. These folds trends NE or ENE parallel with the reverse faults (QUENNELL, 1959). Fold structures are described also west of the Dead Sea by DE SITTER (1962) as a result of thrust faults in the basement and therefore, compressional tectonic events occurred. In NW of Jordan the fold structures are derived from the accumulation of horizontal stresses in the Transjordan block which are also documented by several directions of horizontal stylolites; the 130°-140° direction is older (Lower Tertiary) than the 170° direction (?Pleistocene-Quaternary) (SALAMEH & ZACHER, 1982). Fold in the study area can be classified as:

2.2.2.1.1 Minor Folds

Minor folds occur around Amman and Irbid in the chert-limestone-chalk of Belqa Group (Maestrichtian age) in synclinal areas and less noticeable in anticlinal areas (BURDON, 1959b). The axes of these minor folds have a strike of from 15°-20°. These folds tend to be asymmetrical, with axial plane dipping to the west (BURDON, 1959b) (Figure 2.16).

These minor folds are considered to indicate the first appearance of a general compressive stress in the region that affected from south of east (BURDON, 1959b), the direction shown as 'A' and the folding took place along the 1-1 direction in Figure (2.13).

Minor folds in Amman area was described in the Silicified limestone member (Maestrichtian age) by BENDER (1986b) and MIKBEL & ZACHER (1986). These fold structures are indicated in the eastern part of the geological cross sections BB′, EE′ & FF′ (Plate 5).

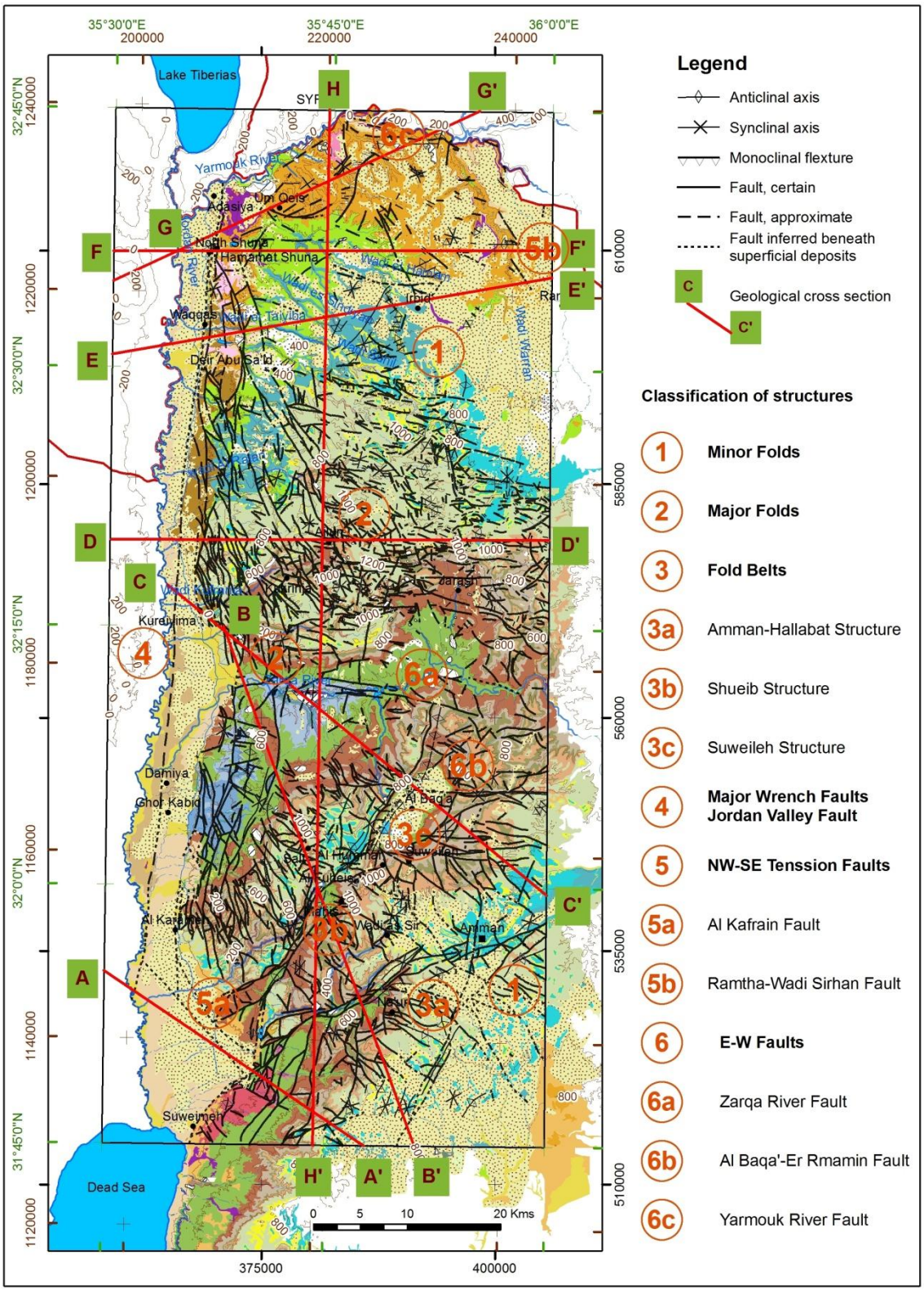


Figure 2.16: Structural pattern NW of Jordan (digitized from NRA geological maps at a scale of 1:50,000) (for more details see Plate 4).

2.2.2.1.2 Major Folds (Ajlun Structure)

Ajlun structure is one of the major fold occurs in the study area, it is described as a major structure forming part of the tectonic framework of Jordan. It is the second major tectonic feature after the Dead Sea Rift (DSR) (Figure 2.16). It is located few kilometers NE of Ajlun, with elevation reaches 1,247 m asl. Therefore, it is at present the structurally highest feature in the area. Upper Cretaceous beds are found in the top of Ajlun Structure; Jurassic and Lower Cretaceous sediments are exposed in its core in the area of Zarqa River (geological cross sections BB′, CC′ & HH′, Plate 5).

Ajlun structure was first known as Ajlun Dome (QUENNELL, 1951; 1959; BURDON, 1959b), and defined as an uplifted anticline (BILLINGS, 1972). The aerial photographic study of BEICIP (1976) delineated that it is not an anticline fold; its actual shape resulted from several deformations. These deformations produced a topographic high surrounded by many faults. Regional northward plunging towards Irbid plain is due to an E-W trending faults, downthrown to the north. To the west, the Cretaceous beds dip strongly towards the rift along N-S trending flexures. The dip may increase during the sinking of the graben. To the east and northeast, the beds are slightly dipping to the east. To the south, beds dip to the south. The deformations of the Jurassic and Lower Cretaceous sediments due to Ajlun structure are shown in the geological cross sections EE′ & HH′ (Plate 3).

The major trend of the Ajlun Structure and the wide range of rock formations involved in the deformation are shown in the detailed geological map for the Ajlun Structure (Figure 2.17) in addition to the detailed N-S trending geological cross section II′ (Figure 2.18) (Geological cross section II′ is almost the middle part of the N-S trending geological cross section HH′, Plate 5).

The formation of the Ajlun structure was related to a renewable clockwise rotation compression stress affected from the SW to NE assigned to lower Miocene (the ‘B’ direction and the axis of structure is parallel to 2-2 in Figure 2.13, BURDON, 1959b). The intensity of this stress was greater, and affected mainly the thick sediments in northern Jordan. Meanwhile, southward where sediments are less thick, some broad folding occurred (such as the fold between Wadi Zarqa Ma’in and Ghor Mazr’a) (BURDON, 1959b). Also a relief of stress was obtained in the crystalline basement by fracture. According to BURDON (1959b) these fractures comprise the compressional fracture of 3-3 axis; the concomitant tension axis 5-5 (e.g. the basalt feeder-dykes; the Wadi Sirhan graben; the Karak graben, the normal faults of Petra and Wadi Khuneizira, etc.) and the two complementary shear axes 4-4 and 6-6 (Figure 2.13, BURDON, 1959b).

This explanation by BURDON (1959b) does not fully agree with newer interpretation of the chronology of tectonic development. In context of the new interpretation first folding started in Late Cretaceous – Early Paleogene with northward till northwestward movement of the Arabian Plate and subduction in the Tethys area. In the Eocene till Lower Miocene due to a main stress component in NW-SE direction a rifting phase occurred with the formation of the Red Sea – Gulf Suez graben or the Sirhan graben system from the Upper Miocene, due to the opening of the Gulf of Aden and the northward movement of the African Plate transform movement started along the Levant Fault System.

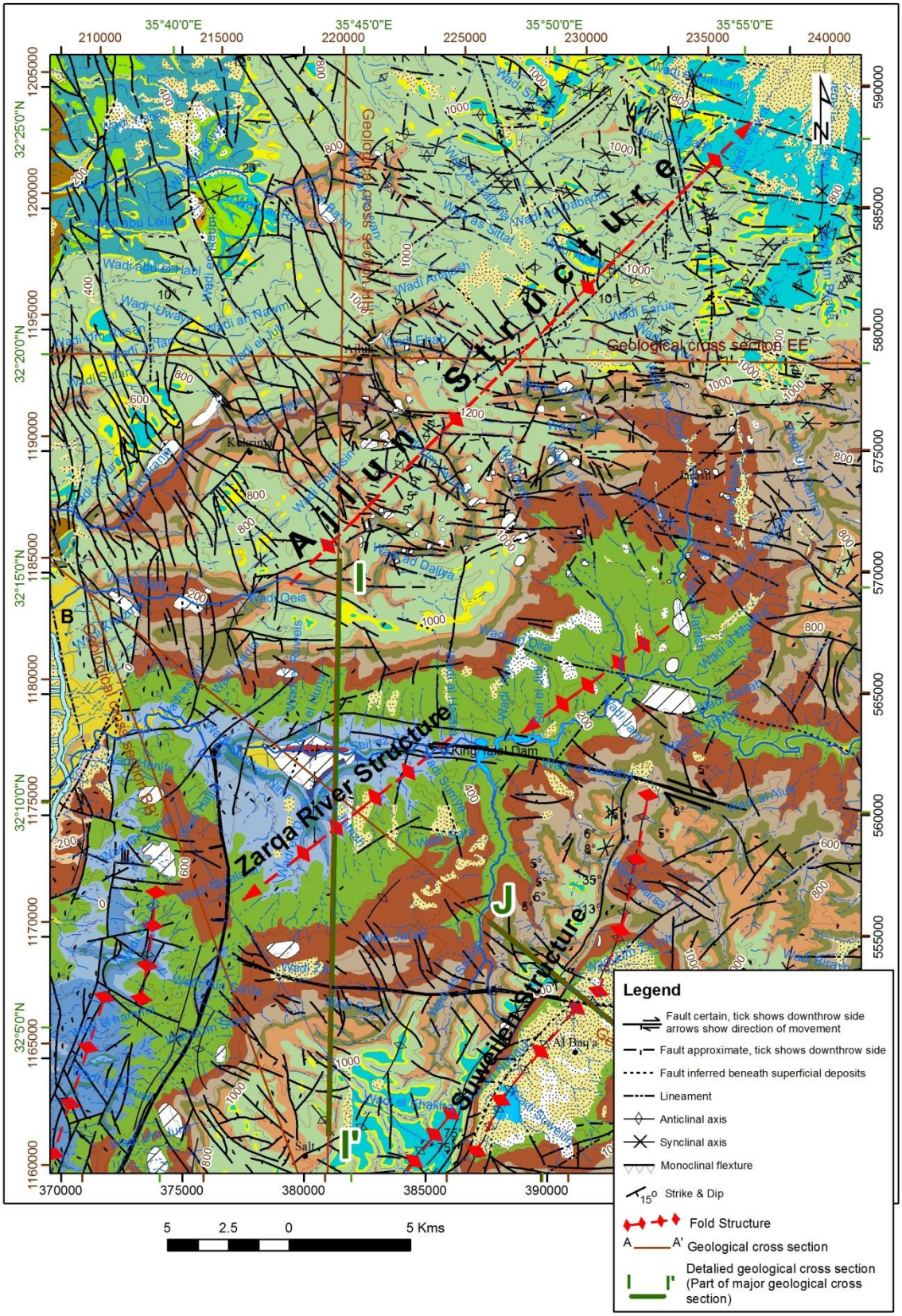


Figure 2.17: Detailed geological map showing the major NE-SW trend of the Ajlun, Zarqa River and Suweileh Structures and the wide range of rock formations involved in the deformation (for more details regarding the legend see the digital geological Map, Plate 4).

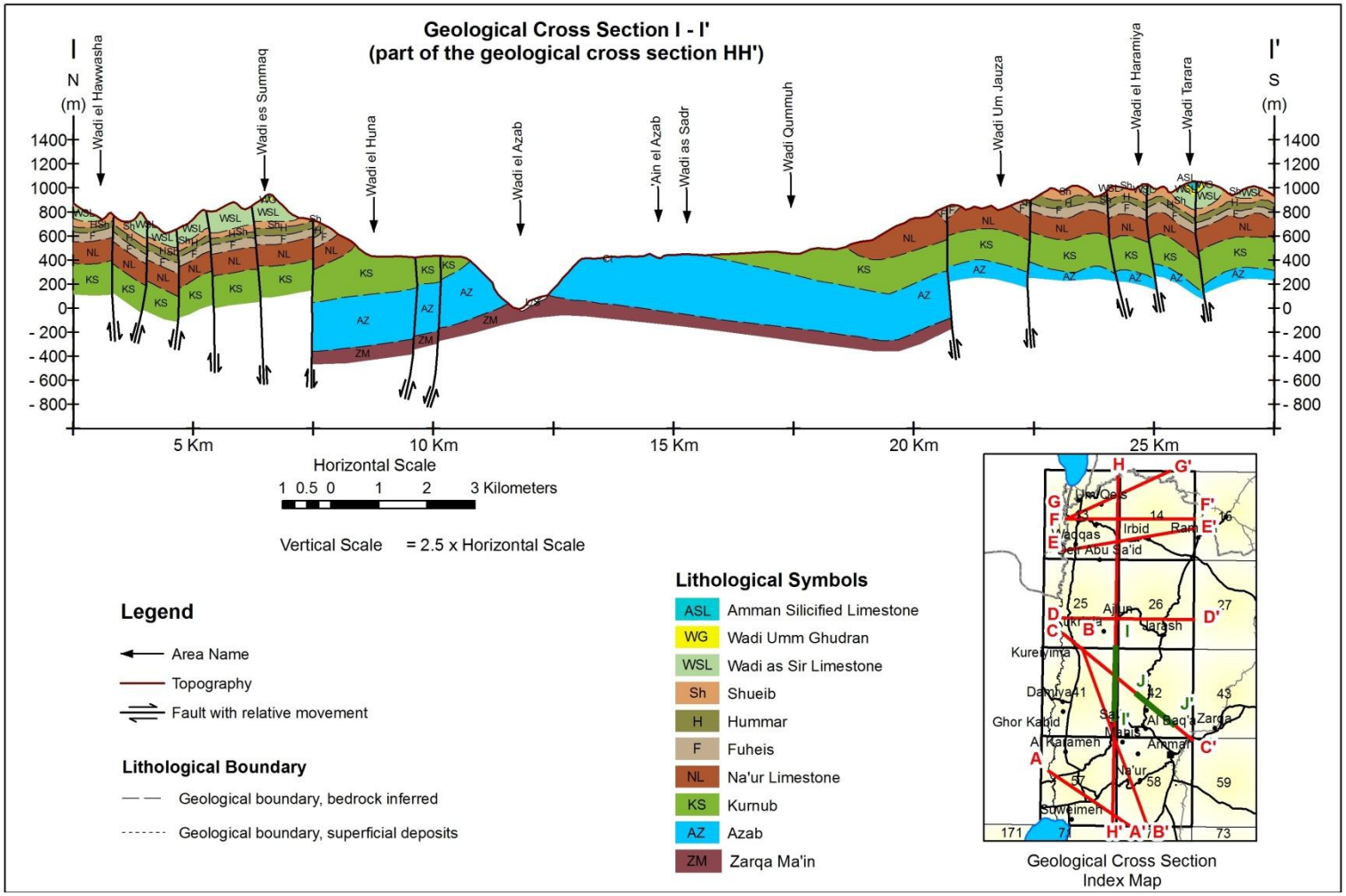


Figure 2.18: Detailed geological cross section showing the deformations of the Jurassic and Lower Cretaceous sediments due to Ajlun structure in Zarqa River area (for more details see the geological cross section HH′, Plate 5).

2.2.1.1.3 Fold Belt Structures

The term fold belts or long extended fold structures was introduced by MIKBEL & ZACHER (1986) for fold structures in Amman area and north of Ajlun that consists mostly of two or three anticlines and synclines and extended for long distance (Figure 2.16). Formerly such structures were referred to as monoclinal structures or normal faults (BURDON, 1959b; BENDER, 1968b; WIESEMANN, 1969).

In north Ajlun three folds belt were described by (ATALLAH & MIKBEL, 1992), between the Jordan Valley to the west and the basalt plateau to the east. These belts are the Halawa-al Husn belt, Ibbin-Hausha and Bal'ama-el Mafraq belt. The major trend in the folds is NE to ENE and the intensity of folding decreases away from the Dead Sea Rift area. Other major fold belt structures within the study area are the **Amman–Halabat Fold Structure**, **Wadi Shueib Structure** and **Suweileh (Al Baqa'a) Structure**.

2.2.1.1.3.1 Amman–Halabat Fold Structure

Amman–Halabat structure considered as one of the most important structural feature in the study area. The structure crosses the entire southeastern part of the study area (Figures 2.16 & 2.19). This fold belt extends for 80 km long and 1-5 km wide, from the northeastern part of the Dead Sea to Suwayma passing to the north of Al Adasiyya (Wadi Na'ur), and extending eastwards passing the southern part of Amman, Zarqa and Qasr el Halabat. This structure strikes ENE-WSW within the study area and then curved in the adjacent area to become NE-SW (Figure 2.20).

Amman-Halabat structure consists of ENE-WSW dextral strike-slip fault (as shown in geological cross section (AA′, BB′ & HH′, Plate 5) accompanied by smaller conjugated antithetic and synthetic faults and sub-parallel anticlines and synclines. Rocks of Cretaceous age are involved in this fold belt; the placement of these rocks indicated 400 m vertical displacement and NNW downthrown for the main fault within this structure.

The stress orientation affecting the several structural elements within Amman–Halabat structure seems to be the same. It is initiated with folding from lateral compression (i.e. 'C' direction in Figure 2.13) which affect from the SSE with reaction from the NNW that took place Upper Cretaceous - Paleogene and faulting in the deeper underground; resulting from the accumulation of horizontal stresses in the Arabian plate (QUENNELL, 1959; BURDON, 1959b; MIKBEL & ZACHER, 1986) and was reactivated from the Upper Miocene with transform movements.

2.2.1.1.3.2 Wadi Shueib Structure

The Shueib structure is a main structure within the study area. The name "Shueib Structure" was introduced by MIKBEL & ZACHER (1981) instead of QUENNELL's (1959) and BURDON's (1959b) "Salt flexure". It runs along the eastern flank of Wadi Shueib with approximately 25 km long and 1-4 km wide fold belt. Rocks of Cretaceous age are involved in this fold belt, deformed by post-Cretaceous tectonic activity (MIKBEL & ZACHER, 1981) (Figure 2.16).

Wadi Shueib structure is one of the offspring faults of the Dead Sea Transform Fault runs along Wadi Shueib and crosses it from the SSW to NNE. The structure consists mainly of a SSW-NNE trending basement fault, which forms along Wadi Shueib a reverse flexure. On its further extension to the NNE the flexure goes over into a monocline bending, where it is known as Suweileh Structure and pinches out south of Jarash near the Zarqa River (Figure 2.19).

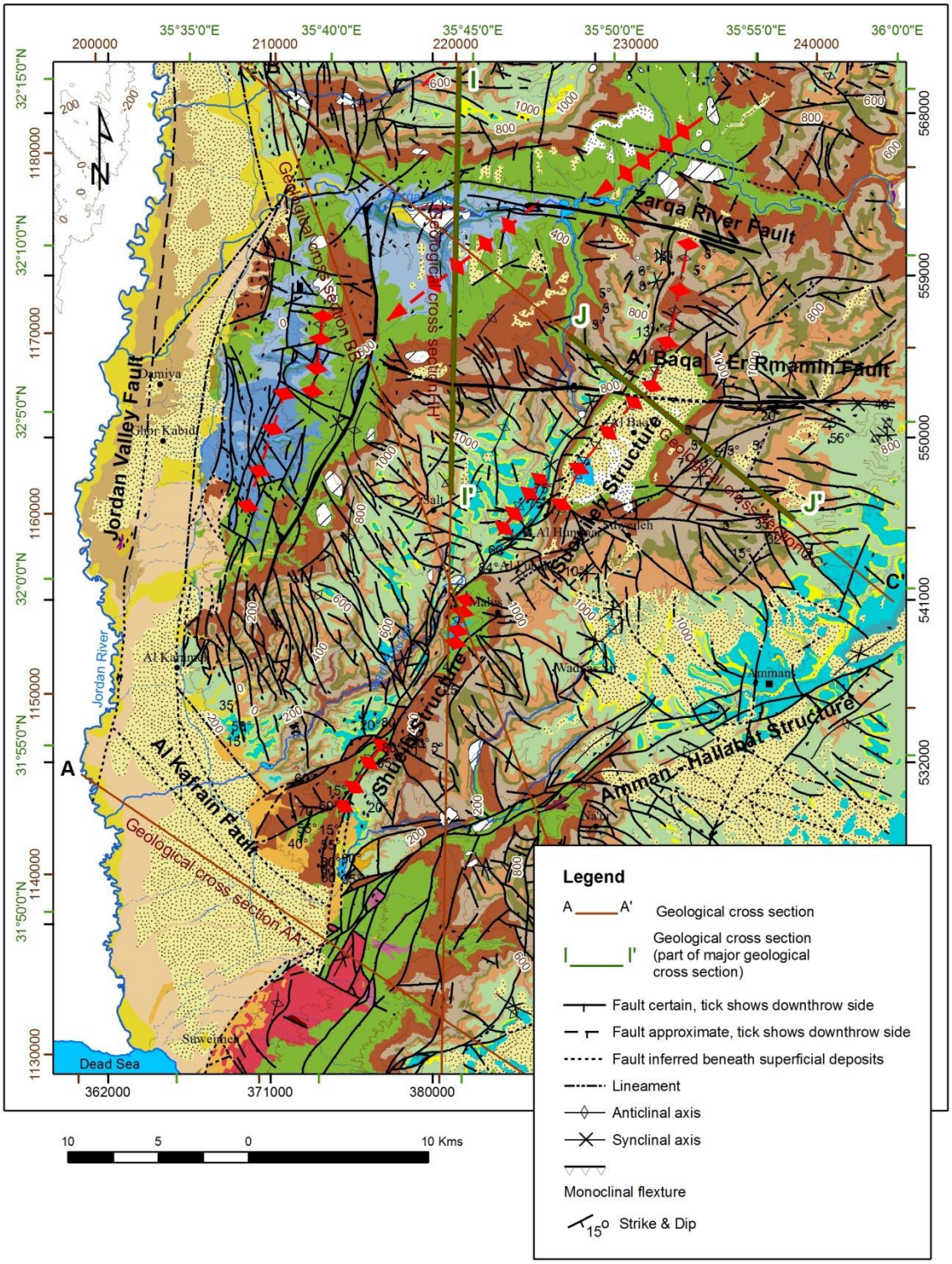


Figure 2.19: Main structural features in the southern part of the study area (digitized from NRA geological maps at a scale of 1:50,000) (for more details regarding the legend see Plate 4).

The Shueib structure starts in the Jordan Valley as a SW-NE trending reverse fault with around 500 m downthrown NW block. This structure starts to take a SSW-NNE direction along the foothills overlooking the Jordan Valley and the reverse faults turns into a reverse flexure, with a strong folding component in the top of Wadi Shueib (Figure 2.20). The rock units are here slightly overturned and highly deformed along this structure, as shown in the geological cross sections (BB′ & HH′, Plate 5). This reverse flexure crosses then the Wadi Shueib and continues further in a NNE direction, where it dies out in a Jordanian plateau in a distance of 15 km.

The initiation of the structure seems to be the SE-NW trending stress system, which produced first undulated sedimentary troughs then folds and later reverse faults. Due to clockwise rotation of the stress field which achieved a maximum stress in a SE-NW oriented direction ('C' direction in Figure 2.13, BURDON, 1959b), the vertical basement fault seems to have developed in the less competent sedimentary cover than the granitic basement underlying the area, a reverse flexure with overturned and strongly folded beds and finally extend shear movement due to return of the maximum stress direction to SSE-NNW.

The flexure along Wadi Shueib is accompanied by numerous vertical and sub vertical faults having the same trend of the flexure. Some faults strike in a NNW-SSE direction and a small number in a WNW-ESE direction. They can be considered as conjugate faults of the NE-SW and SE-NW stress fields of QUENNELL (1959).

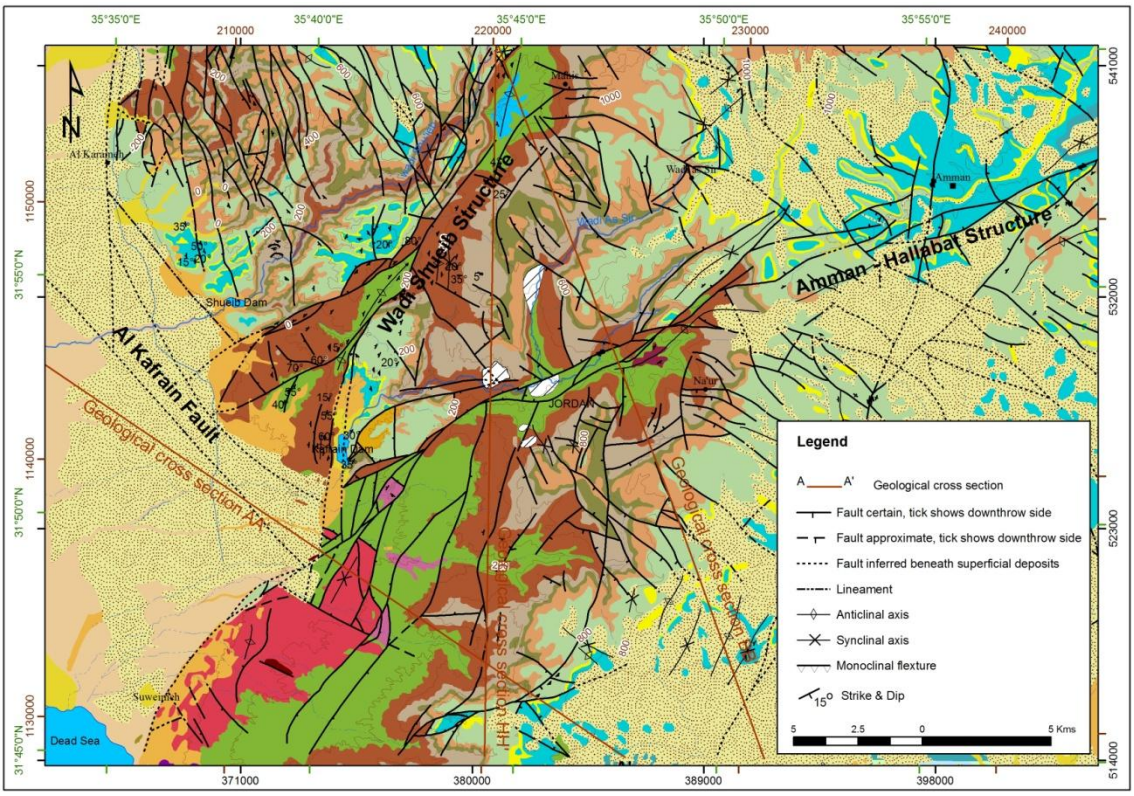


Figure 2.20: Detailed geological map of Amman-Halabat and Shueib Structures (for more details regarding the legend see Plate 4).

2.2.1.1.3.3 Suweileh (Al Baqa'a) Structure

The Suweileh structure is located about 15 km northwest of Amman. BENDER (1968a) described this structure as a SW-NE inclined block of 12 km, dipping to the SE, but later it was described as an uplifted margin of the Jordan Graben by Salameh (1980a). The structure initiated mainly from a fault near the northeast end of the Dead Sea, which is actually the same fault which Wadi Shueib structure developed along. Therefore the Suweileh structure represents the northeast extension of Wadi Shueib Structure. To the northeast of Al Baqa' area the fault gradually turns into a monocline flexture and further northward it dies out in the Jordanian Plateau.

Flexuring, folding and E-W trending faults (Figure 2.19) are the main structural features within the Suweileh structure. Jurassic and Cretaceous ages rocks are involved in this structure, as shown in the geological cross sections BB´ CC´ & HH´, Plate 5 and in Figures 2.21 & 2.22. The flexture strikes NNE-SSW with downthrown NW towards the NW block. The NW block is steeply dipping, while the SE block is gently dipping. The detailed geological map of Suweileh area done by PHILLIPS (1958) in purpose to drill an oil well (SW-1) investigated asymmetrical Suweileh anticline strikes NE-SW and plunges a few degrees in the SSW direction. Philips report related this anticline to be a deep-seated, reverse fault in the upper Cambrian rocks. Two major E-W trending faults (Zarqa River and Al Baqa'–Er Rmamin faults, (Figure 2.23) and few others are reported with some dextral strike-slip movement (SALAMEH, 1980a; BEICIP, 1981; TROLLINGER–MARCH, 1986). The initiation of the Suweileh structure seems to be similar to that of Wadi Shueib. According to BEICIP (1981) Suweileh structure is of compressional type and its microstructural analysis agrees with this result.

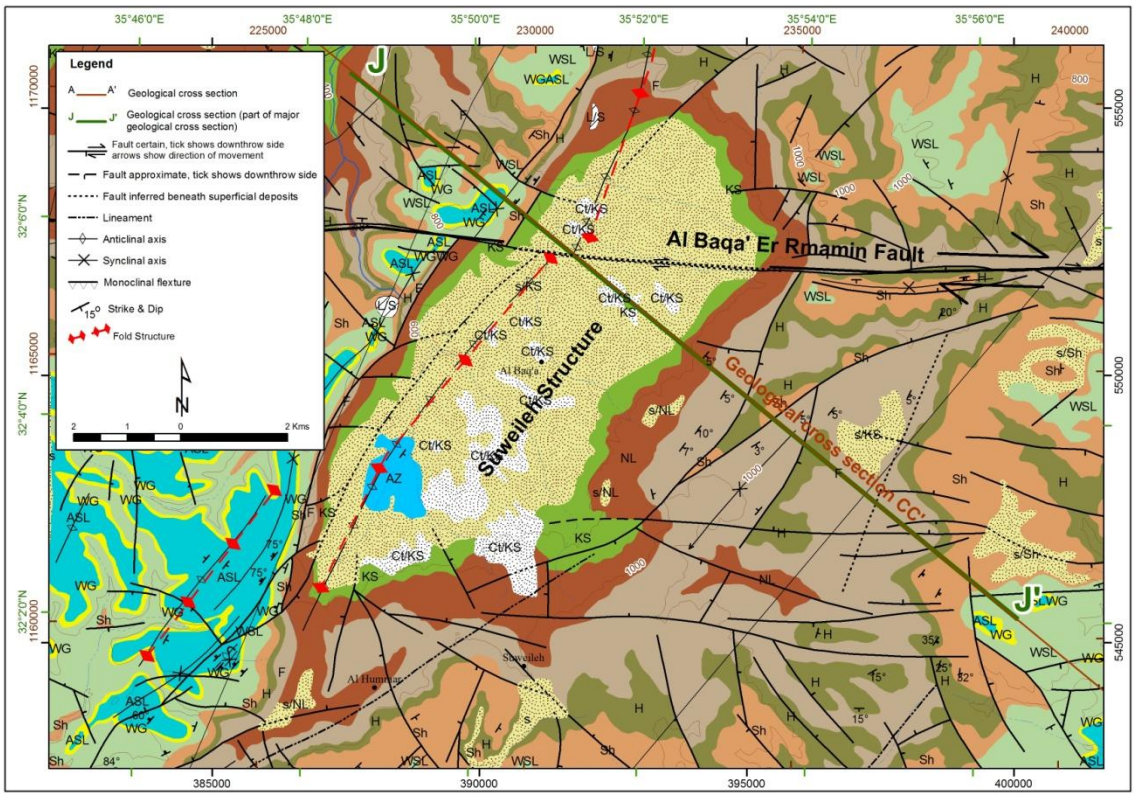


Figure 2.21: Detailed geological map of Suweileh Structure (for more details regarding the legend see Plate 4).

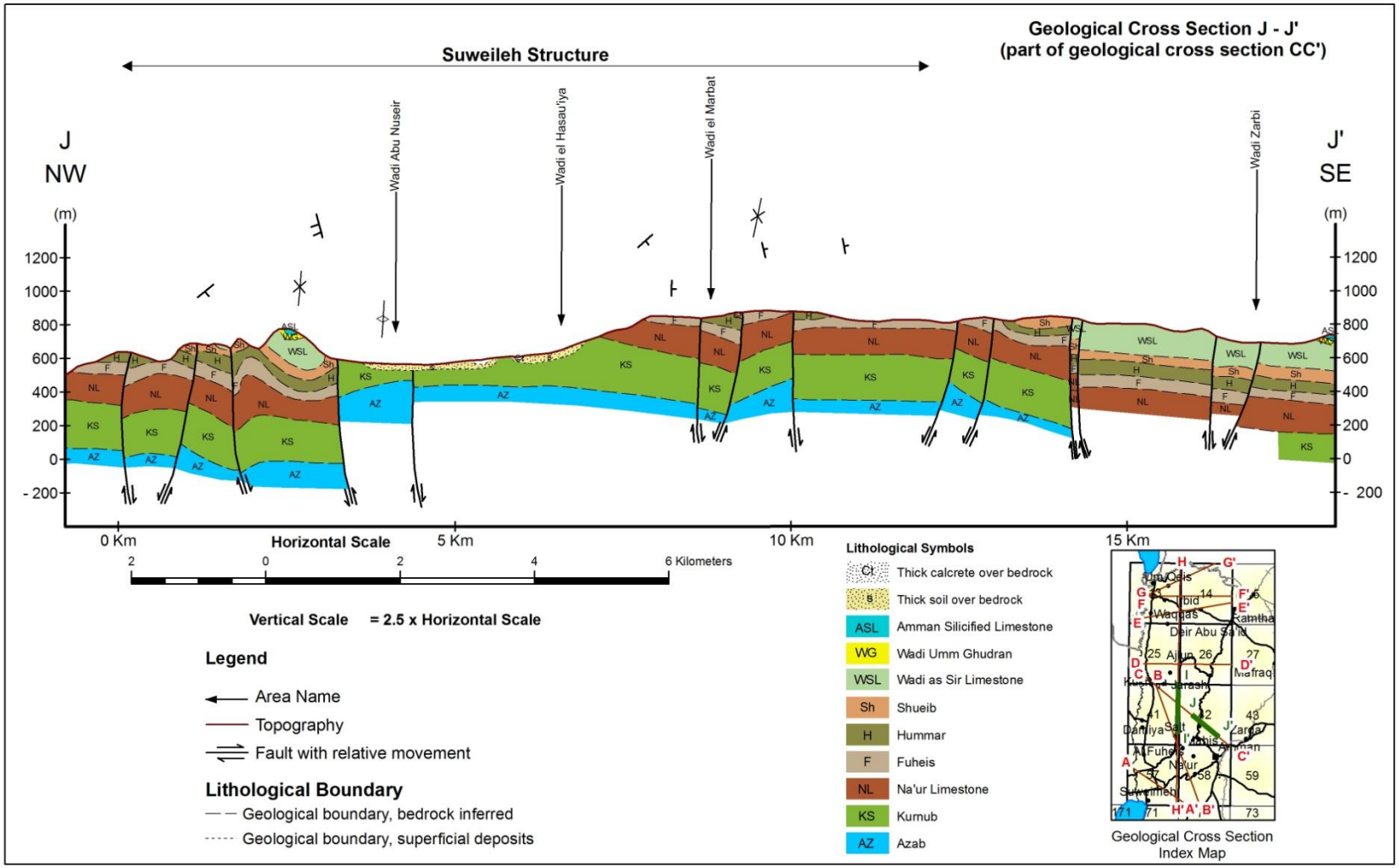


Figure 2.22: Detailed geological cross section JJ′ showing the deformations of the Jurassic and Lower Cretaceous sediments due to Suweileh Structure in Suweileh (Al Baqa'a) area (for more details see the geological cross section CC′, Plate 5).

2.2.2.2 Faults

From a general overall look to Jordan's structural maps it can be concluded that along the main escarpment towards the Jordan Valley the dominant fault trend is parallel to the rift and most of the faults are normal. The downthrown of the faults adjacent to the rift is mainly to the west. In comparison; faults on the Plateau trend NW-SE, following the direction of the major basins which formed within the Plateau (Figures 2.10 & 2.11). The majority of these faults are of low throws without a preferred direction of throw (PARKER, 1969).

Three major fault trends in the study area are believed to have originated in the Precambrian and early Paleozoic times. But due to different tectonic movement beginning since the Late Cretaceous, a different stress fields resulted, producing different fault trends from those prevailing in the pre Cretaceous times. The main faults are related to the Dead Sea stress field acting in the region since Late Miocene with a NNW-SSE maximum horizontal compressional stresses (GARFUNKEL, 1981; GARFUNKEL et al., 1981; BAYER, 1986; BAYER et al., 1988). Older faults were reactivated but with different movements and reactions to the new stress field. New fault trends were produced affecting the area as a whole, especially those areas close to the Rift Valley. Therefore, faults in the study area can be described as follows:

2.2.2.2.1 The Jordan Rift Valley and major Wrench Faults striking sub-parallel with it

The Dead Sea - Jordan Valley fault in the Jordan Valley and the Er Risha fault in the Wadi 'Araba are the main Wrench faults in the region. These two faults are not continuous, but they are crossed diagonally and overlap in the Dead Sea region (Figure 2.10). Within the study area the Dead Sea–Jordan Valley Fault runs from the western side of the Dead Sea to the eastern side of Lake Tiberias (Plate 4 & Figure 2.16). It is not well exposed at the surface due to thick sedimentary fills accumulating in it. These sediments attain 8–10 km south of the Dead Sea (KASHAI & CROKER, 1987). Therefore, the Dead Sea fault is inferred from geophysical and morphological evidence and from steep flexuring of the strata towards the west.

Major wrench faults striking sub-parallel to the Jordan Valley Fault are mostly found in a narrow zone along the Jordan Valley. These faults are longitudinal to the DSR (QUENNELL, 1959; BURDON, 1959b) and associated with some major fold structures described earlier such as Shueib and Suweileh structures (MIKBEL & ZACHER, 1981; SALAMEH, 1980a).

According to QUENNELL (1959) and BURDON (1959b) the effects of rotation of the compressional stress from SE in Lower Miocene age to SSE in Pleistocene age ('B' direction to 'C' direction in Figure 2.13) was responsible to increase the shear stresses on N-S direction (4-4 axis in Figure, 2.13), to diminish it on E-W direction (6-6 axis in Figure, 2.13), and to introduce it on NE-SW direction (3-3 axis in Figure, 2.13). Therefore the sinistral movement increased on the two main shear fault; Jordan Valley and Er Risha faults. Finally, the Dead Sea Rift (DSR) was created. But this interpretation does not agree with the new assessment of the structural deformation (see section 2.2).

2.2.2.2.2 Faults trending NW-SE

These faults are less abundant than other fault trends in the study area. They may represent old extension fractures of Precambrian age, reactivated in the Turonian as a result of the compressional stress that form the Syrian Arc Belt (QUENNELL, 1959; BURDON, 1959b). Later this fault trend was reactivated again, and crossed by an E-W trending faults that formed in Miocene (QUENNELL, 1959; BURDON, 1959b).

Examples of such faults in the study area are:

2.2.2.2.2.1 El Kafrain Fault

The main NW-SE trending fault is Al Kafrain Fault. This fault is inferred and extends from Al Mazar - Er Rama, El Kafrain to Zor Al Mundassa on the Jordan River (Plate 4 & Figure 2.16).

El Kafrain fault represents the northern limit of the Dead Sea and plays a very important role in the evolution history of the Dead Sea Basin (QUENNELL, 1959; BURDON, 1959b). This fault is shown in the geological cross section AA´ (Plate 5).

2.2.2.2.2.2 Ramtha-Wadi Sirhan Fault

The Ramtha–Wadi Sirhan Fault is a regional structure which has a limited effect in the northeastern corner of the study area. This fault system is a major NW-SE trending strike slip fault (BEICIP, 1976; 1981; MIKBEL, 1985), with length exceeds 325 km. It extends from Saudi Arabia, in the southeast; where it's further SE extension is unknown, to Lake Tiberias to the northwest; where it reaches the Dead Sea Fault System.

This fault develops along the major Wadi Sirhan–Azraq Basin which extends into the Ramtha–Mafraq area (northeast of the study area) (Figure 2.16). It is covered with Tertiary and Quaternary deposits. Along this major NW–SE trending basin, the Mesozoic sedimentary cover increases towards the NE as indicated from available gravity maps of Jordan. The thickness within the study area is recorded to be 2650 m at ER-1A oil well, where the sediment of Mesozoic rest unconformably on Lower Permian Formations, the later is known elsewhere in Jordan (TROLLINGER–MARCH, 1986).

It is believed that the basaltic flows in the northern and northwestern parts of the study area are not controlled by the N-S trending Dead Sea Jordan Rift, but it is genetically associated with the NW-SE Sirhan fault trend (5-5 axis in Figure 2.13; BURDON, 1959b).

2.2.2.2.3 Faults trending E-W

These faults are oscillating around E-W, ESE-WNW or ENE-WSW (Figure 2.16). They are the second important set of faulting in the study area because they are intimately associated with and related to the Dead Sea–Jordan Valley Fault (QUENNELL, 1959; BURDON, 1959b).

Faults with these trends are either normal, reverse or strike-slip faults. They originated in Miocene as normal faults during the formation of Traverse Fault System. Then they were reactivated in Mid Miocene-Pleistocene as strike-slip faults during the formation of the Dead Sea Transform Fault System (QUENNELL, 1959). Some of the E-W trending faults may reflect deep seated reverse faults or possibly reflect ancient tectonic lines of weakness reactivated in Tertiary and Quaternary times (BURDON, 1959b). The dextral strike-slip movement is inferred for most of the E-W striking fault zones, like the Siwaqa, the Zarqa-Ma'in and the Zarqa fault (BEICIP, 1976). Also, along some of the E-W trending faults the strike-slip movement is recognized with considerable downthrown (BEICIP, 1976). Due to that it is well recognized in the central and southern parts of the study area that the Triassic rocks are exposed against the Cretaceous sediments as shown in geological cross section (AA′, Plate 5) as well as in geological cross prepared by SAHAWNEH (1991) and SAHAWNEH & ATALLAH (2002).

The E-W trending fault system throughout the study area is responsible for the presence and controls the major wadis with the same trend, and frequently accompanied with extensive land-sliding (Plate 4). The Zarqa River Fault and Yarmouk River Fault are good examples for that.

2.2.2.2.3.1 Zarqa River Fault

The E-W trending Zarqa River Fault is some 60 km long (BEICIP, 1981). It is a wrench type fault with some indication of a dextral strike-slip movement along it (KHALIL & MUNEIZEL, 1998).

The Zarqa River Fault is not well traceable in the central part of the study area, due to nature of both sandstone beds which are exposed on the both sides of the fault (KHALIL & MUNEIZEL, 1998) (Figures 2.16 & 2. 22).

The Zarqa River Fault possibly accompanies pre-Cretaceous anticline as shown in geological cross sections (CC′ & HH′, Plate 5), which is an inferred anticline trending N-S in the Zarqa River vicinity with northward plunging where it truncates the southwestern part of the Suweileh structure (BEICIP, 1981).

2.2.2.2.3.2 Al Baqa'-Er Rmamin Fault

Al Baqa'–Er Rmamin Fault is another E-W trending fault sub-parallel to the Zarqa River Fault (Figures 2.16 & 2. 22). Dextral strike-slip movements are recognized along this fault with variable downthrows. It also, as well as the Zarqa Rive Fault, truncates the Suweileh structure but from its northeastern extension (SALAMEH, 1980a); as shown in geological cross sections (CC′, Plate 5).

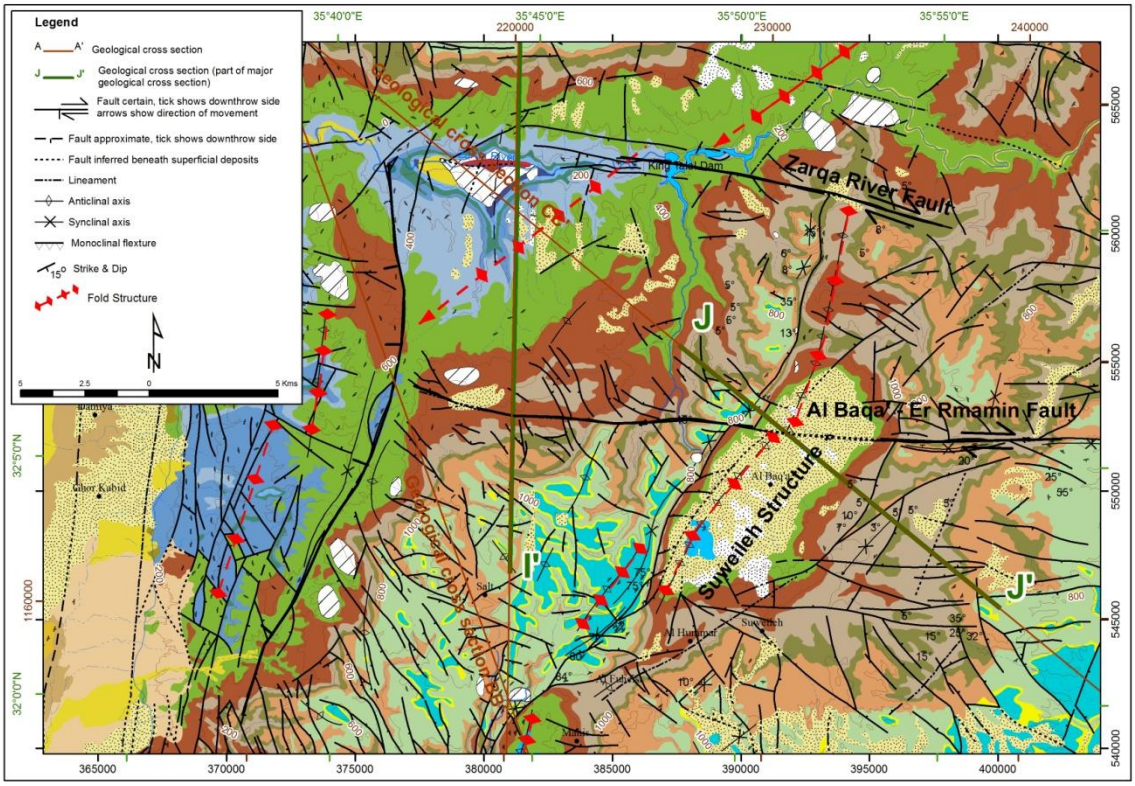


Figure 2.23: Geological map showing some major E-W trending faults in the study area (for more details regarding the legend see Plate 4).

2.2.2.2.3.3 Yarmouk River Fault

Another E-W trending Yarmouk River Fault is recognized, forming the northern limit of the study area (Figure 2.16). This fault has a sub-vertical plane with downthrown towards the north. The Yarmouk River area is characterized by: regional dip of few degrees towards the north, northeast and northwest, and a high dip towards the west along the rift. The aerial photograph interpretation (scale 1:25,000) done by FILON (1975) approved this northward plunging from analysis of both drainage pattern and landform.

2.3 Joints

The joint system in the area parallel to the eastern Jordan River was analyzed and delineated manually from Black and White aerial photographs at a scale of 1:30,000 which was photographed by the Royal Jordanian Geographic Centre (RJGC) in 1992.

Joint directions were delineated for each aerial photograph by using a mirror stereoscope either in the margin of the Jordan Valley; in the Mountain range or in both. Delineation of joints was not easy in the Jordan Valley Floor due to the thick vegetation and soil cover, while it was easy in the Mountain Range because the bed rocks are exposed without any covers. The number of joint measurements was calculated according to their direction either in the margin of the Jordan Valley or in the Mountain range (Table 2.3). Latter, by means of a computer, rose diagrams were plotted for the orientation of joint measurements according to the total number of measurements (Figure 2.24a), and for the total of 3072 joints measured in the analyzed area (Figure 2.24b).

The analysis of joints data show that the densities of joints delineated in the margin of the Jordan Valley are more than that in the Mountain Range. Also, they are dense in the northeastern rim of the Dead Sea more than that in the area between the Zarqa and Yarmouk River. Joints in different directions are found in the analyzed area. They are mainly trending in a NE, NW, NS and EW directions, in descending order.

Although few alluvial fans were delineated in different aerial photographs; their locations were transferred onto topographic maps at a scale of 1:50,000 by using the zoom transferoscope. The location of these fans was digitally marked on (Figure 2.24).

Table 2.3: Number of joint measurements according to their direction in the margin of the Jordan Valley and in the Mountain range.

	Photo No		NS		NE		EW		NW					
Yarmouk River	2446	Mountain range	3	5	39	45	6	6	2	10	50	66	517	1053
		margin of the Jordan Valley	2		6				8		16			
	2448	Mountain range			27	29	10	10	17	22	54	60		
		margin of the Jordan Valley			2				4		6			
	2450	Mountain range	10	11	33	38	7	7	28	36	78	92		
		margin of the Jordan Valley	1		5				8		14			
	2452	Mountain range	6	6	34	34	4	4	48	48	92	92		
	2454	Mountain range	10	10	27	35	3	6	24	29	64	80		
		margin of the Jordan Valley			8		3		5		16			
	2456	Mountain range	7	12	31	54	7	10	30	54	75	130	536	
		margin of the Jordan Valley	5		23		3		24		55			
	2458	Mountain range	4	12	27	54	9	10	28	53	68	129		
		margin of the Jordan Valley	8		27		1		25		61			
	2460	Mountain range	2	7	25	46	4	15	5	13	36	81		
		margin of the Jordan Valley	5		21		11		8		45			
Above Zarqa River	2462			15		50		10		20	323	323		
		margin of the Jordan Valley	15		50		10		20					
	2464			65		85		30		48				
		margin of the Jordan Valley	65		85		30		48					
Zarqa River	2466	Zarqa River Upper part	22		130		17		60		229	399	399	
		Zarqa River Lower part	22		60		6		82		170			
Below Zarqa River	2468	Mountain range	6	76	36	173	11	61	21	121	74	431	256	1574
		margin of the Jordan Valley	70		137		50		100		357			
	2470	Mountain range	14	38	65	210	28	46	30	146	137	440		
		margin of the Jordan Valley	24		145		18		116		303			
	2472	Mountain range	4	40	14	101	3	12	14	75	35	228		
		margin of the Jordan Valley	36		87		9		61		193			
	2474	Mountain range	2	22	8	78		8		67	10	175	1318	
		margin of the Jordan Valley	20		70		8		67		165			
	2476			13		90		15		65		183		
		margin of the Jordan Valley	13		90		15		65		183			
	2478			12		70		5		30		117		
		margin of the Jordan Valley	12		70		5		30		117			
Dead Sea			68	388	366	1382	92	278	247	979				
			320		1016		186		731					
			Total number of joints = 3027											

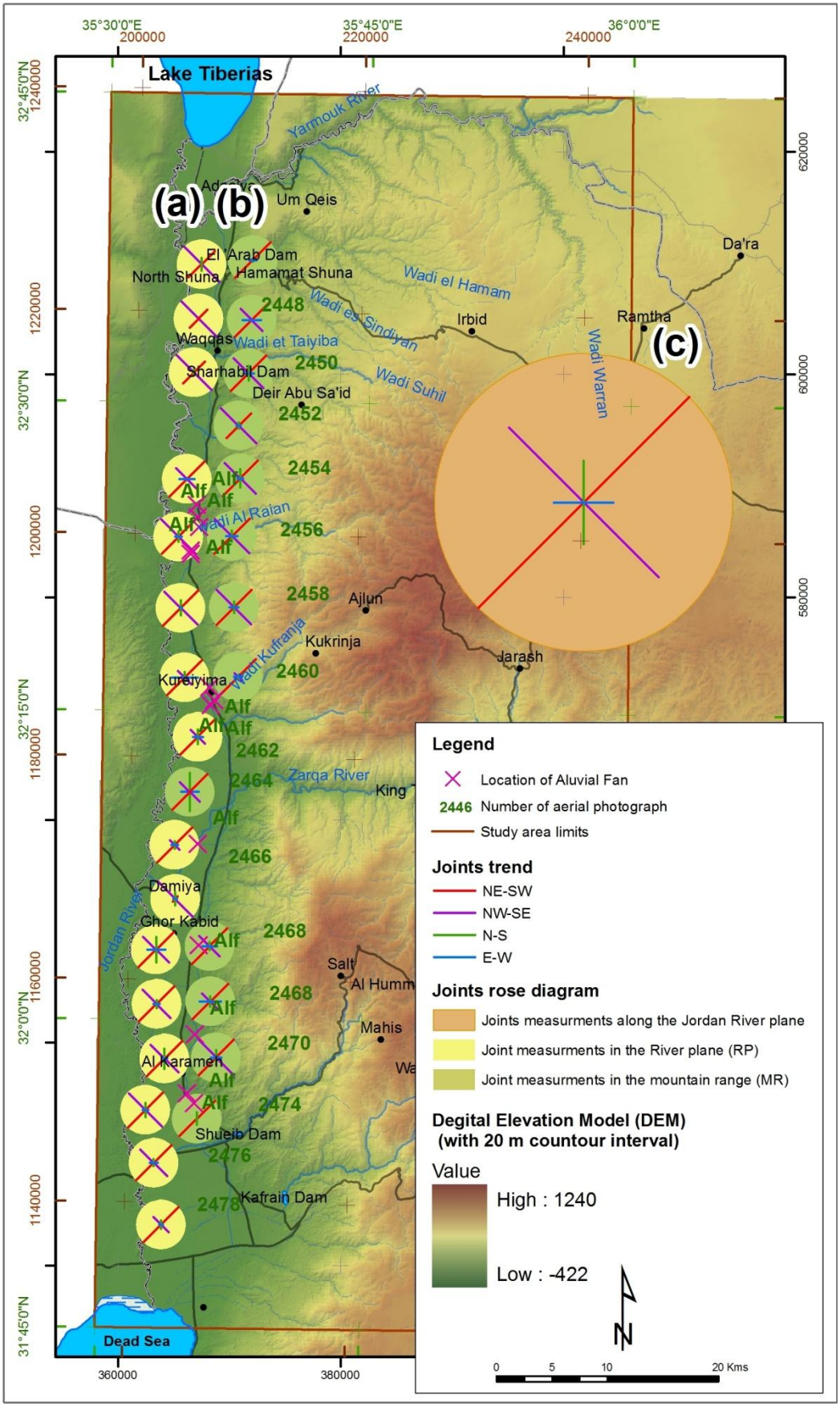


Figure 2.24: Joint measurements (a) in the margin of the Jordan Valley and in the Mountain range (b) Total joint measurement along Jordan River.

3. SUBSURFACE GEOLOGY

Subsurface geology information is required to confirm the depth, thickness and lateral extent of aquifers and aquicludes in the study area. To achieve this, an isopach maps and structural contour maps of the different groups forming aquifers were drawn based mainly on the data from oil wells within the study and adjacent areas and/or from water wells. In some cases it was important to extend the isopach and structural contour maps to cover the whole country, due to lack of adequate information and the limited number of deep oil wells in the study area.

The major formations that make up the stratigraphical column in the study area according to information gained from the drilling of deep oil wells, range in age from Early Paleozoic to Recent and are primarily composed of carbonates, sandstones and shales (according to NRA open files). Figure 3.1 shows the locations of oil wells and the rocks penetrated, in addition to nomenclature and some important geographic areas in Jordan (Details of these wells are shown in Appendixes 3.1, 3.2 & 3.3).

The oil well's data show that the Basement Complex was reached only in well SA-1 in the extreme southeast of the study area. The thickness of sedimentary sequence overlying the Basement Complex, in that area is 2550 m. While further to the east (in Al Azraq Depression), the sedimentary sequences are about 5000 m thick. Hydrogeologically, these sedimentary sequences are subdivided into lithostratigraphic groups; which form systems of aquifers, semi-aquifers and aquicludes (Table 1.1 & 1.2). These groups are:

3.1 Zarqa–Ma'in Group (Permian–Triassic–Jurassic)

The Permian–Triassic-Jurassic succession in Jordan contains three cycles, which lie between the Hercynian unconformity (which has been dated as mid Carboniferous in age) and the base of the Lower Cretaceous unconformity. These three cycles (Permian, Triassic and Jurassic) are considered in the subsurface as three individual groups (Hudayb, Ramtha and Azab) on the basis that they are separated by unconformities (ANDREWS et al., 1992) (Figure 3.2).

These three groups are only exposed in relatively small areas of the Rift margin in northwestern Jordan, but are found in a wide area in the subsurface (no rocks older than Triassic age are exposed in the study area) (Figure 2.3).

In Jordan, up to 2000 m of Permian–Triassic-Jurassic succession is preserved. The occurrences do not extend south of 486398 N JTM coordinate (Jordanian Traverse Mercator) (≈31° 30′ N Geographic coordinate system) (Figure 3.2), but in Palestine due to the strike slip movement along the fault of the rift, they are found 107 km further to the south (ANDREWS et al., 1992).

The Permian (Hudayb Group) – Triassic (Ramtha Group) – Jurassic (Azab Group) successions are described in the following (Table 1.2 & Figure 2.3):

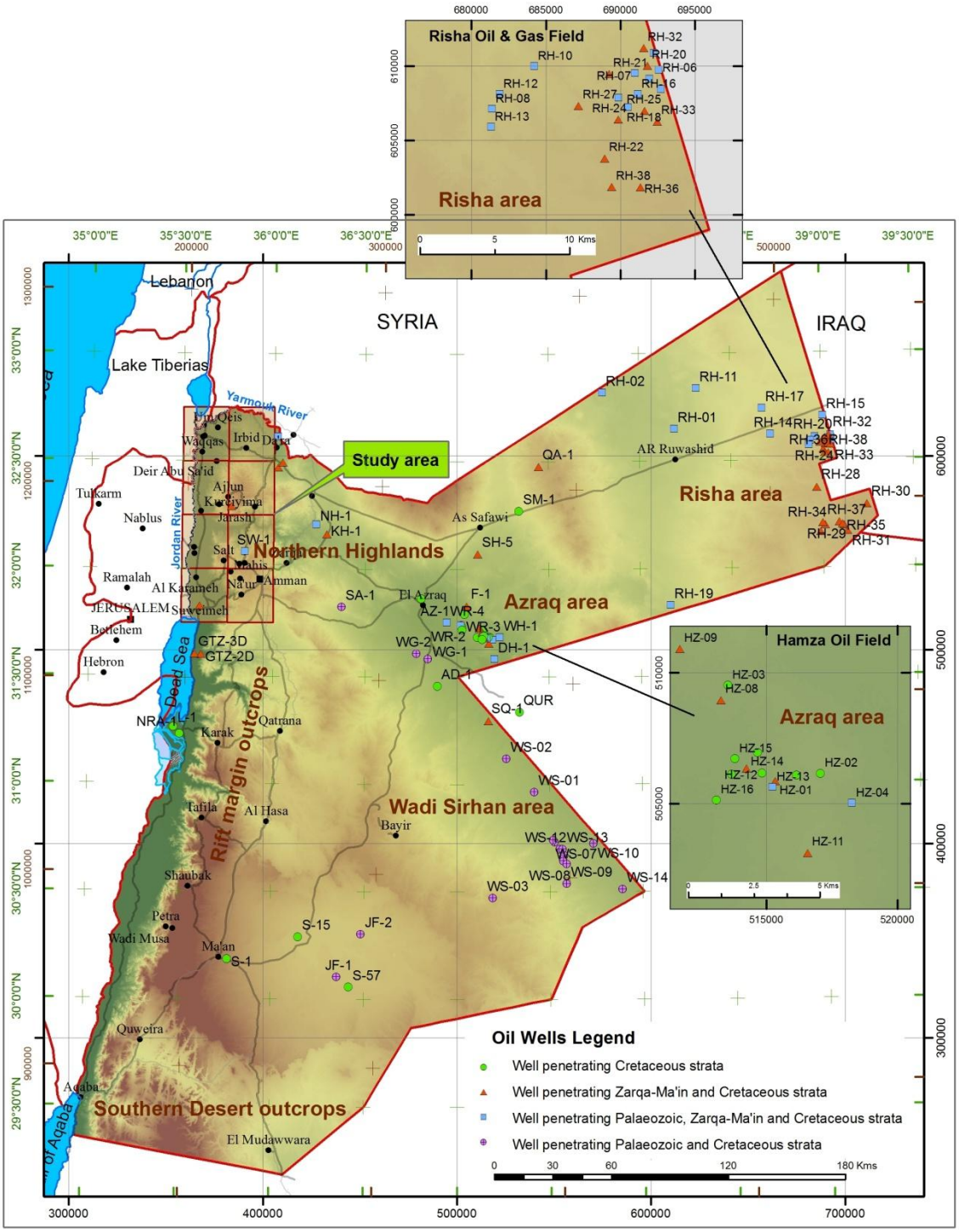


Figure 3.1: Location map showing the position of oil wells penetrating different rock sequences and important geographic areas in Jordan with the location of the study area (Details of these wells are given in Appendixes 1, 2 &3).

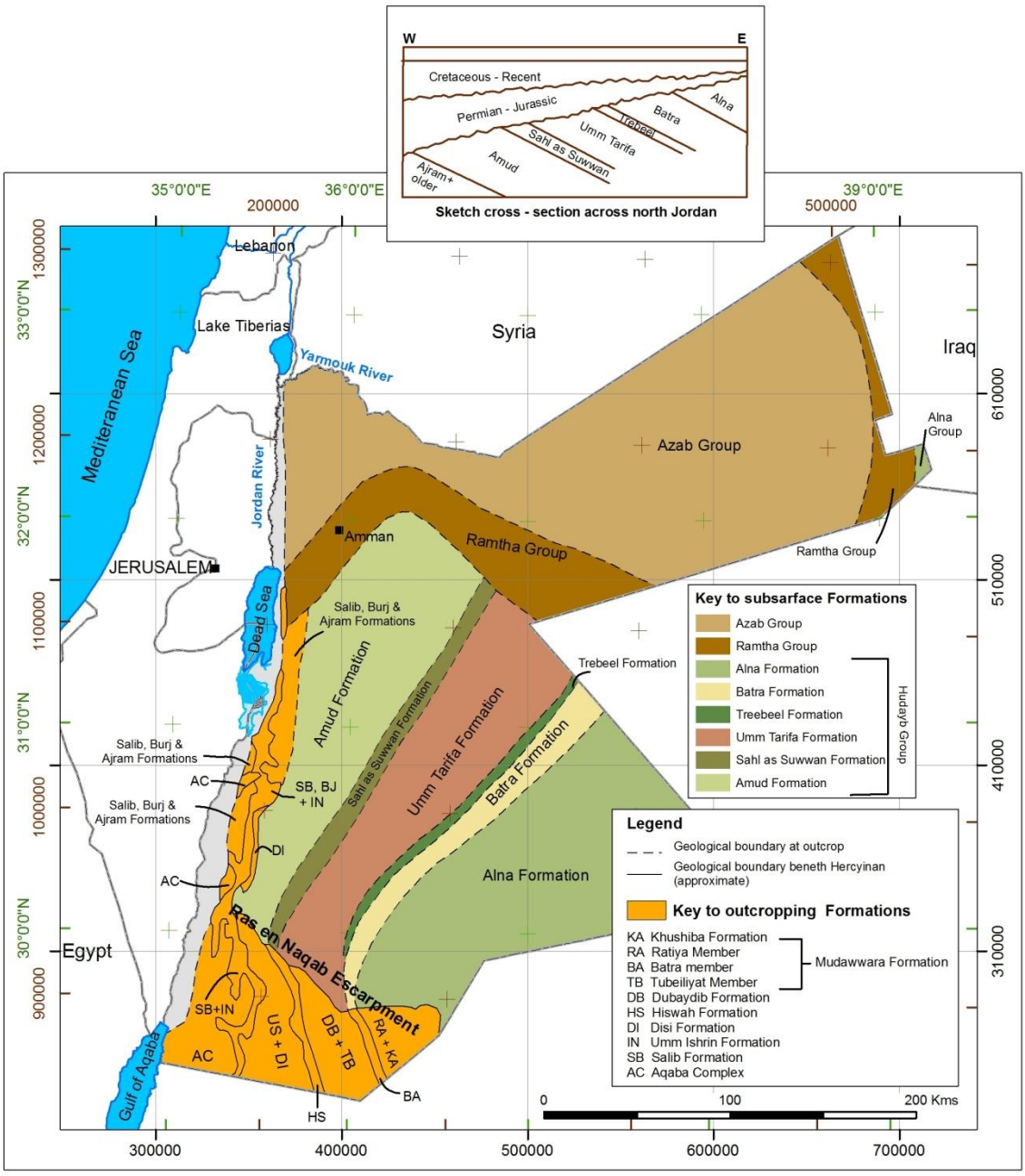


Figure 3.2: Pre-Cretaceous Unconformity Subcrop Map, showing the approximate erosional limits of Azab, Ramtha and Hudayb Groups in Jordan (based on ANDREWS et al., 1991 and ANDREWS et al., 1992; modified after ANDREWS, 1992).

Note: different names are used for the same formation in the outcrop and in the subsurface (e.g. Alna Formation is identical with RA and KA)

3.1.1 **Hudayb Group** (Permian)

The group includes all rocks of Permian age in Jordan. The name is derived from 'Ain Umm Hudayb which is located near the Dead Sea, 3 km south of the mouth of Wadi Zarqa (Figure2.3). The term Hudayb Sandstone Shale Formation was first applied to these Permian exposures and strata drilled in the subsurface by SUNNA' et al. (1988) and subsequently by AHMAD (1989). At outcrops the beds had been assigned to the Um Irna Formation (BANDEL & KHOURY, 1981) and previously Um Irna Formation has also been applied to the borehole succession (Table 3.1). In well ER-1A Total Exploration Co. did not give a name the Permian Formation.

In the subsurface the base of the Hudayb Group is only observed in well AJ-1. In this well the lower part of this group (Anjara Formation) overlies the lower Cambrian rocks (Salib Formation). While the top of Hudayb Group in wells penetrating this horizon in northwestern Jordan, the boundary is clear with a basal limestone of the Suwayma Formation resting on the clastic Buwayda Formation (ANDREWS et al., 1992).

In the subsurface, the Hudayb Group succession is divided into a lower, clastic unit (Ajram Formation), a middle carbonate unit (Huwayra Formation) and on upper clastic unit (Buwaayda Formation) (Table 1.2), where an interbedded sandstones and dark shales are overlain by argillaceous, bioclastic limestones with thin beds of chalky limestone and shale. These are overlain by a mixture of fine to medium- grained sandstone and argillaceous, ferruginous, lignitic, fine- grained sandstone with interbedded siltstones. Fragments of coal occur within the clastic sediments (ANDREWS et al., 1992).

3.1.1.1 **Isopach map of the Hudayb Group** (Permian)

Rocks of Hudayb Group have a restricted distribution in northern Jordan (Figure 3.3). A small outcrop was discovered by BANDEL & KHOURY (1981) on the eastern shore of the Dead Sea where the thickness was estimate to vary from 85 m (BANDEL & KHOURY 1981) to 60 m (MAKHLOUF, 1987). Subsequently, thicker carbonate and siliciclastic units were found in five boreholes further to the north (Table 3.1 & Figure 3.3).

3.1.2 **Ramtha Group** (Triassic) (Tr)

Rocks of Triassic age are referred to by the reports of Subsurface Geology Directorate of the Natural Resources Authority as the Ramtha Group (ANDREWS et al., 1992). The term Ramtha Group was first used in 1978 in the unpublished ER-1A composite log by "TOTAL EXPLORATION" geologists (Jordan Branch) and is taken from the town of Ramtha in north Jordan, near the sites where wells ER-1A and NH-2 were drilled.

The most important lithofacies of the Ramtha group, are: clastic (interbedded shales, siltstones and sandstones), argillaceous fossiliferous limestone or dolomite, interbedded with shale or marl, oolitic, peloidal and bioclastic carbonates, and anhydrite and halite interbedded with shale and thin carbonates (Abu Ruweis Formation only) (ANDREWS et al., 1992).

Table 3.1: Thickness and top from ground surface level for Zarqa–Ma'in Group (Hudayb, Ramtha and Azab Groups) in some oil wells in Jordan. (+ means: base of group not reached) (compiled from NRA open files and after ANDREWS et al., 1992).

Well ID	Hudayb Group				Ramtha Group				Azab Group				Zarqa – Ma'in Group	
	Top	Bottom	Thickness	Top from S.L.	Top	Bottom	Thickness	Top from S.L.	Top	Bottom	Thickness	Top from S.L.	Total Thicknes s	Top from S.L.
AJ-1	2354	2580	226	-1206.9	1311	2354	1043	-163.9	713	1311	598	434.1	1858	434.1
DH-1					2293	2562	269	-1763.6					269	-1763.6
ER-1A	2640	2755	115	-2036.1	1503	2640	1137	-899.1	1114	1503	389	-510.1	1641	-510.1
F-1					258	701	443	322.7					443	322.7
GTZ-2D					486	819.5	333.5	-276					333.5	-276
GTZ-3D					165	456.5	291.5	-435					289.5	-435
JV-1									979	1098	119.0+		119+	
HZ-1					3203	3216.5	13.5+	-2638.5					13.5+	-2638.5
HZ-4					3557	3866	309	-3001.6					309	-3001.6
HZ-8					3508	3595	87	-2946.4					87+	-2946.4
HZ-11					3313	3500	187+	-2738					187+	-2738
HZ-13					3216.5	3482	265.5	-2651.3					265.5	-2651.3
HZ-14					3159	3301	142+	-2601					142+	-2601
KH-1					665	1333.3	668.3+	-57.9					668.3+	-57.9
NH-1					585	1127	542	24.8					542	24.8
NH-2	3283	3722.5	439.5	-2768.6	2044	3283	1239	-1529.5	1556	2044	488	-1041.6	2166.5	-1041.6
QA-1					1634	2823	1189+	-691	1489.5	1634	144.5	-546.5	1333.5+	-546.5
RH-1					853	1791	938	-181	748	853	105	-76	1043	-76
RH-2	2045	2055	10	-1391.6	763	2045	1282	-109.6	687	763	76	-109.6	1368	-33.6
RH-3					276	420	144	576.9					144	576.9
RH-4					282	429	147	581.6					147	581.6
RH-5					275	410	135	579.9					135	579.9
RH-6					275.5	397	121.5	570.7					121.5	570.7
RH-7					272	422	150	578.1					150	578.1
RH-8					300	497	197	549.9	270	300	30	579.9	227	579.9
RH-9					265	420	155	584.6					155	584.6
RH-10					293	477	184	550.1					184	550.1
RH-11	1409	1412	3	-683.1	623	1409	786	102.9	530	623	93	195.9	882	195.9
RH-12					322	507	185	535.9	294	322	28	563.9	213	563.9
RH-13					307	501	194	548.6	275	307	32	580.6	226	580.6
RH-14					460	854	394	374.4	383	460	77	451.4	471	451.4
RH-15					357	525	168	456.5					168	456.5
RH-16					276	414	138	583.3					138	583.3
RH-17					480.5	933.5	453	309.6	429	480.5	51.5	361.1	504.5	361.1
RH-18					285	427	142	589.3					142	589.3
RH-19					878	1326.5	448.5	-183.3	772	878	106	-77.3	554.5	-7730.9
RH-20					272.1	413.1	141	576.5					141	576.5
RH-21					279.5	421.5	142	543.8					142	543.8
RH-22					283.1	426.1	143	589.2					143	598.2
RH-23					350	472	122	562.5					122	562.5
RH-24					276.5	426.5	150	597.9					150	597.9
RH-25					273.5	415.5	142	587.9					142	587.9
RH-26					298.1	327.1	29	631.2					29	631.2
SH-5					900	1405	505+	-220	796	900	104	-116	609+	-116
SW-1					246	933	687	388.3	115	246	131	519.3	818	519.3
S24									119	247	128.0+		128+	
S28									113	191	78.0+		78+	
S42									19	97	78.0+		78+	
S90					1665	2194	529.0+		1262	1665	403		932+	
WH-1					1305	1615	310	-774.4					310	-774.4
WR-2					3081	3420	339	-2530.8					339	-2530.8
WR-4					2770	3056	286	-2530.8					286	-2240.4
	Dead Sea Outcrop			60					Zarqa River Outcrop			400		

In the subsurface of the study area, the base of Triassic rocks is found in the Northern Highlands wells, overlying the Hudayb Group of Permian rocks. But to the east of the study area (Azraq and Risha areas) the Permian is absent and the Triassic Group lies directly on Cambrian and Silurian strata of Palaeozoic age (ANDREWS et al., 1992). In wells NH-1 and KH-1 the top of Jurassic is absent and the Triassic is overlain unconformably by Lower Cretaceous Kurnub Group.

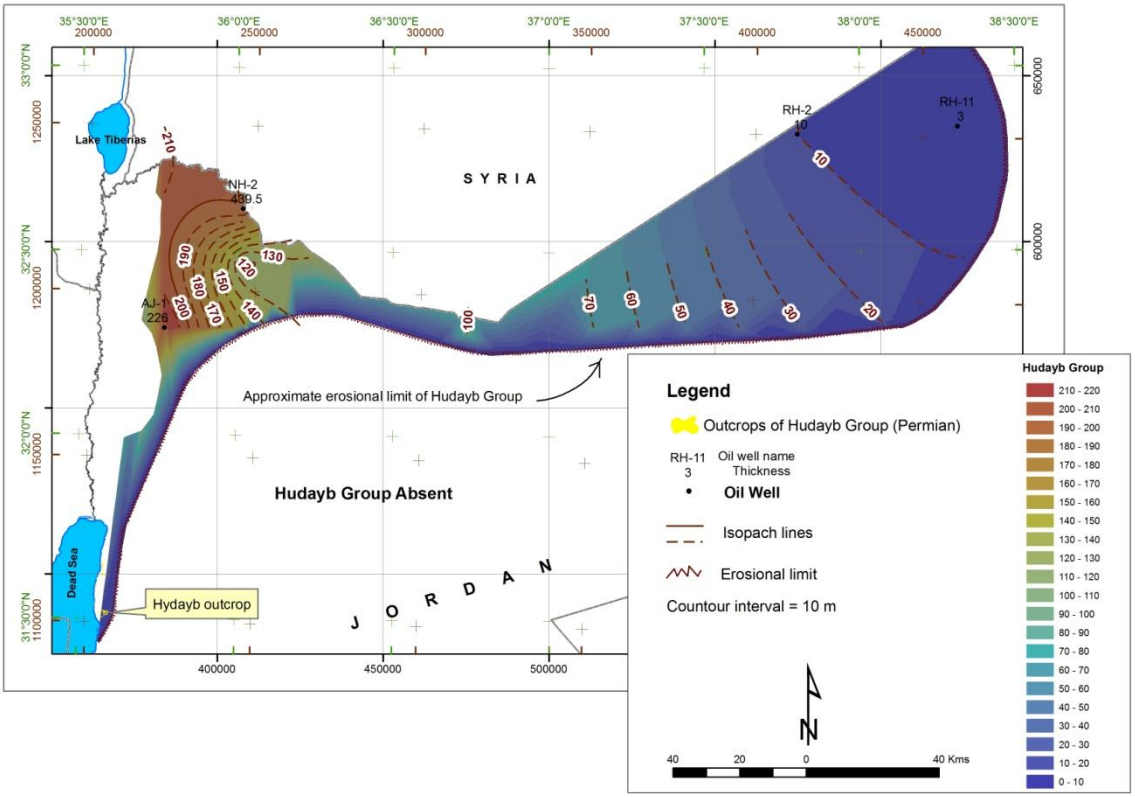


Figure 3.3: Isopach map of Hudayb Group (Permian) in Jordan.

3.1.2.1 Isopach map of the Ramtha Group (Triassic) (Tr)

The Triassic sediments have been described in 43 boreholes drilled in northern Jordan (NRA files, Table 3.1). The maximum penetrated thickness of 1239 m is found in well NH-2. The thickness of the Formation increases in a northward direction as shown in the isopach map (Figure 3.4) and the geological cross section AA′ (Plate 5). Considerably thinner sequences are found to the east of the study area in Azraq area and in the Risha gas field. The map shows that the approximate erosional level of the Ramtha Group runs in a NW-SE direction close and east of wells WG-1 and 2. The increase in thickness is in a NE direction where the group attains a maximum thickness of 1300 m near the Syrian border.

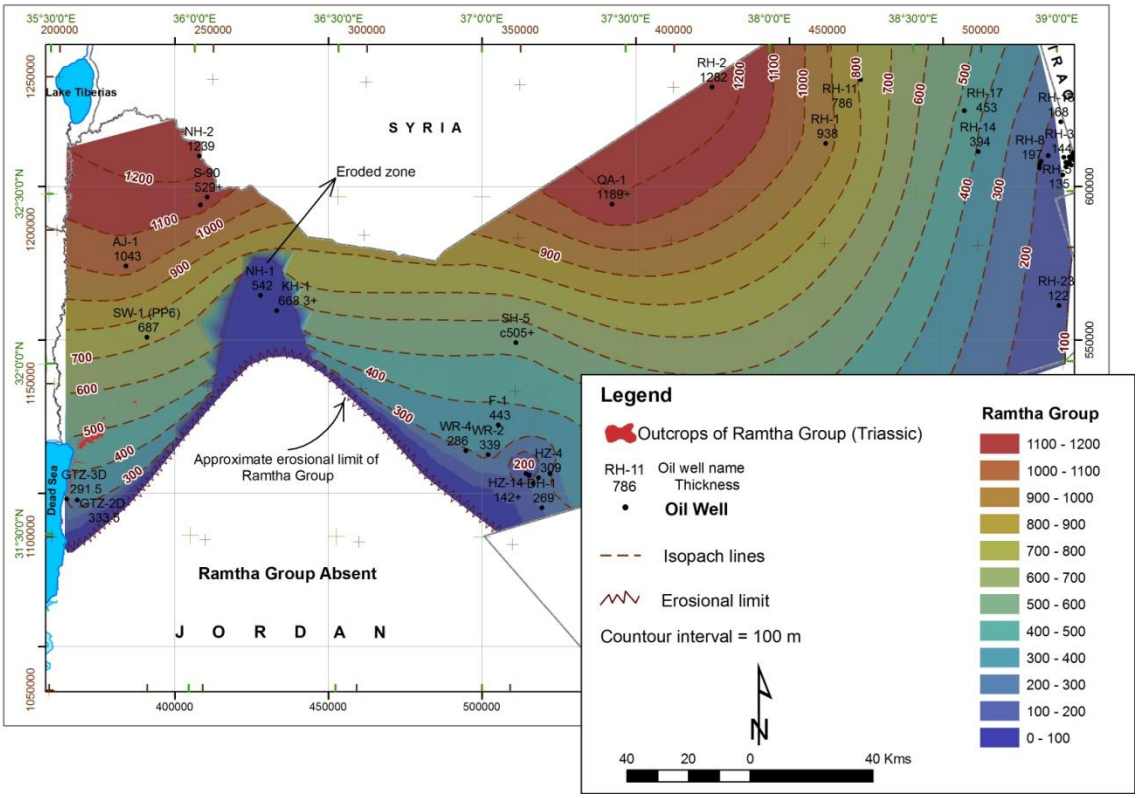


Figure 3.4: Isopach map of Ramtha Group (Triassic) in Jordan.

3.1.3 **Azab Group** (Jurassic) (AZ)

In northern Jordan the Abu Ruweis Formation of the Triassic Group is unconformably overlain by the lower part of Jurassic sediments (Hihi Claystone Formation). This is clear in well NH-2 (ANDREWS et al., 1992). The upper boundary of this Group is unconformably overlain by the Lower Cretaceous, Kurnub Sandstone.

3.1.3.1 **Isopach map of the Azab Group** (Jurassic)

In the subsurface, the Jurassic sediments have been described in 20 boreholes drilled in north Jordan (NRA files, Table 3.1). The distribution extends from Syria, most north-western part of Jordan, north of Amman east-wards beneath the Harrat Ash Sham Basalt to Risha area as shown in the isopach map (Figure 3.5).

The most complete Jurassic succession and maximum thickness is found within the study area, including the outcrops as shown in the geological cross sections BB′, CC′ & HH′ (Plate 5). The total thickness has been estimated by various workers between 400-450 m. except the thickness in borehole AJ-1 of 598 m and NH-2 of 488 m the Jurassic thickness in the subsurface does not exceed the outcrop thickness (Figure 2.3). Beneath the Basalt east of the study area (Al-Harra) and western Risha areas the thickness is much reduced than the outcrop thicknesses with a more uniform 51.5-144.5 m (ANDREWS et al., 1992). A thickness of 28-32 m Jurassic rock was also described west of the Risha gas field.

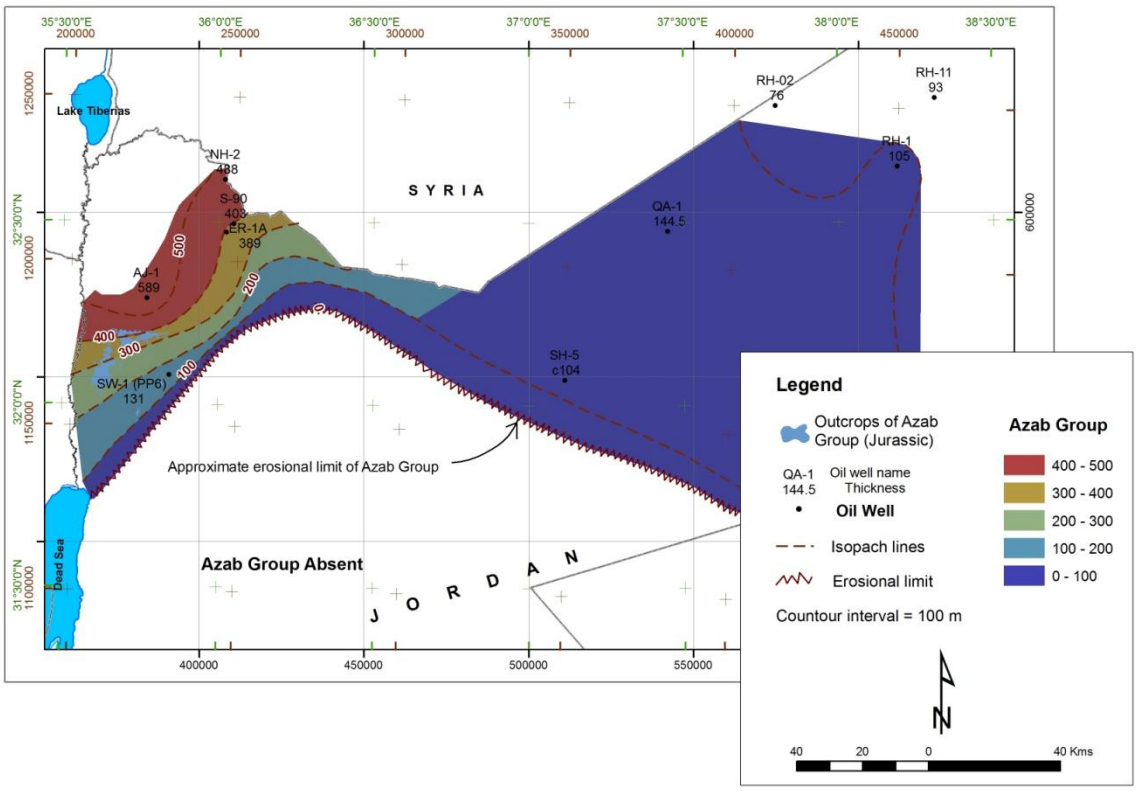


Figure 3.5: Isopach map of the Azab Group (Jurassic) in Jordan.

3.1.4 Zarqa–Ma'in Group

In general, it can be stated that the 2000 m of the Zarqa-Ma'in Group sediments were deposited in a basin that covered northern Jordan and extended northwards into Syria (BEBESHEV et al., 1988) and westwards into Palestine (DRUKMAN, 1974; PICARD & FLEXER, 1974), where both, the thickest, and most complete stratigraphic column had been found.

The nature of the erosional boundary between the Permian to Jurassic cycle and overlying Cretaceous is seen along the shore of the Dead Sea and northwards to the Zarqa River. Only the lowest beds are preserved in the southernmost exposures with progressively younger strata preserved further north.

3.1.4.1 Isopach map of Zarqa–Ma'in Group

The isopach map of Zarqa–Ma'in Group shows that the maximum thickness of this group is found in well NH-2 where a complete, 2167 m thick succession was penetrated (Figure 3.6). While to the east of the study area considerably thinner sequences are found in Al Azraq Basin. The penetrating wells show a range of thickness between 265.5 m in HZ-13, and 1334+ m in QA-1 (Table 3.1 & Figure 3.6). Although the geological cross sections AA′, BB′, CC′ & HH′ (Plate 5) suggests an increase of thickness of the Group towards northeast into the Hermon Basin in Syria, and beneath Al-Harra and western Risha areas, the thickness is much reduced (ANDREWS et al., 1992).

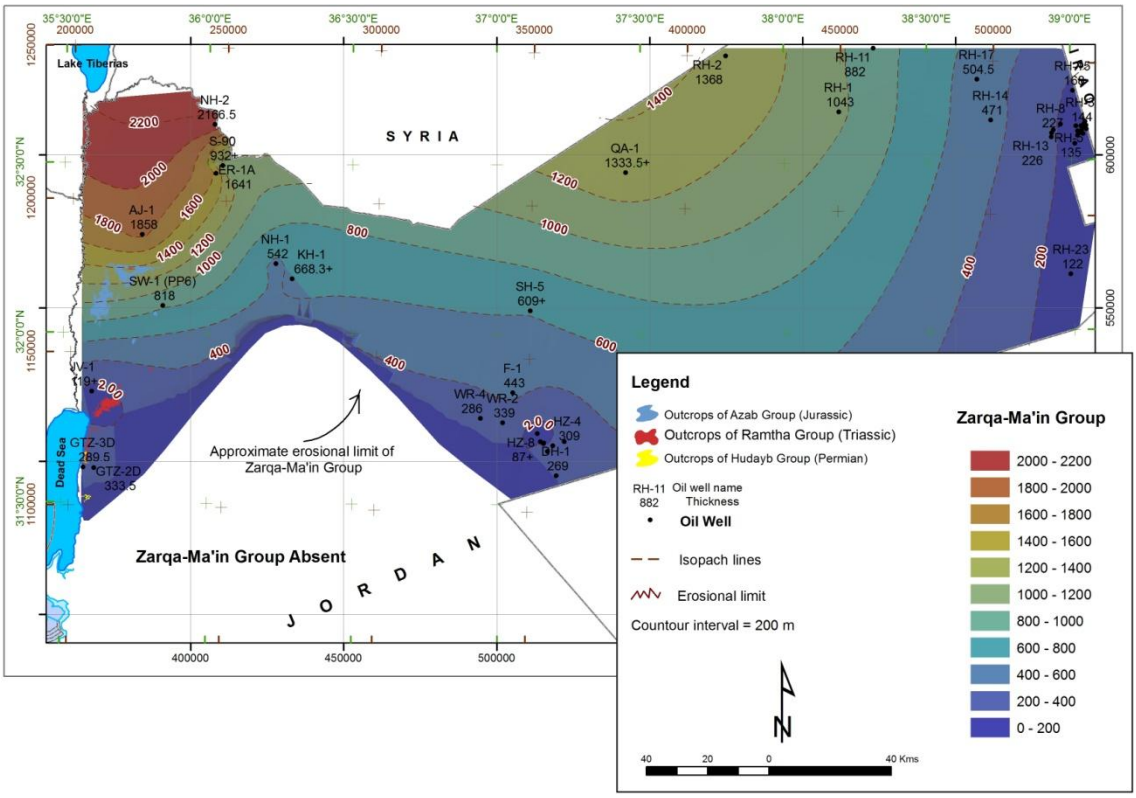


Figure 3.6: Isopach map of Zarqa-Ma'in (Permian–Triassic–Jurassic) in Jordan.

3.1.4.2 Structural contour Map for the Top of Zarqa–Ma'in Group

The Top of Zarqa–Ma'in Group is shown in Table 3.1 and Figure 3.7. The map shows an increase in elevation in well RH-19, where the top of the Zarqa–Ma'in Group reaches its maximum depth of -7730.9 m bsl, while in north and northeast directions, the top of the group varies between 0 and -500 m bsl.

The lowest top elevations of the Zarqa–Ma'in Group at 631.2 m asl is found in well RH-26 and at 519.3 m asl in well SW-1. Within the Azraq depression, the elevation ranges from zero to -2500 m bsl.

COHEN et al. (1990) educated the tectonic regimes controlling the sedimentation during the Permian to Jurassic in the Levant region (eastern Mediterranean). Sedimentation according to COHEN et al. (1990) is considered to be controlled by a series of NE-SW trending fault-bounded horst and graben structures which were periodically active during this period. The grabens were formed in three known phases: pre-Upper Permian, Early to Middle Triassic and Early to Middle Jurassic. Formation of each graben resulted in a depositional sag basin centered above the graben and extending beyond its boundaries. These structures subsequently underwent two types of active tectonic inversion: (1) inversion of regional tilts (e.g. the SE landward Middle Triassic sedimentary wedge and the NW basinward wedge of the Early Cretaceous sequence) and (2) inversion of vertical tectonic movements (e.g. the vertical inversion occurred in the Late Cretaceous). The Paleozoic-Mesozoic grabens became raised blocks, whereas the horsts turned into depressed areas, in which synclinal sediments, rich in organic matter, accumulated in asymmetrical fault-fold sag basins (COHEN et al., 1990).

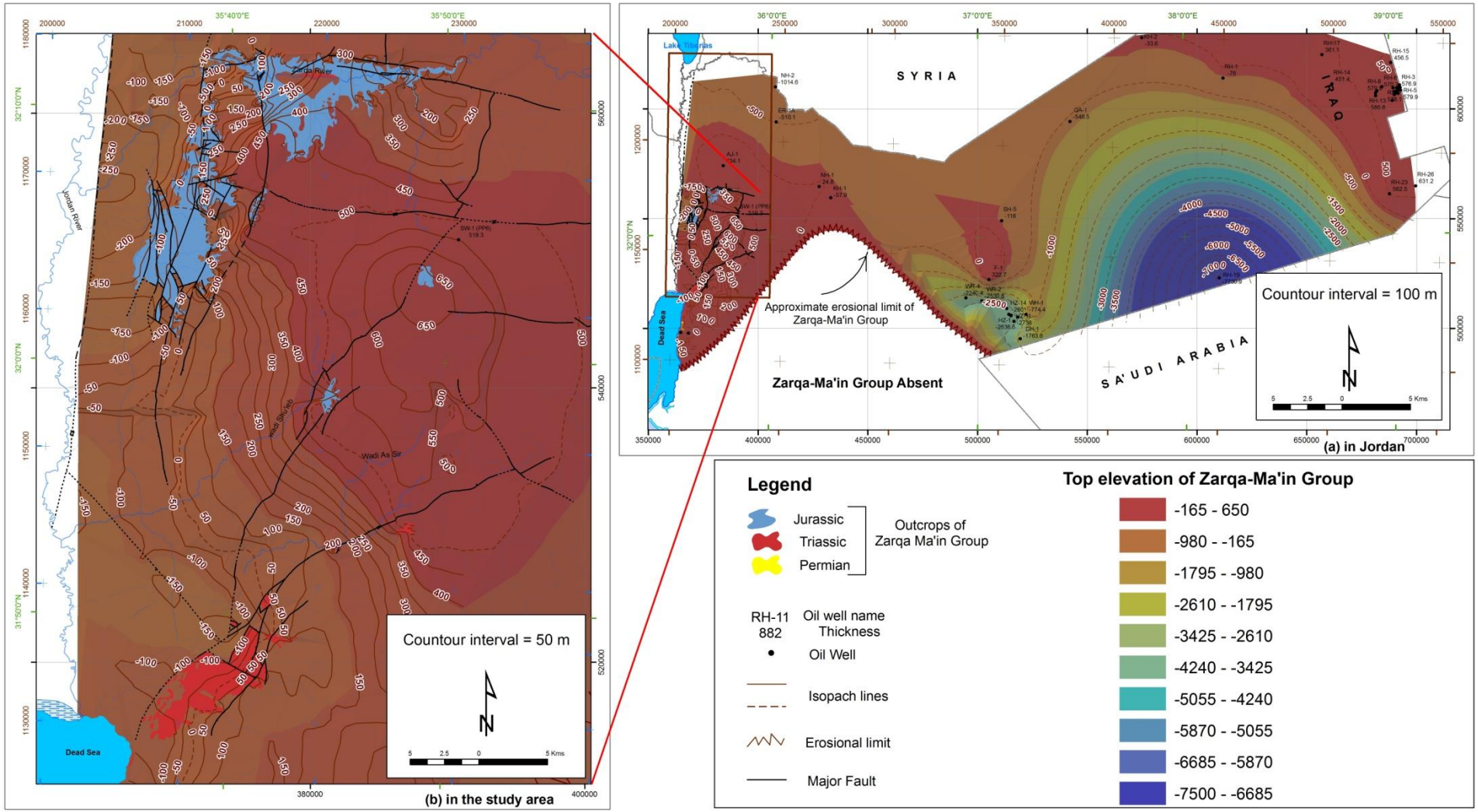


Figure 3.7: Structural contour map of the top of Zarqa-Ma'in Group (Permian–Triassic–Jurassic) (a) in Jordan…..(b) in NW of Jordan. (Note: no structural features outside of the study area are shown).

3.2 **Kurnub Sandstone Group** (Lower Cretaceous) (KS)

In northern Jordan the lower part (Arda) of the Kurnub Sandstones rests unconformably on the Permian to Jurassic sequence. The later is dominated by carbonates (ANDREWS, 1992).

In most areas, the upper part (Subeihi) of the Kurnub Sandstone is overlain by limestones of the Ajlun Group (ANDREWS, 1992). But, in the south of the country the Kurnub Group and Batn al Ghoul Group (or sandy Ajlun Group) are effectively inseparable (MOHD, 1989; AL-MASRI, 1991) and the combined unit is overlain by the Amman-Al Hisa Unit with its carbonate lithologies (e.g. well JF-1) (ANDREWS, 1992).

In the subsurface of the Northern Highlands, the Kurnub Sandstone is white grey, very fine- to coarse-grained sandstone or sand with siliceous or carbonate cement (ANDREWS, 1992).

3.2.1 **Isopach map of Kurnub Sandstone Group** (KS)

The Kurnub Sandstone Aquifer crops out along the lower Zarqa River and along the escarpment of the Dead Sea, Wadi 'Araba and Disi Area. But in the subsurface, the Kurnub Sandstone underlies almost the entire territory of Jordan, except the southern desert area.

The Kurnub Sandstone Aquifer has been penetrated in most of the deep wells throughout Jordan (approximately, sixty wells) and its subsurface distribution are shown in the geological cross sections AA′, BB′, CC′, DD′ & HH′ (Plate 5).

The isopach map (Figure 3.8) generally shows a thinning of the Kurnub Sandstone Group towards the east and southeast. The thickness varies from 238 m in well NH-1 in the north to 120-180 m in well AJ-1 and the Azraq area; whereas to the east and southeast of the study area (Risha and Sirhan areas) the thickness is reduce to 20-80 m and it pinches out in the extreme southeast of Jordan. In the south, if the Batn al Ghoul Group is included in the isopach, thicknesses again increase to 250-400 m (Table 3.2 & Figure 3.8).

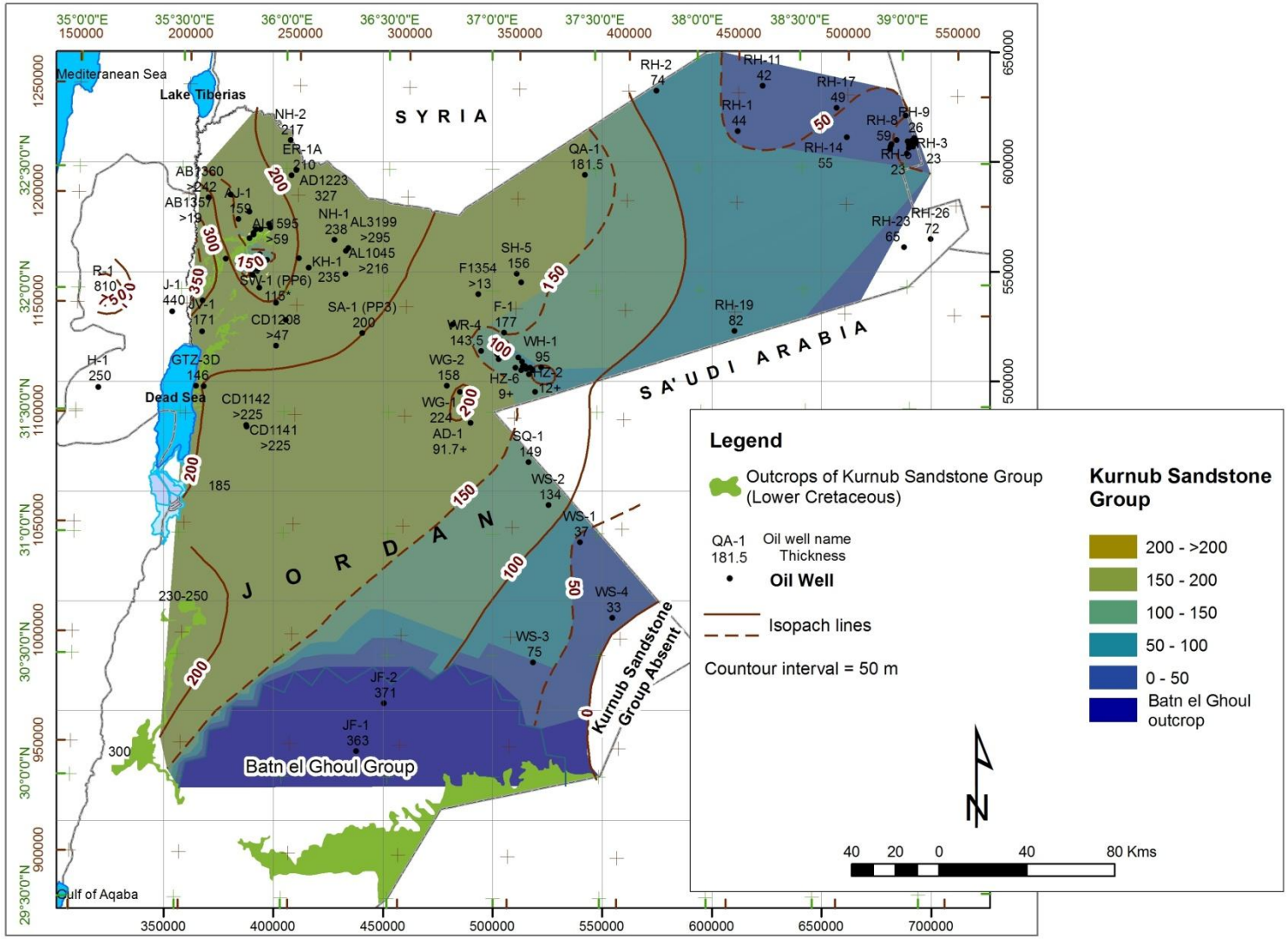


Figure 3.8: Isopach map of Kurnub Sandstone Group (Lower Cretaceous) in Jordan.

Table 3.2: Thickness data and top from ground surface level for the Kurnub Sandstone Aquifer in some wells in Jordan (+ means: base of the group not reached; * means: well spudded in this group) (compiled from NRA open files and after ANDREWS, 1992).

Well ID	Top	Bottom	Thickness	Top from S.L.
AD-1	1691.1	1782.8	91+	-1083.3
AJ-1	554	713	159	593.1
AZ-1	1255	1299	44+	-738.8
DH-1	2175.5	2293	117.5	-1646.1
ER-1A	904	1114	210	-300.1
F-1	81	258	177	499.7
GTZ-2D	267	486	219	-57
GTZ-3D	19	165	146	-289
HO-2	3334	3364	30+	-2786.9
HZ-1	3056	3203	147	-2491.5
HZ-2	3245	3257	12+	-2674
HZ-4	3489.5	3557	67.5	-2934.1
HZ-5	3281	3310	29+	-2730.1
HZ-6	3156	3165	9+	-2606.4
HZ-7	2881.5	2900	18.5+	-2333
HZ-8	3371	3508	137	-2809.4
HZ-9	3446	3580	134+	-2881
HZ-10	3172	3199	27+	-2604.9
HZ-11	3195.5	3313	117.5	-2620.5
HZ-12	3064.5	3084	19.5+	-2506.8
HZ-13	3166	3216.5	50.5	-2600.8
HZ-14	3035	3159	124	-2477
HZ-15	3192.5	3214	21.5+	-2631.5
HZ-16	3149	3161	12+	-2604.8
JF-1	108	471	363	762.8
JF-2	144	515	371	707.3
KH-1	430	665	235	177.2
NH-1	347	585	238	262.8
NH-2	1339	1556	217	-824.4
QA-1	1308	1489.5	181.5	-365
RH-1	704	748	44	-32
RH-2	613	687	74	40.4
RH-3	253	276	23	599.9
RH-4	245	282	37	618.6
RH-5	252	275	23	602.9
RH-6	258	275.5	17.5	588.2
RH-7	245	272	27	605.1
RH-8	211	270	59	638.9
RH-9	239	265	26	610.6
RH-10	241	293	52	602.1
RH-11	488	530	42	237.9
RH-12	247	294	47	610.9
RH-13	215	275	60	640.6
RH-14	328	383	55	506.4
RH-15	305	357	52	508.5
RH-16	248	276	28	611.3
RH-17	380	429	49	410.1
RH-18	253	285	32	621.3
RH-19	690	772	82	4.7
RH-20	254.1	272.1	18	594.5
RH-21	248.5	279.5	31	574.8
RH-22	243.1	283.1	40	638.2
RH-23	285	350	65	627.5
RH-24	236.5	276.5	40	637.9
RH-25	214.5	273.5	59	646.9
RH-26	226.1	298.1	72	703.2
SA-1	900	1100	c200	-151.7
SH-5	640	796	156	40
SQ-1	1176	1325	149	-595.9
SW-1	0	115	115*	634.3*
WG-1	1973	2197	224	-1395.3
WG-2	1797	1955	158	-1228.9
WH-1	1210	1305	95	-679.4
WR-1	2960	3076	116+	-2414.9
WR-2	2963	3081	118	-2412.8
WR-4	2627	2770.5	143.5	-2096.9
WS-1	720	?757	c37	-155
WS-2	790	924	134	-181
WS-3	260	335	75	622.6
WS-4	462	495	33	165.7
Outcrop				350

3.2.2 Structural contour map for the top of the Kurnub Sandstone Group

The top of Kurnub Sandstone Group is given in Table 3.2 and Figure 3.9. The Kurnub Sandstone thicknesses vary considerably over short distance, but this may be due to tectonic rather than depositional controls (ANDREWS, 1992).

The Structural Contour Map of the Top of the Kurnub Group shows an increases in elevation to the north, northeast and south directions. The top of the group varies between 0 and -600 m bsl

The lowest top elevation of the Kurnub Group is found at 800 m asl within the study area. But further to the east, within the Azraq depression, the elevation ranges from -1000 to -2500 m bsl.

The circular shaped phenomenon shown in the structural contour maps Figure 3.9 for the top of Kurnub Sandstone Group, in Al Azraq area is partly artificial due to the limited number and the irregular distribution of the existing deep wells in the study area and the adjacent areas. This phenomenon is frequently the result of the kind of interpolation and showing artificial contour forms which does not agree with the mainly elongated sedimentary (basins and swells) and structural (grabens and horsts) pattern. These circular shaped phenomena will show also on other isopach and structural contour maps of younger formations.

If one try to understand and interpreter the thickness distribution with regards to sedimentary processes, one has to consider that in the normal sedimentary basins the thickness of sediments depends on the central (larger thickness) or the marginal (lower thickness) position if over certain distance the thickness is changing several times. This can indicate the subdivision of the basin in sub-basin and swells. In a profile over Jordan from north to south several basins and swells are indicated and it is partly shown in the geological cross section HH' (Plate 5) which extends from the Yarmouk River in the north to the Dead Sea in the south (almost central of Jordan in N-S trending strip). But in the isopach and the structural contour maps due to the narrow N-S strip which was under investigation, sometimes only few deep wells are available thou that by the interpretation used in the maps, some of the elongated basins and swells are only shown as a circular like highs and lows.

The same miss interpretation might result from the position of wells in the Sirhan-Azraq rift Basin [(2)] of East Jordan (Figure 2.11) due to relatively small area were wells included in the interpolation the low position of top or base of certain layers in the structural contour maps gives the impression of a deep circular shaped hole instead of Showing the NW-SE trending graben depression.

[(2)] The **Sirhan Basin** is a major NW-SE trending rift Basin (Figure 2.11) which contains about 3000 m sediments of Upper Cretaceous and Eocene age. Although this structure is situated mainly in Saudi Arabia, its major western bounding fault is close to the international border and the northern extension of the graben, the **Azraq Basin**, is one of the most important structures in Jordan (ANDREWS, 1992).

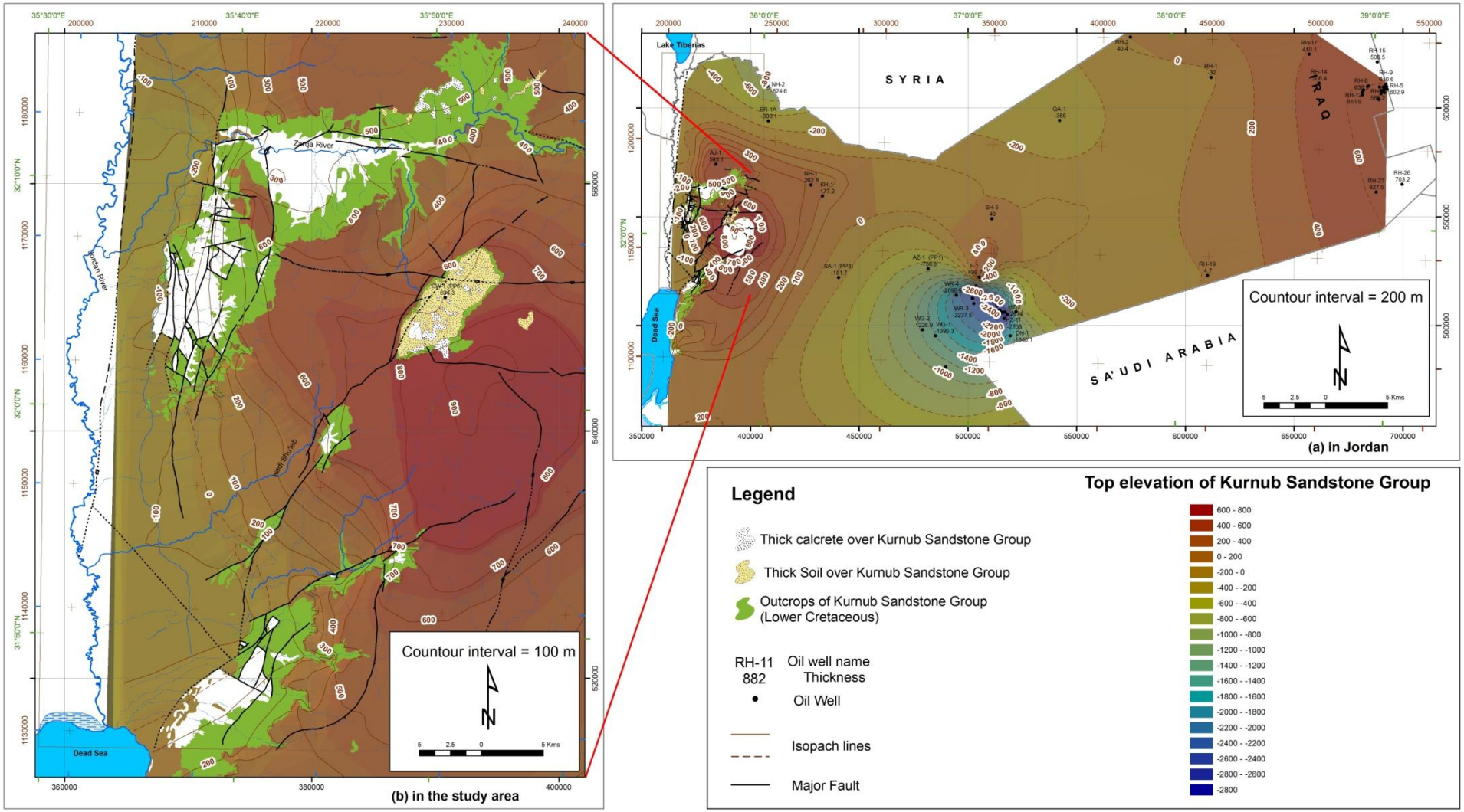


Figure 3.9: Structural contour map of the top of Kurnub Sandstone Group (Lower Cretaceous) (a) in Jordan…..(b) in NW of Jordan. (Note: no structural features outside of the study area are shown).

3.3 **Ajlun Group** (Upper Cretaceous)

3.3.1 **Ajlun Group** (Cenomanian to Turonian age)

Throughout most of Jordan, the Ajlun Group subsurface thickness range from zero in the south-east (Batn al Ghoul) to over 800 m in north Jordan (Irbid) and up to 500 m in the Azraq Basin (Table 3.3).

3.3.1.1 Isopach map of the Ajlun Group

In the geological cross sections (Plate 3) the subsurface distribution of the Lower Ajlun Group is shown.

The thickness of this group as shown in the isopach map (Figure 3.10) reaches a maximum in the northwest of Jordan (801 m in well NH-2), thinning rapidly south of the Siwaqa Fault to 148 m in well WS-2 and east of the Fuluk Fault to 260 m in well QA-1 and to 34 m in well RH-26.

CORE LAB (1987) describes a thinning of the Na'ur to Wadi as Sir rock interval in the Hamza High and suggests that this structure had a control on sedimentation throughout Cenomanian times.

3.3.2 Lower Ajlun Group

In most of Jordan the Lower Ajlun Group is characterized by a rhythmic succession of interbedded shales and carbonates (ANDREWS, 1992). It is distinguished by a relative scarcity of cherts bands (HUMPHREYS, 1977).

The base of the Lower Ajlun Group is the boundary with the Kurnub Group. In the Northern Highlands and Azraq wells the boundary is taken where a limestone-dominated succession (Ajlun) overlies the sandstones (Kurnub). However, in some wells sandstones do occur in the overlying basal Na'ur Formation (ANDREWS, 1992).

The upper boundary of the Lower Ajlun Group was placed by POWELL (1989b) with the Wadi as Sir Formation above a prominent anhydrite bed (ANDREWS, 1992).

3.3.2.1 Isopach map of the Lower Ajlun Group

In the subsurface, the maximum thickness of the four formations (Na'ur, Fuheis, Hummar and Shueib) of the **Lower Ajlun Group** was recorded in northwestern Jordan (474 m in well NH-2 and 436 m in well AJ-1), thinning rapidly south of the Siwaqa Fault and east of the Fuluk Fault [(3)] (Table 3.3 & Figure 3.11).

The geological cross sections AA′, BB′, CC′, DD′ & HH′ (Plate 5) show the subsurface distribution of the Lower Ajlun Group in the study area.

[(3)] The **Fuluk Fault zone** forms the northern bounding fault of the Azraq Basin (Figure 2.11) and has late Cretaceous sedimentary activity. This fault also forms the northern boundary of the Hamza Graben, the deepest part of the Azraq basin, which contains the intra-basinal Hamza High and dependent oilfield (ANDREWS, 1992).

Table (3.3): Thickness data and top from ground surface level for the Ajlun Group in some wells in Jordan (+ means: base of group not reached; * means: well spudded in this group) (compiled from NRA open files and after ANDREWS, 1992).

Well ID	Lower Ajlun Group				Upper Ajlun Group				Total Ajlun Group	
	Top	Bottom	Top from S.L..	Thickness	Top	Bottom	Top from S.L..	Thickness	Top from S.L..	Thickness
AD-1	1435.6	1691.1	-827.8	255.5	1197.9	1435.6	-590.1	237.7	-590.1	493.2
AJ-1	117.5	554	1029.6	436.5	7.1	117.5	1140	110.4*	1140	546.9*
AZ-1	906	1255	-389.8	349	746	906	-229.8	160	-229.8	509
DH-1	2007.5	2175.5	-1478.1	168	1647	2007.5	-1117.6	360	-1117.6	528
ER-1A	472	904	131.9	432	135	472	468.9	337	468.9	769
GTZ-2D	117	267	93	150*					93	150*
GTZ-3D	0	19	-270	19*					-270	19*
HO-2	3018	3334	-2470.9	316	2797	3018	-2249.9	221	-2249.9	537
HZ-1	2899	3056	-2334.5	157+125	2678	2899	-2113.5	221	-2113.5	503
HZ-2	3012	3245	-2441	233+30	2812.5	3012	-2241.5	199.5	-2241.5	462.5
HZ-3	3150.5	3262	-2588.4	111.5+	2896	3150.5	-2333.9	254.5	-2333.9	366+
HZ-4	3223	3489.5	-2667.6	266.5	3028	3223	-2472.6	195	-2472.6	461.5
HZ-5	2981	3281	-2430.1	300	2743	2981	-2192.1	238	-2192.1	538
HZ-6	2903	3156	-2353.4	253	2724	2903	-2174.4	179	-2174.4	432
HZ-7	2578	2881.5	-2029.5	303.5	2332	2578	-1783.5	246	-1783.5	549.5
HZ-8	3070	3371	-2508.4	301	2823	3070	-2261.4	247	-2261.4	548
HZ-9	3141	3446	-2576	305	2887	3141	-2322	254	-2322	559
HZ-10	2901	3172	-233.9	271	2726	2901	-2158.9	175	-2158.9	446
HZ-11	2926	3195.5	-2351	269.5	2823	2926	-2248	103	-2248	372.5
HZ-12	2768	3064.5	-2210.3	296.5	2683	2768	-2125.3	85	-2125.3	381.5
HZ-13	2950	3166	-2384.8	216+25	2761	2950	-2195.8	189+10	-2195.8	440
HZ-14	2775	3034.5	-2217	260	2686	2775	-2128	89	-2128	349
HZ-15	2904	3192.5	-2343	288.5	2722	2904	-2161	182	-2161	470.5
HZ-16	2859	3149	-2314.8	290	2642	2859	-2097.8	217	-2097.8	507
NH-1	57	347	552.8	290	6.8	57	603	50.2*	603	340.2*
NH-2	865	1339	-350.6	474	538	865	-23.6	327	-23.6	801
KH-1	182	430	425.2	248	2.2	182	605	179.9*	605	427.9*
SA-1	700	900	48.3	200	375	700	373.3	325	373.3	525
SH-5	335	640	345	305.0					345	305
SQ-1	921	1176	-340.9	255	715	921	-134.9	206	-134.9	461
WG-1	1670	1973	-1092.3	303	1380	1670	-802.3	290	-802.3	593
WG-2	1468	1797	-899.9	329	1205	1468	-636.9	263	-636.9	592
WH-1	860	1210	-329.4	350	705	860	-174.4	155	-174.4	505
WR-1	2760	2960	-2214.9	200	2420	2760	-1874.9	340	-1874.9	540
WR-2	2654	2963	-2103.8	309	2403.5	2654	-1853.3	250.5	-1853.3	559.5
WR-3	2463	2783	-1917.5	320	2220	2463	-1674.5	243	-1674.5	563
WR-4	2298	2627	-1767.9	329	2055	2298	-1524.9	243	-1524.9	572
WS-2	692	790	-83	98	642	692	-33	50	-33	148
QA-1	1185	1308	-242	123	1048	1185	-105	137	-105	260
RH-1	598	704	-32	44	483	598	189	115	189	159
RH-2	499	613	154.4	114	402	499	251	97	251	211
RH-3					178	253	674.9	75	674.9	75
RH-4					170	245	693.6	75	693.6	75
RH-5					182	252	672.9	70	672.9	70
RH-6					178	258	668.5	80	688.5	80
RH-7					184	245	666.1	61	666.1	61
RH-8					165	211	684.9	46	684.9	46
RH-9					172	239	677.6	67	677.6	67
RH-10					170	241	673.1	71	673.1	71
RH-11	387	488	338.9	101	310	387	415.9	77	415.9	178
RH-12					182	247	675.9	65	675.9	65
RH-13					167	215	688.6	48	688.6	48
RH-14					243	328	591.4	85	591.4	85
RH-15					245	305	568.5	60	568.5	60
RH-16					169	248	690.3	79	690.3	79
RH-17					284	380	506.1	96	506.1	96
RH-18					172	253	702.3	81	702.3	81
RH-19					618	690	76.7	72	76.7	72
RH-20					167.1	254.1	681.5	87	681.5	87
RH-21					178.5	248.5	644.8	70	644.8	70
RH-22					164.1	243.1	717.2	79	717.2	79
RH-23					239	285	673.5	46	673.5	46
RH-24					163.5	236.5	710.9	73	710.9	73
RH-25					163.5	214.5	697.9	51	697.9	51
RH-26					192.1	226.1	737.2	34	737.2	34

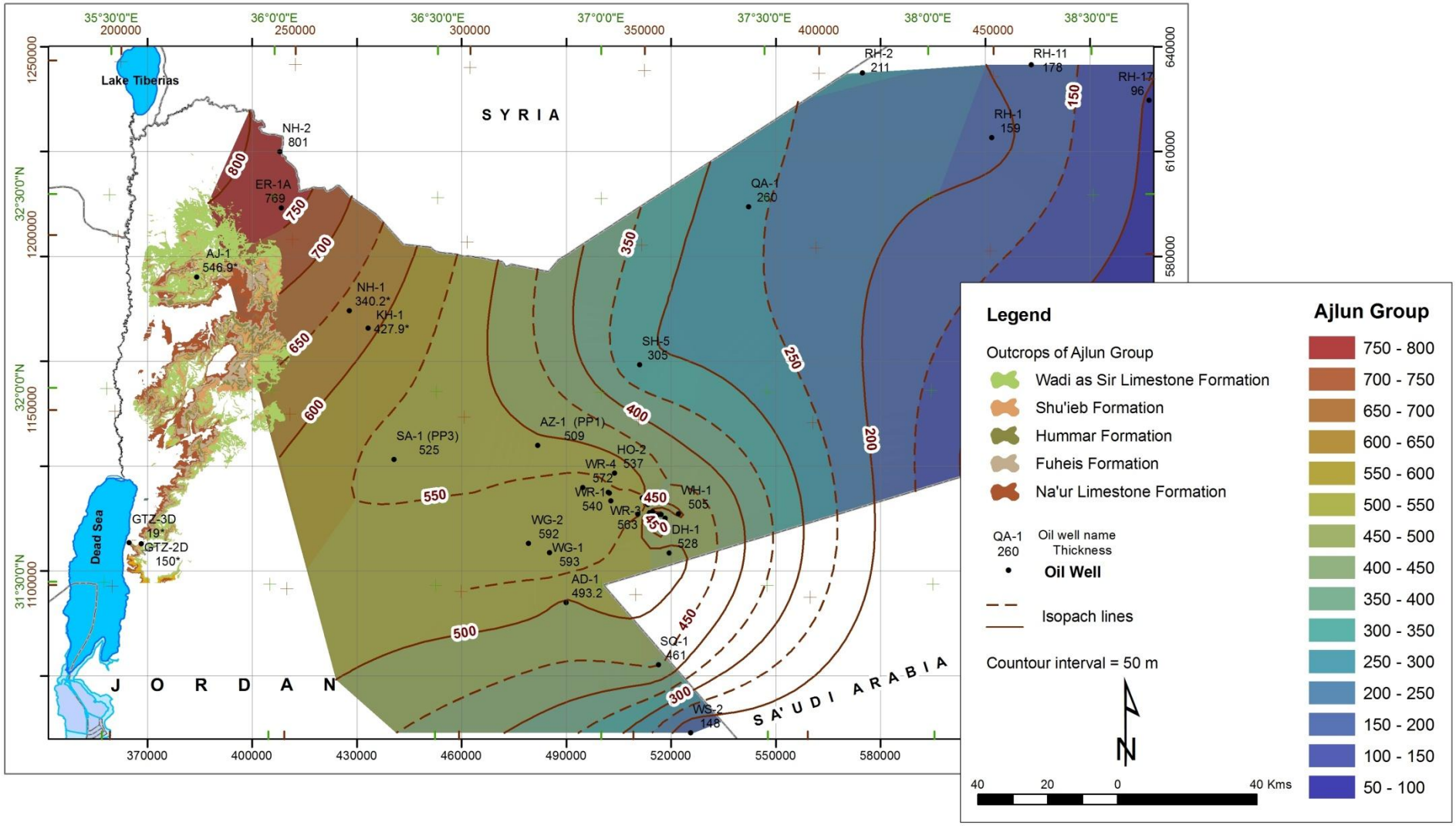


Figure 3.10: Isopach map of Ajlun Group (Upper Cretaceous). (Note: only the outcrop of Ajlun Group in the study area is shown in map).

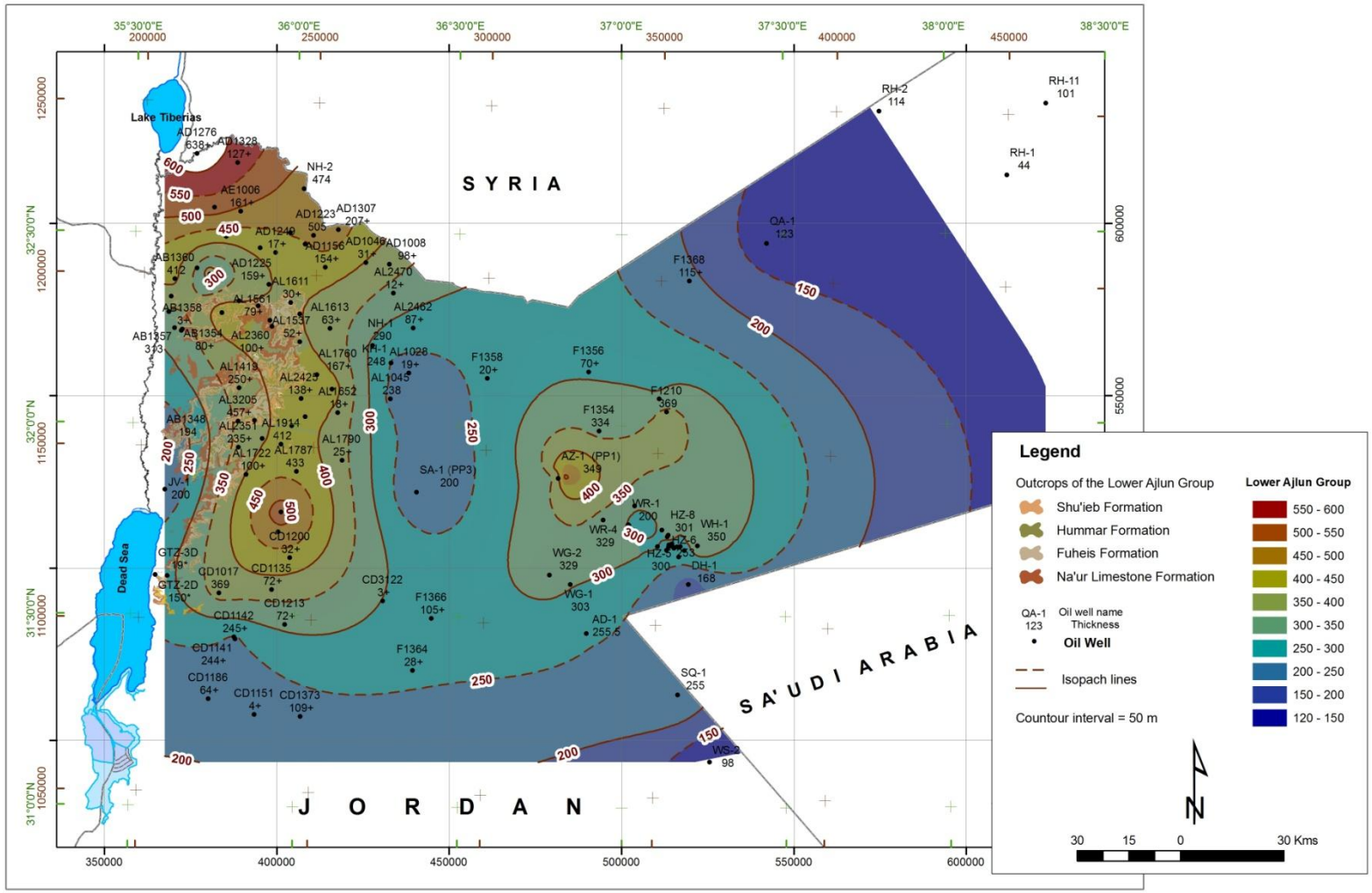


Figure 3.11: Isopach map of Lower Ajlun Group. (Note: only the outcrop of Lower Ajlun Group in the study area is shown in map).

3.3.2.2 Structural contour map for the top of Lower Ajlun Group

The top of the Lower Ajlun Group is shown in Table 3.3 and Figure 3.12. A review of data for the Lower Ajlun Group (Table 3.3) shows a regional westwards thickening from 267-271 m in the eastern Hamza wells (e.g. HZ-4), about 280-300 m in the Hamza Oilfield area, 301-307 m in the northwestern Hamza wells (e.g. HZ-9) to 329 m in wells WR-4 and WG-2 in the west. The Fuluk Fault had not been initiated at this time and displays no control on Lower Ajlun sedimentation (ANDREWS, 1992).

The circular shaped phenomenon shown in the structural contour maps Figure 3.11 for the top of Lower Ajlun Group, east of the study area is explained previously in section 3.2.2.

3.3.2.3 Formations of the Lower Ajlun Group

Due to the importance of the different formations within the Lower Ajlun Group as aquifers or aquitards; a detailed isopach map for each Formation was prepared. Thickness data were taken from WAJ water wells database and NRA oil wells database in order to show the distributions of thicknesses of the main three aquifers within the Ajlun Group. Due to the limited number and irregular distribution of wells the thickness distribution of different formations of the Lower Ajlun Group (Na'ur, Fuheis, Hummar and Shueib Formations, Figures from 3.13 to 3.16; respectively) show a kind of swell trending NE-SW which is follow the formally described trend formed during Permian to Jurassic sedimentation described in section 3.1.4.2. But the increase of the Lower Ajlun Formations towards the southeast indicates the beginning of subsidence of the NW-SE trending Sirhan-Azraq basins (Figure 2.11).

3.3.2.3.1 **Na'ur Limestone Formation (NL)** (Late Albian to Early Cenomanian)

The Na'ur Formation consists mainly of 200 m of marls and limestone. The geological cross sections AA′, BB′, CC′, DD′ & HH′ (Plate 5) show a northward and southeast thickening of the formation.

The isopach map of the Na'ur Limestone Formation (Figure 3.13) shows that the thickness of the Formation reaches a maximum of more than 254 m in Qumeim well (AE 1000) in northwest Jordan. This thickness increases also towards the east (178 m in AL 1546 well) and southeast (220 m in Na'ur outcrops.

3.3.2.3.2 **Fuheis Formation (F)** (Cenomanian)

The Fuheis Formation consists of about 80 m marl and shale overlying the Na'ur Formation and separated from the overlying limestone Hummar Formation (geological cross sections AA′, BB′, CC′, DD′ & HH′; Plate 3).

The isopach map of Fuheis Formation (Figure 3.14) shows almost a uniform 50 to 100 m thickness of Fuheis Formation in the study area.

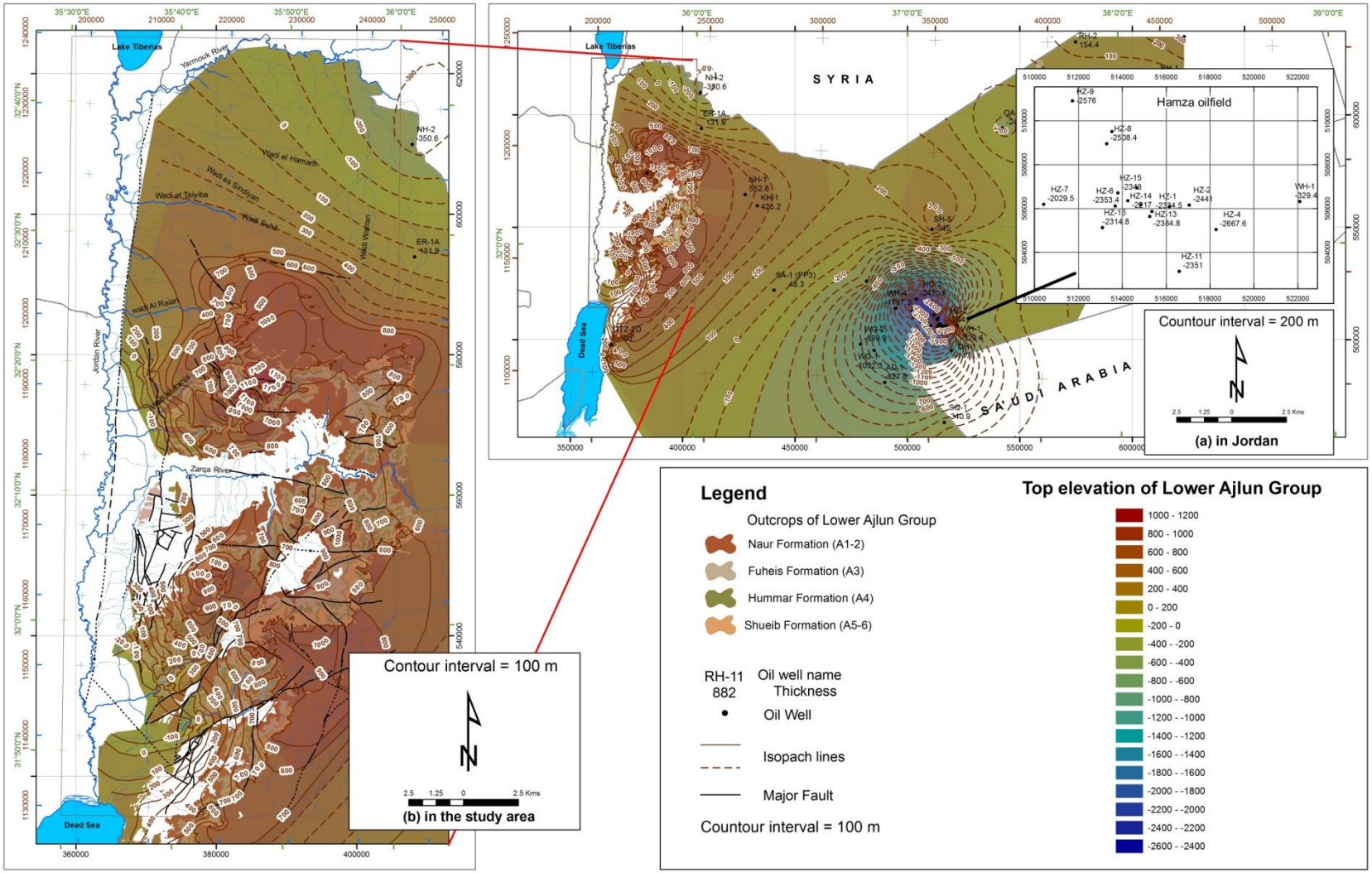


Figure 3.12: Structural contour map of the top of Lower Ajlun Group (a) in Jordan…..(b) in NW of Jordan. (Note: The map shows the outcrop of Lower Ajlun Group and the structural features in the study area only).

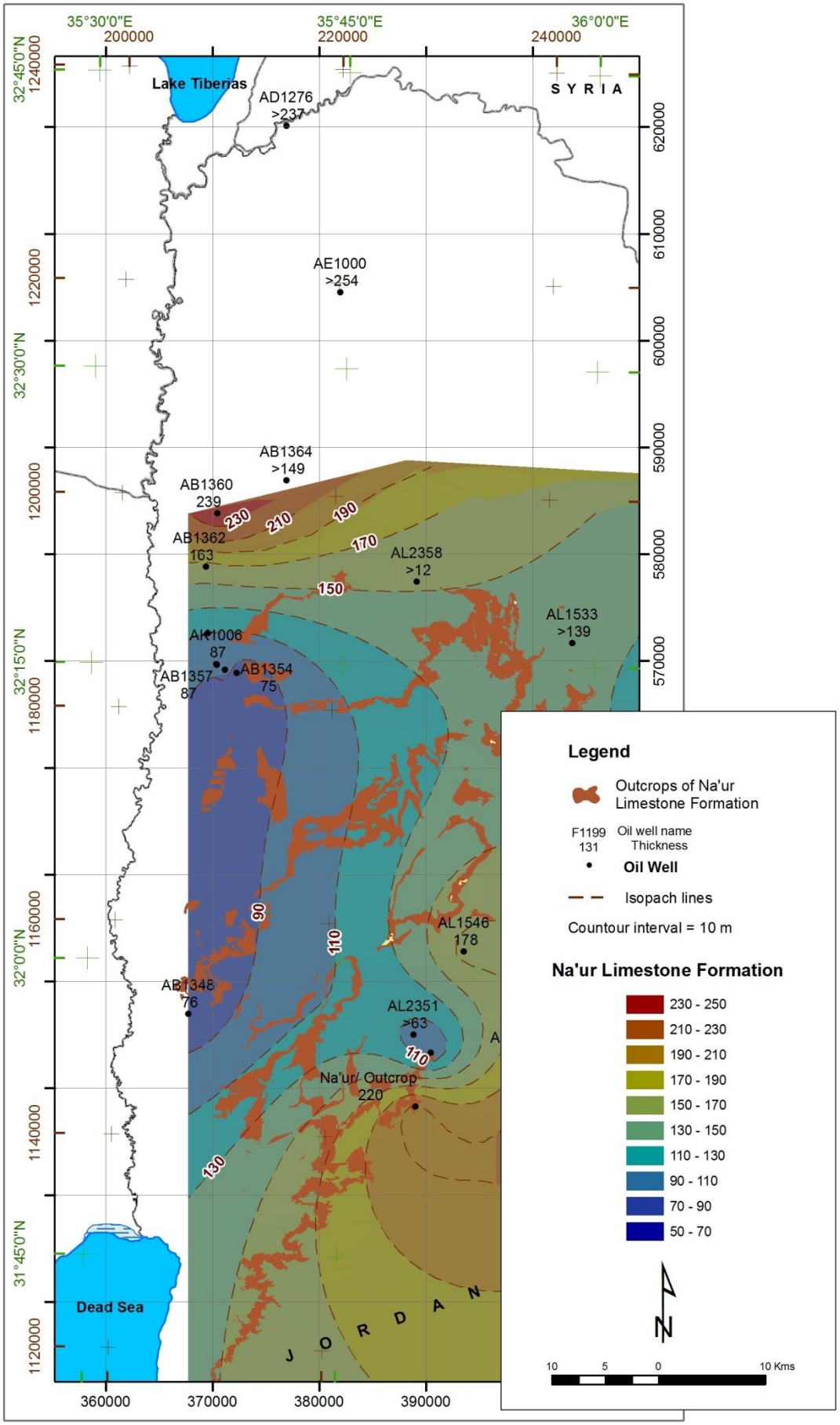


Figure 3.13: Isopach map of Na'ur Limestone Formation in NW of Jordan.

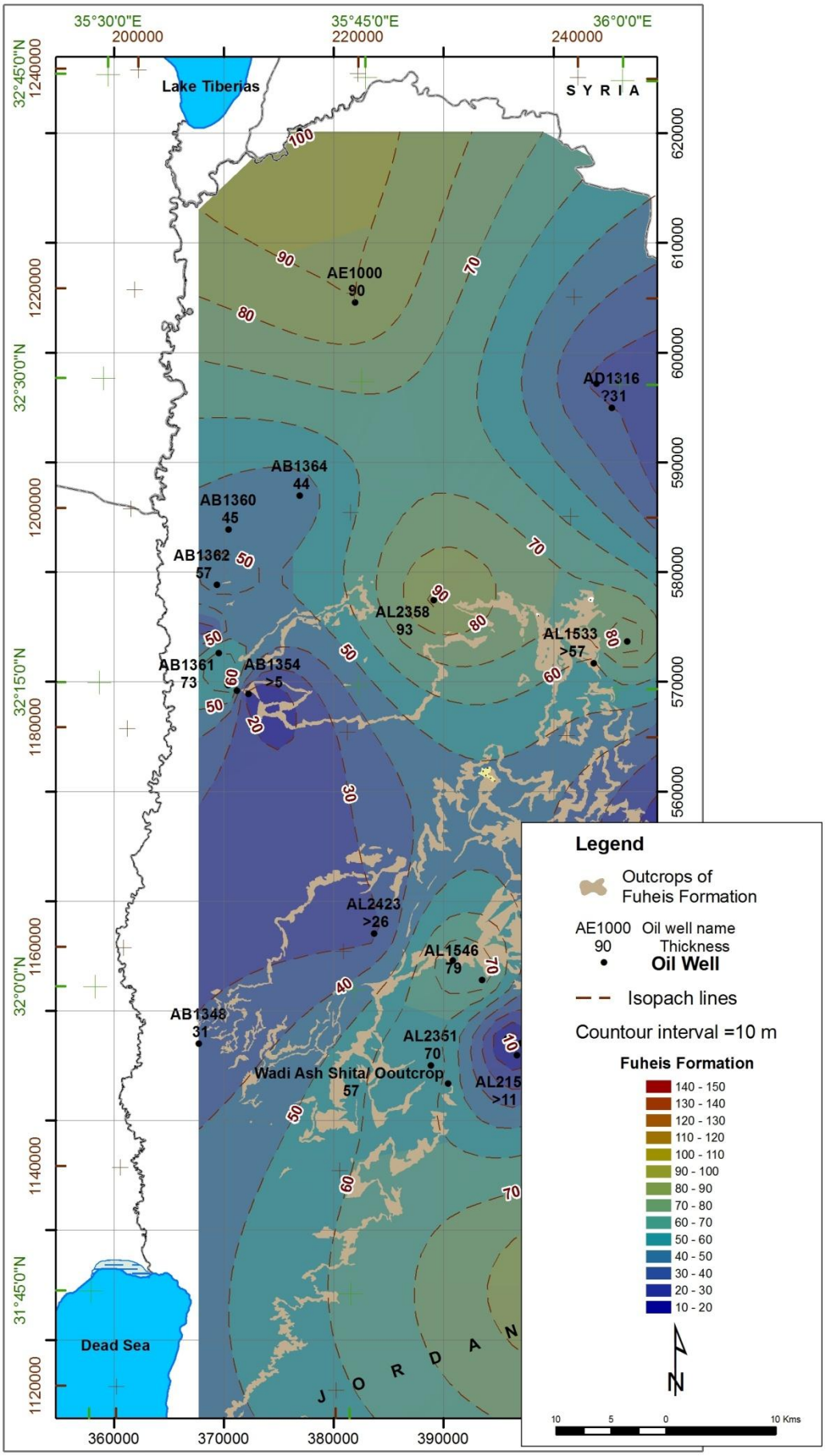


Figure 3.14: Isopach map of Fuheis Formation in NW of Jordan.

3.3.2.3.3 **Hummar Formation (H)** (Late Cenomanian)

The geological cross sections AA′, BB′, CC′, DD′ & HH′ (Plate 5) show that the Hummar Formation crops out along the highlands.

The isopach map of the Hummar Formation (Figure 3.15) shows an increase in thickness towards the northwest and the southeast of the study area. The maximum thickness of 150 m for this Formation is reached in Mukheiba JVR1, well AD 1276 in northwest Jordan.

3.3.2.3.4 **Shueib Formation (Sh)** (Late Cenomanian–Early Turonian)

The Shueib Formation consists mainly of marls and limestone. The geological cross sections AA′, BB′, CC′, DD′ & HH′ (Plate 5) show the subsurface distribution of this Formation in the study area.

The isopach map (Figure 3.16) shows an increase in thickness toward the northwest and the southeast of the study area similar to the Hummar Formation. The maximum thickness of 150 m for this Formation is reached in Mukheiba JVR1, well AD 1276 in northwest Jordan, and of more than 260 m in NDW-7, well F 1350 further southeast of the study area.

3.3.3 Upper Ajlun Group

The Wadi as Sir Formation is a prominent limestone unit forming the upper part of the Ajlun Group.

3.3.3.1 **Isopach map of the Wadi as Sir Limestone Formation (WSL)** (Turonian)

The geological cross section DD′ (Plate 5) shows the major outcrop area of this Formation. It crops out in the elevated area of Ajlun and its surrounding areas and crop further to the north as shown in sections EE′, FF′ & GG′ (Plate 5).

In the subsurface, the greatest thickness of the Wadi as Sir Formation is recorded in Well ER-1 (337 m) and well NH-2 (327 m) northwest of the study area (Figure 3.17). In the Azraq area the drilled thicknesses vary from 85 to 290 m, although the lower thicknesses may result from missing section due to faulting; but the average thickness of the Formation is 240-250 m (ANDREWS, 1992). There is no significant difference between thicknesses on the platform and those in the graben. South of Siwaqa Fault the Wadi as Sir Formation is only present in wells SQ-1 and WS-2, and is absent in the southern Wadi Sirhan area.

3.3.3.2 **Structural contour map for the top of Upper Ajlun Aquifer System**

The top of the Upper Ajlun Aquifer System is given in Table 3.3 and Figure 3.18.

Figure (3.18) shows an elongation ellipsoid contour form for the top of Upper Ajlun Group (Wadi as Sir Formation; Turonian), east of the study area, trending NNE-SSW instead of showing the pre described NW-SE trending Sirhan-Azraq graben/rift system (as described in section 3.2.2). This ellipsoid contour form is also due to the limited number and irregular distribution of deep oil wells used in the interpolation.

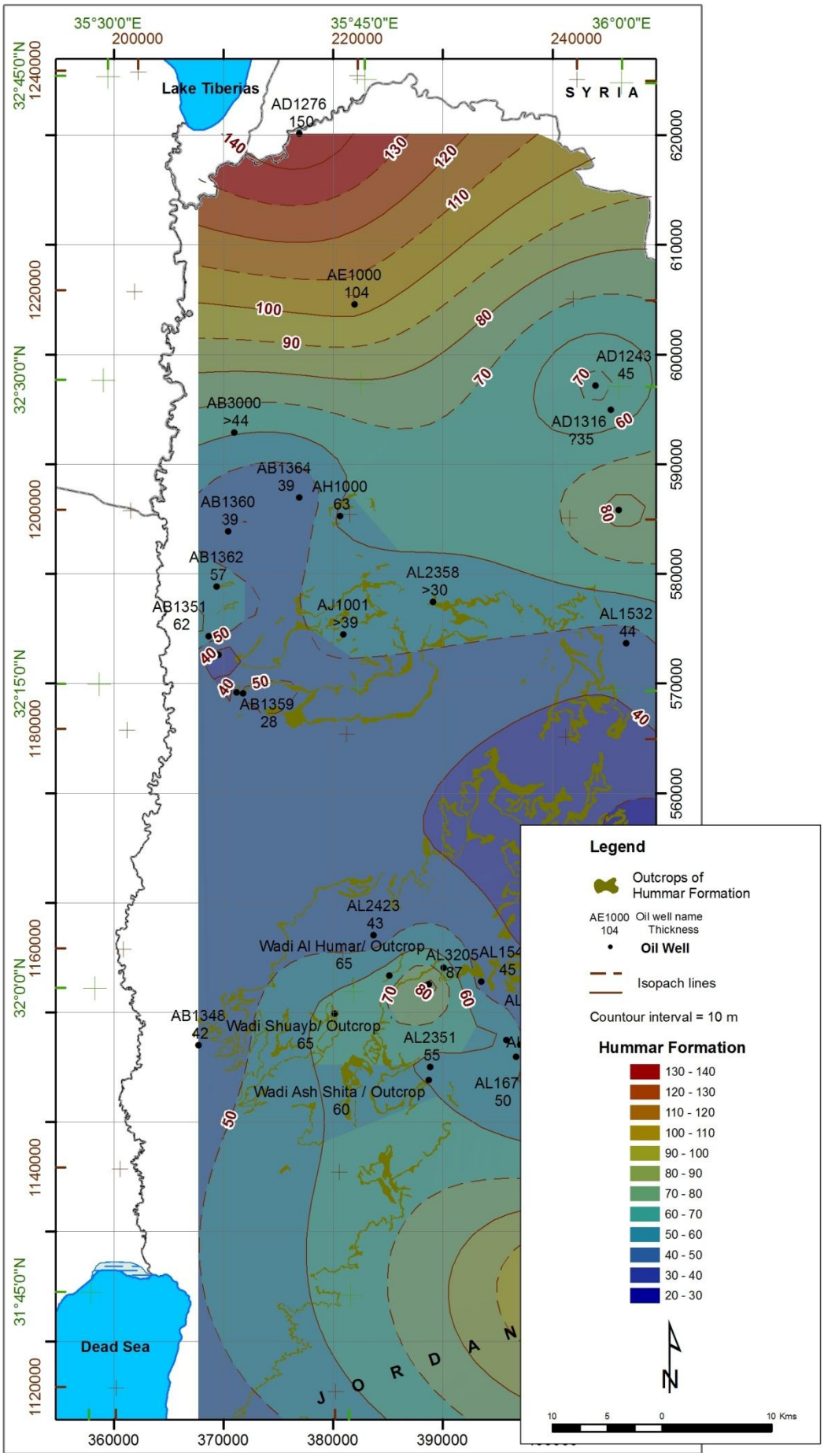


Figure 3.15: Isopach map of Hummar Formation in NW of Jordan.

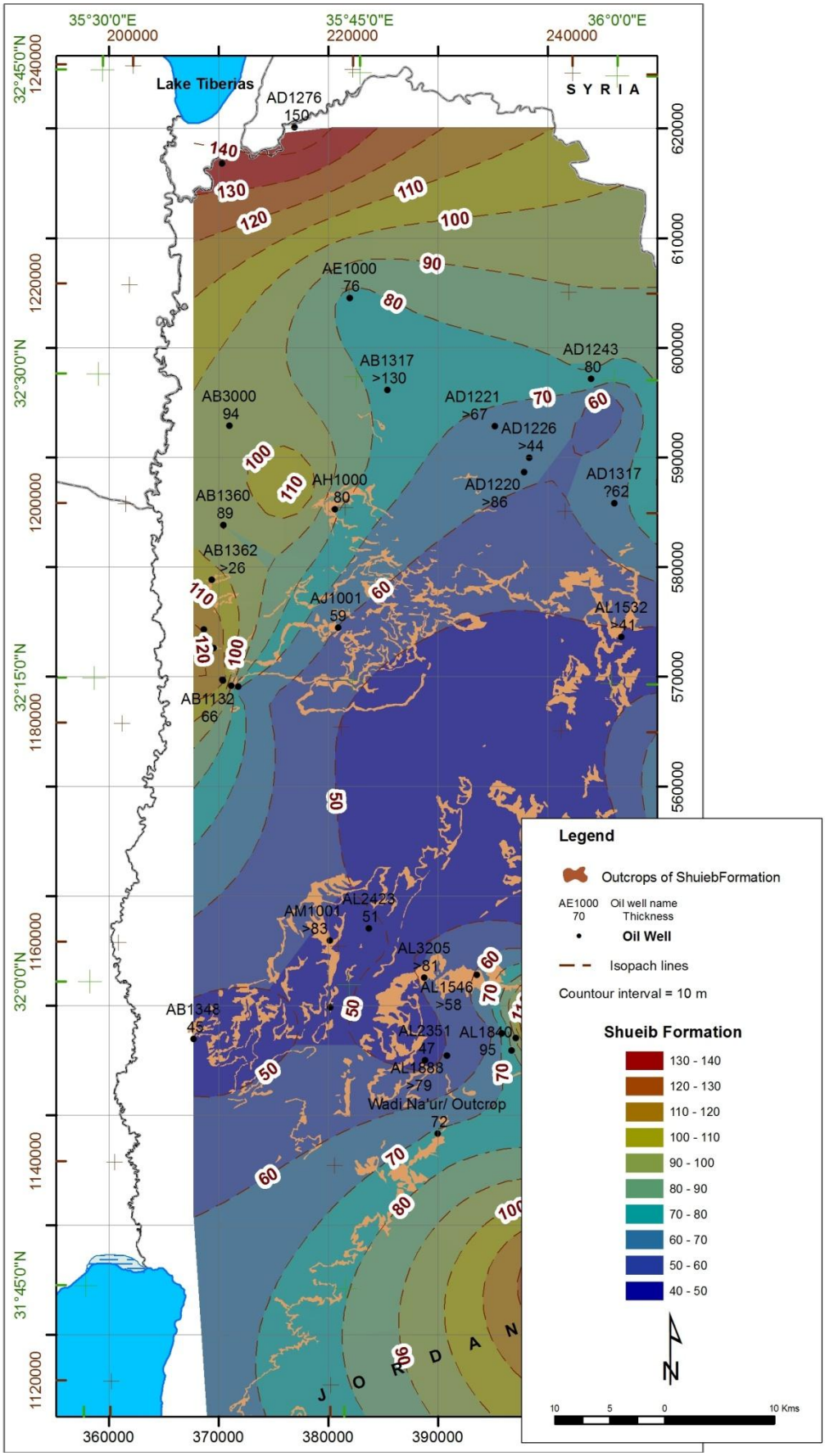


Figure 3.16: Isopach map of Shueib Formation in NW of Jordan.

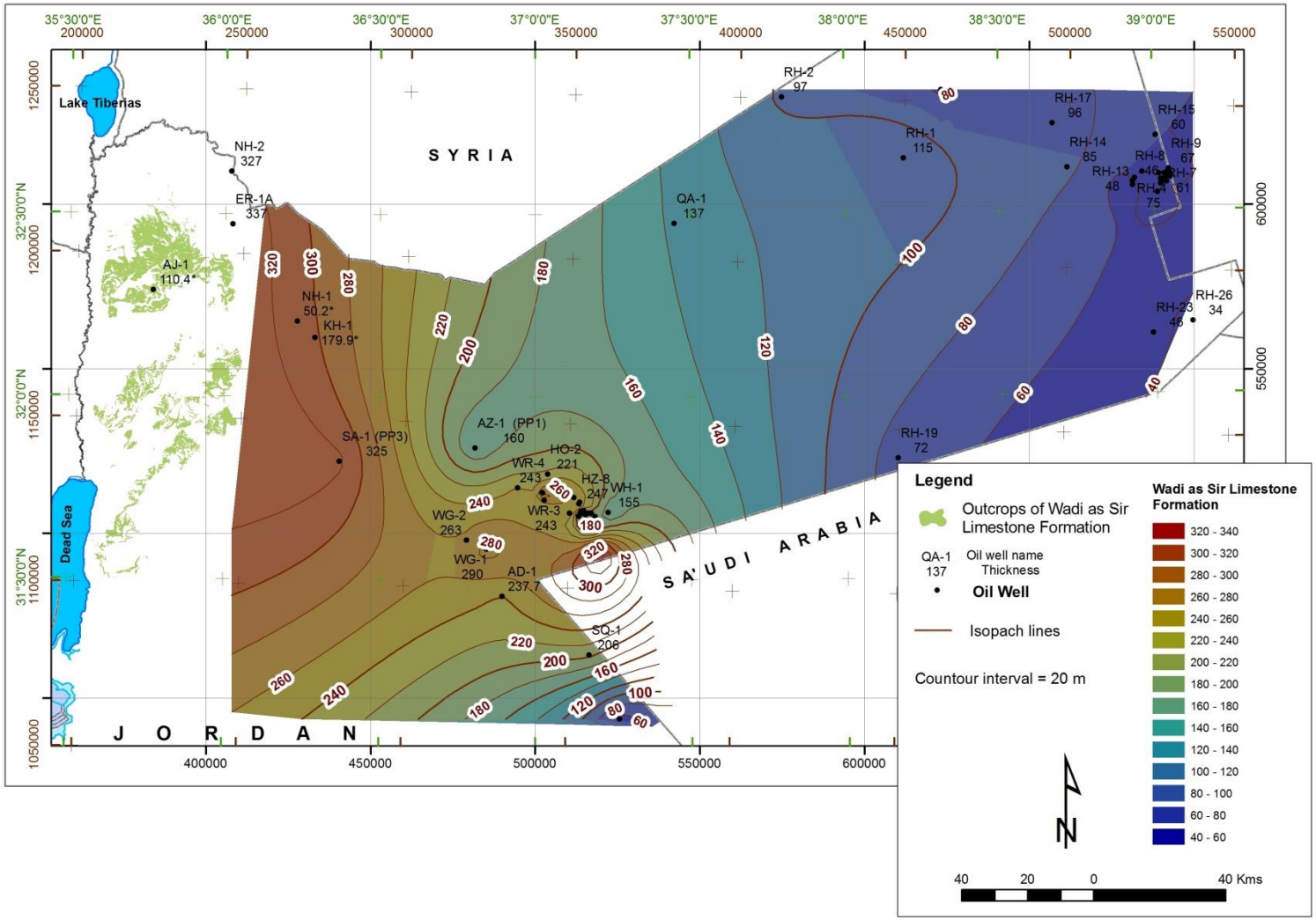


Figure 3.17: Isopach map of Upper Ajlun Group (Wadi as Sir Formation, Turonian). (Note: The map shows the outcrop of Upper Ajlun Group in the study area only).

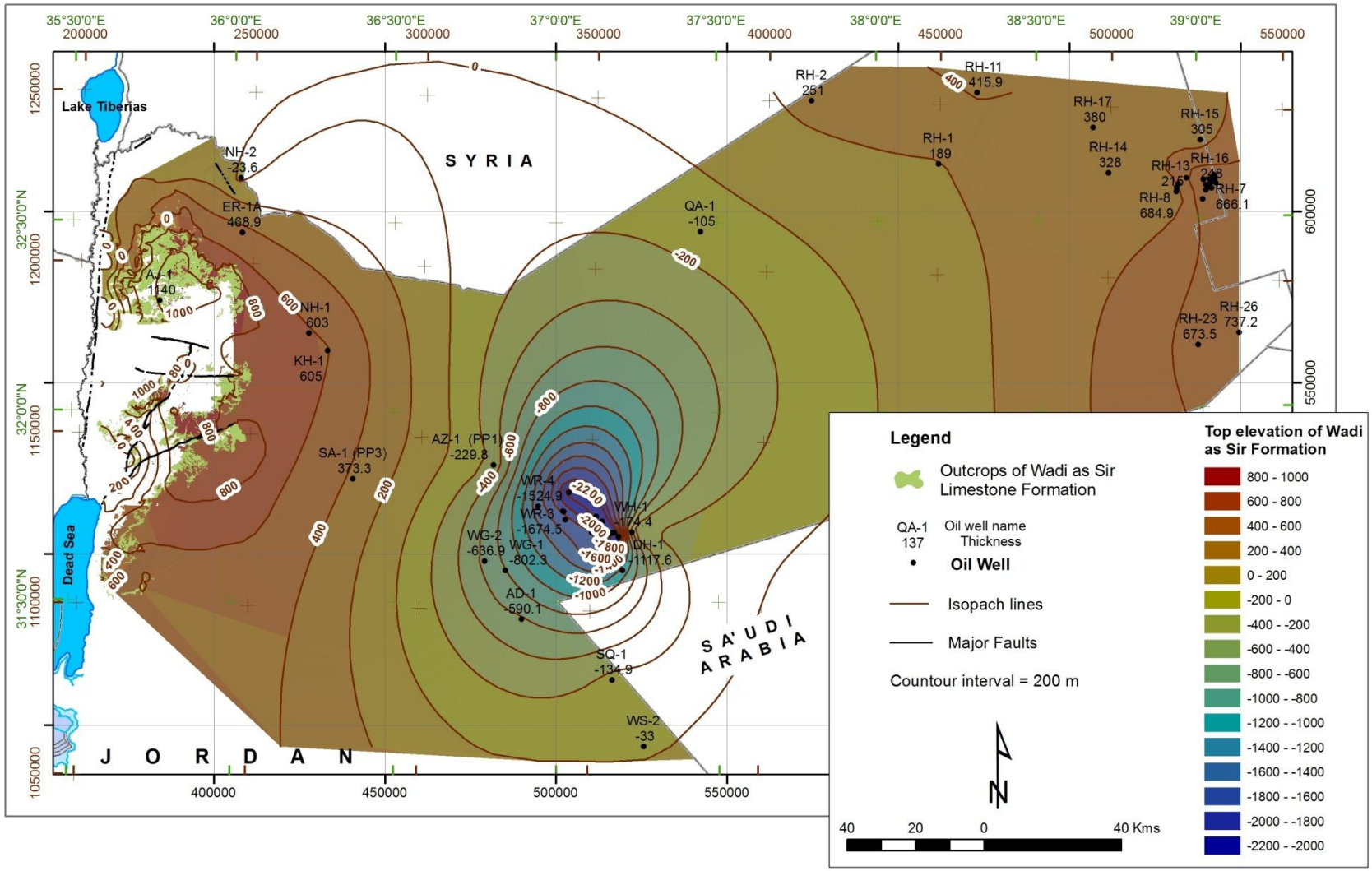


Figure 3.18: Top of Upper Ajlun Group (Wadi as Sir Formation, Turonian). (Note: The map shows the outcrop of Upper Ajlun Group and the structural features in the study area only).

3.4 **Belqa Group** (Upper Cretaceous – Tertiary)

In the subsurface of the study area, the Amman Silicified Limestone and Al Hisa Phosphorite are considered as one unit forming the base of the Belqa Group (ANDREWS, 1992). The top of the Belqa Group (Wadi Shallala Formation) is not fully penetrated in any of the wells, because it crops out at the surface in most areas were wells penetrates the Belqa Group (ANDREWS, 1992).

3.4.1 Isopach map of the Amman Silicified Limestone and Al Hisa Phosphorite Formations (ASL/AHP)

The major outcrop area of the Amman-Al Hisa Formation is shown in (Plate 4) and the geological cross section EE′ (Plate 5). It also, likes Wadi as Sir Formation, sub-crops to the northern of the study area (geological cross sections FF′, GG′ & HH′, Plate 5).

In the subsurface, the thickness of the Amman - Al Hisa Formation shows thinning toward east and southeast (Table 3.4). The isopach maps of the Amman Silicified and Al Hisa Phosphorite Formations show that their thickness vary from 20 to 41 m in the eastern Risha area and 69-91 m in the southern Sirhan area to a maximum of 138.5 m in Azraq area well HZ-11 and 141 m in well NH-2 (Figure 3.19).

The increasing in thickness of the Amman-Al Hisa Formation in the eastern part of Jordan (Hamza oilfield area) (Figure 3.19) indicates the beginning of subsidence of Sirhan-Azraq rift basin.

3.4.2 Isopach map of the Muwaqqar Chalk-Marl Formation (MCM)

The geological cross sections EE′, FF′, GG′ & HH′ (Plate 5) show the surface distribution of the Muwaqqar Chalk-Marl Formation in the study area. They also show the strong dipping of this Formation mainly to the west towards the Jordan Rift Valley.

The Muwaqqar Chalk-Marl Formation was only fully penetrated in northwestern Jordan, well NH-2 where a thickness of 322 m was recorded (Table 3.4). The isopach map of the Muwaqqar Chalk-Marl Formation shows that the Formation thins to the south and southeast; and reaches a maximum of 288 m in the Azraq area, well HZ-4 (Figure 3.20).

3.4.3 Isopach map of the Umm Rijam Chert Limestone Formation (URC)

The Umm Rijam Formation is exposed at the surface in the northern most areas of the study area (geological cross sections FF′, GG′ & HH′, Plate 5). The outcrop thickness there reaches 220 m, but only 67.9 m of this formation is penetrated in well NH-2 (Table 3.4 & Figure 3.21). The Umm Rijam Formation is only fully penetrated in the Azraq and Sirhan areas. The isopach map shows thickening of the Formation in the Azraq area (well HZ-1) reaching a maximum thickness of 311 m.

Table 3.4: Thickness data and top from ground surface level for the Upper Ajlun and Belqa Groups in some wells in Jordan (+ means base of group not reached; * means: well spudded in this Formation) (compiled from NRA open files and after ANDREWS, 1992).

Well	Amman-Al Hisa (ASL) Formation				Muwaqqar (MCM) Formation				Umm Rijam (URC) Formation				Wadi Shalala (WSC) Formation			
	Top	Bottom	Top from S.L..	Thickness	Top	Bottom	Top from S.L..	Thickness	Top	Bottom	Top from S.L..	Thickness	Top	Bottom	Top from S.L..	Thickness
AD-1	464.2	563.9	143.6	99.7	359.1	464.2	248.7	105.1	189	359.1	418.8	170.1	81.1	189	526.7	107.9
AJ-1																
AZ-1	184	256	332.2	72	56	184	460	128	8	56	508.2	48				
DH-1	754	844	-224.6	90	582	754	-52.6	172	310	582	219.4	272	35	310	494	275
ER-1A	45	135	558.9	90	6*	45	597.9	39*								
F-1	34.5	81	546.2	46.5	9*	34.5	571.7	25.5								
HO-1	772.5	885	-330.2	112.5	581	772.5	-38.7	191.5	335	581	207	246	102	335	440.3	233
HO-2	901	1025	-353.9	124	675	901	-127.9	226	450	675	97.1	225	110	450	437.1	340
HZ-1	979	1090	-414.5	111	736	979	-171.5	243	425	736	139.5	311	155	425	409.5	270*
HZ-2	986.5	1110.5	-415.5	124	712	986.5	-141	274.5	420	712	151	292	118	420	453	302
HZ-3	1011.5	1130	-449.4	118.5	785	1011.5	-222.9	226.5	480	785	82.1	305	216	480	346.1	264
HZ-4	1030	1166.5	-474.6	136.5	742	1030	-186.6	288	435	742	120.4	307	120	435	435.4	315
HZ-5	1011	1128	-460.1	117	760.5	1011	-209.6	250.5	435	760.5	115.9	325.5	175	435	375.9	260
HZ-6	1006	1128	-456.4	122	760	1006	-210.4	246	485	760	64.6	275	160	485	389.6	325
HZ-7	904	1024	-355.5	120	688	904	-139	216	415	688	133.5	273	161	415	387	254
HZ-8	1100	1220.5	-538.4	120.5	852	1100	-290.4	248	575	852	-13.4	277	198	575	363.6	377
HZ-9	1066	1188	-501	122	834	1066	-269	232	580	834	-15	254	188	580	377	392
HZ-10	988	1110	-420.9	122	726	988	-158.9	262	428	726	139.2	298	150	428	417.2	278
HZ-11	991.5	1130	-416.5	138.5	708.5	991.5	-133.5	283	415	708.5	160.5	239.5	110	415	465	305
HZ-12	989	1106.5	-431.3	117.5	739	989	-181.3	250	412	739	145.7	327	13	412	414.7	269
HZ-13	973	1089	-407.8	116	720	973	-154.8	253	370	720	195.2	350	149	370	416.2	221
HZ-14	993	1112.5	-435	119.5	744	993	-186	249	458	744	100	286	154	458	404	304
HZ-15	1005.5	1118.5	-444.5	113	761	1005.5	-200	244.5	475	761	86	286	165	475	396	310
HZ-16	982	1104.5	-437.5	122.5	796	982	-251.8	186	565	796	-20.8	231	137	565	407.2	428
JF-1	29	108	841.8	79												
JF-2	55	144	796	89												
NH-2	397	538	117.4	141	75	397	439.4	322	7.1*	75	507.3	67.9*				
QA-1	940	1011	3	71	848.5	940	94.5	91.5	680	848.5	263	168.5	478.5	680	464.5	201.5
QUR	1198	1286	-664	88	969	1198	-435	229	671	969	-137	298	116	671	418	555
RH-1	445	483	227	38	312	445	360	133	113	312	559	199	5.1*	113	666.9	107.9*
RH-2	313	390	340	77	222	313	431.4	91	5.1*	222	648.3	216.9*				
RH-3	152	178	700.9	26	70	152	782.9	82	7*	70	845.9	63*				
RH-4	147.5	170	716.1	22.5	66	147.5	797.6	81.5	5.1*	66	858.5	60.9*				
RH-5	154	182	700.9	28	72	154	782.9	82	8.1*	72	846.8	63.9*				
RH-6	153	178	693.2	25	79	153	767.2	74	5.4*	79	840.8	73.7*				
RH-7	160	184	690.1	24	88	160	762.1	72	8*	88	842.1	80*				
RH-8					94	165	755.9	71	5.3*	94	844.6	88.7*				
RH-9	145	172	704.6	27	84	145	765.6	61	8.1*	84	841.5	75.9*				
RH-10	149	170	694.1	21	68	149	774.6	80.5	5.3*	68	837.8	63.2*				
RH-11	225	310	500.9	85	173	225	552.9	52	8.1*	173	717.8	164.9*				

Page (1)

Table 3.4: Thickness data and top from ground surface level for the Upper Ajlun and Belqa Groups in some wells in Jordan (+ means base of group not reached; * means: well spudded in this Formation) (compiled from NRA open files and after ANDREWS, 1992).

Well ID	Amman-Al Hisa (ASL) Formation				Muwaqqar (MCM) Formation				Umm Rijam (URC) Formation				Wadi Shalala (WSC) Formation			
	Top	Bottom	Top from S.L..	Thickness	Top	Bottom	Top from S.L..	Thickness	Top	Bottom	Top from S.L..	Thickness	Top	Bottom	Top from S.L..	Thickness
RH-12	146	182	711.9	21	55	146	802.9	91	5.4*	55	852.5	49.7*				
RH-13					92	167	763.6	75	8*	92	847.6	84*				
RH-14	202	243	632.4	41	75	202	759.4	127	5.3*	75	829.1	69.7*				
RH-15	209	245	604.5	36	112	209	701.5	97	9.1*	112	804.4	102.9*				
RH-16	145	169	714.3	24	92	145	767.3	53	9.1*	92	850.2	82.9*				
RH-17	263	284	527.1	21	129	263	661	134	9.1*	129	781	119.9*				
RH-18	151	172	723.3	21	99	151	775.3	52	9.1*	99	865.2	89.9*				
RH-19	548	571	146	23	461	548	233.7	87	239	461	455.7	222	5.4*	239	689.3	233.6*
RH-20	144.1	167.1	704.5	23	73.1	144.1	775.5	71	9.1*	73.1	839.5	64*				
RH-21	149.5	178.5	673.8	29	90.5	149.5	732.8	59	5.5*	90.5	817.8	85*				
RH-22	133.1	164.1	748.2	31	74.1	133.1	807.2	59	9.1*	74.1	872.2	65*				
RH-23	216	239	696.5	23	115	216	797.5	101	9.1*	115	903.4	105.9*				
RH-24	142.5	163.5	731.9	21	60.5	142.5	813.9	82	5.5*	60.5	868.9	55*				
RH-25	135.5	163.5	725.9	28	67.5	135.5	793.9	68	5.5*	67.5	855.9	62*				
RH-26	168.1	192.1	761.2	24	117.1	168.1	812.2	51	9.1*	117.1	920.2	108*				
SA-1	320	375	428.3	55	95	320	653.3	225	0*	95	748	95*				
SH-5	285	335	395	50	190	285	490	95	0*	190	680	190*				
SM-1					610	790	145	180	200	610	555	410				
SQ-1	464	715	-65.9	69	545	646	35.1	101	348	545	232.1	197	95	348	485.1	89.5
WG-1	560	600	17.7	40	400	560	177.7	160	182	400	395.7	218	65	182	512.7	117
WG-2	433	505	135.1	72	307	433	261.1	126	185	307	383.1	122	57	185	511.1	128
WH-1	415	618	115.6	203	310	415	220.6	105	41	310	489.6	269	0*	41	530	41*
WR-1	825	965	-279.9	140	640	825	-94.9	185	370	640	175.1	270	45	370	500.1	325
WR-2	802	888	-251.8	86	597	802	-46.8	205	330	579	220.2	267	121	330	429.2	209
WR-3	765	855	-219.5	90	584	765	-38.5	181	350	584	195.6	234	110	350	435	240
WR-4	650	709	-119.9	59	494	650	36.1	156	280	494	250.1	214	120	280	410	160
WS-1	645	720	-80	75	470	645	95	175	5.3*	470	559.7	464.7				
WS-2	585	642	24	57	483	585	126	102	317	483	292	166	5.1*	317	603.9	311.9*
WS-03	133	260	749.6	65	42	133	840	91	5.1*	42	877.5	36.9				
WS-04	383	462	244.7	79	290	383	337.7	93	142	290	485.7	148	2.3*	142	625.4	139.7*
WS-05	407	487	227.2	79	312	407	322.2	95	163	312	471	149	5.4*	163	628.8	157.6*
WS-06	374	452	259.8	78	279	374	354.8	95	132	279	501.8	147	2.3*	132	631.5	129.7*
WS-07	414	486	212.9	72	339	414	287.9	75	202	339	424	137	5.4*	202	621.6	196.6*
WS-08	391	466	249.3	75	290	391	350.3	101	142	290	498.3	148	2.3*	142	638	139.7*
WS-09	360	431.5	322.2	71.5	238	360	444.2	122	105	238	577.2	133	2.3*	105	679.9	102.7*
WS-10	611	680	-15.5	69	507	611	88.5	104	342	507	253.5	165	7.1*	342	588.4	334.9*
WS-11	421	506.5	210.8	85.5	345	421	286.8	76	198	345	433.8	147	5.4*	198	626.4	192.6*
WS-12	485	496	145.9	11	369	485	261.9	116	200	369	430.9	169	5.4*	200	625.9	195*
WS-13	425	499	197.3	74	332	425	290.3	93	183	332	439.3	149	2.3*	183	620	180.7
WS-14	583	674	12.3	91	405	583	190.3	178	247	405	348.3	158	5.1*	247	590.2	241.9

Page (2)

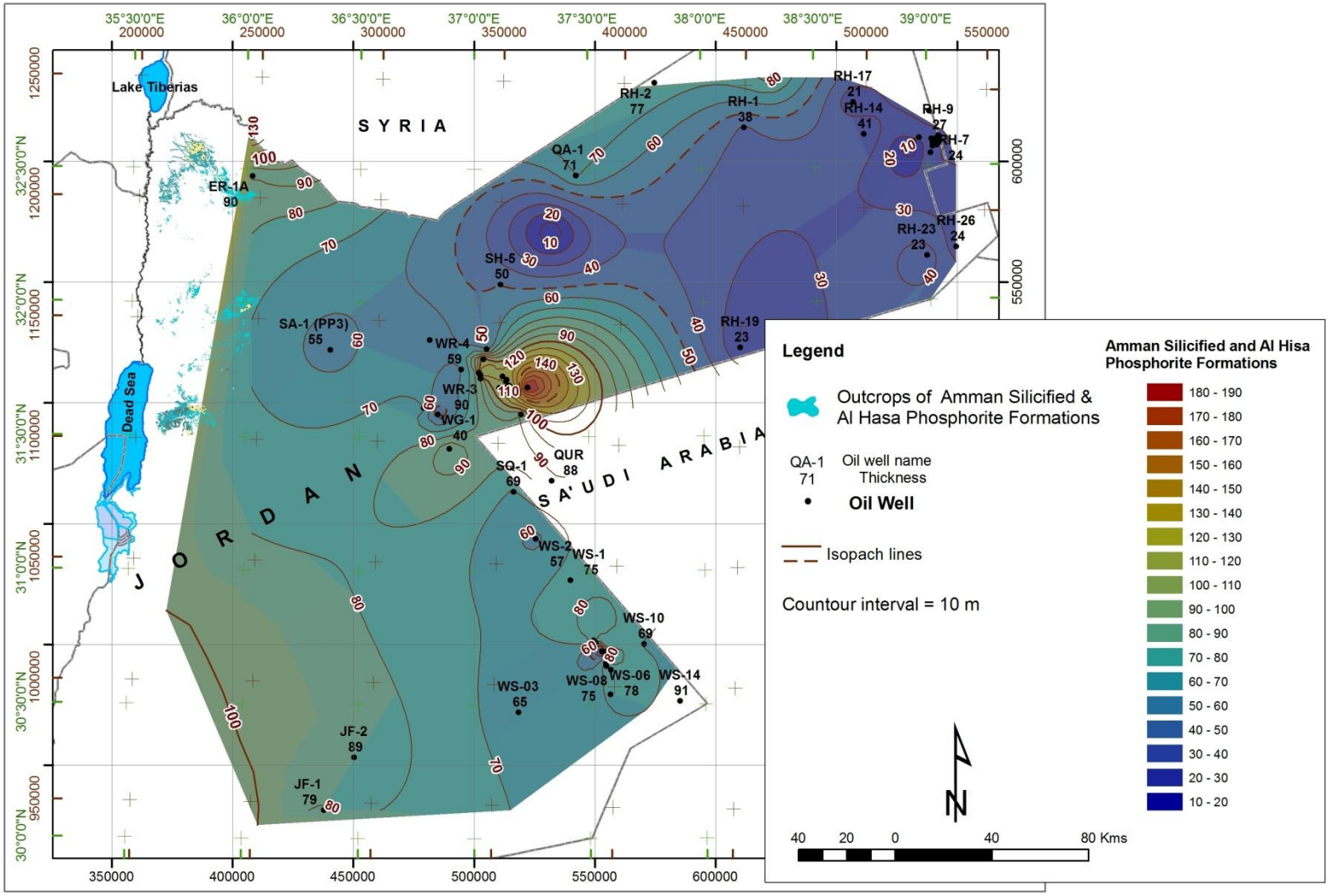


Figure 3.19: Isopach map of the Amman Silicified Limestone and Al Hisa Phosphorite Formations (ASL/AHP). (Note: The map shows the outcrop of ASL/AHP in the study area only).

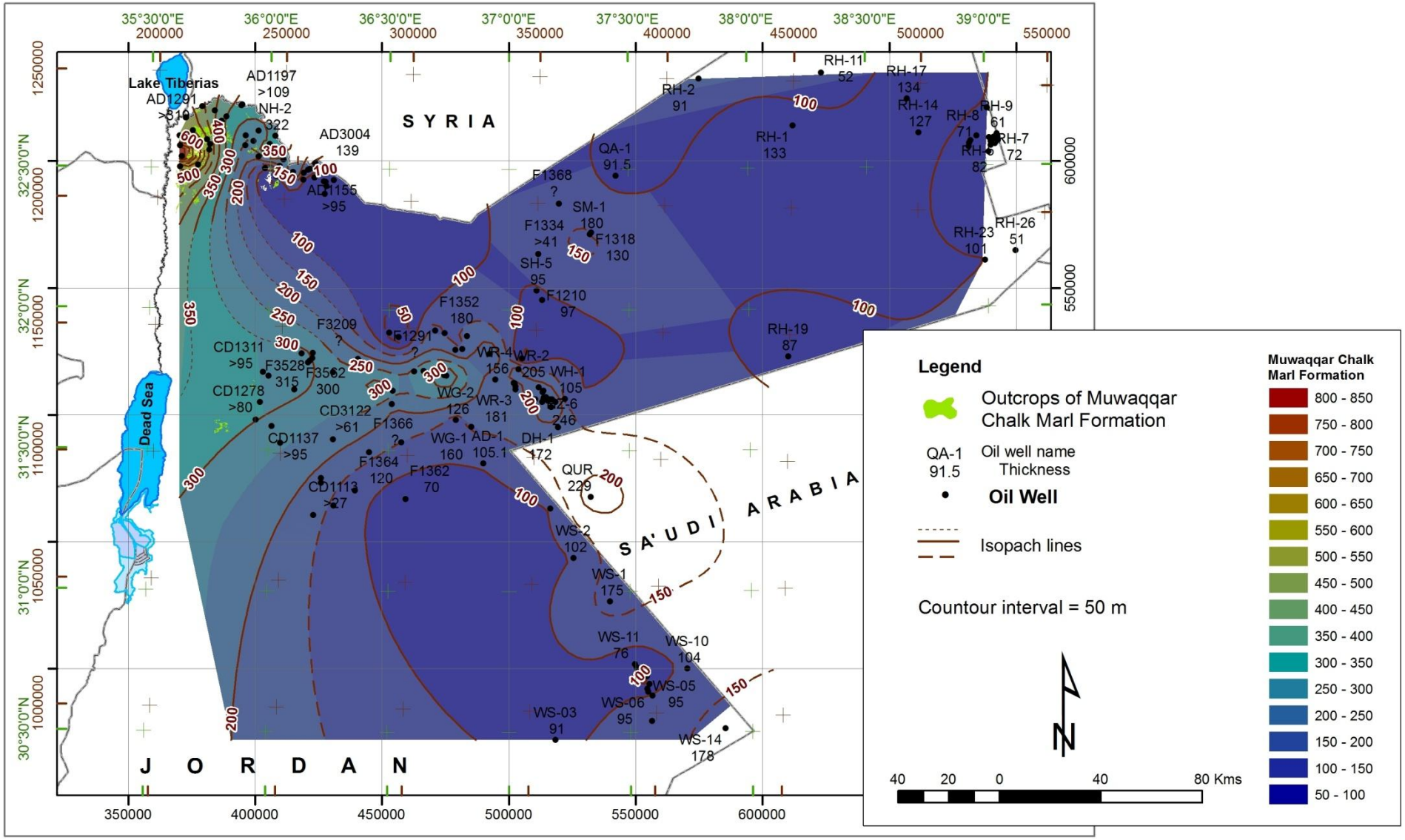


Figure 3.20: Isopach map of the Muwaqqar Chalk-Marl Formation (MCM). (Note: The map shows the outcrop of MCM in the study area only).

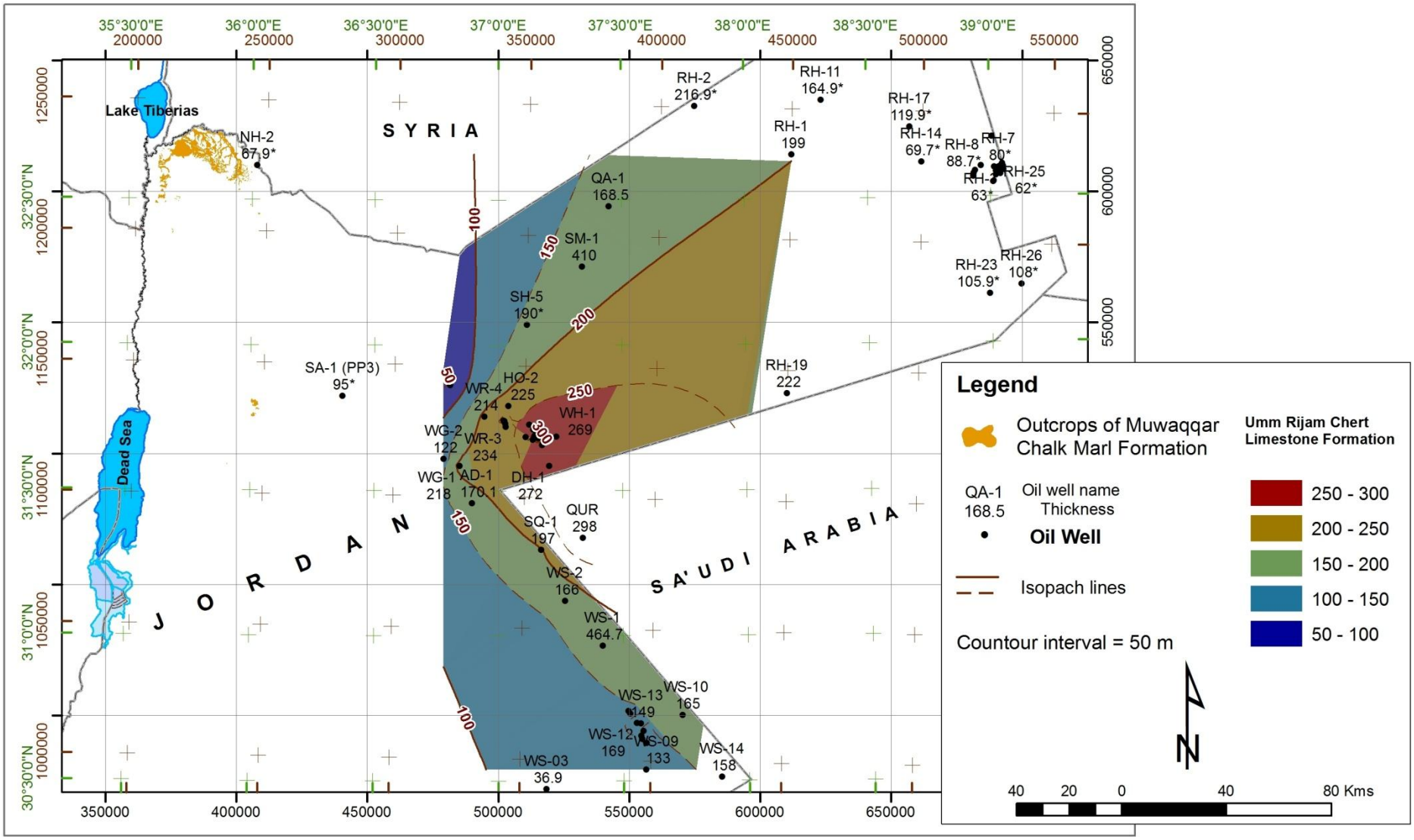


Figure 3.21: Isopach map of the Umm Rijam Chert Limestone Formation (URC). (Note: The map shows the outcrop of URC in the study area only).

3.4. 4 Isopach map of the Wadi Shallala Chalk Formation (WSC)

The Wadi Shalala Formation is exposed in the study area. The exposures are shown in the Geological Cross Sections EE′, FF′ & GG′ (Plate 5). The isopach map of the Wadi Shallala Formation shows an increase of thickness towards the east of the study area (Table 3.4 & Figure 3.22).

3.4.5 Isopach map of the Tayyiba Limestone Formation (TL)

In the subsurface, no rocks of the Tayyiba Formation have been drilled (ANDREWS, 1992).

3.4.6 Wadi as Sir (WSL or A_7)/Amman-Al Hisa Silicified Limestone (ASL or B_2) (Turonian)

The importance of Wadi as Sir Formation (WSL) together with the overlying Amman-Al Hisa Silicified Limestone Formation (ASL) lies in the fact that: it forms a major aquifer, especially considering its cavernous upper 20 m (MASRI, 1963). This aquifer is well known in Jordan as the B_2/A_7 aquifer.

3.4.6.1 Isopach map of the Wadi as Sir (WSL)/Amman-Al Hisa Silicified Limestone (ASL); (B_2/A_7)

The Wadi as Sir and Amman-Al Hisa Silicified Limestone are shown in the isopach map (Figure 3.23). They range in thickness from 180 m along the eastern border of the study area, increasing to 400 m in the Jordan Rift Valley (Table 3.5).

According to GTZ & MWI (2004) "the thickness distribution of the B_2/A_7 unit reflects the high tectonic activity during the time of the deposition of these formations. The thickness is enormously high in a down-faulted tectonic block delineated by the E-W striking Siwaqa Fault, the ENE-WSW striking Zarqa Main-Azraq Fault, and the NW-SE striking Fuluq Fault. In the Hamza Graben the thickness reaches a maximum of more than 3000 m, close to the Fuluq Fault, and thins progressively from there to the west. South of the Siwaqa Fault the thickness of the B_2/A_7 unit decreases from more than 300 m close to the fault in southerly and southeasterly directions. In the Hammad area, east of the Fuluq Fault, the thickness decreases from NW to SE and reaches a minimum of around 40 m in the Risha area". The results from the isopach map (Figure 3.23) and the following structural contour map (Figure 3.24) for the B_2/A_7 agrees with the GTZ & MWI (2004) findings.

In the north-western part of the study area the B_2/A_7 thickness trends to increase towards north and towards the Rift Valley.

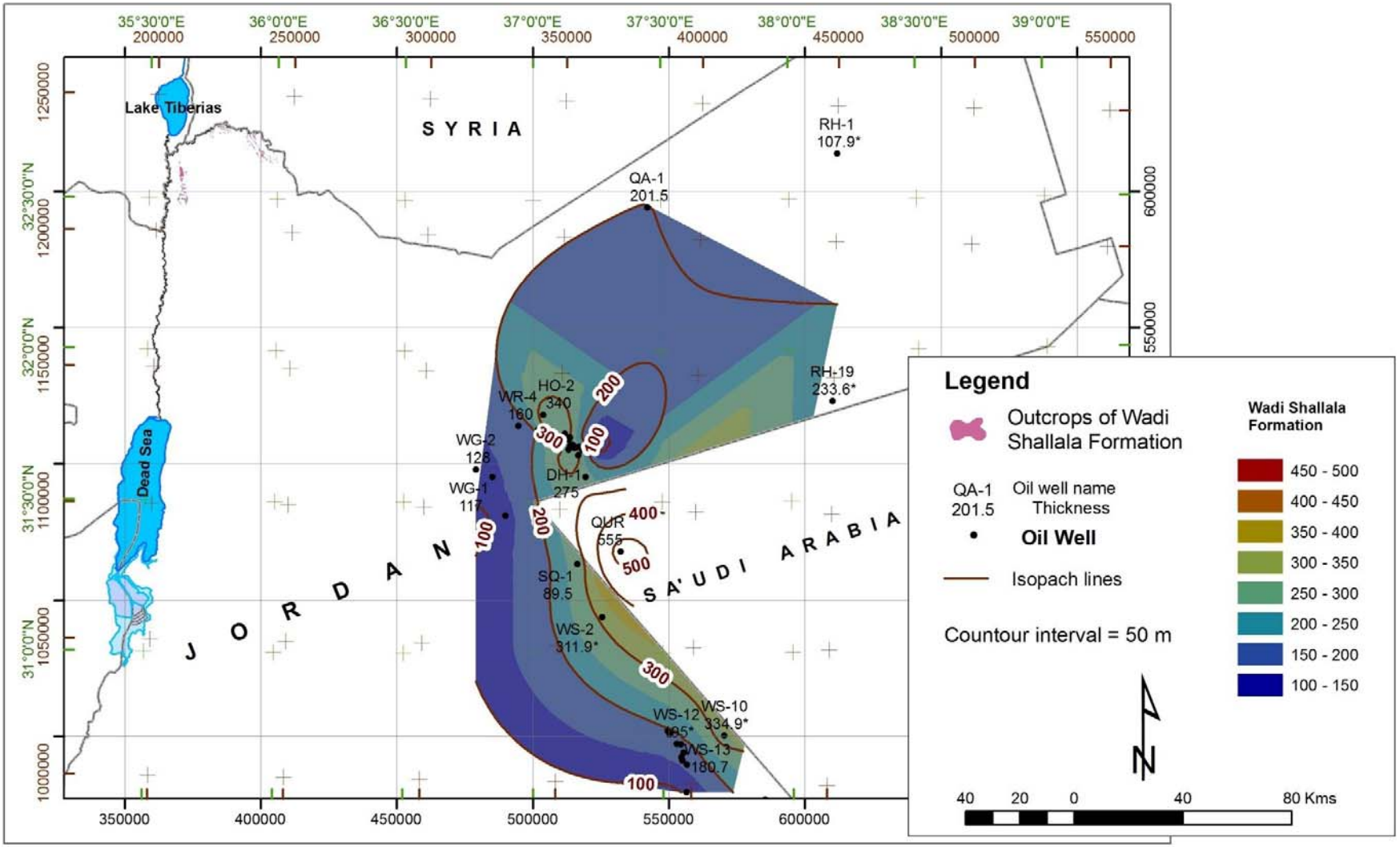


Figure 3.22: Isopach map of the Wadi Shallala Chalk Formation (WSC). (Note: The map shows the outcrop of WSC in the study area only).

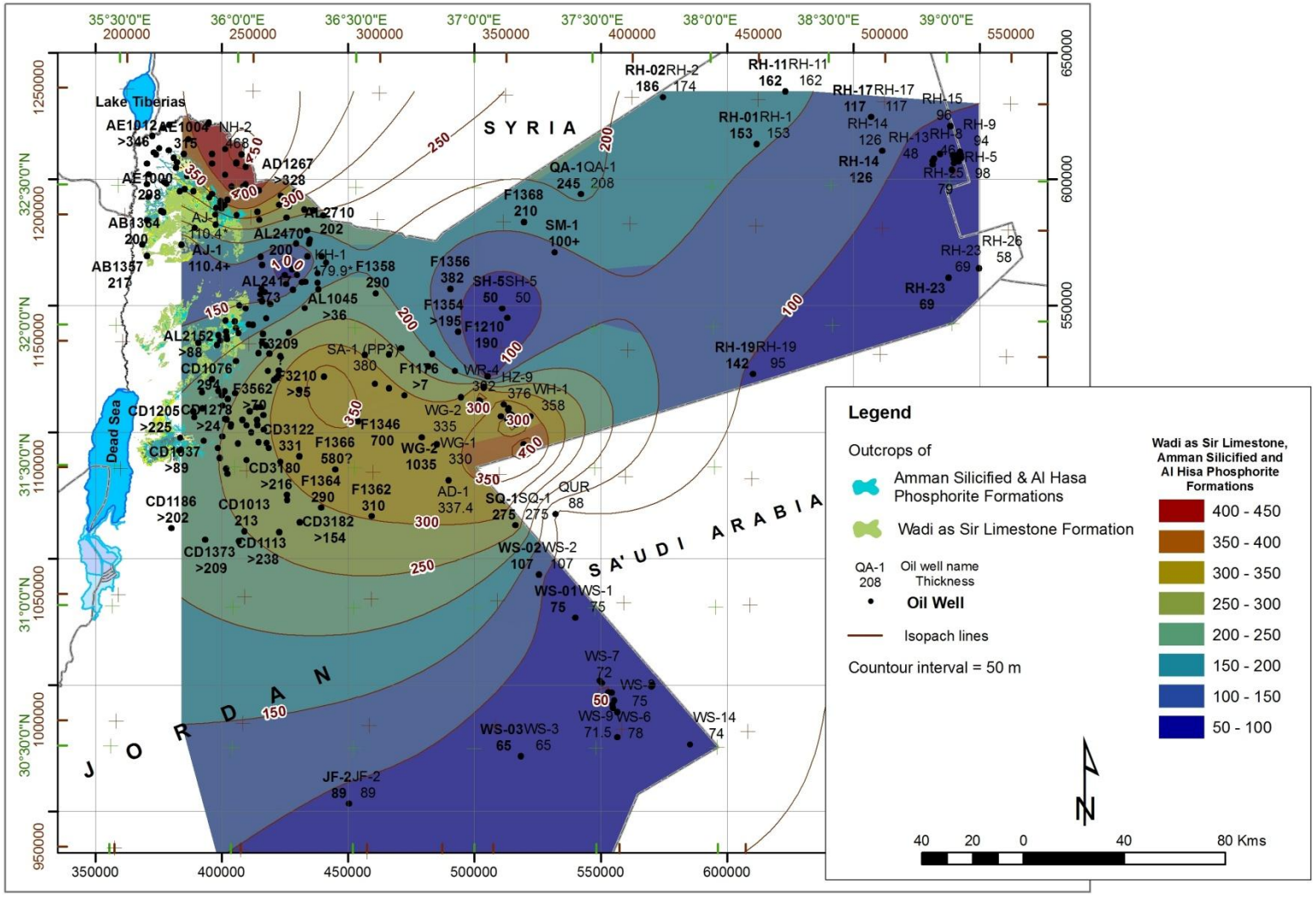


Figure 3.23: Isopach map of the Wadi as Sir and Amman-Al Hisa Silicified Limestone (B_2/A_7). (Note: The map shows the outcrop of B_2/A_7 in the study area only).

Table 3.5: Thickness data and top from ground surface level for the Belqa Group in some wells in Jordan (+ means base of group not reached; * means: well spudded in this Formation) (compiled from NRA open files and after ANDREWS, 1992).

Well	JTM-E	JTM-N	A_7 Top	A_7 Base	A_7 TSL	A_7 Th	B_2 Top	B_2 Base	B_2 TSL	B_2 Th	A_7B_2 Top	A_7B_2 Base	A_7B_2 TSL	A_7B_2 Th
AD-1	489838.698	480934.14	1197.9	1435.6	-590.1	237.7	464.2	563.9	143.6	99.7	464.2	1435.6	143.6	337.4
AJ-1	384068.944	574067.487	7.1*	1117.5	1140	110.4*					7.1*	1117.5	1140	110.4*
AZ-1 (PP1)	481679.25	525972.192	746	906	-229.8	160	184	256	332.2	72	184	906	332.2	232
DH-1	519417.351	495163.716	1647	2007.5	-1117.6	360	754	844	-224.6	90	754	2007.5	-224.6	450
ER-1A	408244.657	593911.937	135	472	468.9	337	45	135	558.9	90	45	472	558.9	427
F-1	505192.749	522237.984					34.5	81	546.2	46.5	34.5	81	546.2	46.5
HO-1	502593.353	511188.971					772.5	885	-330.2	112.5	772.5	885	-330.2	112.5
HO-2	503785.525	517960.75	2797	3018	-2249.9	221	901	1025	-353.9	124	901	3018	-353.9	345
HZ-1	515342.845	505861.842	2678	2899	-2113.5	221	979	1090	-414.5	111	979	2899	-414.5	332
HZ-2	517050.328	506147.649	2812.5	3012	-2241.5	199.5	986.5	1110.5	-415.5	124	986.5	3012	-415.5	323.5
HZ-3	513527.75	509504.078	2896	3150.5	-2333.9	254.5	1011.5	1130	-449.4	118.5	1011.5	3150.5	-449.4	373
HZ-4	518268.864	505028.15	3028	3223	-2472.6	195	1030	1166.5	-474.6	136.5	1030	3223	-474.6	331.5
HZ-5	514663.49	506936.537	2743	2981	-2192.1	238	1011	1128	-460.1	117	1011	2981	-460.1	355
HZ-6	513674.867	506103.066	2724	2903	-2174.4	179	1006	1128	-456.4	122	1006	2903	-456.4	301
HZ-7	510409.51	506183.637	2332	2578	-1783.5	246	904	1024	-355.5	120	904	2578	-355.5	366
HZ-8	513280.643	508948.345	2823	3070	-2261.4	247	1100	1220.5	-538.4	120.5	1100	3070	-538.4	367.5
HZ-9	511718.838	510903.154	2887	3141	-2322	254	1066	1188	-501	122	1066	3141	-501	376
HZ-10	516143.214	506072.584	2726	2901	-2158.9	175	988	1110	-420.9	122	988	2901	-420.9	297
HZ-11	516590.749	503121.525	2823	2926	-2248	103	991.5	1130	-416.5	138.5	991.5	2926	-416.5	241.5
HZ-12	514833.716	506156.987	2683	2768	-2125.3	85	989	1106.5	-431.3	117.5	989	2768	-431.3	202.5
HZ-13	515243.072	505632.546	2761	2950	-2195.8	189+10	973	1089	-407.8	116	973	2950	-407.8	116
HZ-14	514253.762	506343.416	2686	2775	-2128	89	993	1112.5	-435	119.5	993	2775	-435	208.5
HZ-15	513793.707	506701.87	2722	2904	-2161	182	1005.5	1118.5	-444.5	113	1005.5	2904	-444.5	295
HZ-16	513085.88	505124.185	2642	2859	-2097.8	217	982	1104.5	-437.5	122.5	982	2859	-437.5	339.5
JF-1	437791.783	331354.474					29	108	841.8	79	29	108	841.8	79
JF-2	450385.661	353182.106					55	144	796	89	55	144	796	89
KH-1	433136.601	559469.303	2.2	182	605	179.9					2.2	182	605	179.9
NH-1	427780.012	564478.041	6.8*	57	603	50.2*					6.8*	57	603	50.2*
NH-2	407908.66	609920.195	538	865	-23.6	327	397	538	117.4	141	397	865	117.4	468
QA-1	542134.486	594129.676	1048	1185	-105	137	940	1011	3	71	940	1185	3	208
QUR	532164.194	467693.557					1198	1286	-664	88	1198	1286	-664	88

Page 1

Table 3.5: Thickness data and top from ground surface level for the Belqa Group in some wells in Jordan (+ means base of group not reached; * means: well spudded in this Formation) (compiled from NRA open files and after ANDREWS, 1992).

Well	JTM-E	JTM-N	A_7 Top	A_7 Base	A_7 TSL	A_7 Th	B_2 Top	B_2 Base	B_2 TSL	B_2 Th	A_7B_2 Top	A_7B_2 Base	A_7B_2 TSL	A_7B_2 Th
RH-1	611768.076	613968.995	483	598	189	115	445	483	227	38	445	598	227	153
RH-2	574701.333	632447.369	402	499	251	97	313	390	340	77	313	499	340	174
RH-3	691933	609146.743	178	253	674.9	75	152	178	700.9	26	152	253	700.9	101
RH-4	689858.899	607867.592	170	245	693.6	75	147.5	170	716.1	22.5	147.5	245	716.1	97.5
RH-5	692713.029	608454.706	182	252	672.9	70	154	182	700.9	28	154	252	700.9	98
RH-6	692580.064	609733.027	178	258	668.2	80	153	178	693.2	25	153	258	693.2	105
RH-7	690976.946	609527.255	184	245	666.1	61	160	184	690.1	24	160	245	690.1	85
RH-8	681375.7	607124.358	165	211	684.9	46					165	211	684.9	46
RH-9	692240.336	610885.21	172	239	677.6	67	145	172	704.6	27	145	239	704.6	94
RH-10	684214.412	609989.118	170	241	673.1	71	149	170	694.1	21	149	241	694.1	92
RH-11	623067.939	634788.15	310	387	415.9	77	225	310	500.9	85	225	387	500.9	162
RH-12	681901.729	608118.512	182	247	675.9	65	146	182	711.9	21	146	247	711.9	86
RH-13	681306.451	605893.788	167	215	688.6	48					167	215	688.6	48
RH-14	661406.753	611302.817	243	328	591.4	85	202	243	632.4	41	202	328	632.4	126
RH-15	688256.428	621057.471	245	305	568.5	60	209	245	604.5	36	209	305	604.5	96
RH-16	691152.474	608104.956	169	248	690.3	79	145	169	714.3	24	145	248	714.3	103
RH-17	656894.658	624627.548	284	380	506.1	96	263	284	527.1	21	263	380	527.1	117
RH-18	690505.666	607234.319	172	253	702.3	81	151	172	723.3	21	151	253	723.3	102
RH-19	610173.753	522955.493	618	690	76.7	72	548	571	146	23	548	690	146	95
RH-20	691832.153	610010.301	167.1	254.1	681.5	87	144.1	167.1	704.5	23	144.1	254.1	704.5	110
RH-21	689256.299	609464.852	178.5	248.5	644.8	70	149.5	178.5	673.8	29	149.5	248.5	673.8	99
RH-22	688958.467	603785.185	164.1	243.1	717.2	79	133.1	164.1	748.2	31	133.1	243.1	748.2	110
RH-23	687665.021	561180.812	239	285	673.5	46	216	239	696.5	23	216	285	696.5	69
RH-24	689868.778	606399.2	163.5	236.5	710.9	73	142.5	163.5	731.9	21	142.5	236.5	731.9	94
RH-25	691631.537	606987.59	163.5	214.5	697.9	51	135.5	163.5	725.9	28	135.5	214.5	725.9	79
RH-26	699667.857	564810.333	192.1	226.1	737.2	34	168.1	192.1	761.2	24	168.1	226.1	761.2	58
SA-1 (PP3)	440505.728	521940.084	375	700	373.3	325	320	375	428.3	55	320	700	428.3	380
SH-5	510957.17	548992.202					285	335	395	50	285	335	395	50
SQ-1	516311.308	463150.498	715	921	-134.9	206	464	715	-65.9	69	464	921	-65.9	275
WG-1	485094.026	495205.124	1380	1670	-802.3	290	560	600	17.7	40	560	1670	17.7	330
WG-2	479119.018	497922.069	1205	1468	-636.9	263	433	505	135.1	72	433	1468	135.1	335
WH-1	522083.64	506316.024	705	860	-174.4	155	415	618	115.6	203	415	860	115.6	358
WR-1	502207.664	512305.806	2420	2760	-1874.9	340	825	965	-279.9	140	825	2760	-279.9	480
WR-2	501945.387	512468.054	2403.5	2654	-1853.3	250.5	802	888	-251.8	86	802	2654	-251.8	336.5

Page 2

Table 3.5: Thickness data and top from ground surface level for the Belqa Group in some wells in Jordan (+ means base of group not reached; * means: well spudded in this Formation) (compiled from NRA open files and after ANDREWS, 1992).

Well	JTM-E	JTM-N	A_7 Top	A_7 Base	A_7 TSL	A_7 Th	B_2 Top	B_2 Base	B_2 TSL	B_2 Th	A_7B_2 Top	A_7B_2 Base	A_7B_2 TSL	A_7B_2 Th
WR-3	502683.101	510018.858	2220	2463	-1674.5	243	765	855	-219.5	90	765	2463	-219.5	333
WR-4	494678.916	513862.011	2055	2298	-1524.9	243	650	709	-119.9	59	650	2298	-119.9	302
WS-1	539917.65	426616.266					645	720	-80	75	645	720	-80	75
WS-2	525519.28	443666.997	642	692	-33	50	585	642	24	57	585	692	24	107
WS-03	518412.666	371932.173					133	260	749.6	65	133	260	749.6	65
WS-04	554597.006	392197.071					383	462	244.7	79	383	462	244.7	79
WS-05	555381.353	393997.147					407	487	227.2	79	407	487	227.2	79
WS-06	554885.002	391046.604					374	452	259.8	78	374	452	259.8	78
WS-07	550366.907	400688.016					414	486	212.9	72	414	486	212.9	72
WS-08	556604.548	389440.554					391	466	249.3	75	391	466	249.3	75
WS-09	556520.222	379389.057					360	431.5	322.2	71.5	360	431.5	322.2	71.5
WS-10	570356.858	400108.196					611	680	-15.5	69	611	680	-15.5	69
WS-11	549609.826	401729.238					421	506.5	210.8	85.5	421	506.5	210.8	85.5
WS-12	552946.195	397139.743					485	496	145.9	11	485	496	145.9	11
WS-13	554385.828	397005.927					425	499	197.3	74	425	499	197.3	74
WS-14	554385.828	397005.927					583	674	12.3	91	583	674	12.3	91

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Abbreviations

JTM: Jordan Traverse Mercator
Top: Top of unit
Base; Base of unit
TSL: Top from mean sea level
Th: Thickness
A_7: Wadi as Sir Limestone (WSL)
B_2: Amman-Al Hisa silicified Limestone (ASL)
A_7/B_2: A_7/B_2 aquifer

3.4.6.2 Structural contour map for the top of Wadi as Sir (WSL)/Amman-Al Hisa Silicified Limestone (ASL); (B_2/ A_7)

The top of Wadi as Sir Limestone Formation (A_7)/Amman-Al Hisa Silicified Limestone (B_2) Aquifer System is shown in (Table 3.5 & Figure 3.24). The contour lines of the top of the B_2/A_7 show an ellipsoidal updoming striking in the NNW-SSE direction. This ellipsoid is asymmetrical in the E-W direction; its western flank is steeply dipping towards the Jordan Valley while its eastern flank is gently dipping towards the eastern Jordanian Plateau. The updoming in the B_2/A_7 is formed partly by dense normal faults, like in the area of Deir Alla, but in other places it is formed due to flexuring of Cretaceous sediments.

This ellipsoid updoming is crossed by two dextral strike slip faults trending E-W (Figure 3.24). These faults are the Zarqa River Fault and Al Baqa'-Er Rmamin Fault (Figure 2.23). These faults are not disturbing the shape of the updomong in the B_2/A_7 so they so they are pre existing it.

3.5 Tertiary and Quaternary Sediments and Basalt

The importance of the young sediments mainly alluvial deposits and basalt in the study area is that they form local aquifers.

3.5.1 Young Sediments

Various superficial deposits overlying partly the previously mentioned geological formations such as, Hummar, Wadi as Sir–Al Hisa etc. are found in the study area; mainly in the Jordan Valley and along major wadi covers. The main constituents of these deposits are fluviatile gravel, sands and silts deposited as fillings of the wadi channels, partly as wide alluvial fans in the Jordan Valley. They are of different age belonging partly to the Pliocene, Pleistocene or Holocene. In the wadi they reach thickness of 10 - >40 m, in the Jordan Valley they reach up to several hundred meters thickness, where they interfinger with lacustrine sediments of the central Jordan Valley. In the high lands the soil cover according the weathering conditions are rather thin. Only in flat depressions and on flat slopes thicker soil sequences washed in from the steeper adjacent slopes. Areas with thicker soil cover are intensively covered by areas with thicker soil cover.

In the areas of outcropping carbonate rocks frequently only the in situ formed duricrust (calcrete) can be found. It represents partly a several meters thick layer within the typical vertical profile, the hard crust on the top (zone A), the cavernous with small holes (zone B) and the weathered in situ rocks (zone C).

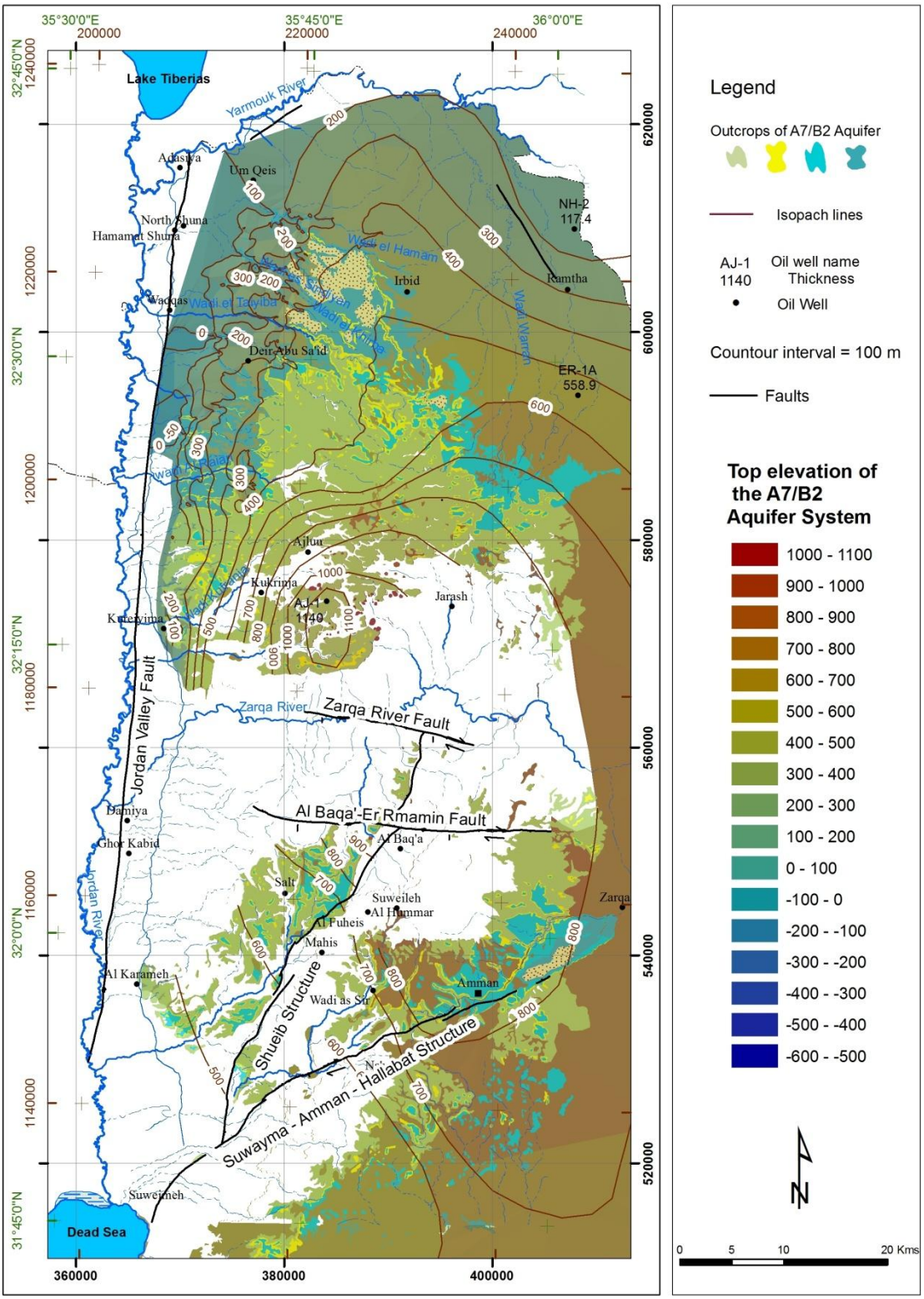

Figure 3.24: Top of Wadi as Sir Limestone Formation (WSL)/Amman-Al Hisa Silicified Limestone (ASL), (A_7/B_2) Aquifer System (Note: The map shows the outcrop of WSL/ASL and the structural features in the study area only).

3.5.2 Basalt

Basalts in the subsurface are mainly found in some wells of the Jordan Valley and in the vast Harrat Ash-Shaam Basaltic province north and east of Azraq.

MARGANE et al. (2002) reported in the contribution to the Hydrogeology of northern and central Jordan that in the western part of the Harrat Ash-Sham area, west of the Fuluq Fault, the basalt appears to be mostly underlain by the Amman–Wadi as Sir Formation (A_7/B_2) as proven by paleontological analyses for some of the recently drilled wells in the Azraq basin (CES & ARABTECH, 1994). Near the Fuluq Fault, prograding towards SE, the basalt is underlain by the Muwaqqar (B_3) and further on by the Um Rijam Formation (B_4). East of the Fuluq Fault basalt overlies successively younger strata towards east and northeast.

3.5.2.1 Isopach map of the Basalt

The maximum thickness of the basaltic successions in Jordan is variable. There are no deep wells penetrating the Basalt within the study area. But further to the east, in Al Azraq Basin, measurements from boreholes are: 469.5 m in QA-1 oil well and 200 m in Smica water well, SM-1 (Table 3.6). According to VAN DEN BOOM & SAWWAN (1966), a thickness of up to 250 m is recorded in the well log of Azraq water deep well (AZ-1). The isopach map (Figure 3.25) shows that the maximum expected thickness Basalt in Jordan is 550 m in the northeastern part of the study area.

The maximum observed thickness of basalt drilled in the Harrat Ash-Sham area of Jordan is 479 m. The thickness increases towards Jebel Druz (Syria) where it may reach approximately 1500 m (WOLFART, 1966).

Table 3.6: Thickness data and top from ground surface level for the Basalt in some wells in Jordan.

Well ID	QA-1	F 1319	F 1318	F 1308	F 1209	F 1077	F 1075	F 1035
Thickness	479	175	170	180	>250	178	>248	88

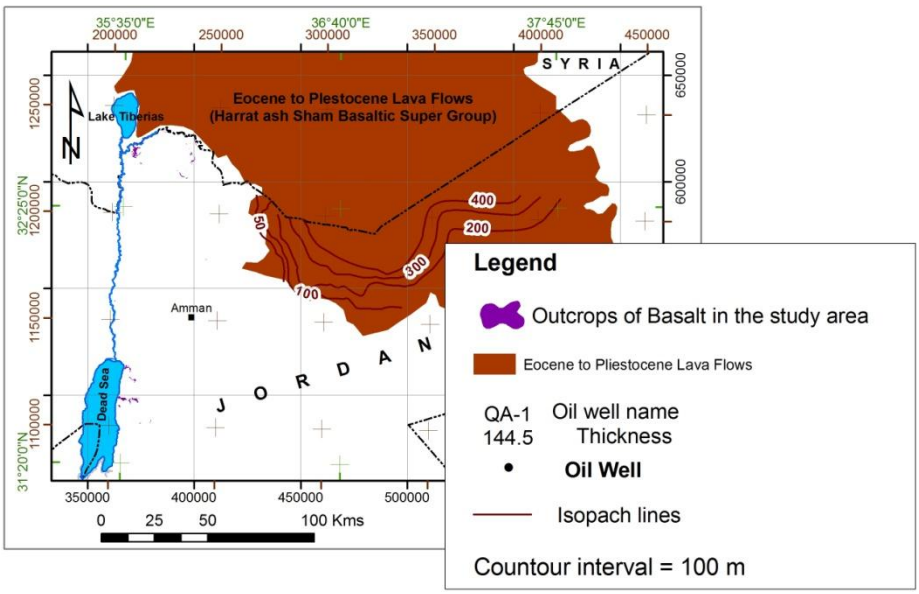

Figure 3.25: Isopach map of Basalt in northern Jordan (modified from BGR, 1995a).

4. HYDROLOGY, HYDROGEOLOGY AND HYDROCHEMISTRY

Several studies have explored the hydrology, hydrogeology and hydrochemistry of wide regions within the study area. Most of these studies indicate the study area as a part of north Jordan. In addition to that, many localities were subjected to more detailed studies of doctoral and master thesis projects. The present study is carried out to investigate the role of different structural features on the groundwater flow and water quality in northwestern Jordan. The main information on water levels and water chemistry data was taken from the Water Authority of Jordan (WAJ) data bank provided through SMART project. The main hydrological, hydrogeological and hydrochemistry studies that have a direct and/or indirect special value on the present study are as follows:

The study area is partly covered by MASRI's (1963) hydrological study of the Amman-Zarqa area. The study was prepared as part of a programme to study qualitatively, the water supply of the cities of Amman and Zarqa and to locate new water resources in the area in general. The work included detailed geological mapping and interpretation in order to determine the thickness and lithology of the sedimentary rock formations. Also, it is covered by 23 monochrome geological maps (Um Qeis, Kharja, Waqqas, Tayyiba, Irbid, Tabaqat Fahl, Rihaba, Kitim, Kuraiyima, Ajlun, Jarash, Deir 'Alla, Allan, El Aluk, Kebid, Salt, Amman, Shunat Nimrin, Na'ur, Er Rajib, Sweimeh, Madaba and Jiza) at a scale of 1:25,000, produced by Hunting Technical Services and incorporated in MACDONALD & PARTNERS (1965a & b) as part of their hydrological survey of the East Bank of Jordan. This study formed the most important source of information on the area of Jordan valley and the adjacent eastern area. The study area was a part of their investigations. The purpose of the survey was to define so far as possible the surface water and groundwater resources and to plan their development. The geology of the area is also included in the hydrological report by PARKER (1970).

The geology of the northern part of the study area is a continuation of southern Syria geology (KRASNOR et al, 1966). Several works has been done there such as WOLFART (1959) who discussed in general the geology, hydrology and groundwater exploration in Irbid area. The geological map of BURDON (1959a) shows the geological features of the Yarmouk Valley scheme. In addition BURDON (1959b) studied in general, the hydrological and hydrogeological problems of aquifers and groundwater quality in Jordan including the basins in the study area and described the water-bearing of the various geological formations.

Several master plan reports about the northern part of the study area (Yarmouk-Jordan Valley) were published such as the master plan by BAKER AND HARZA (1955 vol. 1 & vol. 2) including location, general description and the physiography of different basins in Jordan. The first comprehensive evaluation of the surface and groundwater resources of Jordan was carried out in the late 1970s by the National Water Master Plan (GTZ & NRA, 1977). The hydrogeological evaluation of Jordan resulted from the study of about 400 working water wells and a few deep oil wells at that time. The main results of this study were the evaluation of the hydrological setting of Jordan by studying the amount of rainfall and potential evaporation distribution along whole Jordan. In addition to the calculation of the runoff precipitation ratios for the different parts of Jordan. Again, the German Agency for Technical Assistance (GTZ) is supporting the Jordanian Government in this task **Digital Water Master Plan** (GTZ & MMI, 2004) based on an extensive

Water Information System (WIS). In close cooperation with the Ministry of Water and Irrigation and GTZ, the German consulting company AHT International has developed the **Digital Planning Tools.** These software tools are database applications with a GIS (digital mapping) interface that are applied to: assess the present availability, withdrawals, losses and uses of the water resources; formulate alternative development scenarios for water resources and demand/use at various planning horizons; perform the balancing of resources versus demands for the recent past as well as for the alternative development options and identify technical and operational options in order to bridge the gap between resources and demands.

For different purposes and objectives the hydrochemical characteristics of the aquifers within the study area have been studied, such as HARZA (1978) who classified the water types encountered within the Maqarin area; along Yarmouk River for the proposed dam site. Also, HUMPHREYS (1978) investigated the water chemistry of Amman Wadi as Sir Aquifer (B_2/A_7) for drinking water quality purpose. Latter, Water samples analysis from Rijam (B_4) and Amman Wadi as Sir (B_2/A_7) Aquifers by ABDUL-JABER (1982) explained the presences of high alkaline water at Maqarin area.

SALAMEH (1980b) show a degradation of water quality in King Talal Reservoir in the central part of the study area, due to urbanization, industrial and agricultural activities. In addition to that, SALAMEH & KHUDEIR (1985) in their study "Groundwater qualities in Jordan" classified the groundwater types of different areas. And SALAMEH & REMAWI (1988b) discussed the precipitation water quality in Jordan with respect to a station located in central northern Jordan and supported by analysis from different other locations. The study shows that in contrast to industrialized countries, precipitation over Jordan is dominantly alkaline. Only after heavy rain does the rain water turn acidic.

EL-NASSER (1987) classified the water types in the study area with respect to their aquifer, using samples from wells and springs. Latter, The hydrogeological and hydrochemical characteristics of the northern part of the northwestern Jordan have been studied and investigated by EL-NASER (1991). In addition, a conceptual hydrodynamic model was constructed which shows that an upward leakage from the lower aquifer (Kurnub) to the upper aquifer (B_2/A_7) is taking place. In an attempt to quantify the amount of upward leakage as well as the thermodynamics of both aquifers, El-Naser constructed four hydrochemical models, using hydrogeochemical data from relevant wells and springs of the B_2/A_7 and Kurnub aquifers. By using the results of the above mentioned hydrogeological and hydrochemical investigations and by coupling the mixing ratios and the available hydraulic properties of both aquifers, a quasi three-dimensional groundwater flow model is built and calibrated, which adequately represents the historical behavior of the system.

The result of two conferences organized by the Friedrich Elbert Foundation, in cooperation with the University of Jordan, the Higher Council of Science and Technology and the Goethe-Institute in Amman, entitled: "Water Pollution in Jordan- Causes and Effects" (1990) and "Jordan's Water Resources and Their Future Potentials (1991) concerning the water resources of Jordan was compiled in a new book about water resources of Jordan present status and future potentials by GÄRBER & SALAMEH (1992). Latter SALAMEH & BANNAYAN (1993) represents both integration and expansion of the major findings of these conferences and proposes solution to

meet the future challenges of increased demands and limited supplies; increasing the local water supply; efficient use of the available supply; interstate water transfer and regional cooperation; and restrictions on water use.

SALAMEH (1996) carried out a study concerning water quality degradation in Jordan, in order to define the water quality situation in Jordan and its development as a result of rapid socioeconomic achievements. This study shows that the population growth, higher standards of living, industrialization, irrigation and other activities accelerated the exhaustion of available resources. A hydrochemical overview on groundwater resources on the Jordanian side of the lower Jordan Valley and its surroundings has been published by SALAMEH (2001). The study found that the evaporites within the Jurassic and Triassic rocks are the main contributors to the salizination of groundwater entering the Jordan Valley laterally, from its eastern side, and that the deposits of the ancestors of the Dead Sea; the Lisan Lake (Lisan deposits) are the main contributors to water salinities within the Jordan Valley itself.

A hydrogeological assessment of the groundwater resources of northern and central Jordan was carried out by the staff of a technical cooperation project between the Water Authority of Jordan (WAJ) and the Federal Institute for Geosciences and Natural Resources (BGR) in Germany (1994–1996) and (2001). The main objectives of this study were that, the improvement of the hydrogeological database, the preparation of thematic maps on important aspects of the hydrogeology of the area and documents information relevant to the assessment and exploitation of the groundwater resources and groundwater models. The results have been documented in a set of technical reports.

Previous geological and structural data in the area of Yarmouk Basin were reviewed and evaluate to delineate geological structures related to water exploration studies (SAHAWNEH & SAWARIEH, 1998).

The hydrological and hydrochemical characteristics of the eleven major springs in Wadi Shueib catchment area was studied by TA'ANY (1992). Springs water samples were studied to determine their chemical, biological and microbiological constituents. The discharge of springs was determined using weirs and volumetric tanks when the discharge was so low. The study found that, the water type of the studied springs belongs completely to HCO_3^- group with predominant amount of calcium.

In 1994 and 1995 the Japan International Cooperation Agency (JICA) evaluated the potentials and the quality of the brackish groundwater resource in the Jordan Valley area including an examination of the effects of the development on these resources. The study found that the most promising areas for brackish groundwater development are Deir Alla area and Kafrain area in terms of both volume of flow and quality of brackish groundwater within the Zarqa Group aquifer. The total flow volume in both areas was estimated to be 110 MCM/year and the salinity of the brackish groundwater was estimated to be 7,500 mg/l in Deir Alla area and 5,000 mg/l in Kafrain area.

AWAD (1996) studied the groundwater quality in the area lying on both sides of Zarqa River, downstream of King Talal Dam as affected by the water quality of the dam. Thirty one samples

were studied from wells, springs and seepages. He found that, the King Talal Dam water quality is affecting the groundwater in the immediate surroundings of the dam body itself because elsewhere the groundwater is effluent.

KOUZ (2004) studied the hydrochemistry of the surface and groundwater resources in the central part of the Jordan Valley area through the study of major and minor elements of fifteen samples from different wells and springs. The main results of this study were that the water salinity increases westward in the Jordan Valley area and the water coming into contact with the Lisan Formation has high salinity that may reach 50000 µS/cm.

The role of structures on hydrogeology along the lower reaches of Zarqa River, downstream of King Talal Dam was studied by ODEH (2005; 2009). The study was based on remote sensing, GIS and field methods. The main conclusions of the study are that the area of Zarqa River has a major effect on the groundwater flow regime and the groundwater is highly affected by human activities.

NASHER (2007) carried out A hydrogeological, hydrogeochemical and vulnerability investigation was conducted in the intercatchment area between Wadi Shueib and Zarqa River to evaluate the hydrogeological setting, the hydrogeochemical characteristics and to determine the portability and suitability of groundwater for domestic and agricultural purposes and to assess the vulnerability of groundwater to surficial contamination. The study shows that hydrogeochemically, the groundwater in the study area is generally hard and fresh to brackish in nature. The abundance of the major ions is as follows: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Cl^- > HCO_3^- > SO_4^{2-} > NO_3^-$.

Weathering processes effect on the chemistry of the main springs of the Yarmouk Basin, north Jordan has been studied by BATAYNEH, et al. (2008). Major cations and anions of 36 spring waters in the Yarmouk Basin were measured to assess the effects of weathering and geochemical processes in the basin area. Chemical analysis of spring waters show that the concentration of the cations is of order $Ca^{2+}>Na^+>Mg^{2+}>K^-$ while that of the anions is $Cl^->HCO_3^->NO_3^->SO_4^{2-}$. Water shows varying chemical facies (Ca^{2+}- SO_4^{2-}, Mg^{2+}- SO_4^{2-}, Na^+- SO_4^{2-}), which relates to the interaction with the geological formations of the basin (carbonate, dolomite, marl, basalt and various silicates) and evaporation. The dissolution of halite, calcite, dolomite and gypsum explains part of the observed Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-} and HCO_3^-, but other processes, such as cation exchange and weathering of aluminosilicates also contribute to the water composition.

Another comprehensive hydrogeological study of the region was published by HÖTZL, MÖLLER & ROSENTHAL (2009) with the book on the "Water of the Jordan Valley". The study was carried out within a multilateral project (GIJP, 1998-2004) on the ground water resources of the Jordan Valley. The book focus on hydrochemical studies, where detailed analysis including the rare earth elements were used for a new interpretation of different water sources, where especially some of the brines in the Jordan Valley could be connected to previous marine phases in the Valley. Further on detailed hydrogeological studies were performed on both sides of the Valley including ground water modeling, water balances of specific catchments as well as a study on the origin of the thermal water resources in the middle part of Jordan.

4.1 Introduction to Hydrology and Hydrogeology

Due to the prevailing climatic conditions in Jordan more than 80% of the area of Jordan is indicated as desert receiving rainfall of less than 100 mm/yr. Precipitation in Jordan falls normally in the form of rainfall, frequently with some snow fall which can be observed where the altitude exceeds 700 m and it lasts only for few days. In Jordan as well as in the study area the amount of rainfall decreases from North to South and from the western highlands to the East and the West, to the Jordan Valley. In addition, the amount, the period and duration of events of rainfall are very variable and fluctuate from year to year. The climatic conditions in Jordan not only affect the distribution of rainfall, but also they highly affect the potential evaporation in the country. Generally, in Jordan, the potential evaporation ranges from 1900 mm/yr in the extreme northwestern area of the country to more than 4400 mm/yr in the southern and eastern areas (FARDOUS et al., 2004). The long term volume of water in the whole country for the water years 1937/38-1993/94 is 8307 MCM/yr as calculated by BGR & WAJ (1995b). This volume increases according to SALAMEH (1996) to 12000 MCM/yr in a wet year and decreases to 6000 MCM/yr in a dry year. About 12% of this volume is available for use from springs, runoff or infiltrates to recharge the aquifers while the remaining 88% is lost through evaporation.

Some of the precipitation water runs off in wadis as flood flow during the wet periods, where it gathers in closed basins or being collected in dams for use, especially for irrigation. Surface water flow in some rivers such as in the Zarqa River is derived in part from springs in the upland areas. Plate 6 illustrates the main rivers and wadis, in addition to the location of dams and the location of springs in the study area (WAJ open files; BGR & WAJ, 1996). Surface water in Jordan is distributed in fifteen basins (Table 4.1 & Figure 4.1). These basins have been identified and delineated mainly on the bases of surface drainage (Plate 6).

Table 4.1: Surface Water Basins in Jordan (modified after WAJ open files).

No.	Surface Water Basin					Basin Code	Catchment Area (km^2)	Catchment area %
	Basin/Area			Basin Name				
1	Dead Sea Basin	Jordan River Sub-basin	Northern Basins	Yarmouk (Jordan)		AD	1,391	1.6
2				Amman-Zarqa (Jordan)		AL	3,591	0.8
3				Jordan Valley		AB	708	1.1
4				Jordan Valley Rift Side Wadis	North	AE, AF, AG, AH, AJ, AK	938	0.8
5					South	AM, AN, AP	683	4
6		Dead Sea Sub-basin	Central Basins	Mujib		CD	6,584	1.8
7				Hisa		CF	2,530	7.4
8				Dead Sea Rift Side Wadis		C	1,623	2.8
9				North Wadi 'Araba		D	2,991	3.4
10	Eastern Desert Basin			Azraq (Jordan)		F	11,706	6.7
11				Hammad		H	18,520	4.4
12				Sirhan		J	15,696	13.6
13				Jafr		G	12,062	17.7
14	Southern Basins			South Wadi 'Araba		E	5,998	13.2
15				Southern Desert		K	3,892	20.8
Total							**88,915**	100

Note: Areas are within the Jordanian Territory only. Total area of Jordan is ≈89,455 km^2.
Catchment area calculated from Figure 4.1 using GIS tools.

The major dams in Jordan were constructed in order to store the surface water flow mainly for irrigation. In the study area, Wadi el 'Arab, Wadi Ziglab, King Talal, Kafrain, Wadi Shueib, Al Karama dams and Al-Wehdeh dam were constructed on the major wadis. The capacity and location of dams in Jordan are listed in (Table 4.2) and the locations of dams in the study area are shown in Plate 6 and Figure 4.2.

Another part of the precipitation infiltrates and joins the groundwater of the country. Infiltration takes place in the western highlands due to the exposure of suitable aquifers. The dry climate, the atmospheric dust and the low intensity of precipitation affects also the quality of precipitation water, generally reflected in increasing salt contents. Groundwater resources either renewable or non-renewable are considered the major water sources in many areas of Jordan, and it is the only source in others. It is used for irrigation and for the supply of the main cities and villages with domestic and industrial water.

According to the aquifer types, the groundwater aquifers in Jordan can be grouped into three main complexes. Each of these complexes comprises one or more aquifer (Table 1.2).

Table 4.2: Existing Large Dams in Jordan (source: MWI data). Note: RCC-Roller compacted concrete.

Governorate	Basin Code	Name of Dam	Completion Year	Dam Type	Catchment Area (km^2)	Dam Height (m)	Live Storage (MCM)	Purposes	Water Resource
Irbid	A	Wadi el 'Arab	1986	Earth fill	262	84	16.9	Irrigation of 12,500 dunum in the northern JV, domestic water supply, power generation	From KAC in winter and the floods of Wadi el 'Arab
Irbid	A	Wadi Ziglab	1967	Earth fill	106	48	3.9	Irrigation of 12,500 dunum in the northern JV & electricity	Flood and base flows of Wadi Ziglab
Jarash	AL	King Talal	1977/1987	Earth fill	3,700	108	75	Irrigation of 82,000 dunum in the middle JV, power generation	Zarqa River and As-Samra TP wastewater
Belqa	A	Kafrain	1967 & raised 1997	Earth fill	163	37	8.5	Irrigation of 1,274 dunum upstream of KAC & Recharge	Flood and base flows of Wadi Kafrain
Belqa	A	Wadi Shueib	1969	Earth fill	178	32	2.1	Irrigation of 2,500 dunum and artificial recharge	Base and flood flows of Wadi Shueib
Belqa	A	El Karama	1997	Earth fill	61	45	55	Irrigation of 40,000 dunum in the southern JV	Surplus water from KAC in winter
Madaba	CD	El Wala	2003	RCC/ Earth fill	1770	45	9.3	Multi-purpose	Flood and base flows from Wadi el Wala (Hidan)
Al Karak / At Tafilah	CF	Tannour	2003	RCC	2160	60	16.8	Multi-purpose	Flood and base flows from Wadi Hisa
Karak	CD	Mujib	2003	RCC/ Earth fill	4380	62	30	Multi-purpose	Flood and base flows from Wadi Mujib
Irbid	A	Al-Wehdeh	2006	RCC	-	171	80	Multi-purpose	Flood and base flows from Yarmouk River
		Total					**297.5**		

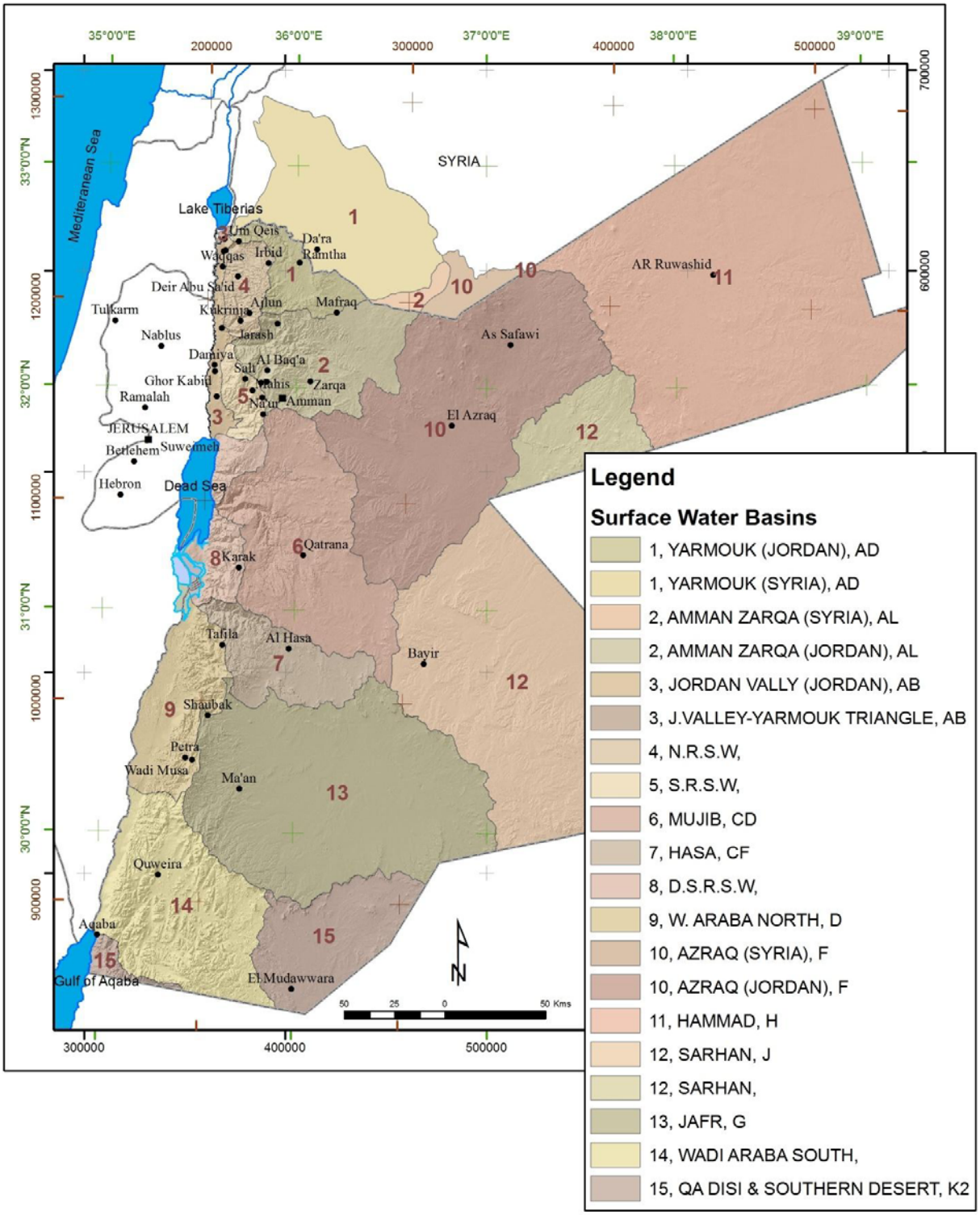

Figure 4.1: Surface water basins in Jordan.

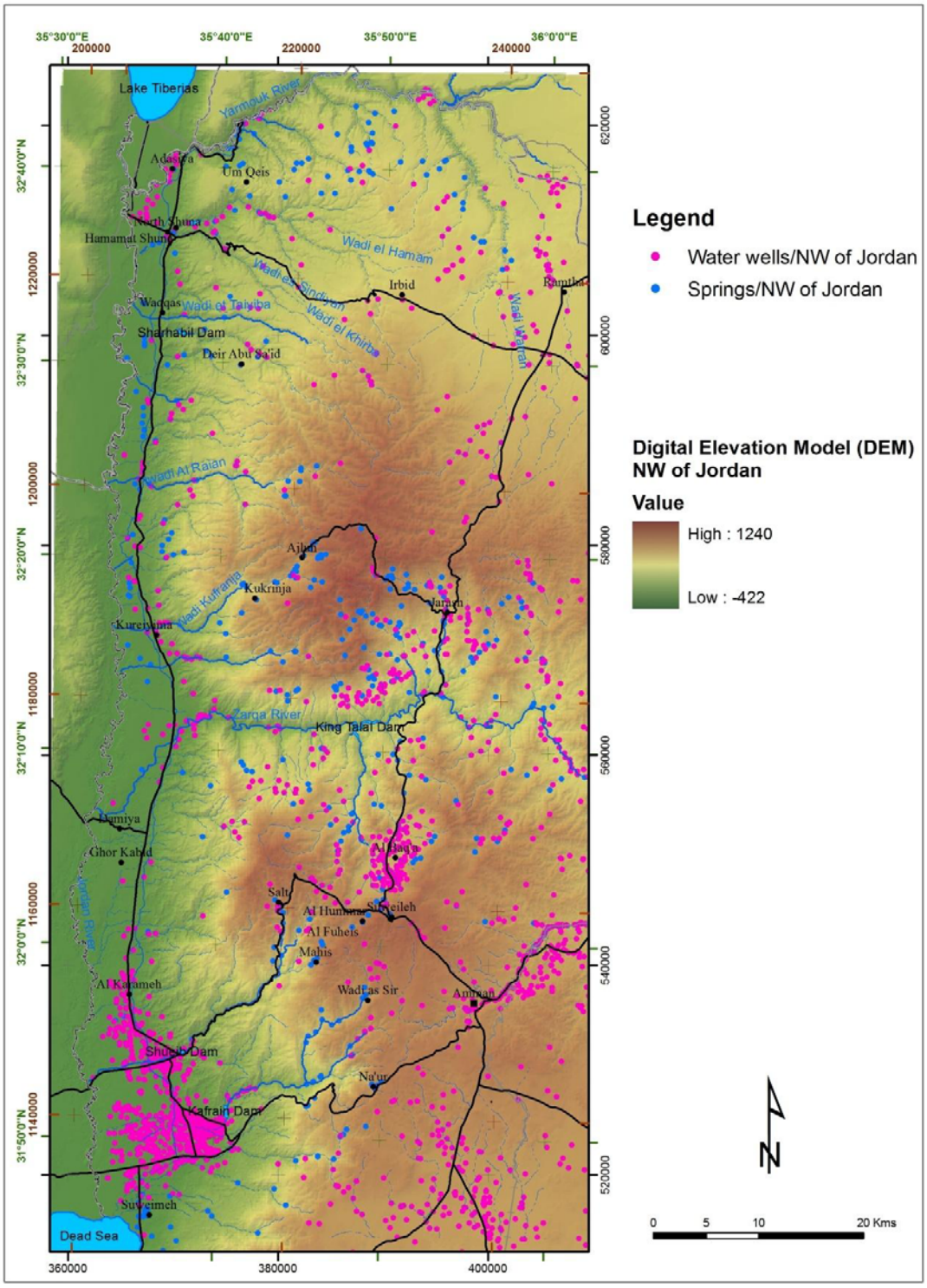

Figure 4.2: Springs and water wells in the different aquifer systems in NW of Jordan (The map based on the Triangular Irregular Network (TIN) with hill shade illumination effect in 2D display and improved by overlying it with Digital Elevation Model (DEM) in order to enhance the relief condition in the study area).

The surface extension of the groundwater aquifers and aquitards in Jordan are shown in Figure 4.3. These aquifer complexes are:

- Deep aquifer complexes or Ram-Zarqa-Kurnub aquifer system: It includes the Ram aquifer, the Khreim aquitard, the Zarqa aquifer and the Kurnub aquifer.

- Middle aquifer complexes or Upper Cretaceous Limestone aquifer system: It includes the Na'ur (A_{1-2}) aquifer, the Fuheis (A_3) aquitard, the Hummar (A4), the Shueib (A_{5-6}) aquitard and the Amman/Wadi as Sir (B_2/A_7) aquifer.

- Shallow aquifer complexes or Tertiary-Quaternary shallow aquifer system: It includes the Muwaqqar (B_3) aquitard, the Umm Rijam and Shallala (B_4/B_5) aquifer, the Basalt aquifer and the alluvial deposits.

Jordan's groundwater resources are distributed among twelve basins. Most basins are comprised of several aquifer systems. Mainly Amman/ Wadi as Sir (B_2/A_7), Basalt and Ram aquifer systems contain about 80% of Jordan groundwater resources (Figure 4.4).

The renewable groundwater recharge in Jordan is estimated to about 533 MCM/yr (GTZ & MMI, 2004) (Table 4.3). About 395 MCM/yr groundwater recharge occurs from precipitation, especially in the western highlands due to exposure of suitable aquifers in the area. 68 MCM/yr renewable trans-boundary recharge from shared water resources occurs along the border with Syria, mainly in the B_4/B_5, basalt and A_7/B_2 aquifers (estimated by the Water Resources and Planning Department of the MWI). And 70 MCM/yr occurs from return flows from irrigation, leaks from pipes, reservoirs, and wastewater treatment plants. The non-renewable resources in Jordan are found mainly in Jafr area from the B_2/A_7 aquifer and Disi area from the Ram aquifer, they have a safe yield of 18 MCM/yr and 125 MCM/yr, respectively for the next 50 years. In addition to that the abstraction rate from the non-renewable brackish groundwater resources from the deep sandstone aquifer, were estimated to be about 77 MCM/yr.

Most of the infiltrated water from precipitation appears once again as springs. Due to the physiographic situation of the study area springs discharge from the different aquifers along the escarpment area. Some of these springs are used for domestic water supply and others for irrigation purposes (Figure 4.2). The majority of springs are structurally controlled. The discharge quantities of fresh water issuing from the carbonate rocks of the Upper Cretaceous change during the year. The discharge of springs increases during and after the rainy season and decreases in dry season. Some small springs and seepages dry up in the late summer. This is related to the high hydraulic conductivity and the short distance of the flow path from the recharge site to the discharge site.

Because of the basic importance of groundwater, extensive number of production wells was drilled in Jordan, where major populated cities are located (Figure 4.2). Unfortunately, Water resources are being over-exploited for domestic use, irrigation and industry. The quantity and quality of ground water in Jordan as well as in the study area are directly affected by the high discharge of production wells in most areas. This effect will, eventually, increase the salinity of the aquifer and cause decrease in the static ground water level.

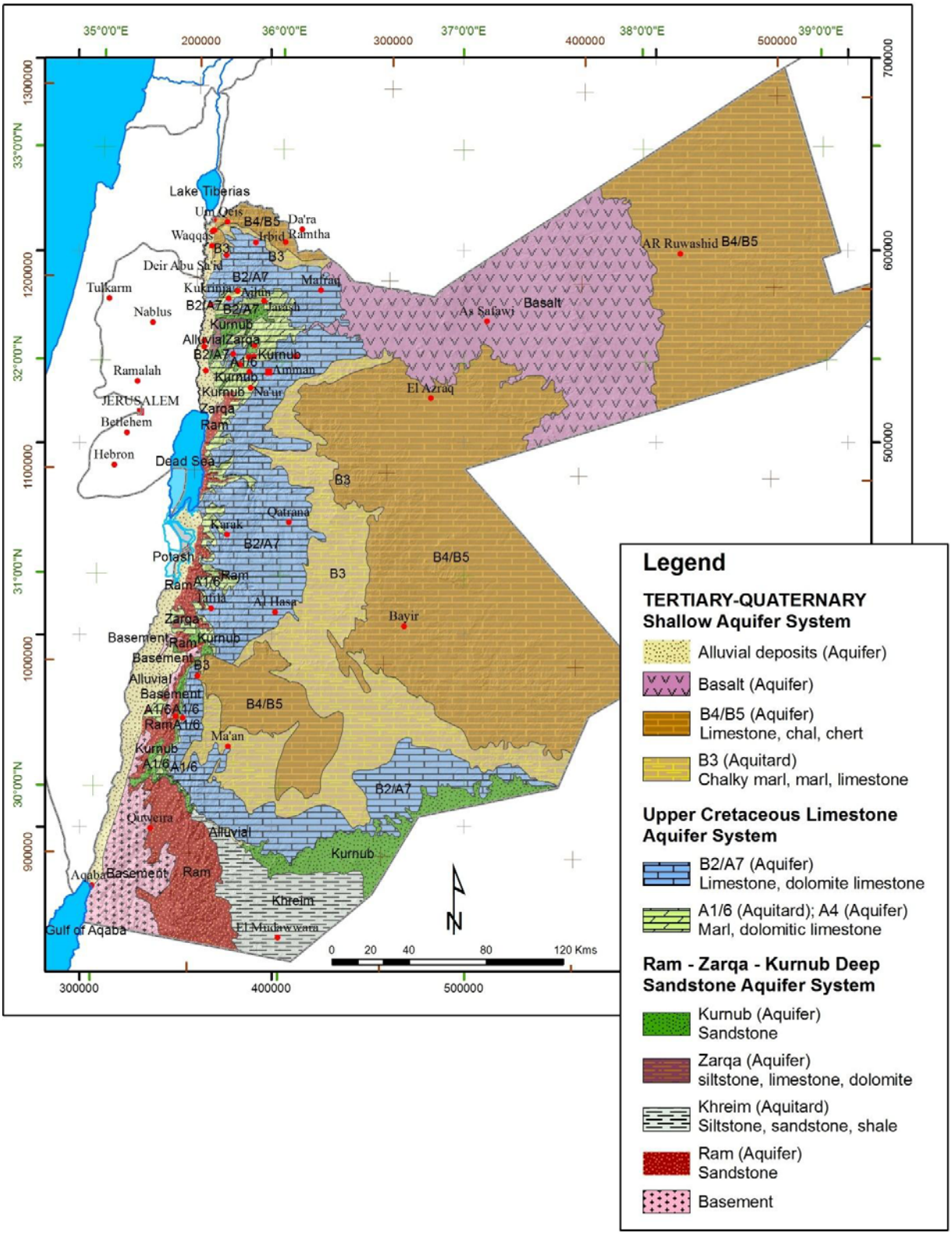

Figure 4.3: Surface extension of groundwater aquifer and aquitard systems in Jordan (modified after GTZ & MWI, 2004).

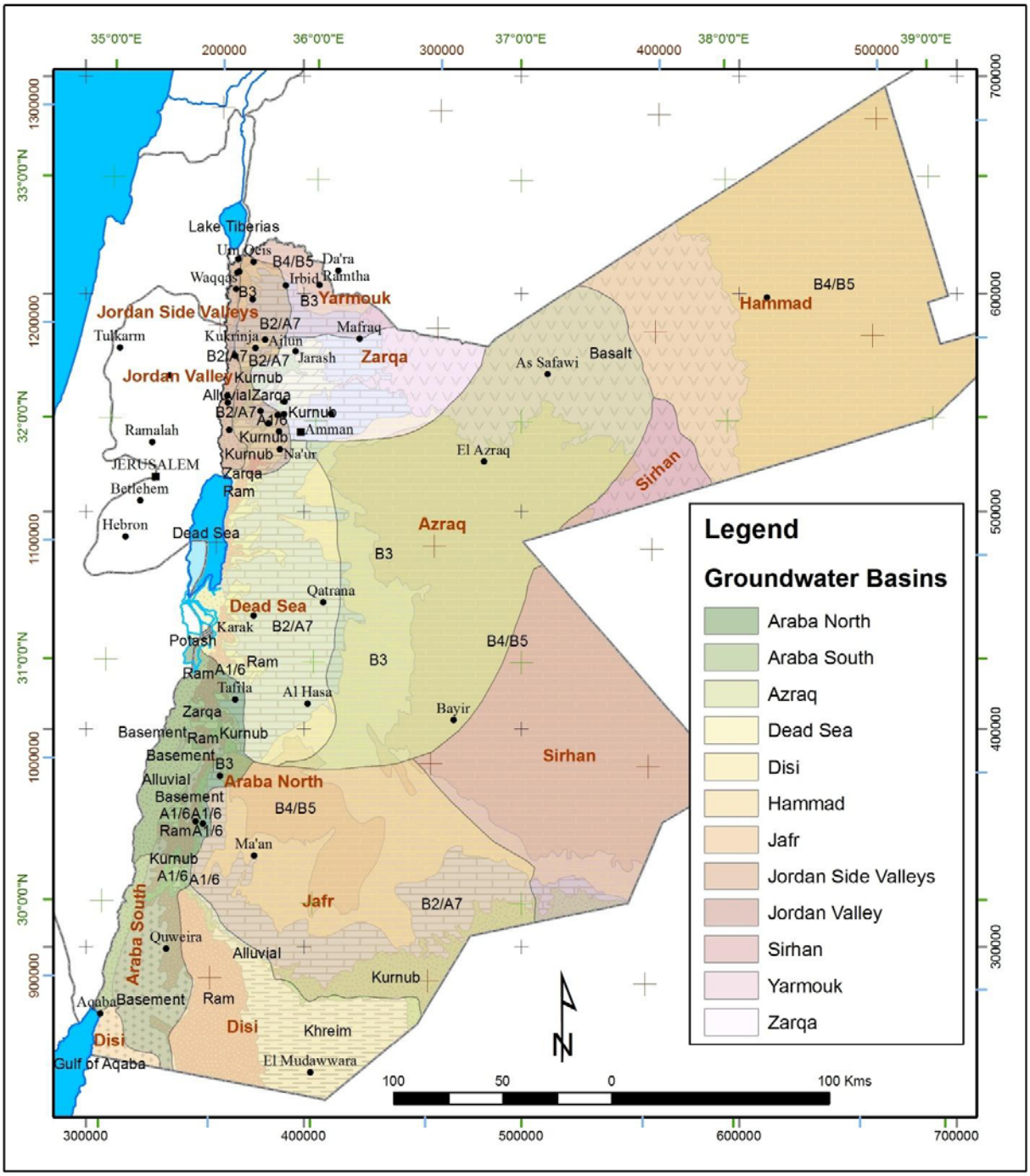

Figure 4.4: Groundwater basins in Jordan.

Groundwater discharge in Jordan is estimated to about 637 MCM/yr (GTZ & MWI, 2004) (Table 4.3). The discharge from groundwater basins is distributed as: 440 MCM/yr groundwater discharge from abstraction by pumping wells and springs. According to the previous mentioned recharge of 533 MCM the natural discharge should be the same range. The GTZ & MWI (2004) (Table 4.3) were calculating the discharge in the period from 1999 to 2003 with a yearly of 637MCM/yr. This represents an overexploitation rate of 104 MCM/yr which finally is one of the sources of the observed depletion of ground water levels. Most of this water (420 MCM/year) is pumped by wells, and only about 20 MCM/year are pumped from springs, for municipal purposes. Beside this amount of abstraction there is still a natural baseflow of 197 MCM/yr. Baseflow is defined as outflow from groundwater bodies by springs and effluents into stream courses. The occurrence of baseflow in Jordan is restricted to wadis draining into the Jordan Rift Valley along the eastern escarpment. The comparison between the total natural recharge of 533 MCM/yr with the total amount of 637 MCM/yr (440 MCM/yr abstraction + 197 MCM/yr baseflow) shows that there is recently an overexploitation of the aquifers of around 104 MCM/yr. It shows a high risk that the storage of water in the aquifer will break down completely and the aquifers will be completely exhausted, if there is no change in the resources managements.

Table 4.3: Description of the mean annual budget of the renewable groundwater and the corresponding quantities in the period from 1999 to 2003 in Jordan (GTZ & MWI, 2004).

Budget component	Quantity MCM/Year
Groundwater recharge from precipitation	395
Trans-boundary groundwater inflow from Syria	68
Return flow from irrigation, leaks from pipes, reservoirs, wastewater treatment plants	70
Total inflow	533
Groundwater abstraction (wells, springs)	440
Baseflow	197
Total outflows	637
Change in storage (inflow-outflow)	-104

The GTZ & MWI, 2004 concluded that the total safe yield of renewable groundwater from the total annual recharge to the aquifers in Jordan is approximately 275 MCM/yr. The estimation of the groundwater basins safe yield in Jordan was made by using simple balancing calculation. The equation used is: GWSY= Recharge – Baseflow (GTZ & MWI, 2004). The sustainable groundwater abstraction rates (safe yields) in MCM/yr for the different groundwater basins in Jordan are shown in Table 4.4 (GTZ & MWI, 2004). The groundwater abstraction rates indicate that the groundwater basins are being overpumped mainly in 7 basins, with abstraction ranging from 135 to 225% of the safe yield. The abstraction rates and the deficit for the different basins in Jordan as indicated from MWI open files concluded that a reduction in groundwater abstraction must be done mainly in Amman-Zarqa, Dead Sea, Azraq, Yarmouk, Jordan Valley and Jafr basins. In the other 4 basins, abstraction equal to safe yield (Plate 6).

Table 4.4: The mean annual recharge and discharge of the renewable groundwater and their estimated safe yield in Jordan (all figures in MCM/yr) (after GTZ & MWI, 2004).

No.	Groundwater Basin	Recharge (modelled)	Inflow from Syria	Recharge adjusted	Recharge + Syria	Total Baseflow (1)	Spring flow recorded (2)	Baseflow corrected (3)	Wells Safe Yield	Range Wells SY
		C	D	E	F=E+D	G	H	I	J=F-I	
1	Yarmouk	9.7	15	28.0	43.0	15	12	10	**33**	30 - 35
2	Zarqa	63.2	30	72.0	102.0	40.5	21	40	**62**	60 - 70
3	Jordan Side Valleys (4)	111.1		110.0	110.0	85.3	49	79	**31**	28 - 32
4	Jordan Valley	6.5		20.0	20.0	0	15	0	**20**	15 - 20
5	Dead Sea	98.0		100.0	100.0	84.0	65	56	**44**	40 - 50
6	Azraq	16.7	18	16.0	34.0	0	0	0	**34**	30 - 35
7	Hammad	12.2	5	10.0	15.0	0	0	0	**15**	12 - 16
8	Araba North	44.6		18.0	18.0	11.6	5	11.6	**6.4**	5 - 7
9	Araba South	4.5		5.0	5.0	0	0.1	0.1	**5**	4 - 6
10	Sirhan	5.1	0	5.0	5.0	0	0	0	**5**	4 - 6
11	Jafr	22.8		8.0	8.0	0	0.6	0.6	**7.4**	7 - 10
12	Disi	3.1		3.0	3.0	0	0	0	**3**	2 - 3
		397.5	**68.0**	**395.0**	**463**	**236**	**168**	**197**	**266**	

(1) Baseflow balance; including fossil groundwater.
(2) For information only.
(3) Same as column G, but without fossil groundwater and including latest changes of groundwater development.
(4) Considering latest developments of Wadi el ‘Arab and Wadi Jurum.

4.2 Hydrology of the study area

Since the formation of the Dead Sea structure, it has been acting as a base level for all the surface and groundwater in the region. Plate 6 shows the drainage system in the NW of Jordan. The Yarmouk and Jordan Rivers form the natural boundary between Jordan and adjacent countries (Syria, Palestine and Israel). A number of major wadis drain the study area such as Zarqa River, Wadi el 'Arab, Wadi Ziglab, Wadi Kufranja, Wadi Shueib, Wadi Kafrain…..etc.

4.2.1 Surface Water Resources

The main surface water resources in the study area are illustrated in Plate 6, these are:

4.2.1.1 The Jordan River

The Jordan River is an international River, which drains a total area of about 18,000 km^2. Its three headwater tributaries originate from the slopes of Mount Hermon. It drains the upper Jordan River basin and flow southward into Lake Tiberias. The headwater of Jordan River originated from three main springs: the Hisbani, coming from Lebanon, the Banias, coming from Syria and the Dan coming from Syrian Golan Heights, occupied by Israel since 1967. The Jordan River flows southwards along a nearly 130 km-long longitudinal depression, the Jordan Valley before discharging into the Dead Sea.

Prior to the water developmental projects in Jordan, Syria Palestine, Lebanon and Israel, the total discharge of the Jordan River into the Dead Sea varied between 1,100 and 1,400 MCM/yr (KLEIN, 1998; EL-NASSER, 1998; AL-WESHAH, 2000).

4.2.1.2 The Yarmouk River

Ten Kilometers downstream of Lake Tiberias, the lower Jordan River receives water from its major tributary, the Yarmouk River. Originally, the Yarmouk River coming from northeast of Syria and drains as base or flood flows at the borders of Syrian and Jordan and join the Jordan River in the border area of Jordan and Israel. The Yarmouk River drains a total of 6790 km^2 of which 1160 km^2 lie within Jordan upstream of Adasiya (Table 4.1). The average total discharge of the Yarmouk River is around 360 MCM/yr (SALAMEH, 1996).

4.2.1.3 The Zarqa River

The Zarqa River is the second largest river in the area of its drainage basin and its mean annual discharge. It consists of two main branches; the eastern branch (Wadi Dhuleil) which drains only flood flows as a result of precipitation, whereas the western branch (Sail-Zarqa) drains flood as well as base flows. The Zarqa River flows on porous sandstone of the Kurnub Sandstone Group and older rocks to the west in the vicinity of King Talal Dam.

The Zarqa River drains a total area of 4025 km^2 and extends from the foothills of Jabel Arab-Druz (JAD) to the Jordan River. The natural average annual discharge of Zarqa River at Deir Alla used to be 64.88 MCM/yr from 1950 to 1976 (Table 4.5). This average increased mainly, due to the import of water into the catchment.

4.2.1.4 Side Wadis (Tributaries)

Several streams named "Side Wadis", with exception of the large Zarqa River, come from two mountains banks and feed the Lower Jordan River. The side wadis with their total drainage areas and the average annual discharges are listed in (Table 4.5).

Table 4.5: Main surface water basins in Jordan (after [(a)]BELBEISI, 1992 & [(b)]SALAMEH, 1996).

No.	Surface Water Basin			[(a)]Total flow MCM/yr	[(b)]Total flow MCM/yr	Catchment area (km^2)
	Basin Name		Basin Code			
1	Yarmouk		AD	285	360	6970
2	Amman-Zarqa		AL	59.18	65	4025
3	Jordan Valley		AB	21.7	-	-
4	Jordan Valley Rift Side Wadis	North	AE, AF, AG, AH, AJ, AK	49.98	28 (Wadi el 'Arab) 10 (Wadi Ziglab)	267 106
5		South	AM, AN, AP	30.34	5.71 (Wadi Shueib) 6.4 (Wadi Kafrain)	180 189
6	Mujib		CD	83.64	83	6596
7	Hisa		CF	36.44	34	2520
8	Dead Sea Rift Side Wadis		C	61.15	30 (Wadi Zarqa Ma'in) 18 (Wadi Karak 30 (wadis in between)	272 190 972
9	North Wadi 'Araba		D	18.2	26	2938
10	Azraq (Jordan)		F	27.4	27	11600
11	Hammad		H	13	10	19270
12	Sirhan		J	10	-	15155
13	Jafr		G	11.29	15	12200
14	South Wadi 'Araba		E	5.6	1	1278
15	Southern Desert		K	2.2	1.5 (Wadi Yutum)	4400

The study area is divided into seven sub-catchments according to the drainage system and the topographic characteristics of the main wadis. The sub-catchments vary in altitude from 422 m bsl to 1240 m asl, with an area of approximately 4496.3 km^2 (Figure 4.5 & Table 4.6).

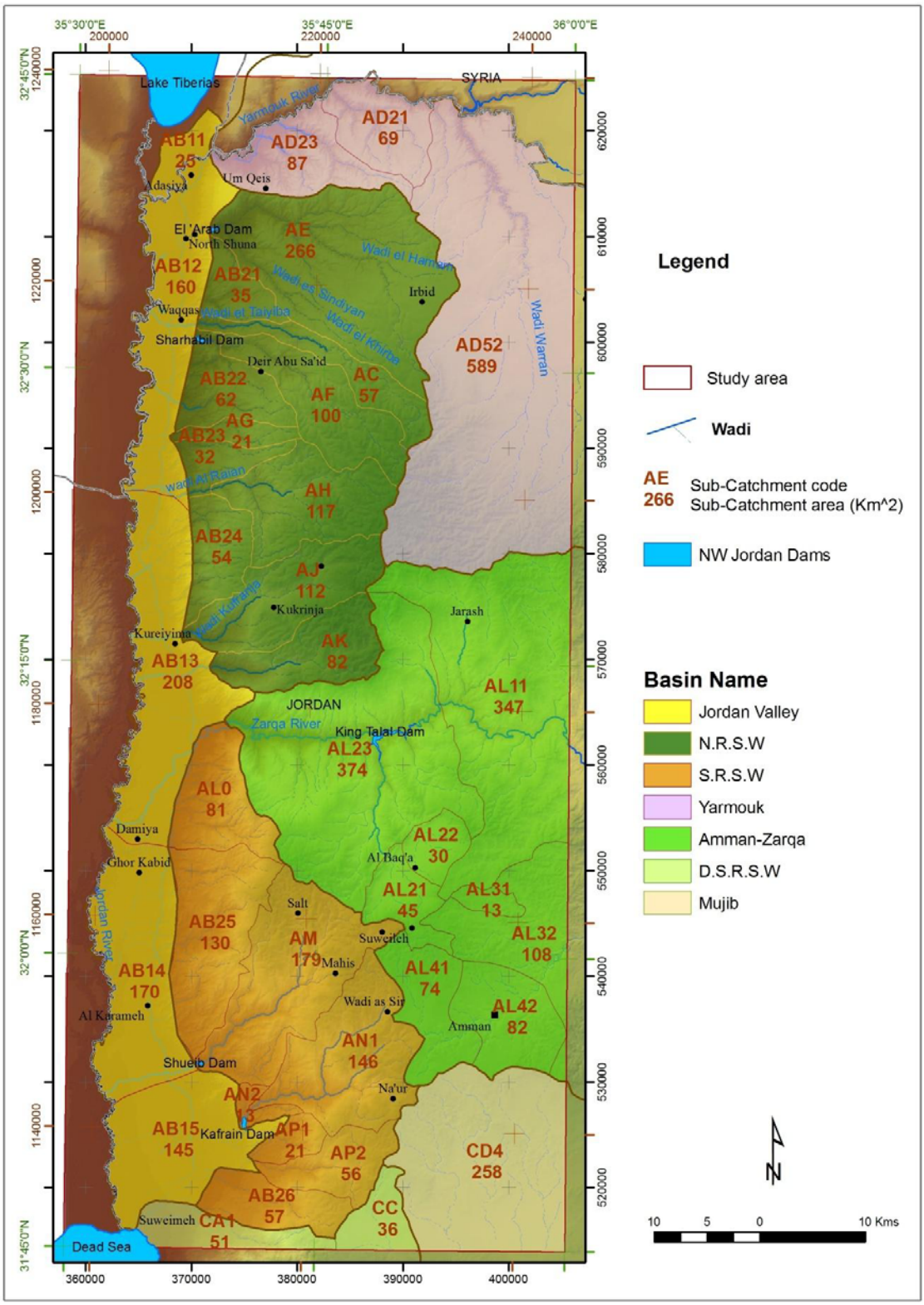

Figure 4.5: Surface water basins and sub-basins in the study area (for more detail see Plate 6) (Background represent the DEM of the study area).

Table 4.6: Summary of surface water basins and sub-basins in the study area.

Catchment Code	Catchment Description	Total Catchment Area (Jordan km^2)	Sub Catchment Code	Sub Catchment Descriptions	Sub Catchment Area (Study area km^2)	Total Sub Catchment Area (Study area km^2)	Sub Catchment Area (Study area Percentage %)	
AD2	YARMOUK (JORDAN)	1391.5	AD21	Catchment between AD0020 & W. Raqqad Conflict	69	745	1.5	16.6
AD2			AD23	Catchment down stream of W. Raqqad Conflict	87		1.9	
AD5			AD52	Jordan Territory	589		13.1	
AB1	JORDAN VALLY (JORDAN)	713.1	AB11	Jordan Valley - Yarmouk Triangle	25	708	0.6	15.8
AB1			AB12	Area between Yarmouk River & W. Yabis	160		3.6	
AB1			AB13	Area between W. Yabis & Zarqa River	208		4.6	
AB1			AB14	Area between Zarqa & W. Shueib	170		3.8	
AB1			AB15	Area between W. Shueib & Dead Sea	145		3.2	
AB2	N.R.S.W	938.2	AB21	Catchment between W. el 'Arab & W. at Tayyiba	35	938	0.8	20.9
AB2			AB22	Catchment between W. at Tayyiba & W. Jurum	62		1.4	
AB2			AB23	Catchment between W. Jurum & W. Yabis	32		0.7	
AB2			AB24	Catchment between W. Yabis & W. Kufranja	54		1.2	
AC			AC	W. at Tayyiba	57		1.3	
AE			AE	W. el 'Arab	266		5.9	
AF			AF	W. Ziglab	100		2.2	
AG			AG	W. Jurum	21		0.5	
AH			AH	W. Yabis	117		2.6	
AJ			AJ	W. Kufranja	112		2.5	
AK			AK	W. Rajib	82		1.8	
AB2	S.R.S.W	684.1	AB25	Catchment between W. Ar Ramleh & W. Shueib	130	683	2.9	15.2
AB2			AB26	Catchment between W. Hisban & Dead Sea Basin	57		1.3	
AL0			AL0	Lower Catchment between Deir Alla & W. Ar Ramleh	81		1.8	
AM			AM	W. Shueib	179		4.0	
AN			AN1	W. Kafrain up stream	146		3.3	
AN			AN2	W. Kafrain down stream	13		0.3	
AP1			AP1	W. Hisban	21		0.5	
AP2			AP2	W. Quseib	56		1.2	
AL11	AMMAN ZARQA (JORDAN)	3590.1	AL11	Catchment up stream of Jarash Road bridge station (AL0060)	347	1073	7.7	23.9
AL2			AL21	W. Um Ad Dananir at station AL0040	45		1.0	
AL2			AL22	W. Sleihi at station AL0061	30		0.7	
AL2			AL23	Lower W. Catchments	374		8.3	
AL3			AL31	W. Muruj	13		0.3	
AL3			AL32	Other Tributaries Catchments (W. Hammam)	108		2.4	
AL4			AL41	W. Abdoun (AL0065)	74		1.6	
AL4			AL42	Amman Area between stations AL0062 & AL0065	82		1.8	
CA	D.S.R.S.W	1549.0	CA1	Area between Jordan River Basin & W. Zarqa Ma'in	51	87	1.1	1.9
CC			CC	W. Zarqa Ma'in	36		0.8	
CD4	MUJIB	6584.4	CD4	W. Wala Catchment at Karak Road (station CD0038)	258	258	5.7	5.7
Total		15450			4492	4492	100	100

4.2.2 Rainfall

In Jordan, the amount of rainfall is mainly governed by the topographic elevation of a location (BGR & WAJ, 1995b). In the study area, the topographic elevations vary from 422 m bsl (the Dead Sea level 2009) to a maximum altitude of 1240 m asl, northeast of Umm al Julud village (Jarash sheet), in the central eastern part of the study area (as described previously in chapter 1.3) (Plate1). Accordingly, a total number of 98 rainfall stations in the study area with monthly rainfall measurements were reviewed for the water years from 1937/38 to 2008/09 (MWI open files). The distribution of these stations is shown in (Figure 4.6).

The MWI monthly rainfall amounts data from 1937/38 to 2008/09 show that the rainfall is seasonal in the study area, occurring in a period from October to April where rainfall before or after this period is rare event. The profiles of rain distribution in different stations over the observed period in the study area are shown in Figure 4.7. In general, Figure 4.7 (from I to XVIII) shows that the highest annual rainfall occurs in the mountainous region mainly in the central part of the study area (Figure 4.7; II, V, VII, XI, XIV & XVIII) from there it decrease towards the east (Figure 4.7; I, IV, VII, X, XIII & XVI) and the west (Figure 4.7; III, VI, IX, XIII, VI & XVIII). The monthly rainfall depth in the different stations in the study area (Figure 4.7) indicates that the highest rainfall occurs from December to March while the lowest rainfall occurs between April and October. The maximum annual rainfall was recorded in Ajlun station (159.8 mm) while the lowest annual rainfall was observed at south Shuna station (30.9 mm).

The MWI monthly rainfall amounts data from 1937/38 to 2008/09 were used to calculate the long term average amount of rainfall for stations in the study area in normal year, wet year and dry year. The long term averages are illustrated in Appendix 4.1. The 72 years of rainfall amount averages of the time period 1937/38 to 2008/2008 in the study area as shown in Figure 4.8 is 398.5 mm. In addition to that the long term rainfall averages in normal years, wet year and dry year from 1937/38 to 2008/2008 are represented as isohyetal map by using ArcMap 9.3 application (Krigging interpolation) (Figures 4.9, 4.10 & 4.11).

Figure 4.9 shows that the highest amount of rainfall is recorded in the northern highlands around Ajlun (AJ0001), Kufranja (AJ0002) and Salt (AM0001), where the 72 years average (1937/38-2008/09) reaches a maximum of 631.5 mm/yr, 605 mm/yr and 600.3 mm/yr respectively. It decreases to 70.5 mm/yr in the Kafrain dam station (AN0005) southwest of the study area.

The long term rainfall averages in wet and dry years were calculated also as shown in Appendix 4.1. The wet and dry conditions were calculated by taking to consideration that rainfall rates of less than 25% or more than 25% of the long term average in normal year is dry or wet year respectively (Figure 4.10 & Figure 4.11).

The long term averages of dry rainfall years (Figure 4.10) shows that the Northern Highlands receives around 581.3 mm/yr in Ajlun Police Post (AJ0001) and in ‘Ain al Basha (AL0041) and decreases to 13.9 mm/yr in Kafrain dam (AN0005) in the Jordan Valley.

The long term averages of Wet rainfall years (Figure 4.11) shows that rainfall limited in wet years exceeds 780 mm/yr in Ajlun Police Post (AJ0001) in the central part of the study area; with a peak in January-February. The rainfall decreases to 155.5 mm/yr in Kafrain dam area (AN0005) in the Jordan Valley.

The long term average rainfall in normal, wet and dry years were used also to calculate the amount of rainfall NW Jordan's area receives. The results are summarized in Table 4.7. In addition to that, the long term total amounts of rainfall volumes in the study area (from 1937/38-1944/45 to 2001/02-2008/09) were calculated from the thematic layers in (Figures 4.9, 4.10 & 4.11) for normal, dry and wet years respectively. The total calculated rainfall volume over the NW part of Jordan in a normal year is around 1760.4 MCM while in a wet year it increases to around 2263.7 MCM which represent 128.6% of a normal year. In a dry years, the calculated volume of rainfall is around 1324.6 MCM, that means a sever depletion in the volume of rainfall reaching 75.2% of a normal year (Table 4.7).

Table 4.7: The average annual precipitation received, the percentage area and the average rainfall volume in the NW part of Jordan for a normal, dry and wet years (long term average for the water years from 1973/38 – 2008/09).

	Normal rainfall year			**Dry rainfall year**			**Wet rainfall year**		
Rainfall depth (mm/yr)	Covered area (km^2)	Covered area %	Rainfall volume (MCM/yr)	Covered area (km^2)	Covered area %	Rainfall volume (MCM/yr)	Covered area (km^2)	Covered area %	Rainfall volume (MCM/yr)
200				614	13.7	122.8			
250	328	7.3	82.0	904	20.2	226.1			
300	550	12.3	165.0	1337	29.9	401.1			
350	762	17.1	266.6	1394	31.2	488.0	339	7.6	118.6
400	1152	25.8	460.7	217	4.9	86.7	490	11.0	196.0
450	1109	24.8	498.9				611	13.7	274.7
500	481	10.8	240.6				1018	22.8	509.0
550	85	1.9	46.6				875	19.6	481.1
600							1060	23.7	636.1
650							74	1.7	48.1
Total	4466	100	1760.4	4466	100	1324.6	4466	100	2263.7

Moving averages for 6 year periods (from 1937/38-1944/45 to 2001/02-2008/09) were calculated for selected rainfall stations in the NW part of Jordan, that have sufficient long term time periods with only few missing records, especially in Deir Alla Agricultural station (AL0010) (Figure 4.12). The long term averages were calculated also for each station. Generally, the rainfall stations show averages close to long term averages. Most stations show a dropdown trend in the periods 1952/53-1960/61 and 1992/93-2000/2001. While in the periods 1960/61-1968/1969 and 1984/85-1992/93 the rainfall averages were higher than the long term averages. The long term averages for rainfall stations east of the Dead Sea was calculated by (AL-RAGGAD, 2009), the study shows also that the year 1995 was the driest in the period 1985 to 2008 while the year 1991/1992 was a good example for wettest years. It also shows a decline of rainfall averages from 2003 to 2009. This decline is clear also in the NW part of Jordan as shown in Figure (4.12).

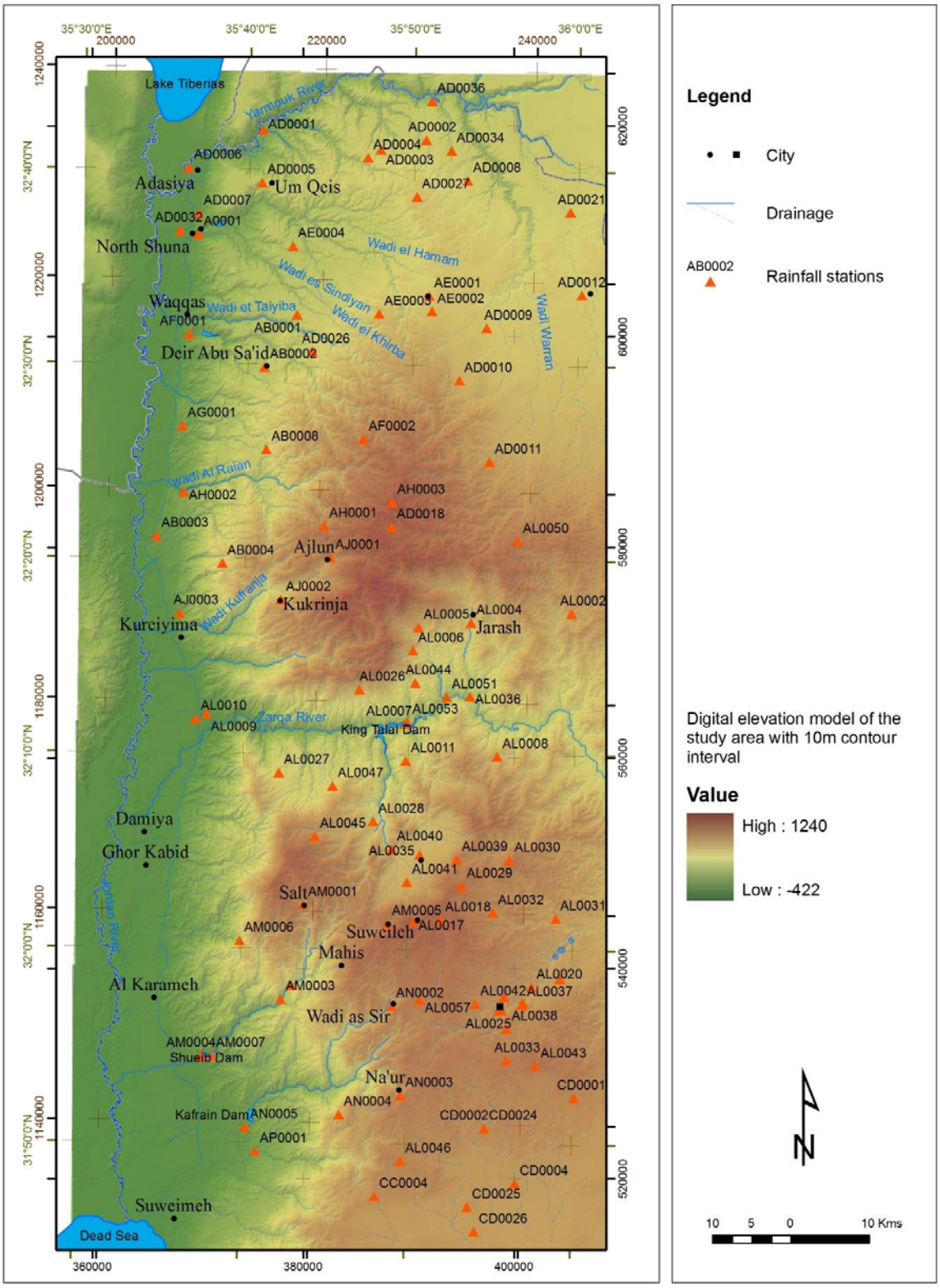

Figure 4.6: Distribution of rainfall stations in the study area (for details refer to Appendix 4.1).

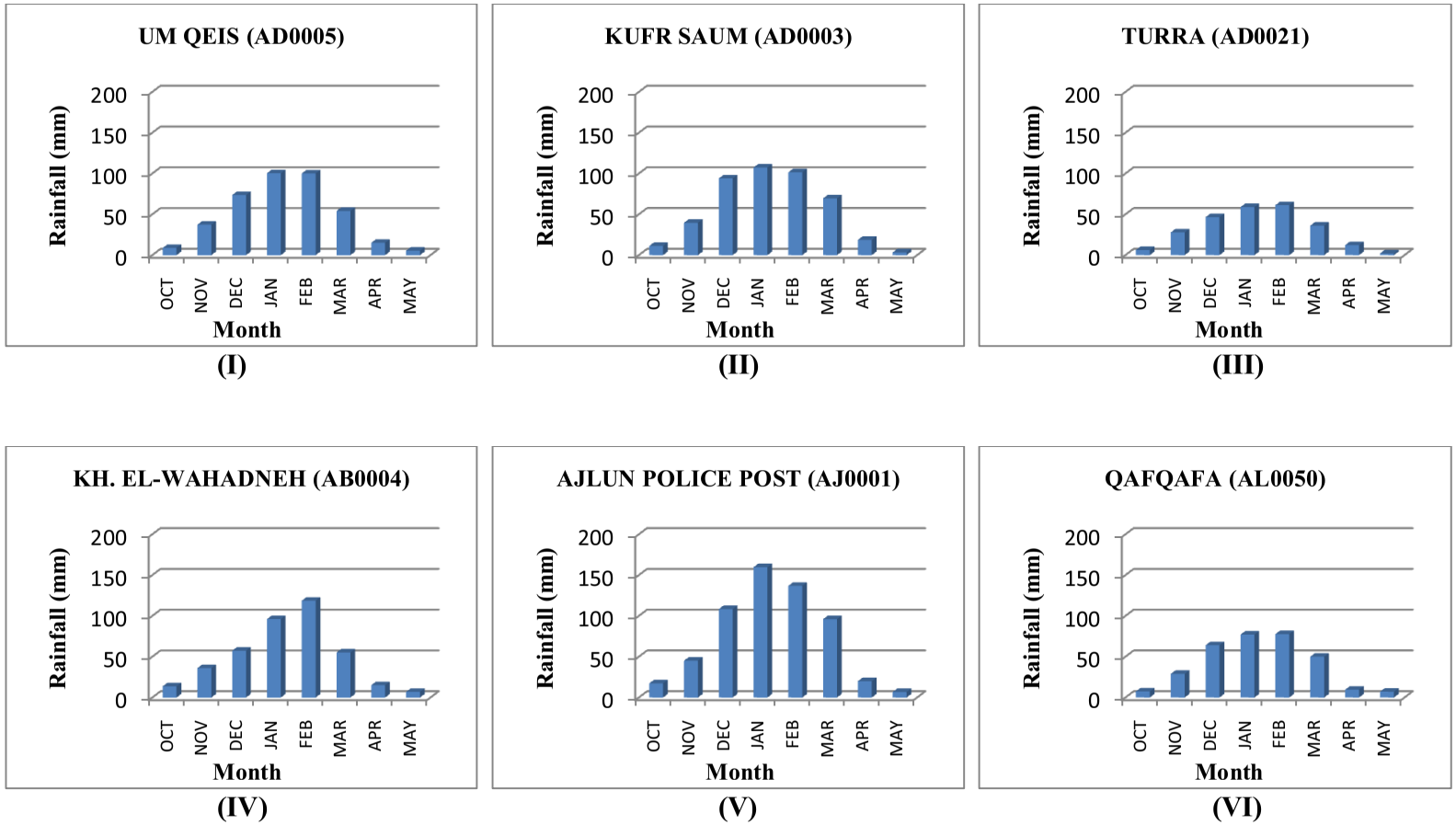

Figure 4.7 (from I to VI): Histogram of the monthly rainfall depth in different stations in the study area.
(Note: stations in row refer to stations from west to east and in columns refer to stations from north to south)

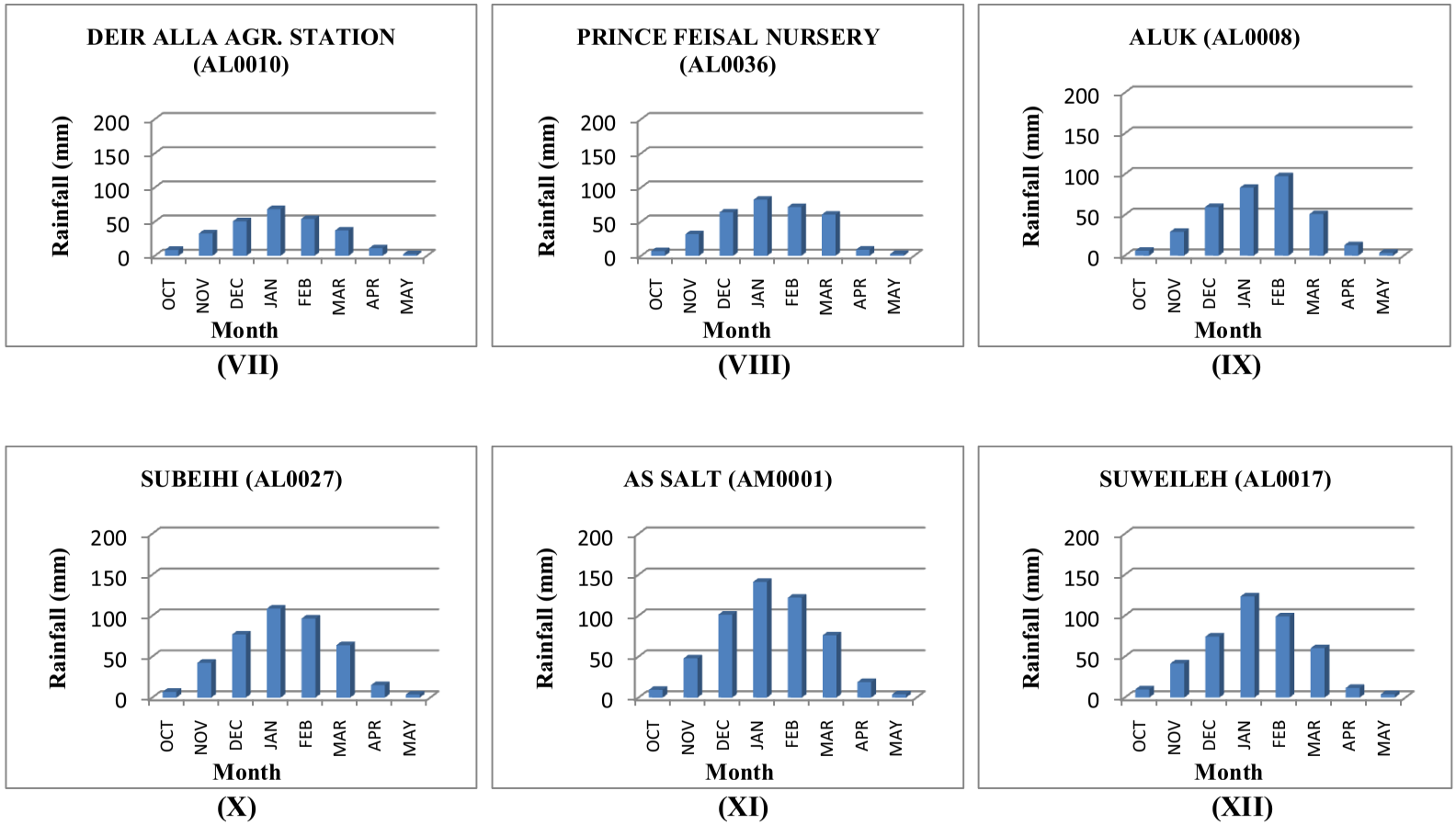

Figure 4.7 (from VII to XII): Histogram of the monthly rainfall depth in different stations in the study area. (Note: stations in row refer to stations from west to east and in columns refer to stations from north to south)

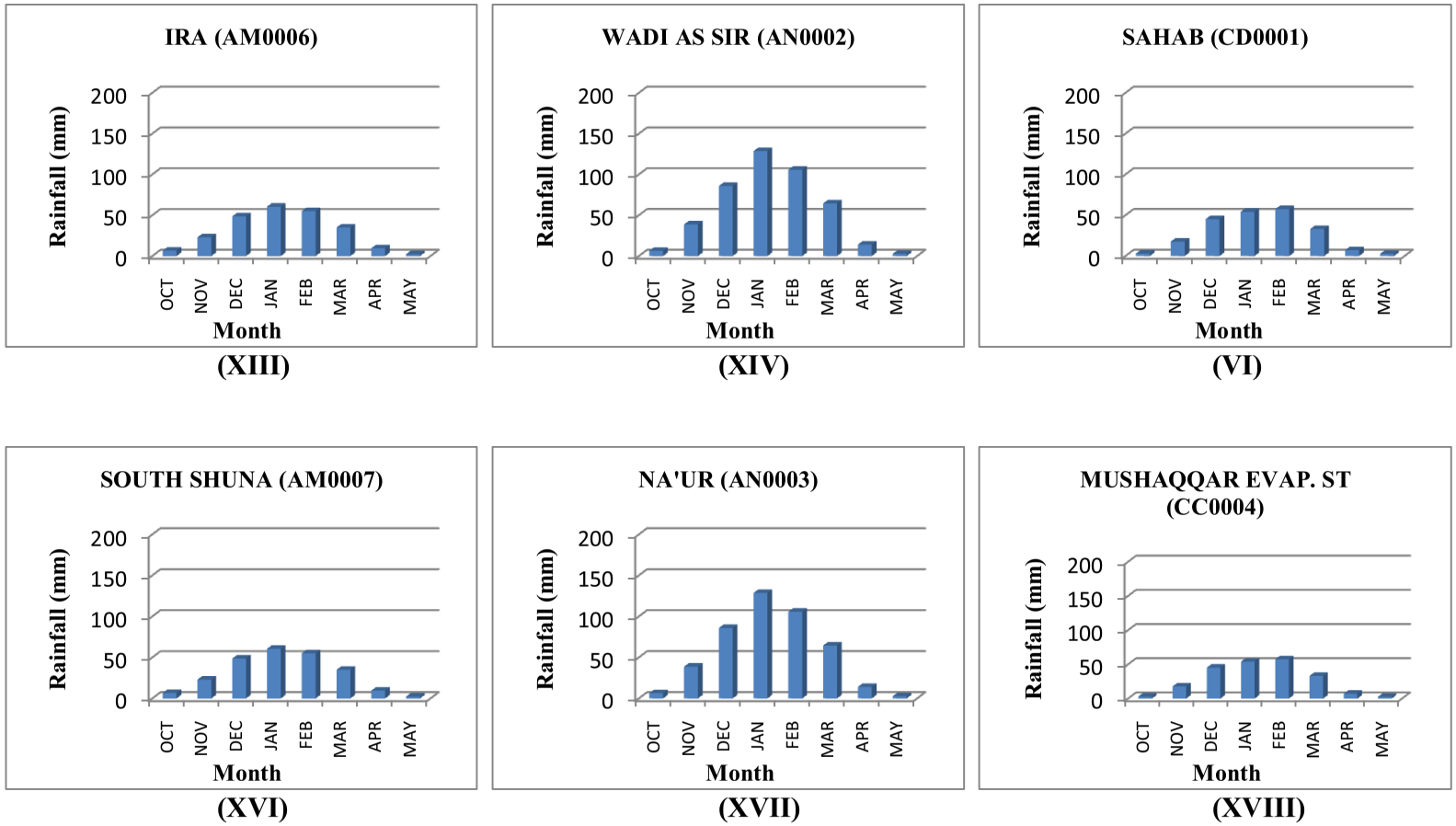

Figure 4.7 (from XIII to XVIII): Histogram of the monthly rainfall depth in different stations in the study area. (Note: stations in row refer to stations from west to east and in columns refer to stations from north to south)

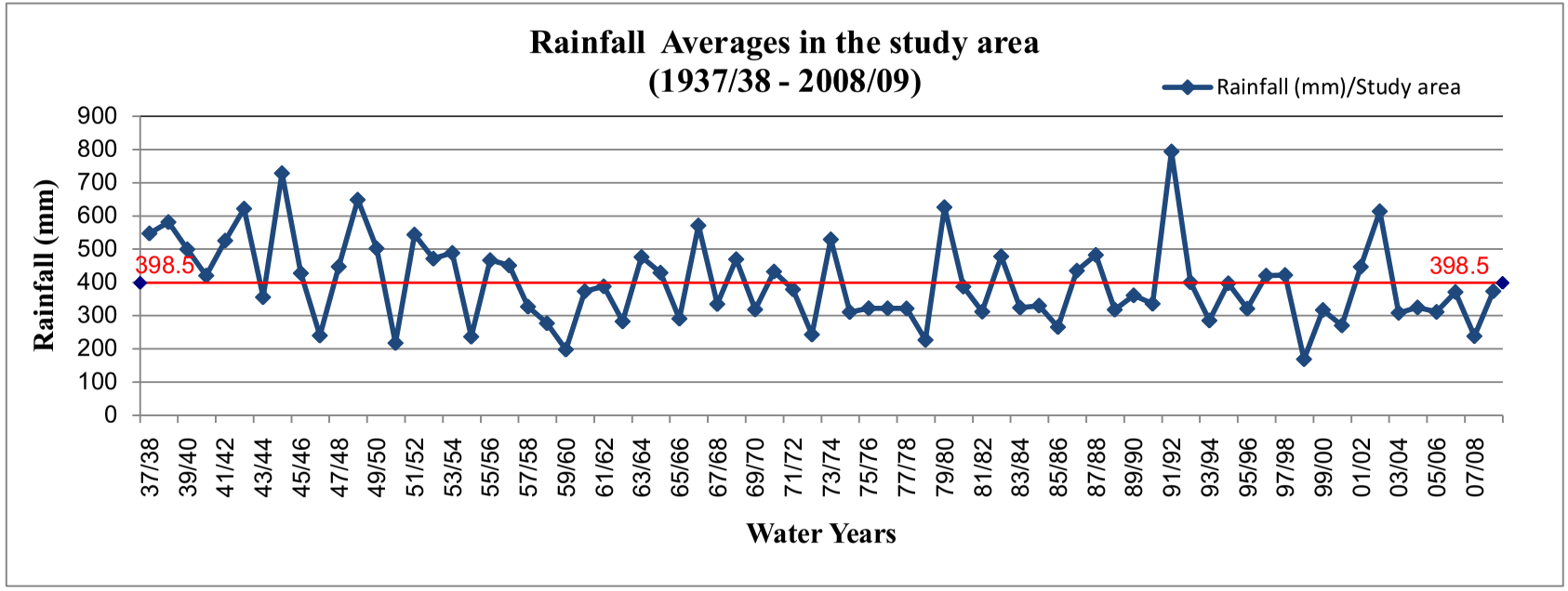

Figure 4.8: The long term rainfall averages in the study area for stations listed in Appendix 4.1 (in normal water year from 1937/38 to 2008/09 in mm from MWI files).

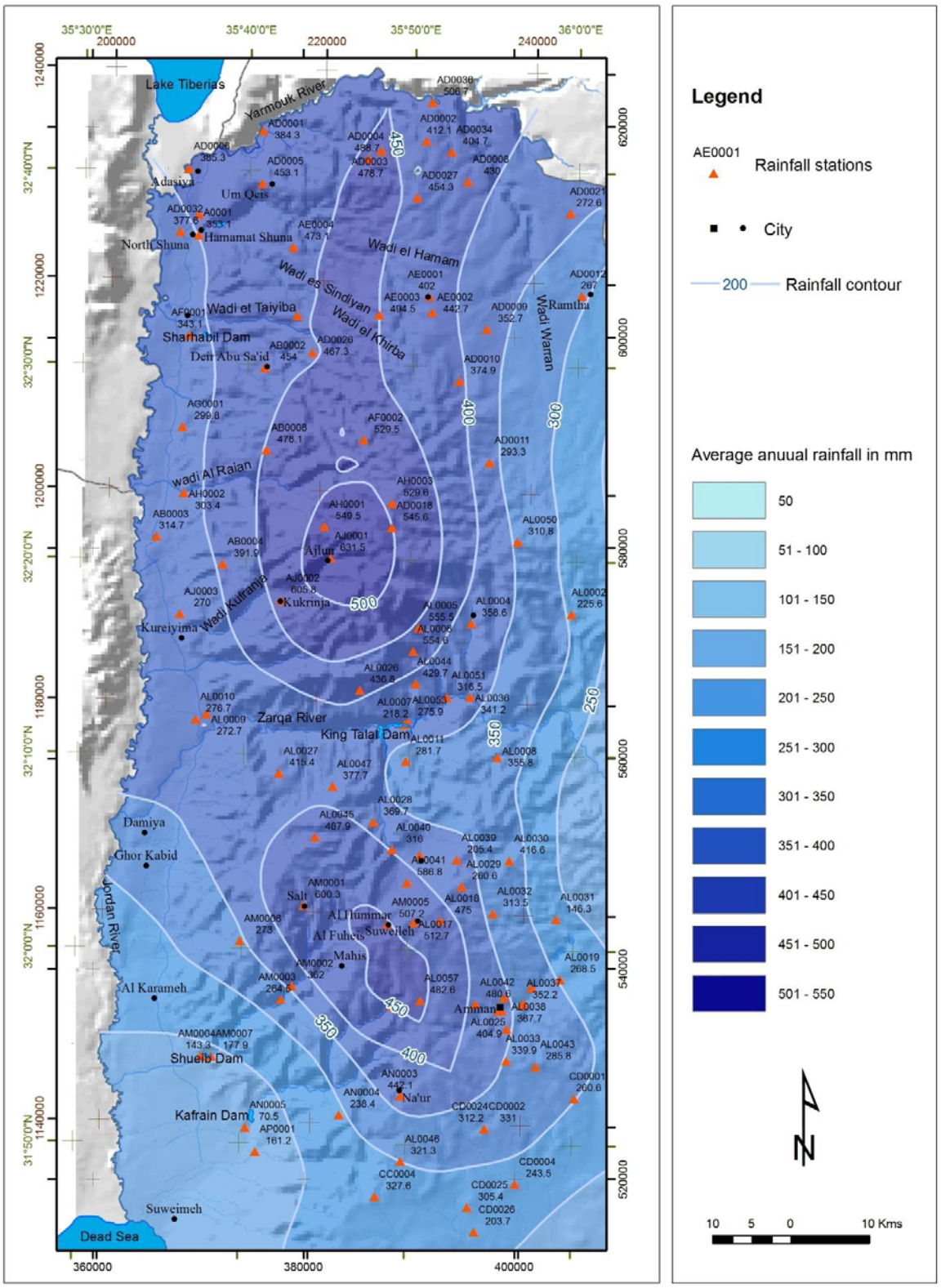

Figure 4.9: The long term average rainfall distribution as isohyets in the study area for normal water years (1937/38 - 2008/09) – mm/year.

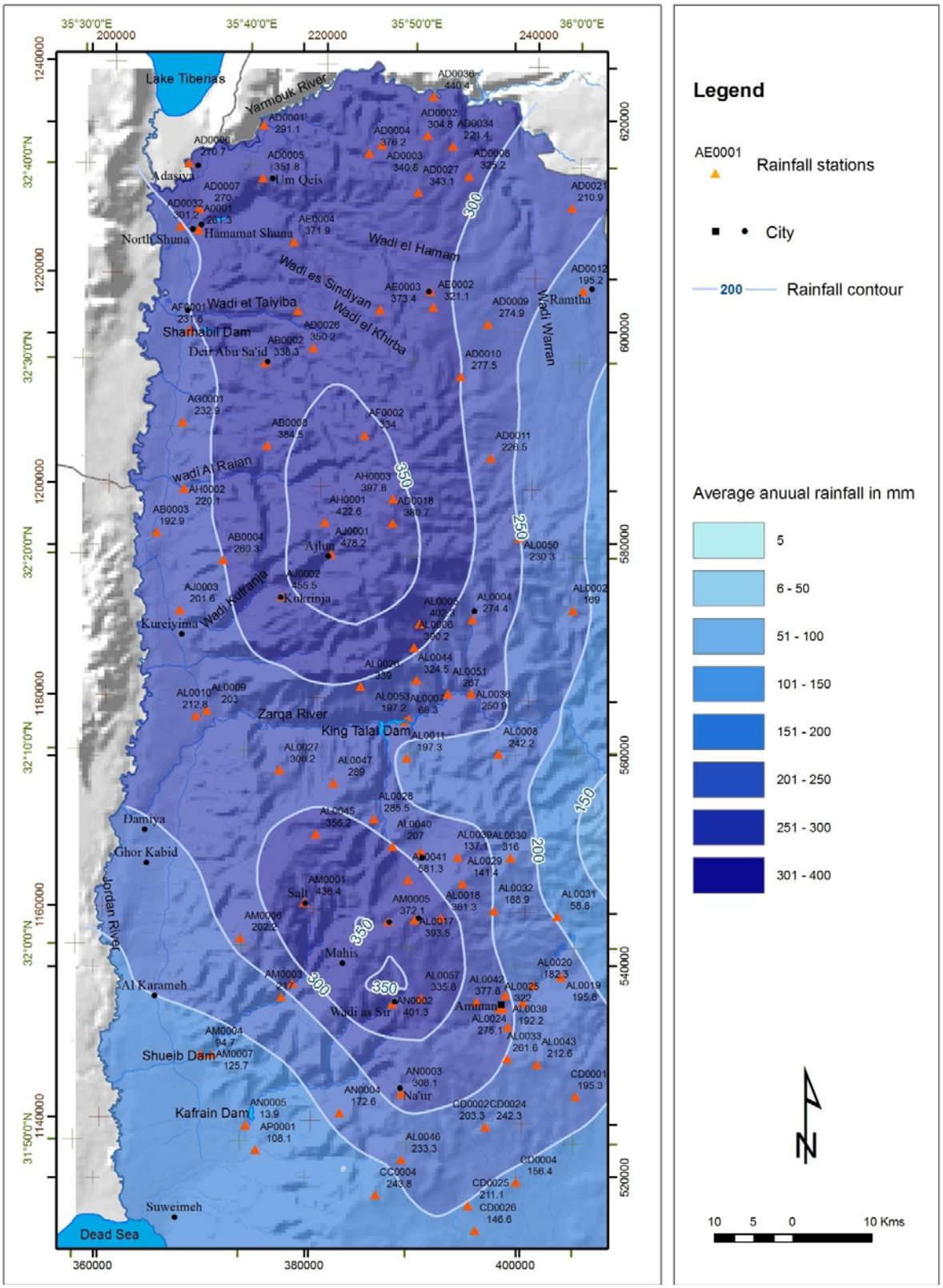

Figure 4.10: The long term average rainfall distribution as isohyets in the study area for dry water years (1937/38 - 2008/09) – mm/year.

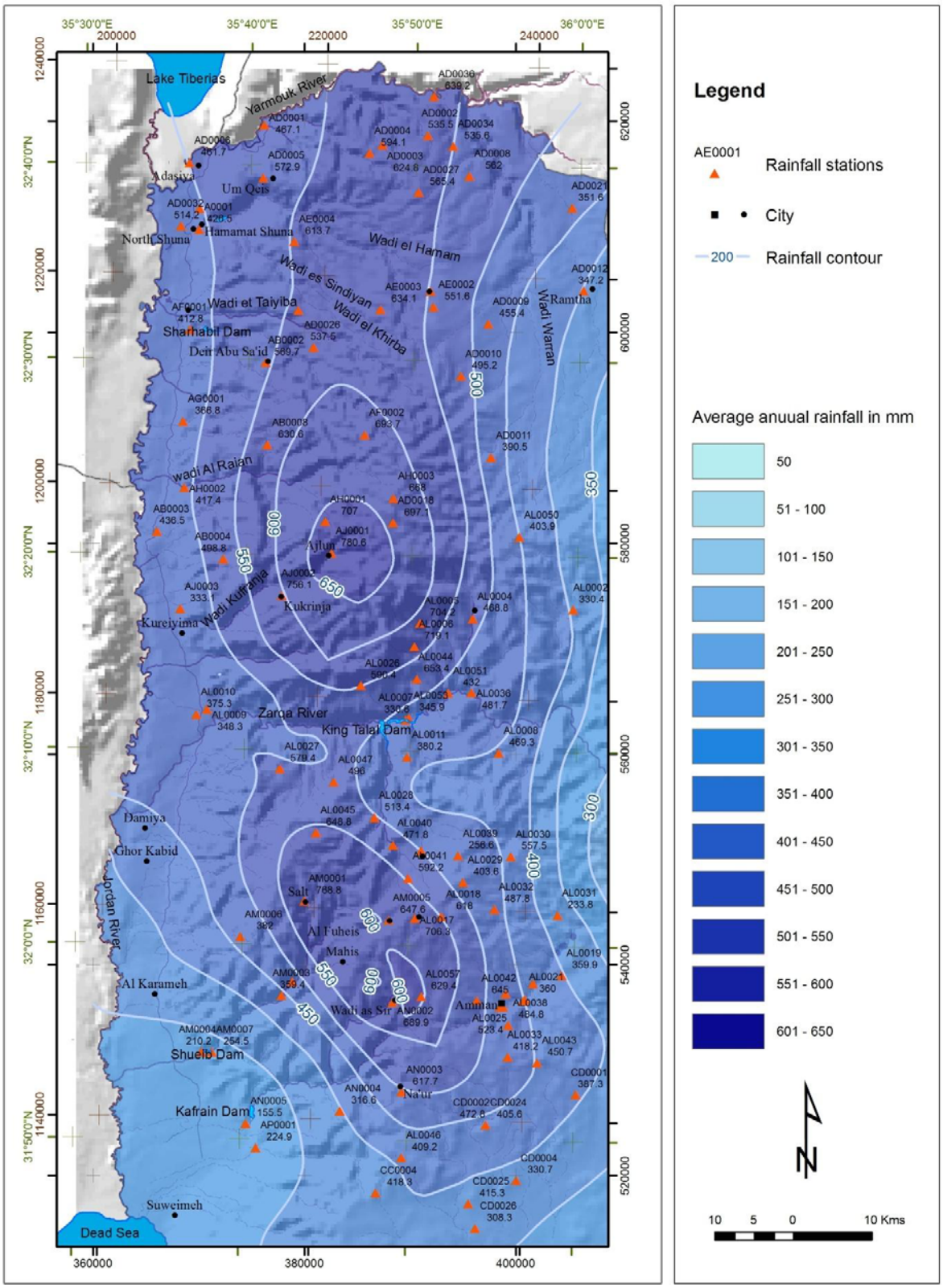

Figure 4.11: The long term average rainfall distribution as isohyets in the study area for wet water years (1937/38 - 2008/09) – mm/year.

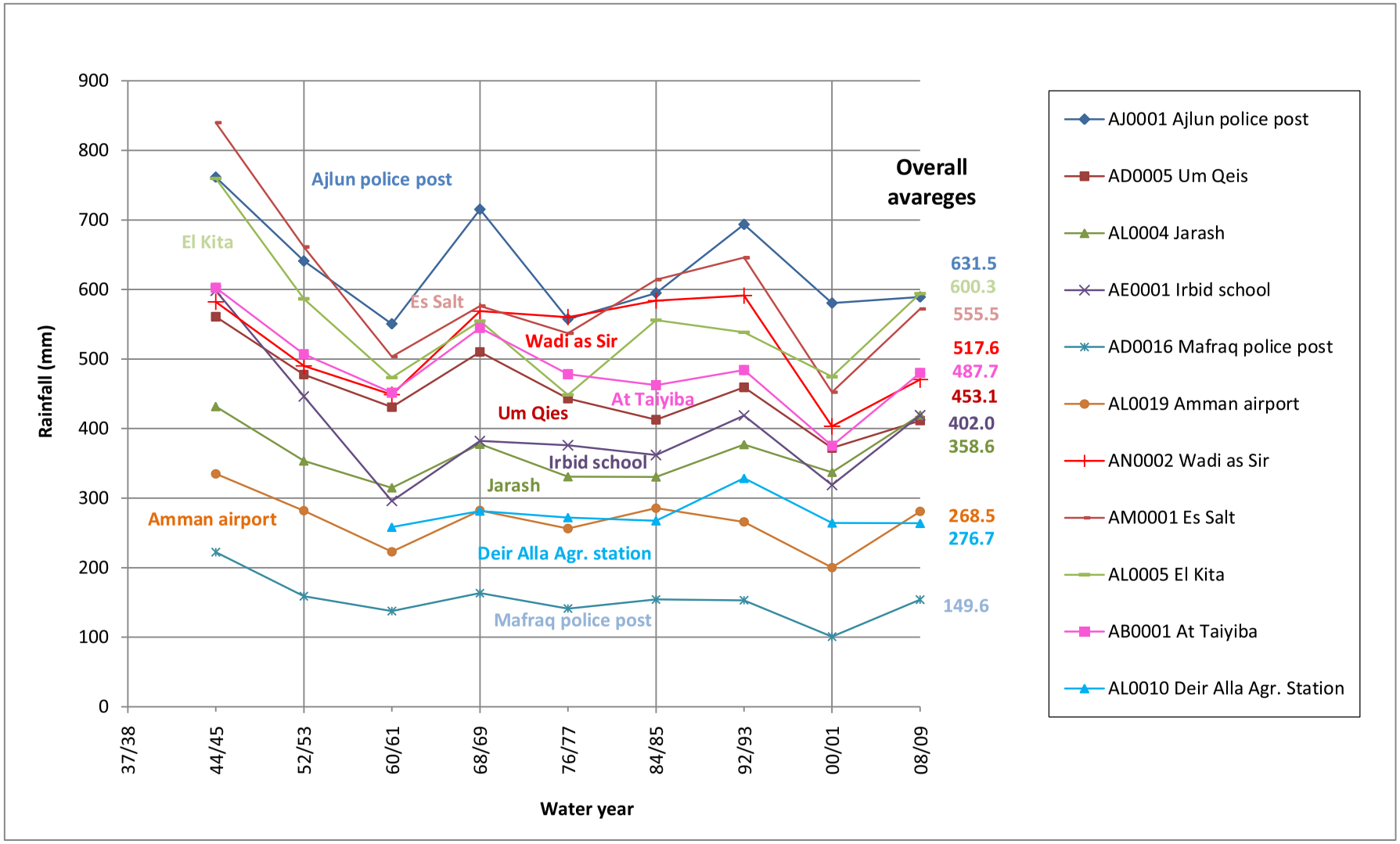

Figure 4.12: Comparison of rainfall averages in NW of Jordan; (6 years moving average) from 1937/38-1944/45 to 2001/02-2008/09.

4.2.3 Evaporation

As have their climatic conditions affect the amount and distribution of precipitation, they also impact on the potential evaporation. In the study area, the strong seasonal variation of the key climatic parameters rainfall, temperature and evaporation is shown on climate charts (Figure 4. 13).

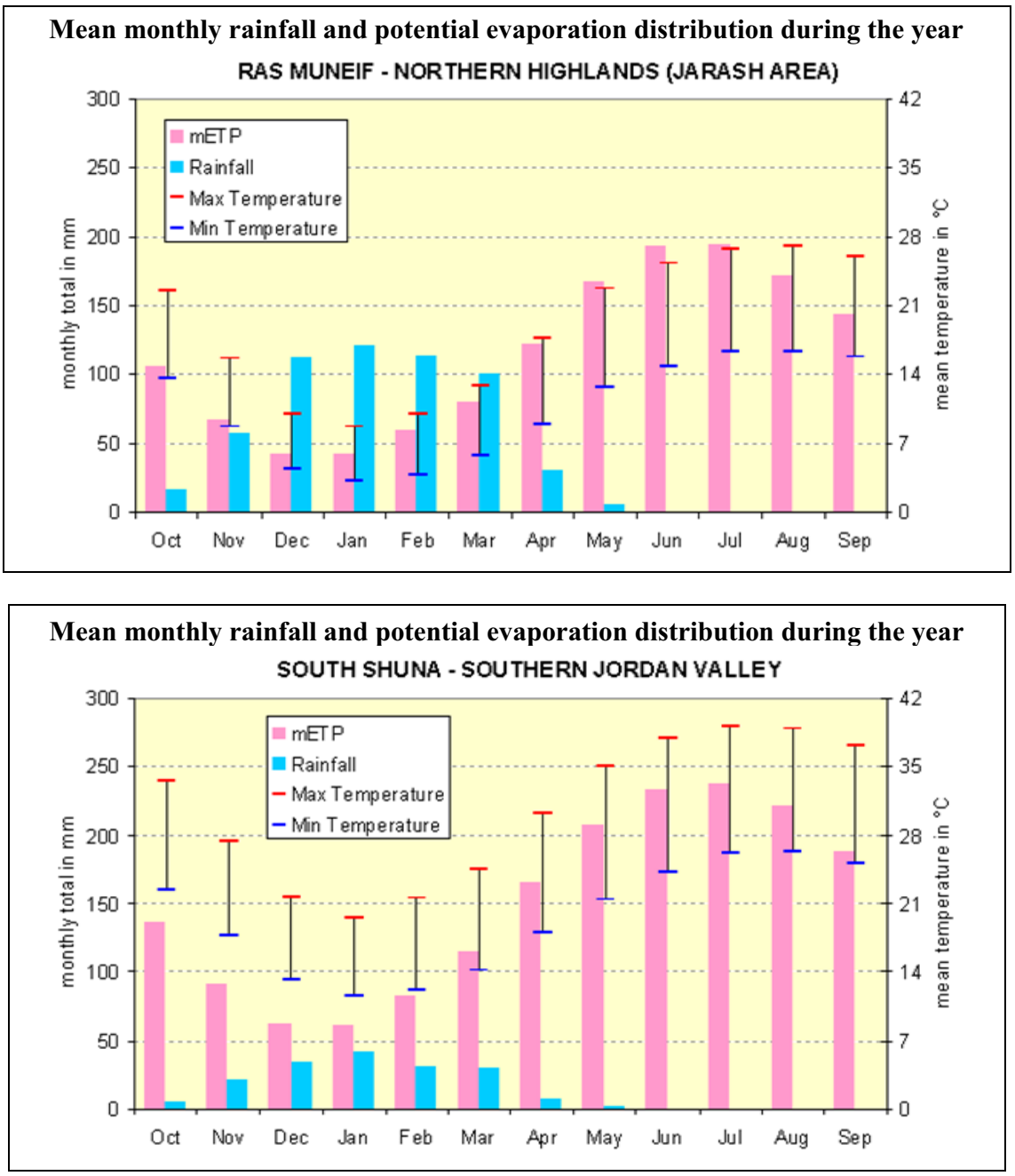

Figure 4.13: Climate charts of meteorological stations representative for different climatic zones in the study area (GTZ & MWI, 2004).

Only a limited number of evaporation values but no direct evapotranspiration measurements are available in the study area. SALAMEH (2009) adapted a new procedure for the calculations of evaporation in the northwestern part of Jordan, based on the fact that evaporation takes place only when soil moisture is available for evaporation. This period for Jordan extends from November to the end of March. In April soil moisture or water retained in the soil is also added to evaporation. It was considered that any rainfall events before and after this period will be totally consumed by evaporation.

The local distribution of potential evaporation (in mm per year) average of calculated values period 1965 – 1972 in the study area (modified after GTZ & NRA, 1977) is shown in Figure 4.14. The mean annual potential evaporation exceeds by far the annual rainfall in the area (SALAMEH et al., 2004). The mean annual potential evaporation rates of 1900 mm/yr are typical in the highlands (GTZ & NRA, 1977), while the mean annual rainfall is not more than 550 mm/yr (Table 4.8). In the Jordan Valley, the mean annual potential evaporation increases to 2600 mm/yr (GTZ & NRA, 1977), while the mean annual rainfall decreases to less than 250 mm/yr (Table 4.8). In the western part of the Jordan valley (Jericho station), the mean annual potential evaporation averages to 2082 mm/yr for the period from 1968 till 1999), while for the same period, the mean annual rainfall is merely 163 mm/yr (TOLL, 2007). In the highlands, groundwater recharge takes place only after runoff and evaporation take whatever they can from precipitation water.

Table 4.8: Mean monthly temperature, rainfall and evaporation for different stations in the study area (after SALAMEH, 2009).

Month	November			December			January			February			March		
Parameter / Station	Temp. C°	ppt	Total Evap.	Temp. C°	ppt	Total Evap.	Temp. C°	ppt	Total Evap.	Temp. C°	ppt	Total Evap.	Temp. C°	ppt	Total Evap.
Salt area	18.6	51.9	50.6	13.2	105.9	27.4	11.1	140.2	20.7	11.7	119.6	19.9	15.1	94.6	46.5
Baqaura area	26.5	45.1	77.2	20.2	80	41.1	18.4	93.5	33	19.7	74.8	32.8	32.2	56	82.6
University of Jordan	18.1	48.5	49.1	12.3	94.8	31.4	10.2	116.9	22.6	11.7	105.1	24.8	15.2	85.1	54.7
Wadi Raian	26.7	35.4	64.7	20.5	62.8	33.9	18.8	71.6	27.4	20.3	58	29.8	23.8	44.4	61.4
Irbid	20.6	50.4	56.2	15	82.1	24.2	13	109.1	24.2	14.8	97.1	26.8	17.1	85.9	51.7
Deir 'Alla	20.2	37.4	53	14.1	64.1	28.2	12.7	84.1	22.6	14.1	74.4	26.2	14.5	61.4	56.8

Temp (C°) = Average monthly maximum daily temperature (centigrade).
ppt = Precipitation amount in month (mm).
Total Evap. = Total calculated evaporation for a specific month (mm).

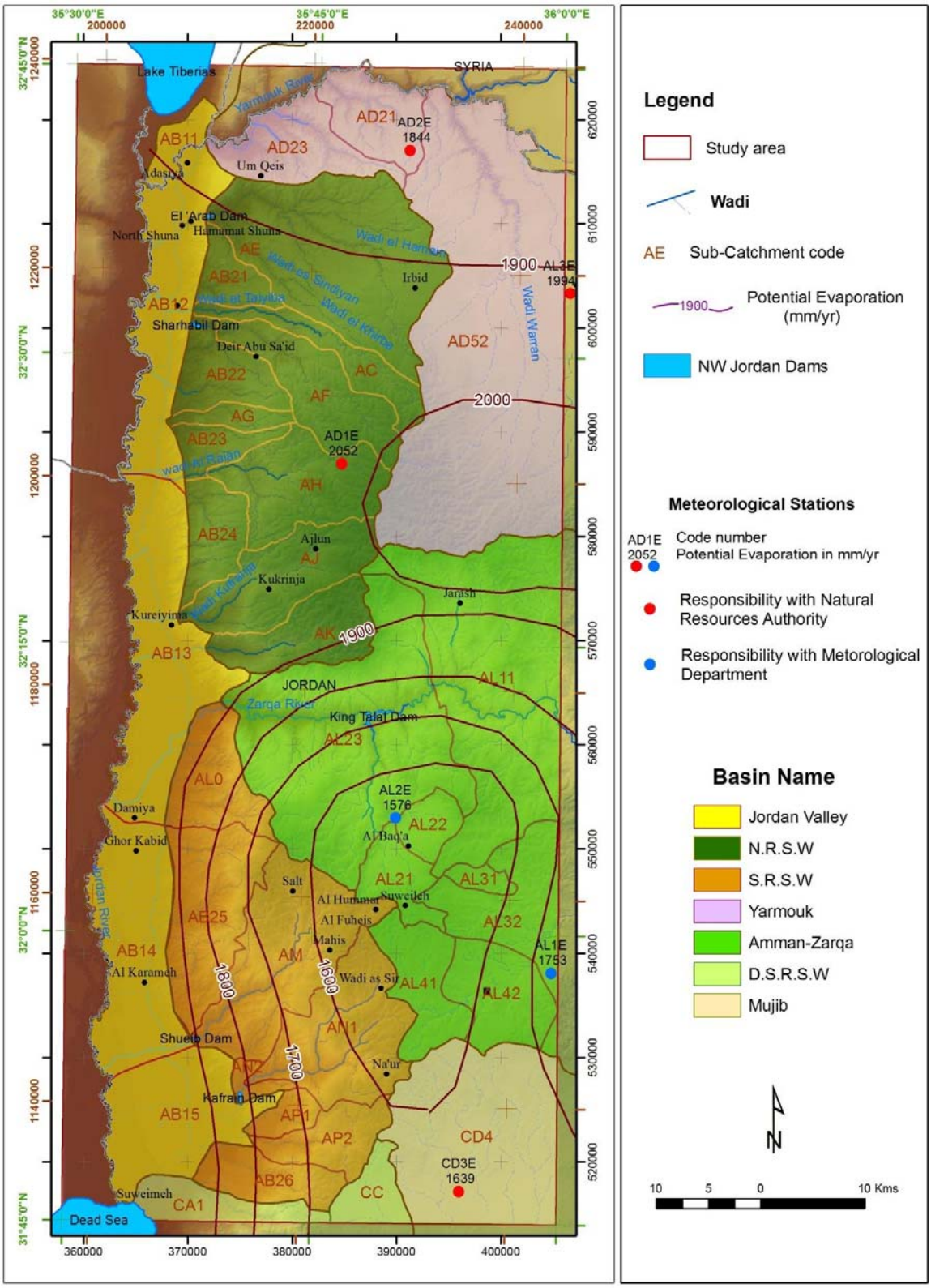

Figure 4.14: Potential Evaporation (in mm per year) average of calculated values period 1965 – 1972 in the study area (modified after GTZ & NRA, 1977).

4.2.4 Runoff

Runoff precipitation ratios were calculated in normal, dry and wet years by the GTZ & NRA (1977) as a part of National Water Master Plan (NWMP) for the different parts of Jordan. The term, runoff ratio, is the percent of drainage basin precipitation that becomes stream flow.

The GTZ & NRA (1977) runoff ratios were applied to different catchment and sub-catchments in the study area, in order to calculate the runoff volumes in the NW part of Jordan. Catchments and sub-catchments runoff ratios are illustrated in Table (4.9).

By using GIS, Arc Map 9.3 these ratios were used to draw the spatial distribution of runoff over the study area as given in Figures 4.15, 4.16 & 4.17 for normal, dry and wet years respectively.

The rainfall depth maps (Figures 4.9, 4.10 & 4.11) and the spatial distribution maps (Figures 4.15, 4.16 & 4.17) were used to calculate the runoff volume in MCM/yr for the study area as given in Figures 4.18, 4.19 & 4.20, in normal, dry and wet years respectively. The result of calculations are summarized in (Table 4.10) which shows that the total catchment area of 4445 km^2 produces a runoff of around 83.55 MCM/yr in a normal year, increasing to around 151.44 MCM/yr in a wet year representing 181.25 % of a normal year. Dry year mean sever depletion in rainfall volume reaching 43.96% of a normal average, with a calculated volume around 36.73 MCM/yr (Table 4.10).

The runoff/ rainfall ratio in a normal, dry and wet years are represented in Figure (4.21), which shows that runoff/ rainfall ratio decreases with decreasing rainfall and that the runoff in the NW part of Jordan is only proportional to rainfall.

Table 4.9: Runoff coefficient of catchments and sub-catchments NW of Jordan; in normal, dry and wet years (GTZ & NRA, 1977).

Catchment Code	Catchment Description	Sub Catchment Code	Sub Catchment Description	Average runoff coeff. (%)	Dry runoff coeff. (%)	Wet runoff coeff. (%)
AD2	YARMOUK (JORDAN)	AD21	Catchment between AD0020 & W. Raqqad Conflict	9.8	6.8	12.8
AD2		AD23	Catchment downstream of W. Raqqad Conflict			
AD5		AD52	Jordan Territory			
AB1	JORDAN VALLY (JORDAN)	AB11	Jordan Valley - Yarmouk Triangle	0	0	0
AB1		AB12	Area between Yarmouk River & W. Yabis			
AB1		AB13	Area between W. Yabis & Zarqa River			
AB1		AB14	Area between Zarqa & W. Shueib			
AB1		AB15	Area between W. Shueib & Dead Sea			
AB2	N.R.S.W	AB21	Catchment between W. el 'Arab & W. at Tayyiba	5	3.1	7.5
AB2		AB22	Catchment between W. at Tayyiba & W. Jurum	3	1.2	5.2
AB2		AB23	Catchment between W. Jurum & W. Yabis	1.5	0	2.6
AB2		AB24	Catchment between W. Yabis & W. Kufranja	0	0	0.5
AC		AC	W. at Tayyiba	5	3.1	7.5
AE		AE	W. el 'Arab	5.2	3.2	7
AF		AF	W. Ziglab	4.2	2.3	6.3
AG		AG	W. Jurum	2.4	0.6	4.8
AH		AH	W. Yabis	2.5	0.9	4
AJ		AJ	W. Kufranja	1.7	0	4.2
AK		AK	W. Rajib	3	1	5.6
AB2	S.R.S.W	AB25	Catchment between W. Ar Ramleh & W. Shueib	3.5	2.1	5.4
AB2		AB26	Catchment between W. Hisban & Dead Sea Basin	0	0	0.7
AL0		AL0	Lower Catchment between Deir Alla & W. Ar Ramleh	3.8	1.8	5.8
AM		AM	W. Shueib	2.5	0.8	4.6
AN		AN1	W. Kafrain up stream	1.8	0.2	3.6
AN		AN2	W. Kafrain down stream	1.8	0.2	3.6
AP1		AP1	W. Hisban	1.9	0.6	3.8
AP2		AP2	W. Quseib	1.9	0.6	3.8
AL11	AMMAN ZARQA (JORDAN)	AL11	Catchment up stream of Jarash Road bridge station (AL0060)	6	3.6	8
AL2		AL21	W. Umm Ad Dananir at station AL0040	6.5	2.4	10.2
AL2		AL22	W. Sleihi at station AL0061	2.7	0.9	6.5
AL2		AL23	Lower W. Catchments	6.8	4.2	9.4
AL3		AL31	W. Muruj	4.6	1.6	8
AL3		AL32	Other Tributaries Catchments (W. Hammam)	2.2	0.9	4
AL4		AL41	W. Abdoun (AL0065)	9	4	13
AL4		AL42	Amman Area between stations AL0062 & AL0065	11	7.8	14.3
CA	D.S.R.S.W	CA1	Area between Jordan River Basin & W. Zarqa Ma'in	1.3	0	2.8
CC		CC	W. Zarqa Ma'in	3.6	1.4	6.3
CD4	MUJIB	CD4	W. Wala Catchment at Karak Road (station CD0038)	4.2	2.5	5.8

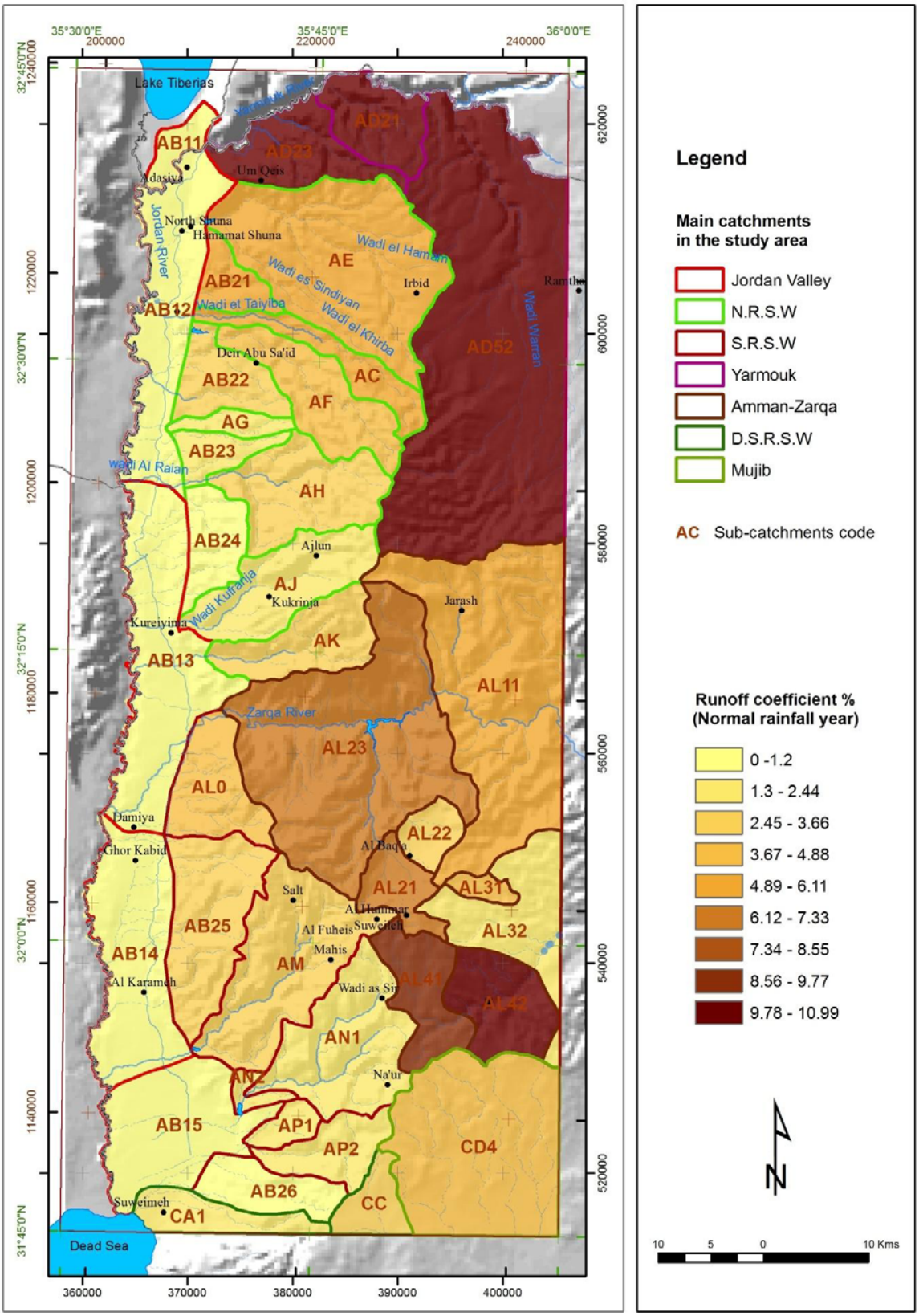

Figure 4.15: Spatial distribution of runoff in a normal rainfall year, NW of Jordan.

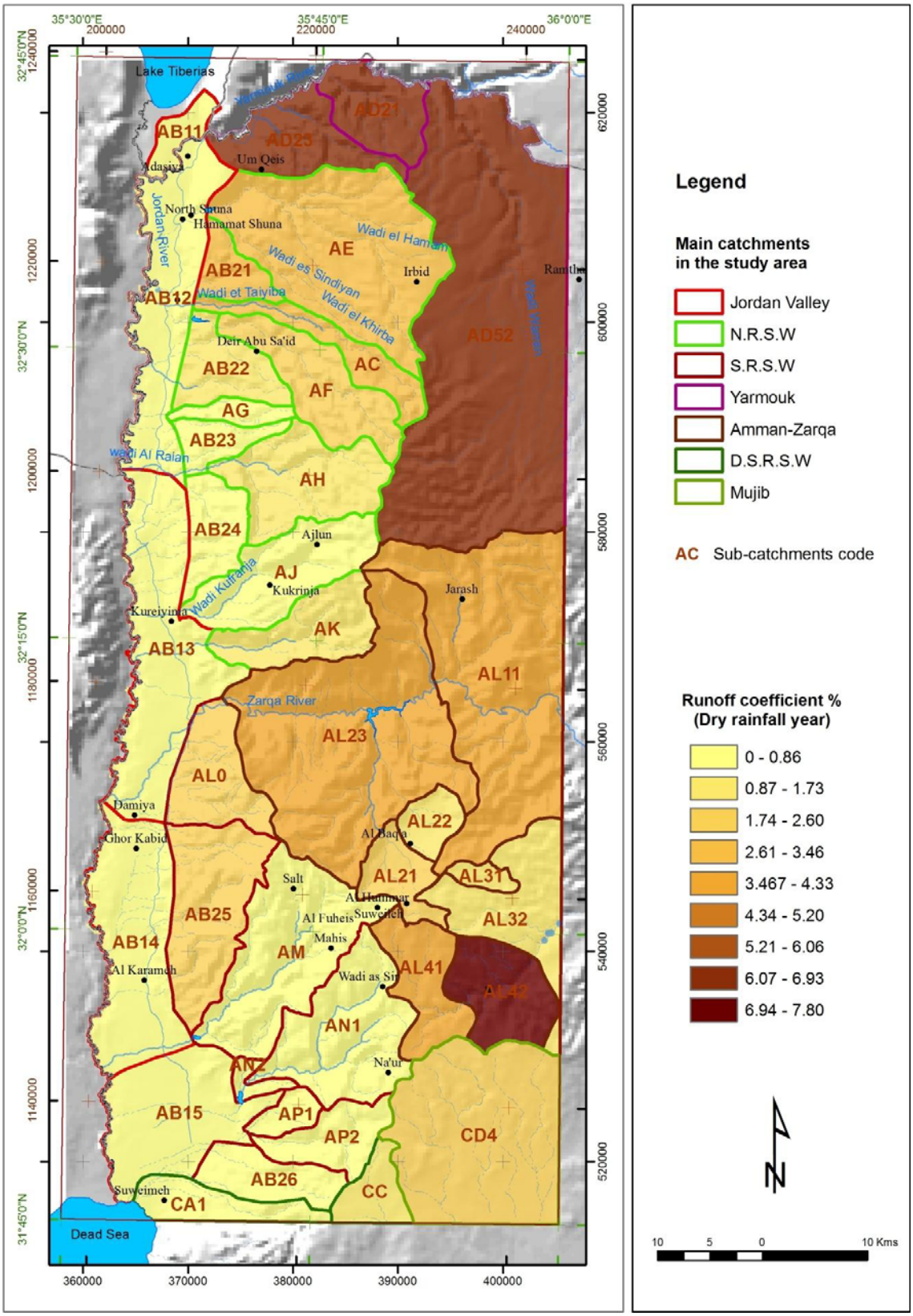

Figure 4.16: Spatial distribution of runoff in a dry rainfall year, NW of Jordan.

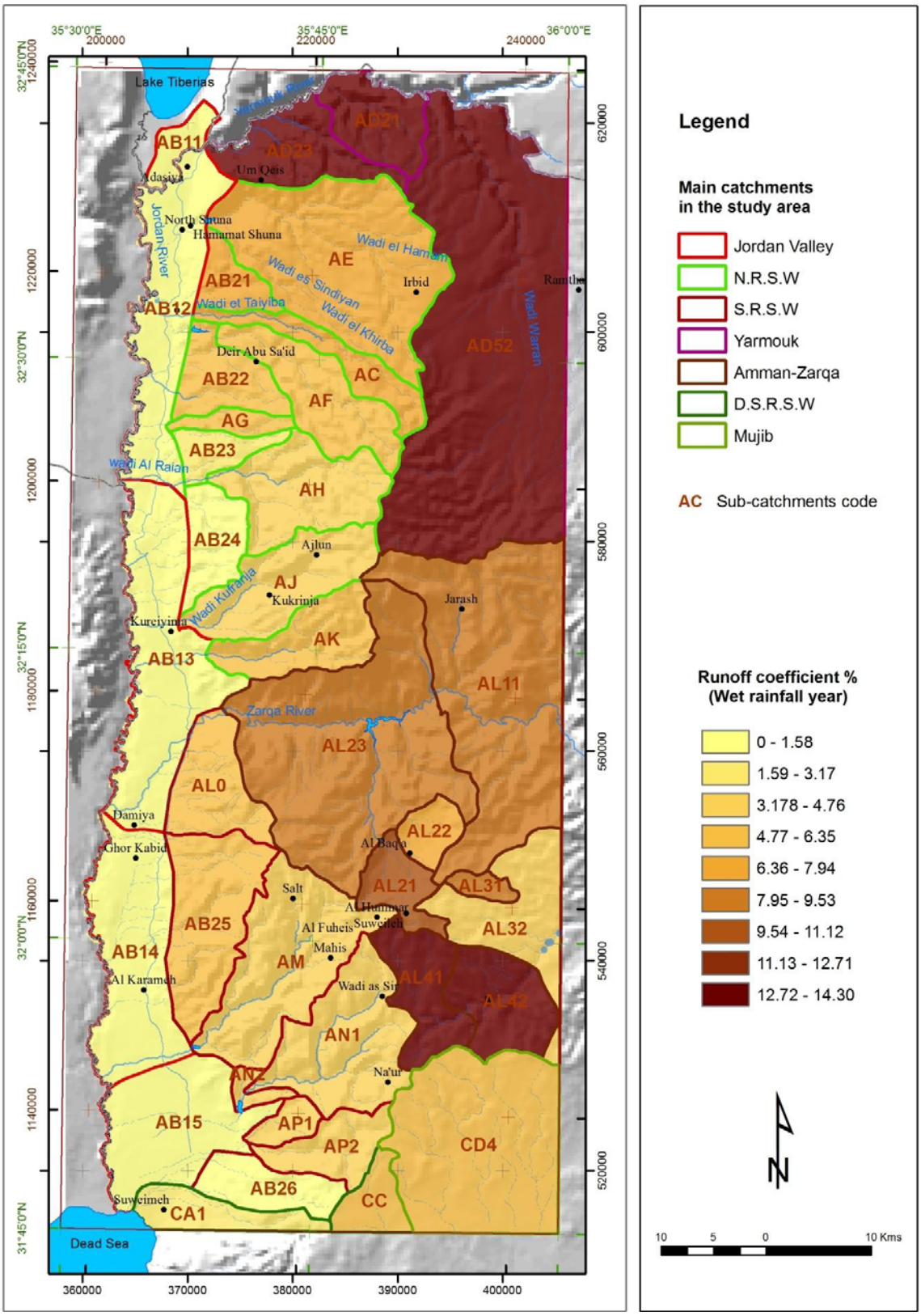

Figure 4.17: Spatial distribution of runoff in a wet rainfall year, NW of Jordan.

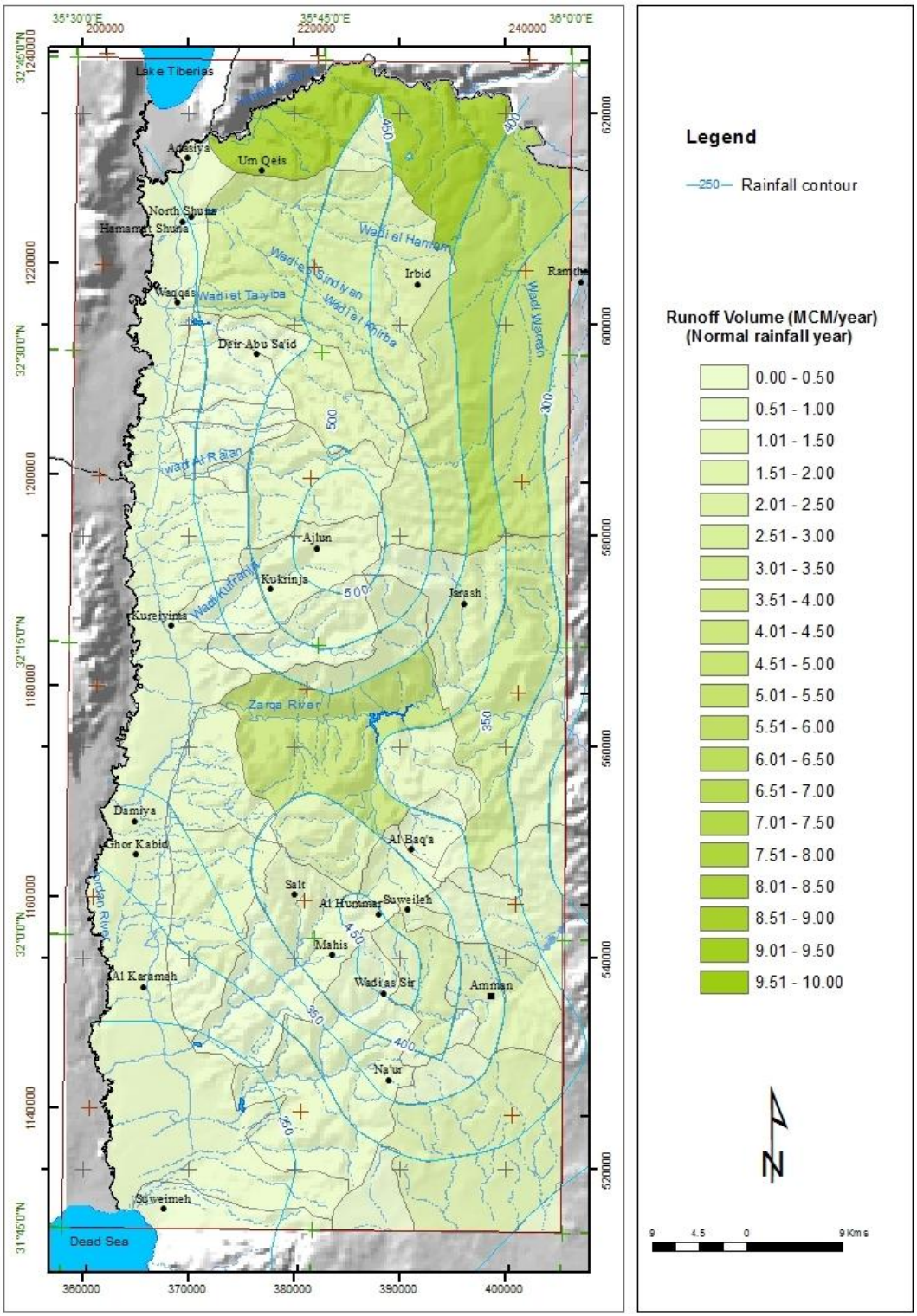

Figure 4.18: Runoff volumes in a normal rainfall year, for the basins described in Table 4.9, NW of Jordan. (Note: the isolines are the isohyetal lines in a normal rainfall year; some of the basins are additionally subdivided by the isohyetal lines).

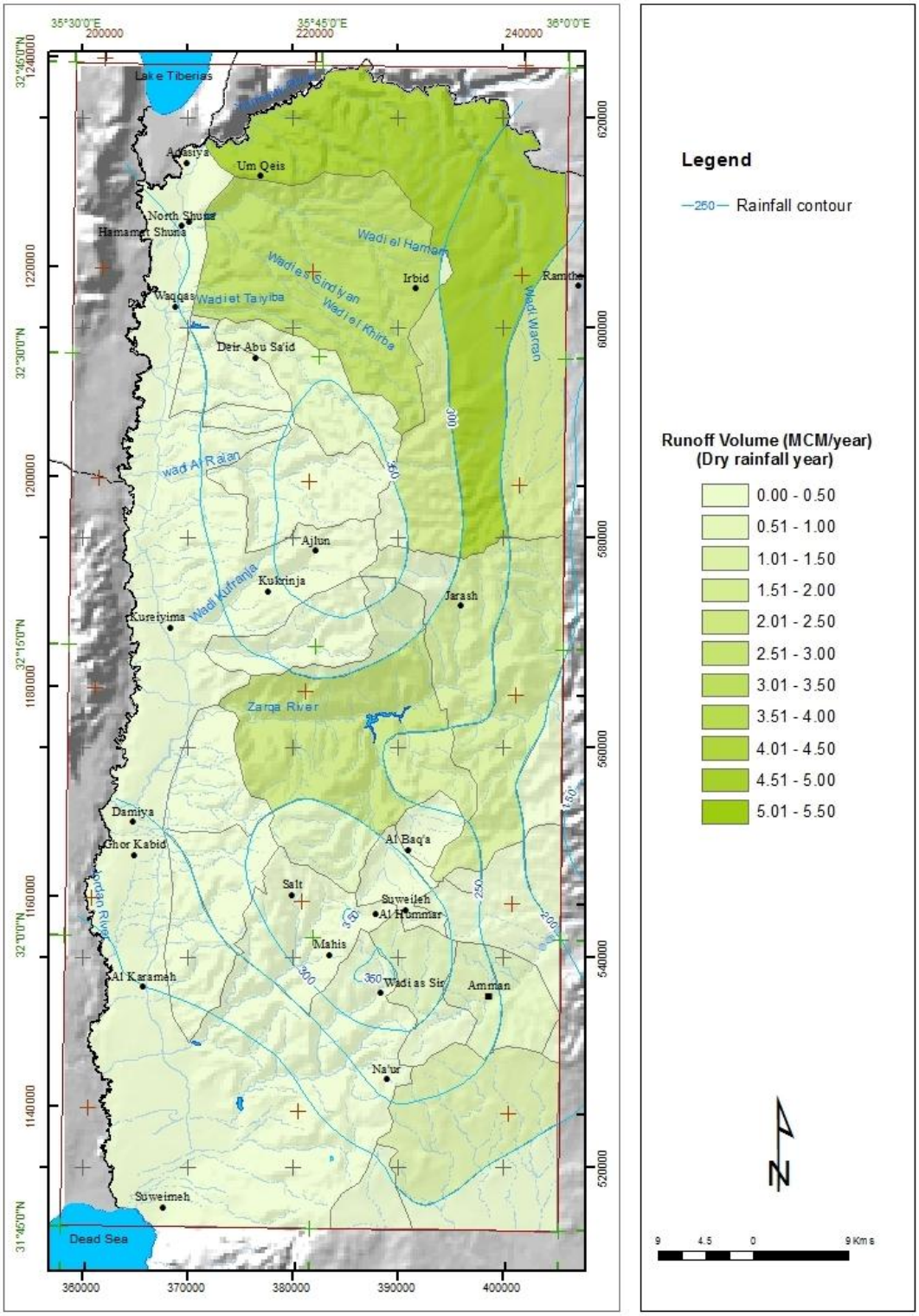

Figure 4.19: Runoff volumes in a dry rainfall year, for the basins described in Table 4.9, NW of Jordan. (Note: the isolines are the isohyetal lines in a dry rainfall year; some of the basins are additionally subdivided by the isohyetal lines).

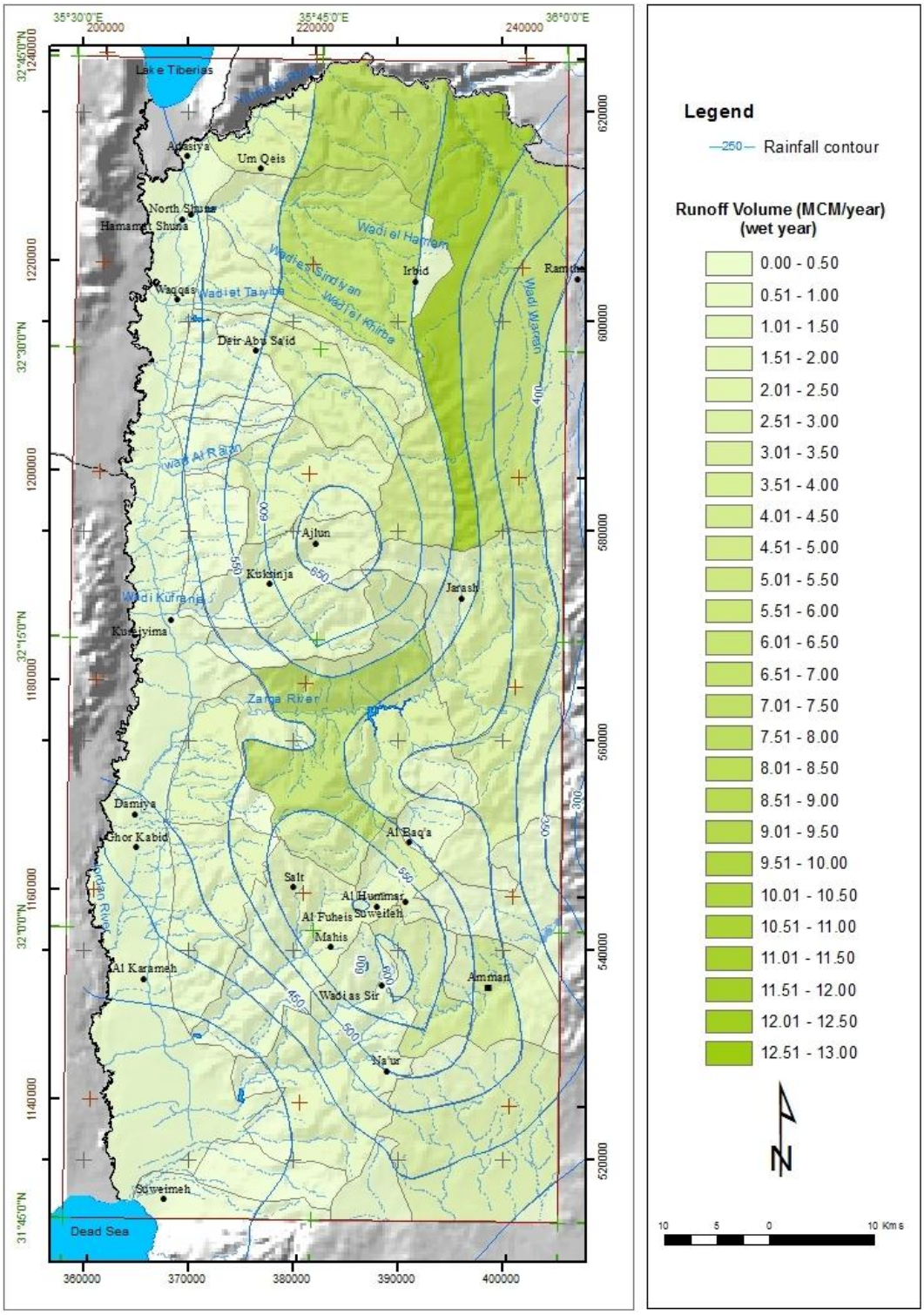

Figure 4.20: Runoff volumes in a wet rainfall year, for the basins described in Table 4.9, NW of Jordan. (Note: the isolines are the isohyetal lines in a wet rainfall year; some of the basins are additionally subdivided by the isohyetal lines).

Table 4.10: Rainfall depth and runoff volumes of normal, dry and wet years in the, NW part of Jordan.

	Normal rainfall year		Dry rainfall year		Wet rainfall year	
Runoff depth (mm)	covered area (km^2)	Runoff (MCM)	covered area (km^2)	Runoff (MCM)	covered area (km^2)	Runoff (MCM)
1	777	0.78	1299	0.15	666	0.67
3	50	0.15	505	1.52	111	0.33
5	121	0.61	280	1.40		
7	264	1.85	286	2.00		
9	208	1.87	310	2.79	38	0.34
11	229	2.52	538	5.92	12	0.13
13	398	5.17	298	3.88	43	0.56
15	237	3.56	100	1.51	128	1.92
17	113	1.92	140	2.38	111	1.89
19	30	0.57	44	0.84	80	1.51
21	230	4.82	261	5.48	112	2.36
23	379	8.72	368	8.46	242	5.57
25	124	3.09	15	0.41	179	4.48
27	220	5.94			275	7.44
29	86	2.49			179	5.19
31	97	3.05			107	3.32
33	20	0.66			84	2.79
35	156	5.47			133	4.65
37	1	0.03			94	3.46
39	236	9.20			186	7.24
41	43	1.77			242	9.91
43	34	1.45			58	2.50
45	326	14.67			47	2.12
47					140	6.58
49	63	3.07				
51	2	0.11			200	10.18
57					228	12.99
61					25	1.50
63					140	8.82
65					30	1.95
71					296	21.02
77					235	18.09
79					14	1.14
83					1	0.08
85					8	0.72
Total	4445	**83.55**	4445	**36.73**	4445	**151.44**

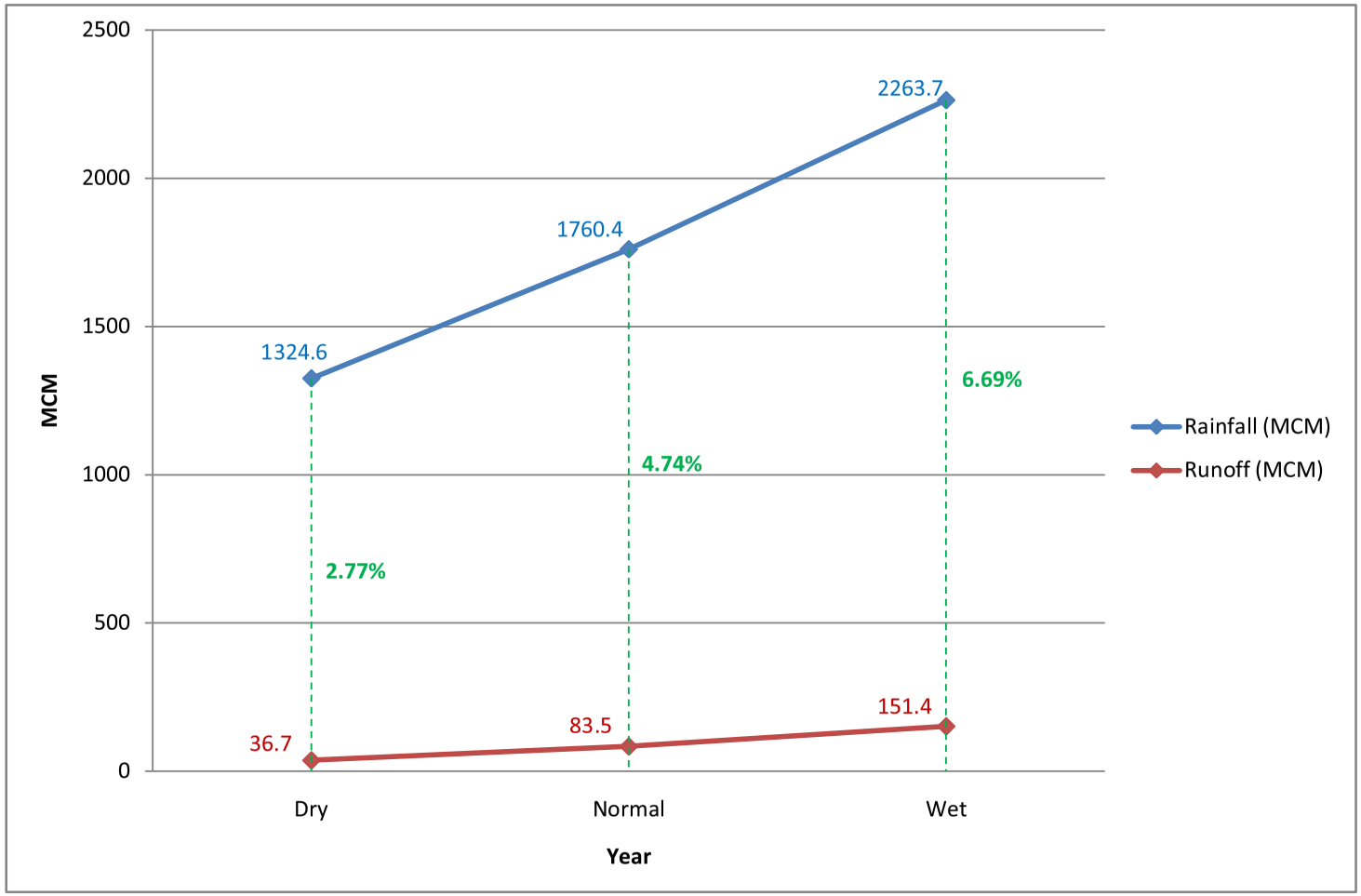

Figure 4.21: Rainfall/ runoff relation in normal, dry and wet years, NW of Jordan.
(Note: The data for rainfall derived from Table 4.7 and the runoff are from Table 4.10).

4.3 Hydrogeology of the study area

In Jordan, The classification of the geological succession into hydrogeological rock units has been established since 1970s (such as MACDONALD & PARTNERS 1965a & b; FAO & NRA 1969/70; FAO & NRA, 1972; GTZ & NRA, 1977; ABU-AJAMIEH et. al., 1989; BGR & WAJ, 2001). This classification is shown in Tables (1.1 & 1.2).

In the study area, the stratigraphic column exposed range in age from Triassic to Recent, which consists mainly of carbonates, chert, chalk, gravels and sandstone and evaporite layers (as discussed in chapter 2.1.1; from Figure 2.3 to Figure 2.9). The limestone and sandstone layers of Cambrian to Turonian Formation comprise the regional aquifers in the highlands on both sides of the Rift. As a result of the formation of the Rift Valley, the aquifers of Triassic to Lower Cretaceous were only exposed on the eastern side of the Rift. Inside the valley, young formations build of gravels, sand, clay and evaporites comprise the aquifer.

The aquifers and their extension at depth at a given location are shown in the eight geological cross section (Figure 2.3) described in chapter 2 (Plate 5; AA´, BB´, CC´, DD´, EE´, FF´, GG´ & HH´).

4.3.1 Aquifers

4.3.1.1 Deep Sandstone Aquifer Complex in the study area

4.3.1.1.1 Zarqa/Kurnub Aquifer System (Triassic-Jurassic- Lower Cretaceous ages)

The Zarqa/Kurnub Aquifer is a sandstone aquifer composed in the study area of three groups Ramtha (Triassic), Azab (Jurassic) and Kurnub Sandstone (Lower Cretaceous). The Zarqa Aquifer (Z) consists mainly of sandstone interbedded with siltstone, limestone and dolomite, which changes to limestone, argillaceous rocks with shales, dolomites and siltstones to the north and west of Jordan. The Zarqa Group (Permian, Triassic and Jurassic ages) can be characterized as a multi-layered bedrock aquifer caused by the vertical change of different units (porous and fractured sandstones, fractured limestone and dolomite). Nevertheless the Zarqa Aquifer can be considered as one hydraulic system, because the aquifers are hydraulically connected to each other (GTZ & MWI, 2004). While the Kurnub Group (Lower Cretaceous age) can be characterized as a fractured-rock aquifer. Groundwater movement is primarily through secondary openings, such as joints, fractures and bedding-plane openings (GTZ & MWI, 2004). The hydraulic conductivity of the Zarqa and Kurnub hydrogeological units are shown in Table 4.11.

The Zarqa/ Kurnub Aquifer System are limited to the north and northeast of Jordan and are missing in the southern part of the country (see chapter 3). The Kurnub Aquifer System (KS) is also a sandstone aquifer underlying Jordan, except the southern desert area in the extreme southeastern part of Jordan. It overlies the Zarqa Group Aquifer System (Figure 4.3) and mainly consists of sandstones with carbonate rocks in Northwest and east Jordan.

Both Zarqa and Kurnub Groups crop out in the study area. The Zarqa Group crops out only in relatively small areas along the lower Zarqa River and along the escarpment of the Dead Sea

(chapter 2, Figure 2.4), but are found in a wide area in the subsurface (chapter 3, Figure 3.2). The Kurnub Group crops out along the slopes of the rift escarpment from the Zarqa River in the north to the south. It is also crops out in the study area, in the deeply eroded cores of anticlines and domes structures, such as Al Baqa'a Valley north of Suweileh, Mahis east of Wadi Shueib, the area east of Shunt Nimrin, the Wadi as Sir, Wadi Na'ur area and Wadi Hisban (see chapter 2, Figure 2.5).

In the largest part of the Zarqa/Kurnub extents, where the aquifer is overlain by younger sedimentary deposits or the Lower Ajlun Group (A_{1-6}), the Zarqa/Kurnub Aquifer is confined. Only in the outcrop areas the aquifer is unconfined (Figure 4.3). The Zarqa Group thickness increases from the central part of Jordan to the north and west to up to 1800 m. It reaches a maximum of 2167 m in well NH-2 (oil well) in the northwestern part of the study area and thins towards the east (see chapter 3, Figure 3.6). The top of the aquifer, relative to sea level is shown in chapter 3, Figure 3.7. The Kurnub Group reaches a maximum of 238 m in NH-1 (oil well), in the northwestern part of the study area. In general, this aquifer system thins gradually to the southwestern part of the country and rapidly towards the east and the southern parts of Jordan. It is absent in the extreme southeastern part of Jordan (see chapter 3, Figure 3.8). Generally, the Kurnub Group dips gently to the east and to the north at about 5 degrees. The top of the aquifer, relative to sea level is shown in chapter 3, Figure 3.9.

Very few wells have been developed in this aquifer system. As a result very little is known about its hydraulic characteristics and its hydrochemistry. This aquifer system probably has its highest potential in North Jordan.

Table 4.11: Hydraulic conductivities of the main aquifers in NW of Jordan (after MARGANE et al., 2002).

Geological formation		Aquifer characteristic	Hydraulic conductivity (m/s)	Lithology (thickness)	
Basalt	(B)	Aquifer	4.0 E-04 *	basalt	
Shallala Fm.	(B_5) and	Aquifer	5.0 E-05 *	marl, limestone	
Um Rijam Fm.	(B_4)			limestone	
Muwaqqar Fm.	(B_3)	Aquitard	1.0 E-09 **	marl	
Amman Fm.	(B_2)			limestone	
Wadi Ghudran Fm.	(B_1)	Aquifer	2.0 E-05 *	marl, limestone	
Wadi as Sir Fm.	(A_7)			limestone	
Shueib Fm.	(A_{5-6})	Aquitard	1.0 E-09 **	marl	(~100 m)
Hummar Fm.	(A_4)	Aquifer	2.0 E-05 *	limestone	(~70 m)
Fuheis Fm.	(A_3)	Aquitard	1.0 E-09 **	marl	(~80 m)
Na'ur Fm.	(A_{1-2})	Aquifer	1.0 E-05 **	marl, limestone	(~150 m)
(average)			(7.0 E-06 **)		(total ~ 400 m)
Kurnub		Aquifer	3.0 E-05 *	sandstone	
ZARQA GROUP		Upper part	1.0 E-05 **	Silt-, sand-, limestone	
Azab Fm.		Aquiferous,	1.0 E-07 **		
		Aquitard			
		Aquitard	1.0 E-07 **	silt-, sandstone, shale,	
Ramtha Fm.				limestone, anhydrite, halite	
		Aquitatd		silt-, sandstone, shale,	
Hudayb Fm.			1.0 E-07 **	limestone	

* Statistical evaluation of pump test data ** estimation

4.3.1.2 Middle Aquifer Complex in the study area (Upper Cretaceous Limestone Aquifer System)

The Middle or Upper Cretaceous Aquifer Complex includes the following most important systems: the Na'ur (A_{1-2}) semi aquifer, the Fuheis (A_3) aquitard, the Hummar (A_4) aquifer, the Shueib (A_{5-6}) aquitard and the Amman/Wadi as Sir (B_2/A_7) aquifer.of **Cenomanian-Maestrichtian** age. The total thickness of this complex in central Jordan is 700 m. It consists of an alternating sequence of limestones, dolomites, marl stones and chert beds. A detailed lithological description of the formation is given in chapter 2. The limestone and dolomite units form excellent aquifers. The Upper Cretaceous Aquifer Systems can be divided into: the Lower Ajlun aquifers/aquitards and the Upper Ajlun A_7/B_2 aquifer (Figure 4.3). The hydraulic conductivity of the Lower Ajlun (A_{1-6}) and Upper Ajlun (B_2/A_7) hydrogeological units are shown in Table (4.11).

4.3.1.2.1 Lower Ajlun Aquifer/Aquitard System

The Lower Ajlun Aquifer System (A_{1-6}) overlies disconformably the Kurnub Aquifer System over much of Jordan; excluding the southern desert, south of Ras En Naqab escarpment and the southern part of Wadi Sirhan. However, within the sequence marl, limestones, dolomites and some shale form local aquifers (Figure 4.3). The Lower Ajlun Aquifer System (A_{1-6}) is characterized by large variations in lithology and thickness. It reaches its widest surface distribution on the slopes of the Zarqa River Valley (see chapter 2, Figure 2.6). From there to the south, its outcrops are common on the slopes of the rift escarpment and the side wadis. In general, the thickness of the Lower Ajlun Group decreases from N to S and reaches its maximum thickness of >638 m in Mukheiba well (AD1276) (see chapter 3, Figure 3.22).

4.3.1.2.1.1 Na'ur Aquifer/Aquitard (A_{1-2})

The Na'ur Aquifer/Aquitard (A_{1-2}) consists of marls and limestone. The marls form the confining layer that separates the aquifer from the underlying Kurnub aquifer. The thickness of the limestone layers reaches its maximum of about 220 m thick (type section near Na'ur village) in the study area and decreases towards central and north Jordan areas where the thickness varies between 30 and 40 meters (see chapter 3, Figure 3.13). Therefore, the (A_{1-2}) possess in some areas relatively high permeability and form a potential aquifer.

4.3.1.2.1.2 Fuheis Aquitard (A_3)

The Fuheis Aquitard (A_3) consists of about 80 m of marl and shale, intercalated with marly limestone. It extends from Ajlun in the north to Ras En Naqab in the south (see chapter 3, Figure 4.14) and overlies the Na'ur Aquifer (A_{1-2}) and separates it from the overlaying Hummar Aquifer (A_4).

4.3.1.2.1.3 Hummar Limestone Aquifer System (A_4)

The Hummar Limestone Aquifer System (A_4) consists of pure semi-crystalline karstic dolomite and limestone and hence it has very high permeability and porosity. It crops out along the

highlands with an average thickness of 45 m and about 150 m in Mukheiba well (AD1276). The outcrop area is limited to an area of about 20 km^2 extending from the eastern part of the study area (namely, Sukhna area) through Suweileh and around the south-western edge of the Amman-Zarqa Syncline (Wadi as Sir) where it is recharged (chapter 3, Figure 3.15). This aquifer is confined, to the east by the overlying Shueib Aquitard (A_{5-6}).

4.3.1.2.1.4 Shueib Aquitard (A5-6)

The Shueib aquitard (A_{5-6}) is composed of fossiliferous limestone, massive crystalline and thinly bedded porcellaneous limestone. Its thickness ranges from about 30 to 150 m, which acts as an aquiclude (see chapter 3, Figure 3.16).

4.3.1.2.2 Amman/Wadi as Sir Aquifer System (B_2/A_7)

The uppermost unit of the Ajlun Group; Wadi as Sir Limestone Formation (A_7) and the lower part of the Belqa Group; Wadi Umm Ghudran (B_1) and Amman Silicified Limestone Formation (B_2) form one hydrogeological unit. It is the most important and extensive aquifer of the sequence; namely the B_2/A_7 Aquifer. It consists of limestone, dolomitic limestone and dolomite with intercalated beds of sandy limestone, chalk, marl, chert and phosphorite. The B_2/A_7 Aquifer can be described as a karstified bedrock aquifer. The Karstification in the limestones and dolomite is unevenly distributed which leads to large heterogeneities in permeability and storability (GTZ & MWI, 2004). Parts of the aquifer are highly cavernous. In these parts the movement of groundwater is quite rapid, thus restricted its filtering ability (GTZ & MWI, 2004). Table (4.11) shows the hydraulic conductivity of the uppermost of the Ajlun hydrogeological units.

To the east, similar to the Hummar Limestone Aquifer System (A_4), it goes over in a confined aquifer, overlain by layers of marls of Muwaqqar Chalk Marl Aquitard (B_3) of Upper Cretaceous and Lower Tertiary age.

The B_2/A_7 Aquifer crops out in the western highlands where it receives the high rainfall and is recharged there (see chapter 2 for more details of the B_2/A_7 Aquifer). The B_2/A_7 Aquifer reaches the highest thickness of 400 m in the northwestern part of the study area (see chapter 3, Figure 3.23). The top of the aquifer, relative to sea level is shown in chapter 3, Figure 3.24.

4.3.1.3 Shallow Aquifer Complex in the study area (Tertiary–Quaternary)

The Upper Aquifer System which include the following important systems: the Muwaqqar Chalk Marl (B_3) aquitard, the Umm Rijam/Shallala (B_4/B_5) aquifer, the Basalt aquifer and the Alluvial Deposits of Tertiary-Quaternary age. The hydraulic conductivity of the Tertiary-Quaternary age hydrogeological units is shown in Table 4.11.

4.3.1.3.1 Muwaqqar Chalk Marl Aquitard (B_3)

The Muwaqqar Chalk Marl (B_3) Aquitard consists of about 40 to 900 m (Figure 3.20) of marl, and chalky limestone, chert and phosphate. It overlies the whole B_2/A_7 Aquifer in the central desert, forming a competent confining bed which has a low permeability thus, acts as an aquitard. Therefore, in some locations flowing artesian wells are drilled into the B_2/A_7 Aquifer.

4.3.1.3.2 Umm Rijam and Shallala Aquifer System (B_4/B_5)

The Umm Rijam and Shallala Aquifer System (B_4/B_5) are exposed in the northwestern most of the study area, north of Irbid (Figure 2.7). The thickness of the (B_4/B_5) aquifer is reduced in most of the area, due to erosion. The maximum thickness is more than 300 m has been recorded to the east of the study area; in Hamza oil field (Figure 3.21). It consists of chalk, chert and limestone which are jointed and fractured with solution channels and cavities in the carbonates portions (GTZ & MWI, 2004). The (B_4/B_5) aquifer plays an important role for the water supply especially in the area north of Irbid, and in areas east of the study area (Azraq and Hammad areas). In the study area, numerous springs emerge from the B_4 aquifer.

4.3.1.3.3 The Basalt Aquifer (Oligocene-Pleistocene age)

The Basalt is mainly found in the extreme northern part of the study area (for more detailed see chapter 2) (Figure 2.9). It extends from the Syrian Jabel Arab-Druz (JAD) area southwards to the Azraq and Wadi Dhuleil areas and continues southward into Saudi Arabia forming good aquifer of significant hydrogeological importance. The permeability and storability of the basalt Aquifer is generally provided by joints and inter-connected vesicular holes in the basalt rocks and by gravels and sandy layers of the interflows (GTZ & MWI, 2004). The hydraulic conductivity of the Basalt is shown in Table 4.11.

4.3.1.3.4 Jordan Valley Alluvial Aquifer System (Tertiary and Quaternary ages)

Along the eastern part of the Jordan Valley Alluvial Aquifers between the Jordan River in the west and the eastern escarpment of the rift in the east, it extends for about 100 km from the Yarmouk River in the north to the Dead Sea in the south. The width of the aquifer in the study area ranges from a minimum of about 2 km in El Karama area to a maximum of 13 km in Wadi Hisban area. The average width is about 8 km.

The lithological composition of the aquifer is extremely heterogeneous. It consists of sand, gravel, conglomerate, sandstone, marl, travertine, limestone and evaporites (Figure 4.22). The thickness of the Alluvium in the Jordan Valley Series varies from zero along the eastern boundary to about 750 m in the deepest part of the basin near the Jordan River. An average thickness of 400 m may be reasonable for the purpose of hydrogeological consideration (GTZ & MWI, 2004).

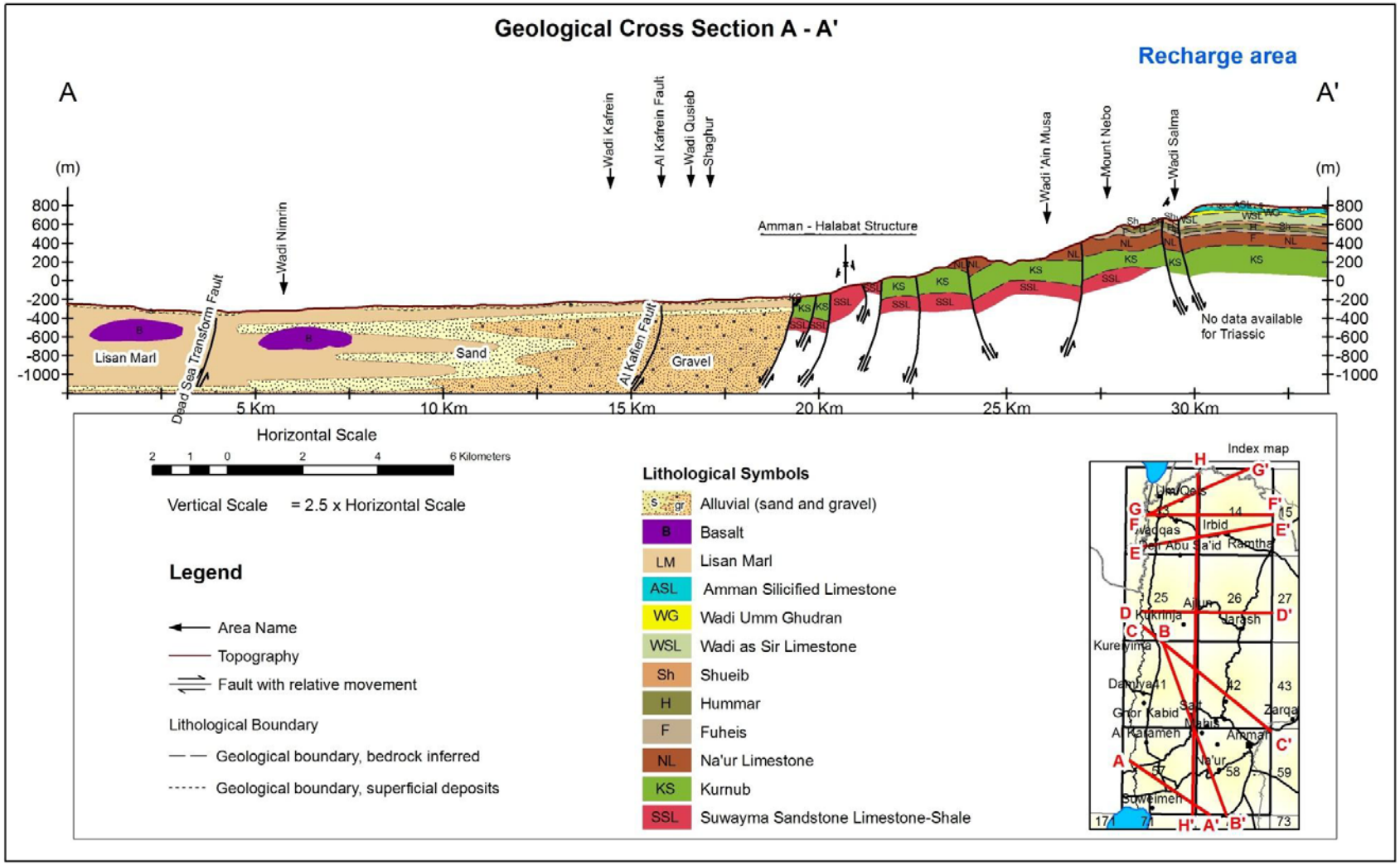

Figure 4.22: Geological cross section AA'. In the of the marginal part of the Jordan Valley show schematically the inter-fingering of the different facies from coarse material in the marginal parts to fine materials in the central parts.

4.3.2 Groundwater recharge, level and flow direction

Several climatic factors such as rainfall intensity, duration, evaporation, soil types and thicknesses and rock types of the catchments areas control the amount of surface runoff and groundwater recharge into aquifers. The development of the three complex hydraulic aquifer systems with considerable differences in groundwater head levels and in flow directions can be related to the development of the Dead Sea–Jordan Valley Rift in the western part of the study area. This has resulted in lowering of the base levels for parts of the aquifers as shown in the various structural contour maps for the different geological units (chapter 3).

The groundwater contour maps for different aquifers were constructed from the available static water level (SWL) measurements of wells and springs distributed in the study area, for the year 2009. The SWL from the wells was obtained from WAJ data base files and from the altitude of the springs obtained from the Digital Elevation Model (DEM) (Plate 3). Generally, all krigged groundwater flow pattern maps for different aquifers show that the steep groundwater gradient is found where topography is steep; also they indicate that the groundwater divides are associated with topographic features in the study area. In addition to topography, the dominant lithology and the structural features play an important role in defining the recharge areas and the groundwater flow in the study area. Generally, groundwater flows in the different aquifers coincide with the trend directions of joints (Figure 2.24).

4.3.2.1 Deep Sandstone Aquifer Complex

4.3.2.1.1 Zarqa/Kurnub (Z/KS) Aquifer System (Triassic-Jurassic- Lower Cretaceous ages)

The aquifer receives direct and indirect recharge where it outcrops on the eastern escarpment of the Jordan Valley and the northern part of the Dead Sea. In Jarash, Al Baqa'a and along the Zarqa River (see chapter 2, Figures 2.4 & 2.5) direct recharge from precipitation occurs. In the Highlands recharge to the aquifer occurs by leakage from the Upper Cretaceous aquifers, percolating through fractures and faults. On the other hand, in the eastern and northern parts of Jordan, where the aquifer occurs at considerable depths, direct groundwater recharge from precipitation is not possible. The groundwater, apart from the recharge areas, is generally highly mineralized (SALAMEH, 1996) (for more details on hydrochemistry see section 4.4).

In the study area, most water wells in the deep sandstone aquifer penetrate only the Zarqa and Kurnub Groups. These wells are located in the Zarqa and Al Baqa'a Vallies, where a number of springs emerge from this aquifer (Figure 4.23). The figure also shows that the water level indicates two main mounds, one north of Suweileh (Al Baqa'a area), where the water level reaches around 650 m asl., and the other between Jarash and Ajlun, where the highest water level is at around 550 m asl. The groundwater flow from both of these recharge mounds is directed in radial directions, finally being drained towards the Dead Sea, Jordan Valley and the Yarmouk River. These two main mounds represent the main direct recharge areas of the Deep Sandstone Aquifer in north Jordan. On a regional scale for whole Jordan (out of the range of Figure 4.23) the direction of groundwater flow in the Kurnub aquifer system according to SALAMEH & UDLUFT

(1985) is towards the northeast in the southern part of Jordan, towards the west in central Jordan and towards the southwest in northern Jordan.

The area of Zarqa River represents an area of a major anticline structure (geological cross sections BB´, CC´ & HH´; Plate 5). The hydrogeological profile II' illustrated in Figure 4.24 shows the main aquifers and the static water level (SWL) (2009), and the location of some springs issuing from different aquifers in Zarqa River area. But the Zarqa-Ma'in Group crop out there due to the weathering of the Kurnub Sandstone, forming an easier discharge pathway for the groundwater in that area. Also, geological cross sections BB´ & CC´ (Plate 5) indicate a depressional area south of Zarqa River area.

The central portion of the geological cross section HH' at scale 1:50,000 (Plate 5) is illustrated in Figure 4.24 as geological cross section II' at a scale of 1:100,000. Figure 4.24 shows the main aquifers in the Zarqa River area. In addition to that it shows the static water level for the Kurnub Sandstone Aquifer in the year 2009 (the static water level is drawn along the same section from the prepared map Figure 4.23; Krigged potentiometric surface and groundwater flow pattern for the Kurnub Sandstone (KS) and Zarqa-Ma'in (ZM) Aquifer System).

4.3.2.2 Middle Aquifer Complex

4.3.2.2.1 Na'ur (A_{1-2}) and Hummar (A_4) Aquifer Systems

The outcrop area of the A_{1-2} and A_4 aquifers is limited in extent and receives small amount of direct recharge in the study area. Although the thicknesses of the A_{1-2} and the overlying A_4 are comparably low, they form aquifers of local importance in areas where B_2/A_7 aquifer is missing for instance in Azraq and Wadi Shueib areas.

The water level of A_{1-2} and A_4 aquifers (Figures 4.25 & 4.26) in the northern Highlands distribute in two main areas, the first recharge mound around Ajlun, where the highest water level is around 850 m asl, and the second recharge mound around Wadi as Sir where the highest water level is around 900 m asl The groundwater flow from both these recharge mounds is directed radially from the highest elevation towards the lower elevations.

In the study area, the geological cross sections BB´ & CC´ (Plate 5) as mentioned earlier show a morphological depression, due to erosion in the area of Zarqa River. Therefore, in the surrounding of the depression all the discharge of the A_{1-2} and A_4 aquifer is directed to the base level of the Zarqa River. While north and south of the Zarqa depression the groundwater flow is mainly directed towards the Jordan Valley.

Figures 4.21 & 4.22 indicated that the area south of Amman flexure, which strikes in an ENE-WSW direction parallel to the Amman syncline, forms the south-eastern limit of the groundwater flow in the A_{1-2} and A_4 aquifers. Also, both figures show N-S oriented groundwater divide that passes between Wadi as Sir and Suweileh. East of this divide, the groundwater flows to the southeast towards Amman flexture, where it then changes its flow direction to the east and northeast.

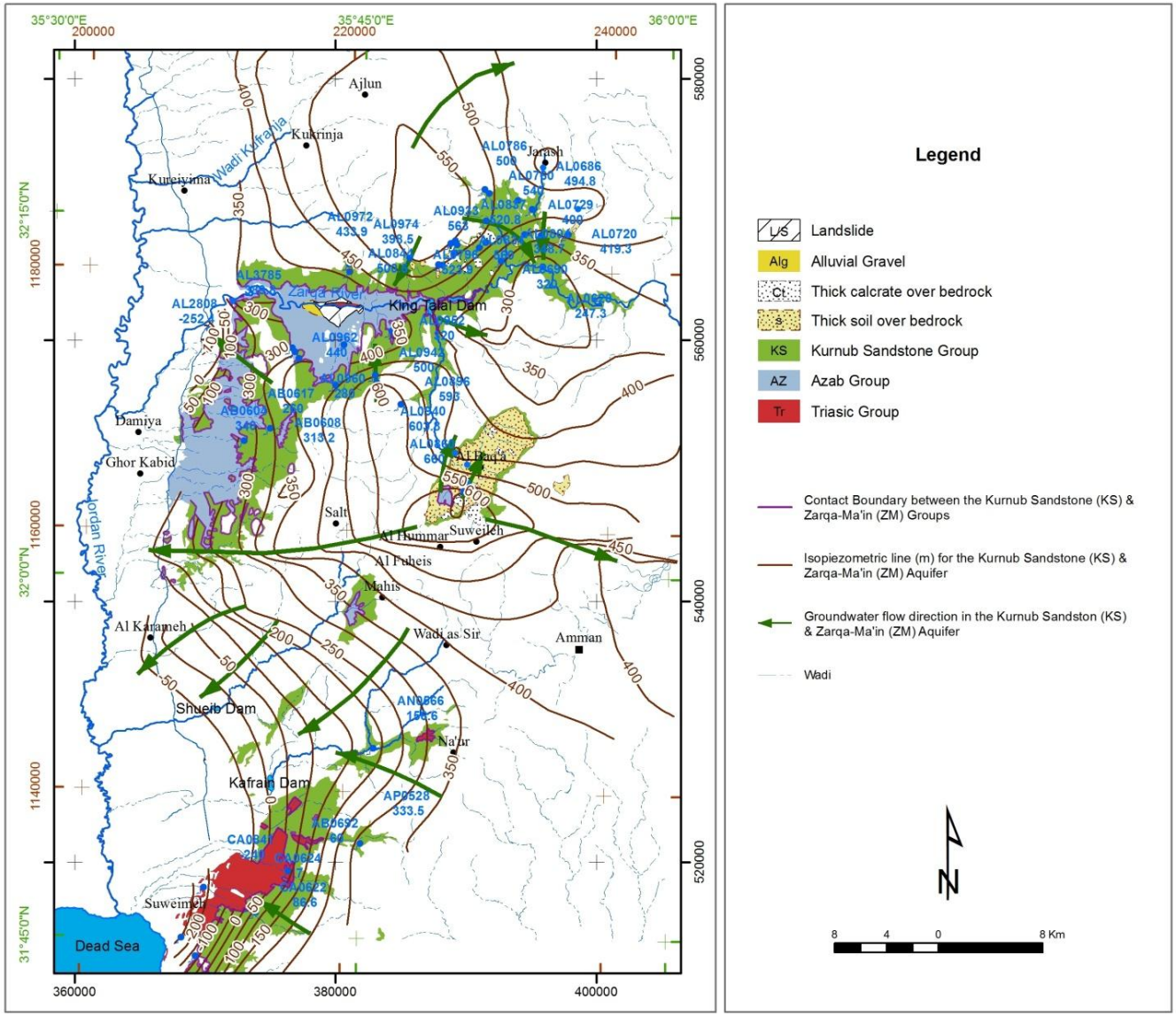

Figure 4.23: Krigged potentiometric surface and groundwater flow pattern for the Kurnub Sandstone (KS) and Zarqa-Ma'in (ZM) Aquifer System.

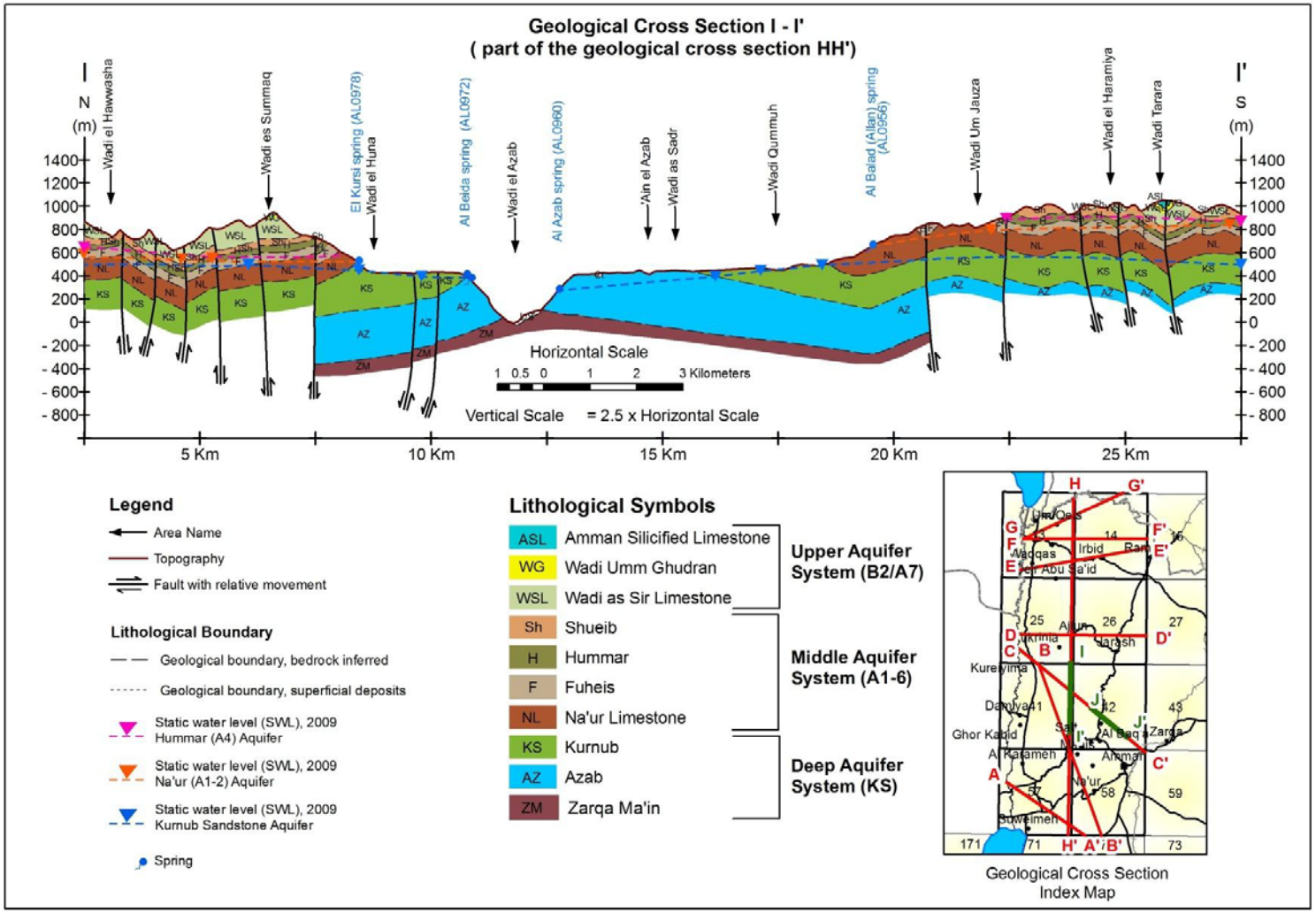

Figure 4.24: Hydrogeological N-S profile along the escarpment from Wadi el Hawwasha and Wadi Tarara (profile II' in the index map). The profile shows the main aquifers, the static water level (SWL) (2009), and the location of some springs issuing from different aquifers in Zarqa River area (Note: the static water level along II' geological cross section was drawn for Deep and Middle Aquifer Systems from Figures 4.23, 4.25 & 4.26, respectively).

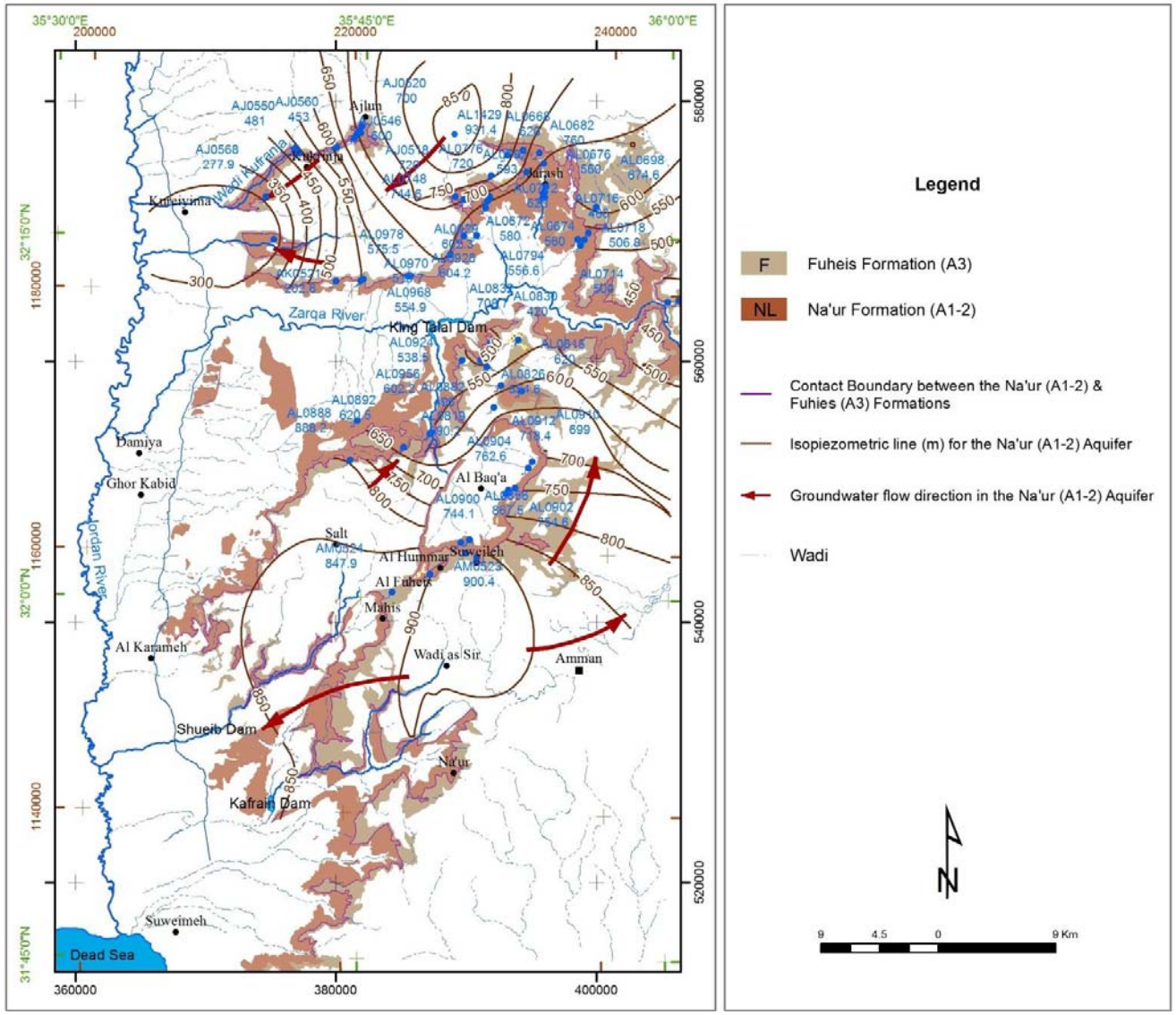

Figure 4.25: Krigged potentiometric surface and groundwater flow pattern for the Na'ur (A_{1-2}) Aquifer System.

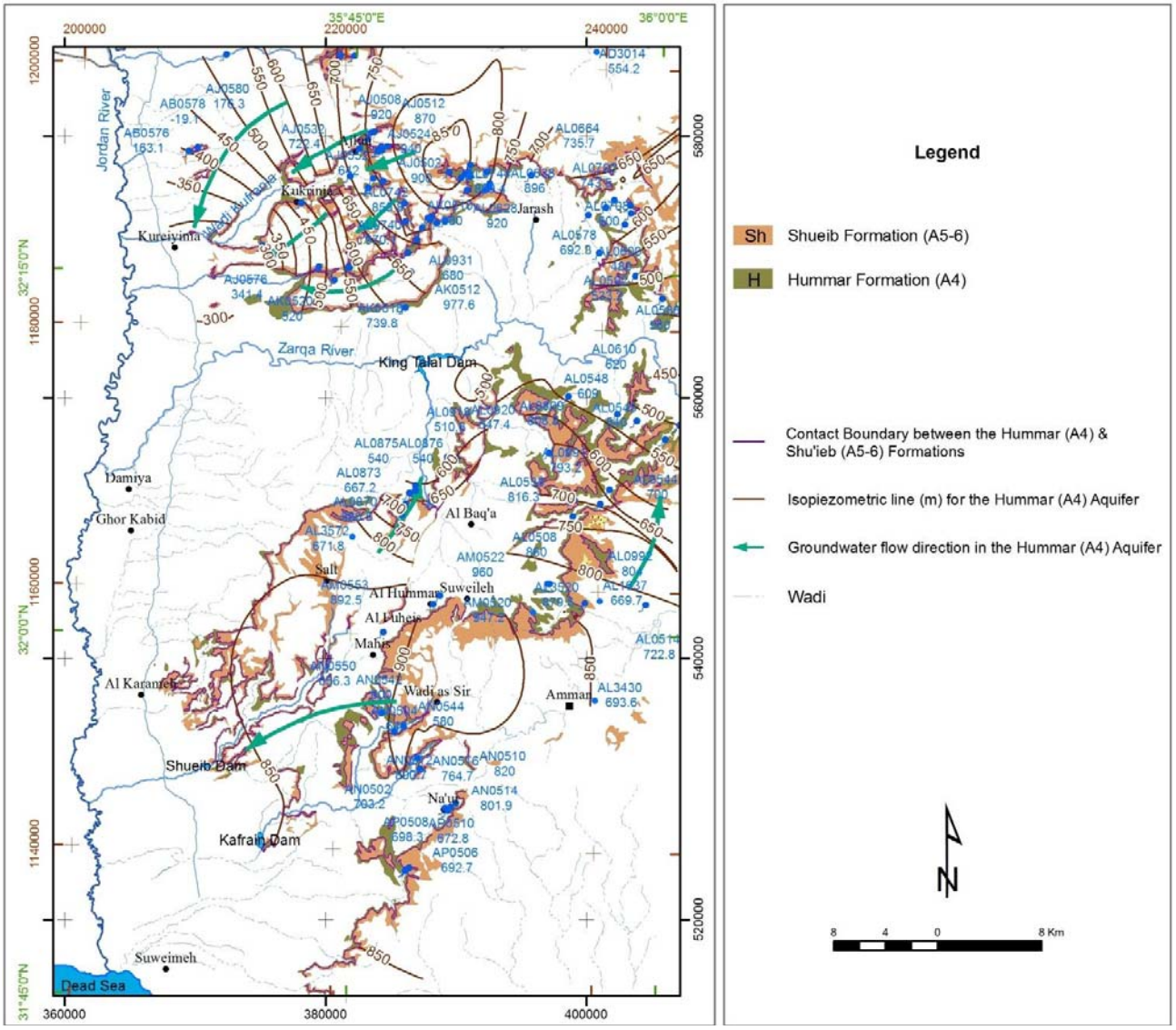

Figure 4.26: Krigged potentiometric surface and groundwater flow pattern for the Hummar (A_4) Aquifer System.

4.3.2.2.2 Amman/Wadi as Sir Aquifer System (B_2/A_7)

The B_2/A_7 aquifer outcrop areas coincide with the areas of relatively high precipitation and represent as well the highest recharge areas of this aquifer in the country, i.e. around Ajlun Dome. Nevertheless, the B_2/A_7 is not saturated along the main outcrops of the aquifer. The limit of saturation zone (after BGR, 1995c) for the Aquifer is shown in Figure 4.27.

From the recharge areas the groundwater in the B_2/A_7 flows mainly to the east towards lower topographic elevations, forming a groundwater divide between the groundwater that flows towards the Jordan Valley and the groundwater that flows eastwards. The divide lies 20 - 30 km to the east of the Dead Sea escarpment. The main base levels of the groundwater flow in this aquifer are: the Azraq depression, the Yarmouk River, the Jordan Valley and the Dead Sea. According to SALAMEH & UDLUFT (1985) the easterly-directed groundwater current leaks through the (A_{1-6}) aquitard down to the Deep Sandstone Aquifer Complex and flows back towards the Dead Sea.

Figure 4.27 shows that, the groundwater flow within the B_2/A_7 aquifer system in the southern part of the study area, i.e. southeast of Amman flexure, is directed partly northwest towards Zarqa River and partly southwest towards Wadi el Wala. Further to the south of the study area the east-west trending Siwaqa fault marks, at least partly, a barrier to the B_2/A_7 aquifer system groundwater flow (GTZ & MWI, 2004). On the other hand, north of Zarqa River, i.e. in the area between Ajlun and Jarash, the groundwater flow is directed from the Ajlun Mountain mainly in northeasterly direction and it flows partly to the northwestern to the western escarpment within the faulted blocks. Both directions converge in the Yarmouk River area due to circumclinal strike of the B_2/A_7 and the overlying sediments.

4.3.2.3 Shallow Aquifer Complex

4.3.2.3.1 Um Rijam Aquifer System (B_4)

The main area of groundwater production from the Um Rijam aquifer (B_4) is the Azraq depression to the east of the study area. This depression receives its recharge from Syria, from Jabel Arab-Druz (JAD) and from the east, the Al Harra and western Hammad in addition to small contributions from the south and west (GTZ & MWI, 2004).

Within the study area, the B_4 aquifer is of local importance in the area north of Irbid and Ramtha. This area is characterized by deeply incised wadis, which act as drainage channels. Numerous springs mark spots of emergence of groundwater. Figure 4.28 shows that the groundwater flow in the B_4 aquifer system is mainly towards the Yarmouk River, but a small part also to wadi el ‘Arab and the Jordan River.

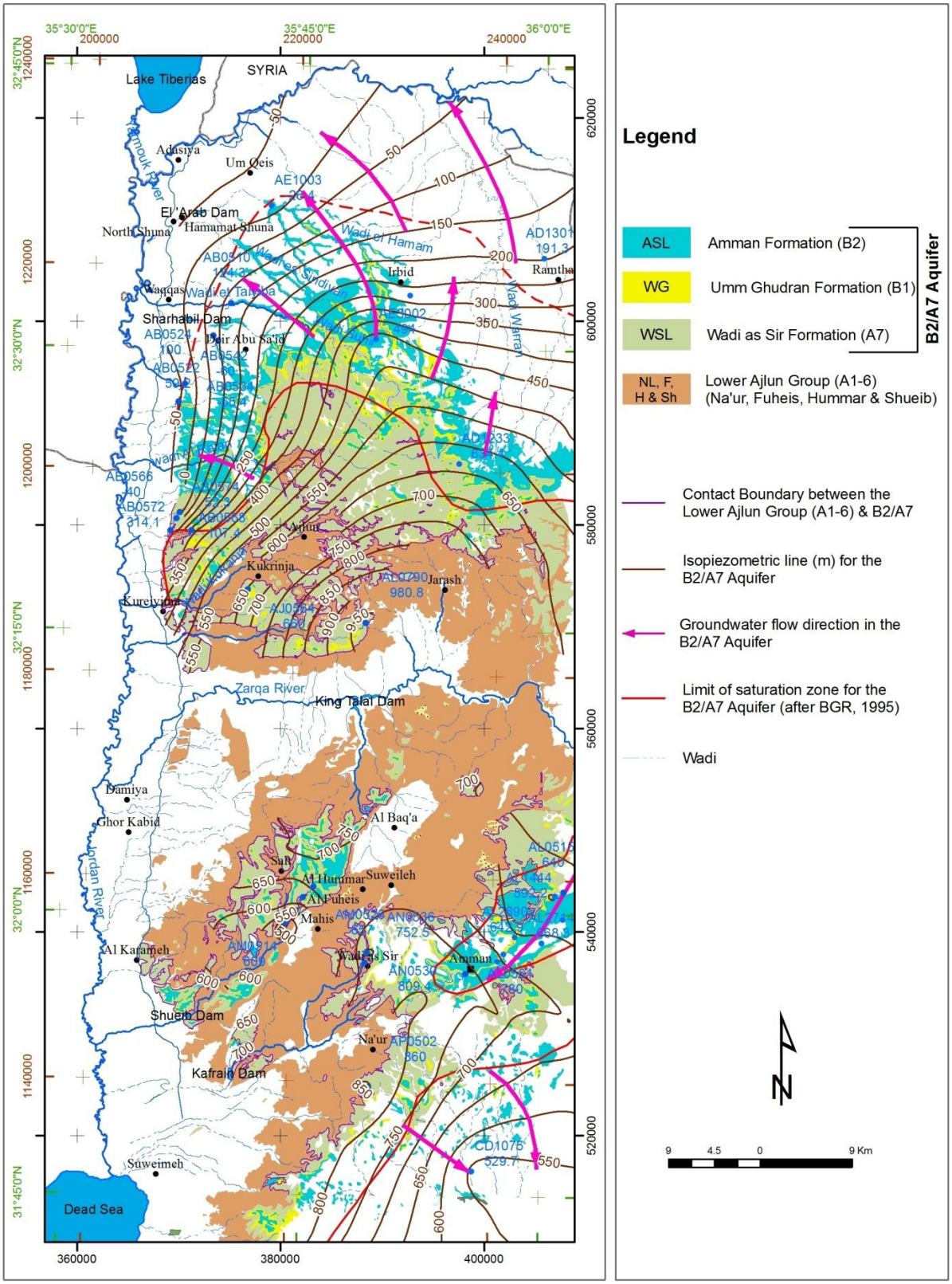

Figure 4.27: Krigged potentiometric surface and groundwater flow pattern for the Amman (B_2)/ Wadi as Sir (A_7) Aquifer System.

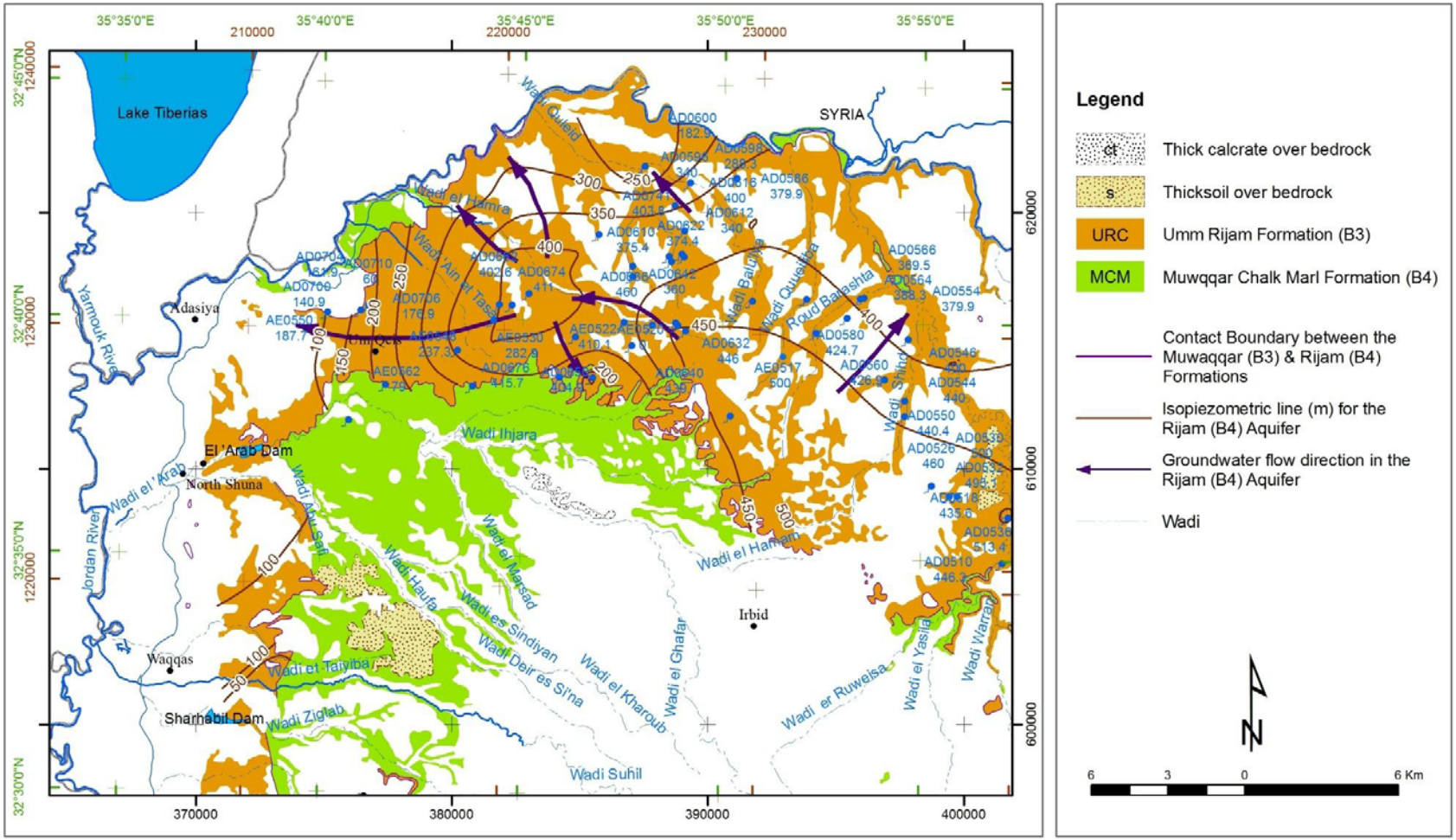

Figure 4.28: Krigged potentiometric surface and groundwater flow pattern for the Rijam (B_4) Aquifer System.

4.3.2.3.2 Basalt

The recharge to the Basalt aquifer system is provided by precipitation in the elevated area of Jabel Arab - Druz (JAD). From there the groundwater moves radially in all directions (Figure 4.29). The direct groundwater recharge from rainfall infiltrating into the basalt is estimated at 44 MCM/year (GTZ & MWI, 2004).

In the study area the Basalt overlies directly the B_4 aquifer and feeds it. To the east and southeast of the study area, in the Mafraq–Wadi Dhuleil areas, the Basalt aquifer directly overlies the B_2/A_7 aquifer waters connected to the basalt waters. Further to the east, in the Hammad Basin, the Basalt aquifer overlies and is hydraulically interconnected to the B5 (Shallala) aquifer.

4.3.2.3.3 Jordan Valley Alluvial Aquifer System

Alluvial fans in the Jordan Valley area extend from the foothills of the eastern mountains towards the Jordan River. These alluvial fans receive their groundwater mainly by lateral flows from the mountain aquifers, especially the B_2/A_7.

In the study area, the groundwater flow in the Valley takes place mainly from the escarpments into the valley deposits (Figure 4.30).

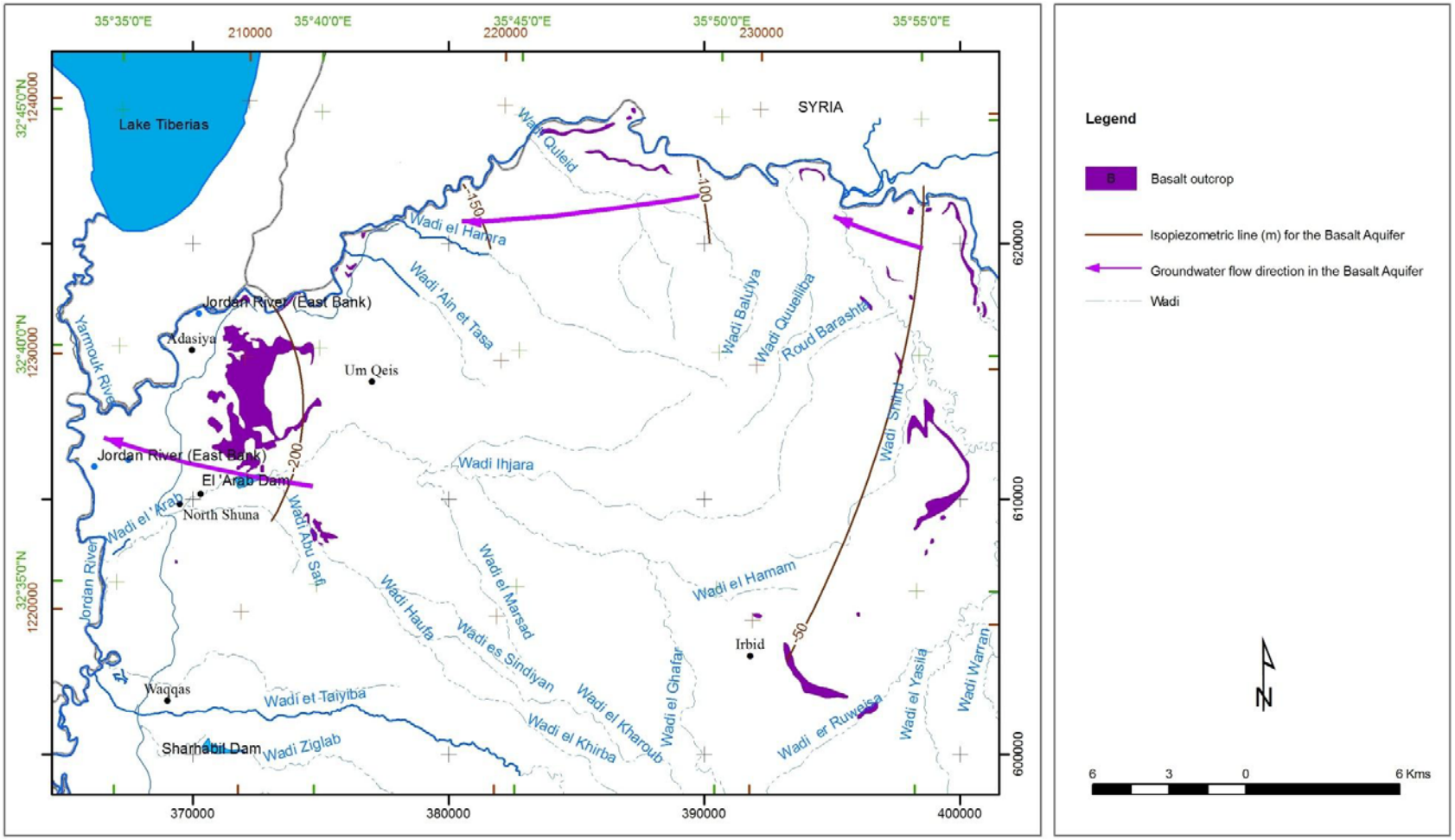

Figure 4.29: Krigged potentiometric surface and groundwater flow pattern for the Basalt (B) aquifer System.

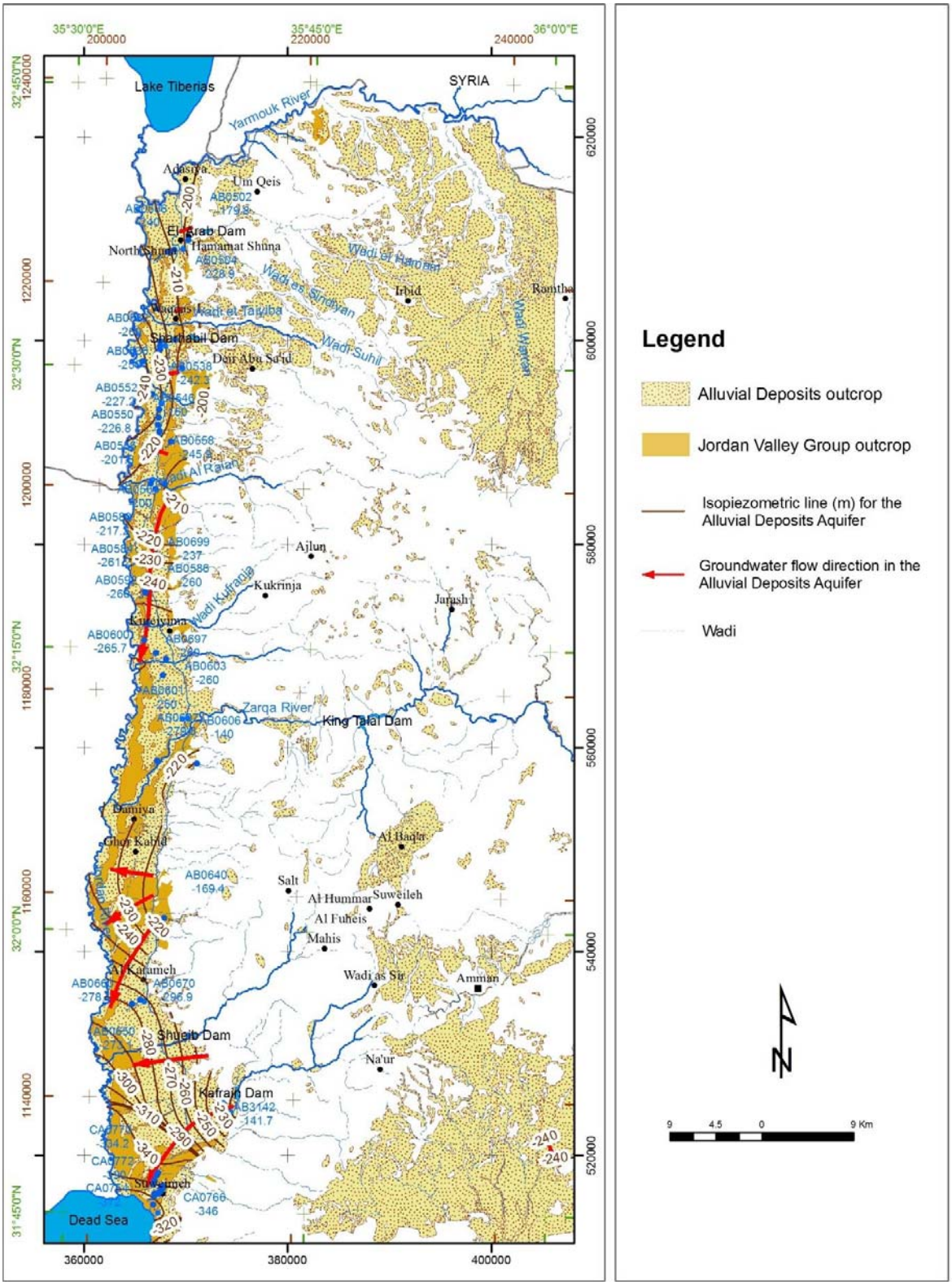

Figure 4.30: Krigged potentiometric surface and groundwater flow pattern for the Alluvial Deposits Aquifer System.

4.3.3 Decline in water level

Decline in water level is affecting almost all aquifers in the study area as well as in almost all areas in Jordan (BGR & WAJ, 1995c). The decline is related to intensive over-exploitation of aquifers. The discharge of some wells and adjacent springs is influenced by the drop of groundwater levels that emerge from the same aquifers. It is worth to mention here that the water levels of the main aquifer (i.e. the B_2/A_7 aquifer) are declining rapidly in the study area, due to enormously increased exploitation over the last decade. In many areas water levels declined by about 2 m/yr (GTZ & MWI, 2004).

The distribution of some wells showing the drop or decline in water level according to aquifer type is shown in Figure 4.31. The decline in water level in the different aquifers located NW of Jordan is illustrated on the examples of wells given in Figures (4.32 from I to VIII) (data source: WAJ open files, 2009). The decline of water level in different wells is related as mentioned earlier to enormously increased exploitation over the last decade. But the fluctuation of water level is related the amount of rainfall received in each well, in addition to its topographic location in relative to the recharge areas.

Figures 4.32-I & 4.32-I represent hydrographs for the Deep Sandstone Aquifer. Both figures show a decline of water level in JICA-1 (AL 2808) and Baqa'a-3 (AL 1430) observation wells, respectively (its location is shown in Figure 4.31). This decline is related to the high abstraction from the Deep Aquifer in Zarqa Basin (east of the study area) for purposes of drinking, industrial and agricultural activities. It is worth to mention that the area of Zarqa Basin is occupied by one of the highest populated cities in Jordan; Zarqa city.

Figures 4.32-III & 4.32-IV represent hydrographs for the Middle Ajlun Aquifer (Na'ur (A_{1-2}) and Hummar (A_4) Aquifers; Ain Ghazal deep No. 4 (AL 3324) and Wadi el Yabis-2 (AH 1002) wells, respectively) (their location are shown in Figure 4.31). The Na'ur (A_{1-2}) and the Hummar (A_4) Aquifers show a general decline in water level. The fluctuation of water table is related to the amount received in each year.

Figures 4.32-V & 4.32-VI represent hydrographs for the Upper Aquifer (Amman Silicified and Wadi as Sir (B_2/A_7) and Umm Rijam (B_4) Aquifers; AWSA-5 (AL 1813) and A'zreet observation (AD 3029) wells, respectively). The B_2/A_7 is the main aquifer in the study area and it is widely used for different purposes while the B4 is a major aquifer in the northern part of the study area. Both Figures (4.32-V & 4.32-VI) show a decline of water level in B_2/A_7 and B_4 Aquifers (their location are shown in Figure 4.31). The previously calculated rainfall moving averages for 6 year periods (from 1937/38-1944/45 to 2001/02-2008/09) (Figure 4.12) shows a general decline of rainfall averages from 2003 to 2009. But the B_2/A_7 (AWSA-5, AL 1813) and the B_4 (A'zreet observation, AD 3029) wells hydrographs (Figures 4.32-V & 4.32-VI, respectively) show a rise of water level mainly in the year 2005 due to the high amount of precipitation in that specific year and due to their location in the recharge area of the B_2/A_7 and B_4 Aquifers.

Figure 4.32-VII represents hydrographs for the Alluvial Deposits Aquifer (well AB 1341) (its location is shown in Figure 4.31). The fluctuation of water level in is related to the amount of

rainfall received in each year. The previously calculated rainfall moving averages for 6 year periods (from 1937/38-1944/45 to 2001/02-2008/09) (Figure 4.12) shows that in the periods 1984/85-1992/93 the rainfall averages were higher than the long term averages This explains the raise in water level in well AB1341 in that period, especially, in the rainfall year 1992/1993 which considered the wettest year in the period from 1937/38-1944/45 to 2001/02-2008/09. Figure 4.12 also shows a decline of rainfall averages from 2003 to 2009 which explains the lowering of the water level in that period.

Figure 4.32- VIII represents hydrographs for the Basalt Aquifer (well AB 1164) (its location is shown in Figure 4.31). The fluctuation of water level in well AB 1164 is related to the same reasons explained in Figure 4.32- VII.

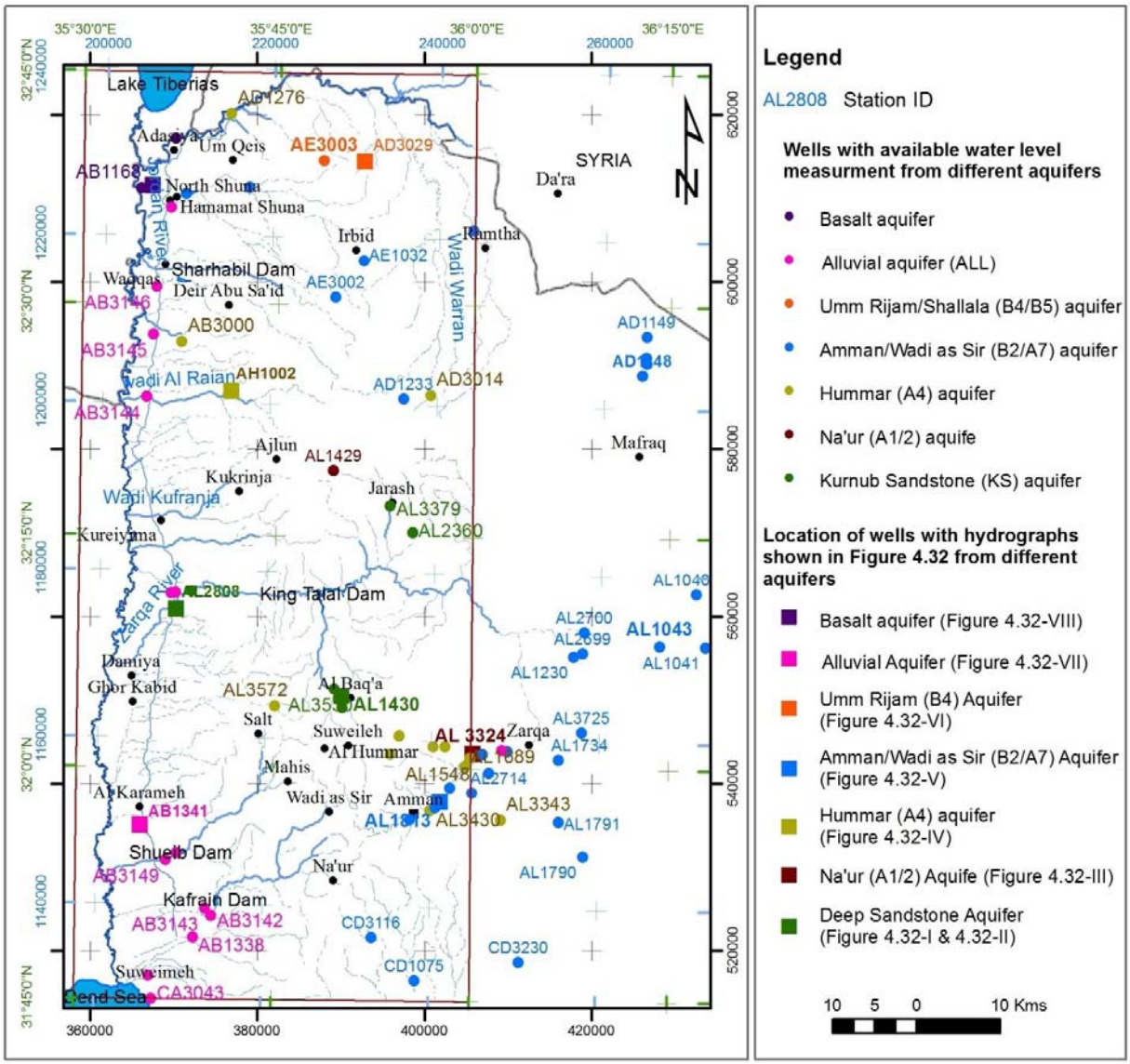

Figure 4.31: Distribution of wells in the different areas aquifers showing drop in water level.

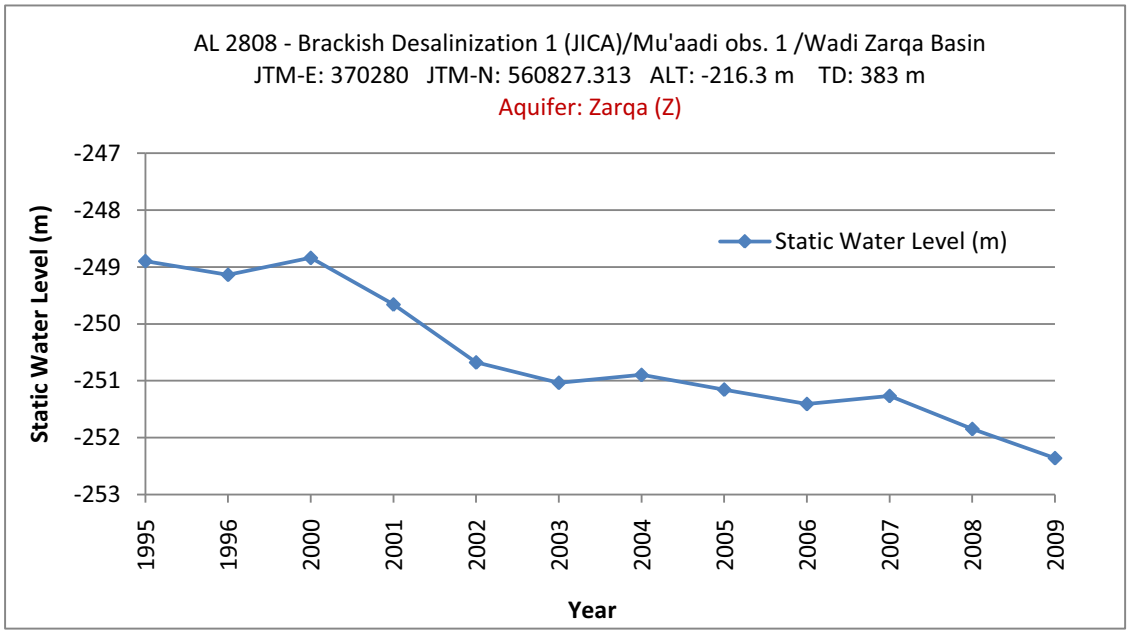

Figure 4.32-I: Well (AL 2808) hydrograph; Zarqa Aquifer (Z).

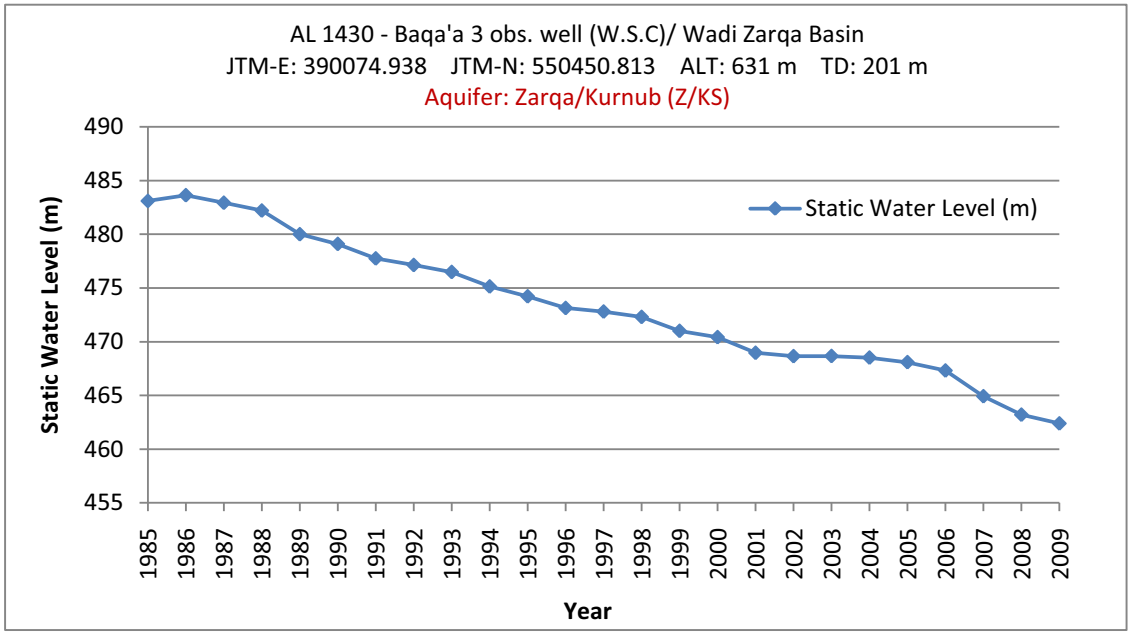

Figure 4.32-II: Well (AL 1430) hydrograph; Zarqa and Kurnub Aquifers (Z & KS).

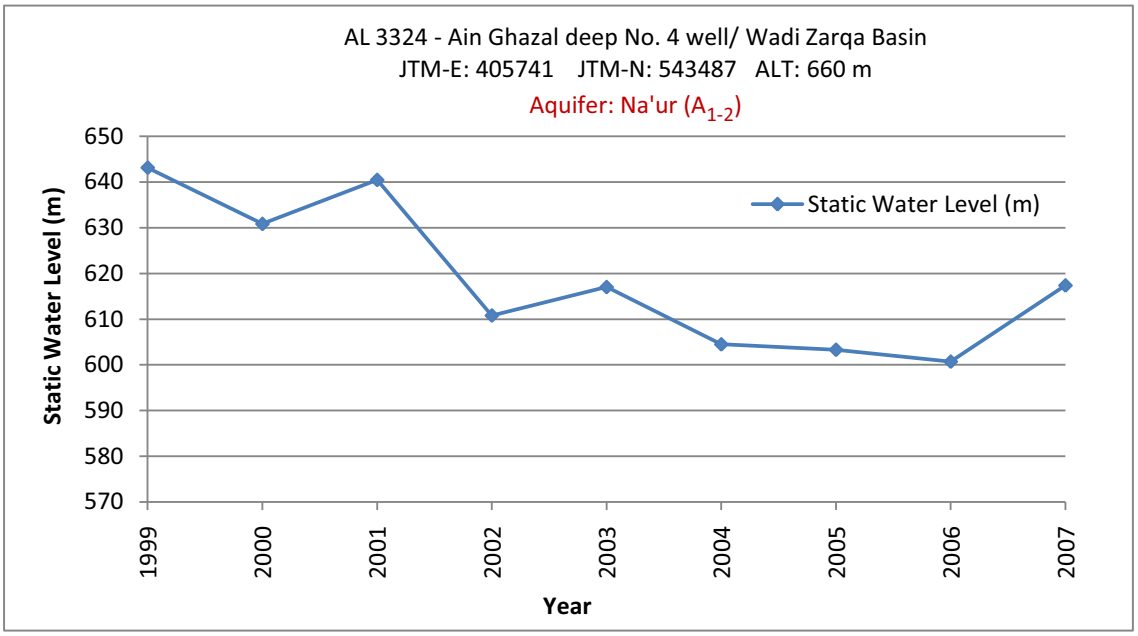

Figure 4.32-III: Well (AL 3324) hydrograph; Na'ur Aquifer (A_{1-2}).

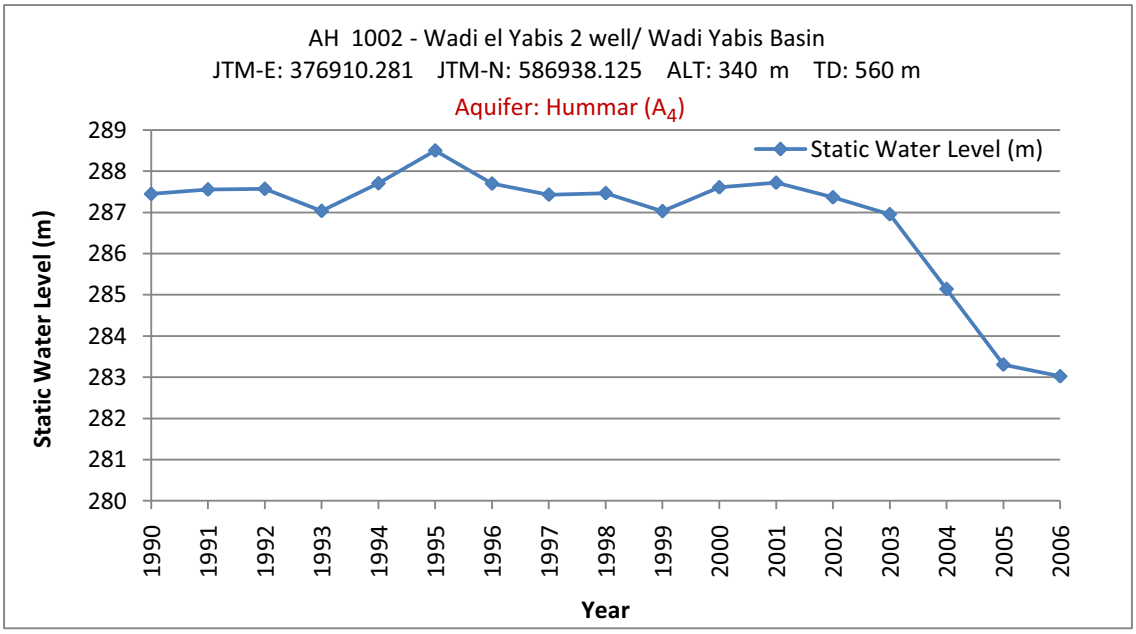

Figure 4.32-IV: Well (AH 1002) hydrograph; Hummar Aquifer (A_4).

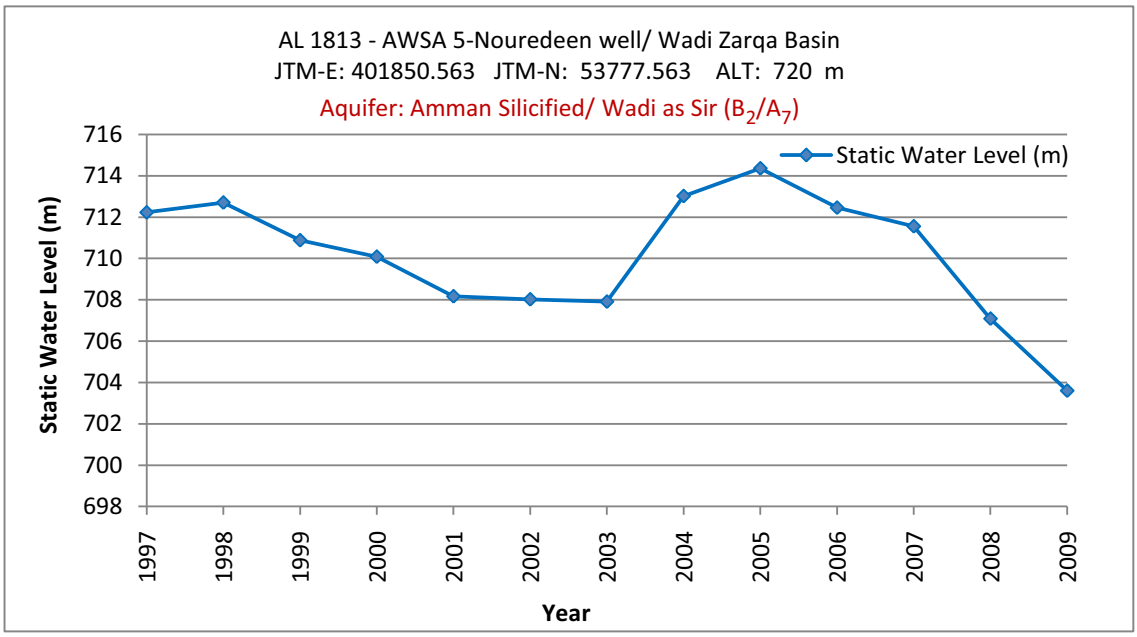

Figure 4.32-V: Well (AL 1813) hydrograph; Amman Silicified/ Wadi as Sir Aquifer (B_2/A_7).

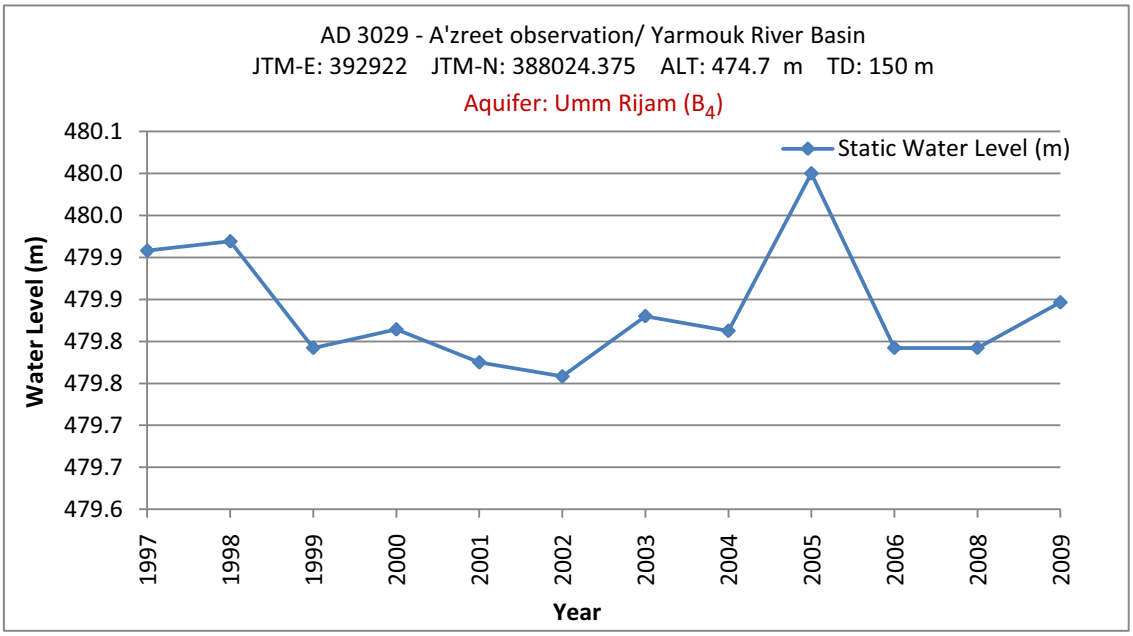

Figure 4.32-VI: Well (AD 3029) hydrograph; Umm Rijam Aquifer (B_4).

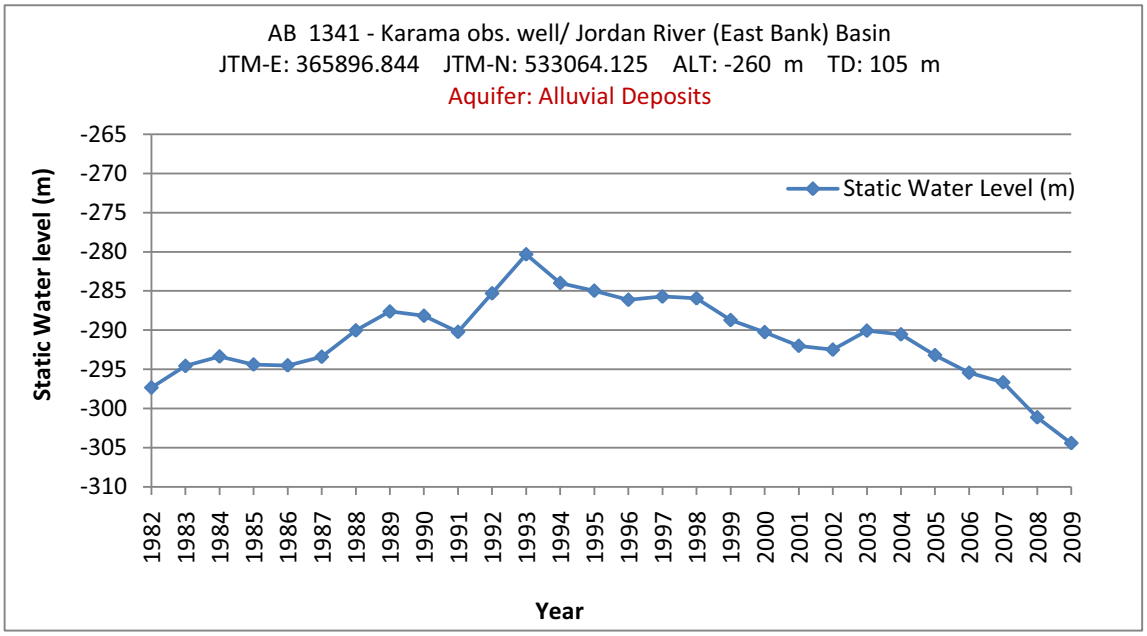

Figure 4.32-VII: Well (AB 1341) hydrograph; Alluvial Deposits Aquifer.

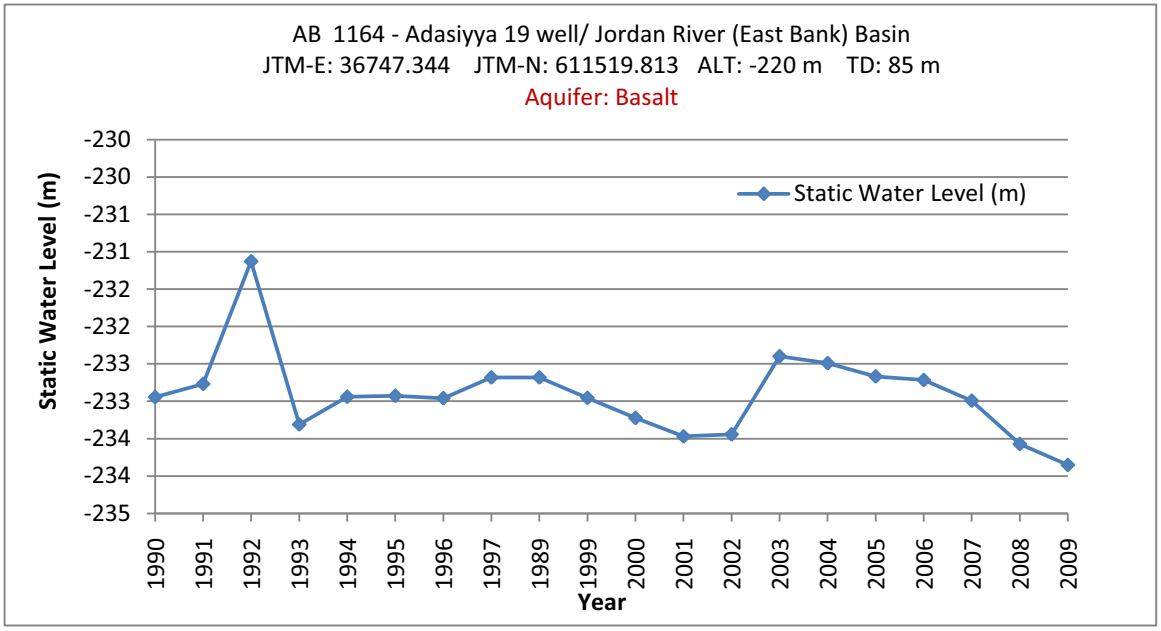

Figure 4.32-VIII: Well (AB 1164) hydrograph; Basalt Aquifer.

4.3.4 Effects of structural features on groundwater movement

The geological structures and the physiographic situations of the study area play an important role and have a major influence on: the interconnection between the aquifers, the locations of the natural discharges of the aquifers and the groundwater flow regime from different aquifers towards the Jordan Rift Valley. The sinistral strike-slip movement along the Dead Sea Transform, the formation of the Dead Sea Basin (DSB) and the adjacent mountain ridge are consequences of major geological processes which generated several horizontal and vertical fault systems, major fold system and a series of pull apart basins (See Chapter 2.2 and Plate 4). Accordingly, since the formation of the Dead Sea Basin this basin has acted as a base level for the mountain ranges extending to both sides of the Jordan Valley. Furthermore, the physiographic situation of the NW part of Jordan is characterized by steep slopes with deeply incised wadis draining westwards toward the Jordan Valley and eastwards to the high plateau region slopping slightly towards the east of Jordan (Plate 1, Plate 3 & Plate 6).

Along the highlands of the NW part of Jordan a water divide developed separating the groundwater flows to the west or to the east. This condition is similar to that in the central part of Jordan according to SALAMEH & UDLUFT (1985) (Figure 4.33). The westwards flowing groundwater is discharging in form of springs which are situated mainly at the base of the aquifer above the impermeable layers. Together with a direct influence of the groundwater into the river or the wadi fillings, they form the base flow of rivers and wadis directed to the Jordan Valley and the Dead Sea. The eastwards flowing groundwater feeds the overflowing springs at the top of the aquifer according the westward deepening of the sediment layers. Part of the groundwater flow keeps in the eastward confined aquifer. The base level for this flow is created by the Azraq basin; this basin is bordered or formed by faults permitting and upraise of water even from deeper aquifers or infiltrates slowly from the overlying Upper Cretaceous rock unit into the deeper units to finally reach the Lower Aquifer Complex (indirect recharge). For regional view see the geological map (Plate 4) and the geological cross sections DD´. EE´, FF´ & HH´ (Plate 5).

In the past before the development of the Jordan Valley – Dead Sea Structure an old drainage system was existing this was oriented towards the NW probably following the tectonic depression along the Sirhan – Fuluq Fault Systems. With the development of the Jordan Valley and the Dead Sea a new base level was crated which by backward erosion (both on the surface by the backward erosions of rivers and wadis as well as by backward erosion of the water passes in the underground) caused a slowly capturing of the old eastwards directed flow system towards the new base level in the Jordan – Dead Sea Valley. This base level was known as the Lisan Lake (LL) with a catchment area of around 157,000 km^2 during Late Pleistocene, but it shrinks to form the recent Dead Sea (DS) base level with a catchment area of around 43,000 km^2 presently (SALAMEH & FARAJAT, 2007). The reduction in the catchment area of the base level according to SALAMEH & FARAJAT, (2007) resulted from the eruption and spread of the basalt flows of Jabel Arab-Druz (JAD), which together with the resulting deposition of thick rock debris and gravels occupied the drainage system. The filling of the pre-basalt drainage system, which used to feed the Dead Sea, with basalts and alluvial sediments blocked the inflows from reaching the Dead Sea. Local base levels along the basalt flow boarders such as Azraq Oasis, Sirhan Basin and Damascus Oasis, and numerous pools and mud flats were created.

Due to the leakage of the Aquifer in the Cretaceous sedimentary sequence, now more water of the Upper Aquifer is leaking into the deeper sandstone Aquifer which oriented towards the Dead Sea as it is shown by the piezometric water level in Figure 4.33.

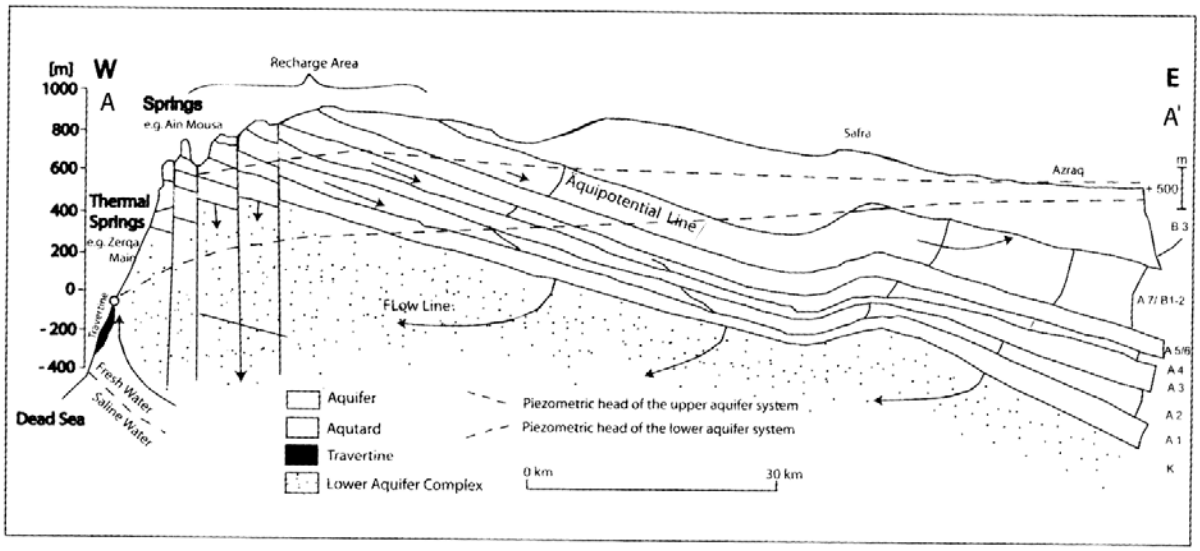

Figure 4.33: Hydrodynamic pattern of the central part of Jordan (after SALAMEH & UDLUFT, 1985).

The groundwater flow direction of the different aquifer is indicated in section 4.3.2. The distribution of spring's discharges from different aquifers (Figure 4.2) is highly governed by the geological structures and the outcrop of the aquifer related to the morphology of the study area (Figure 4.34). Therefore, the dominant structural features and their effects on groundwater flow directions in the different aquifers are discussed below:

<u>Ajlun Uplift and Dipping strata</u>

The major dominant structures in the northern area are the **Ajlun uplift** and the **Circumclinal Strike of the geological units** in the most northern part of Jordan. In addition to the presence of the northern extension of the **Dead Sea–Jordan Valley Fault Transform** in the west.

The Syrian Jabel Arab-Druz (JAD) in the northeastern part of these structures functions as a recharge area, as a result of its elevation above sea level ≈1500 m and hence its relative high precipitation rate of around 450 mm/yr. A component of the radial flow is directed towards west and south where then the groundwater flow meets in Irbid Mafraq area with the groundwater flow coming from Ajlun recharge mound and flow together towards the Yarmouk and Jordan Valleys.

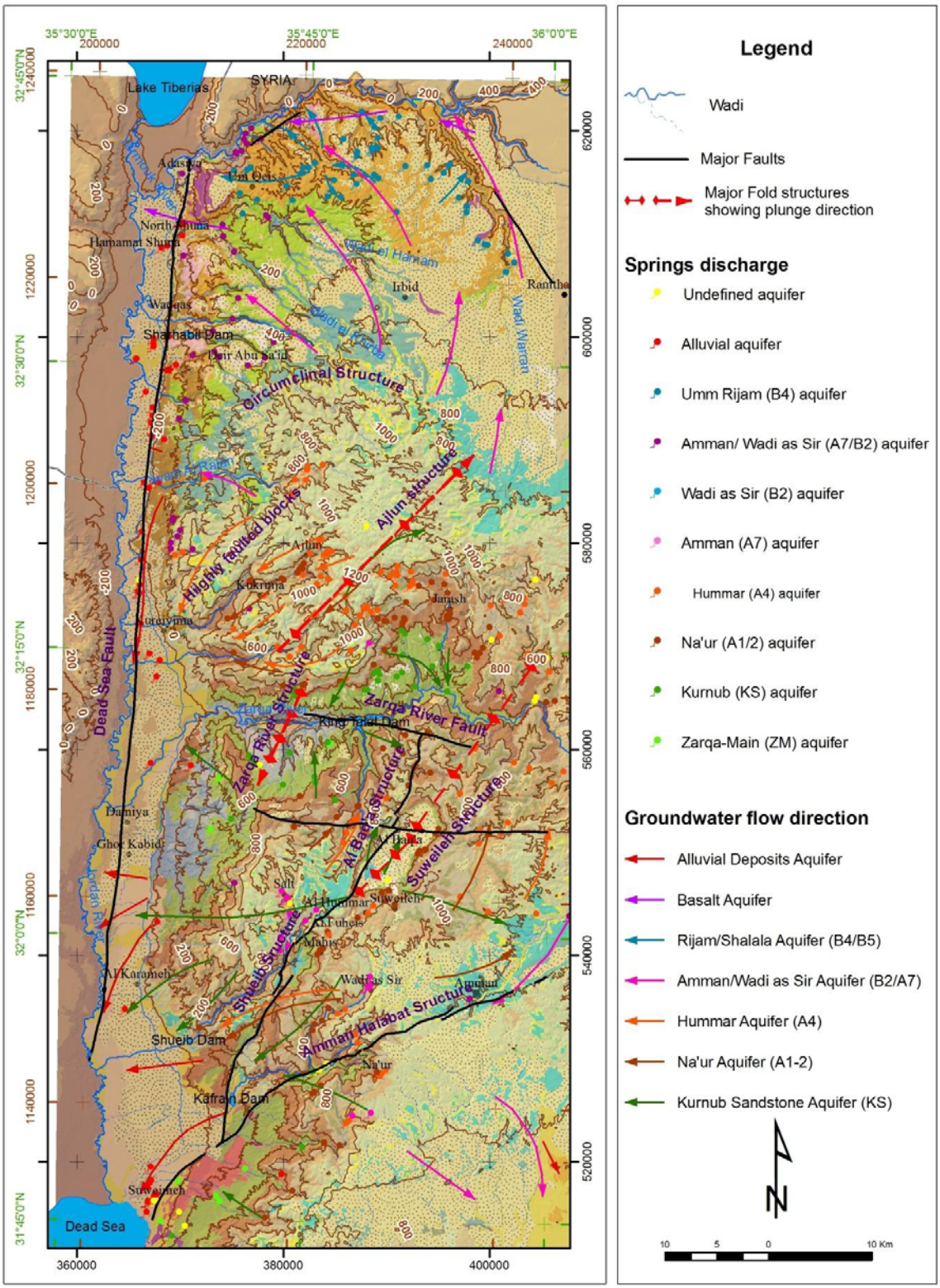

Figure 4.34: The effect of the major geological structures on the direction of groundwater flow in different aquifers and the distribution of spring's discharges from different aquifers, in the NW of Jordan.

The presence of the **Ajlun uplift**, the **Circumclinal Strike of the geological units** in the most northern part of Jordan and the presence of the northern extension of the **Dead Sea–Jordan Valley Fault Transform** in the west have major effects on the groundwater flow direction of the Middle (B_2/A_7, A_4 & A_{1-2}) and the Shallow (B_4/B_5, Basalt & Jordan Valley Alluvial) Aquifer Systems (Figure 4.34).

In the **Basalt** Aquifer, the groundwater flows radially from the Jabel Arab-Druz (JAD) to all directions (Figure 4.29), in the Um Rijam (**B_4**) Aquifer, which is an aquifer of local importance in northern Jordan groundwater flows mainly towards the Yarmouk River and partly towards Wadi el 'Arab and Jordan River (Figure 4.28).

In the **B_2/A_7** Aquifer the flow is directed from the recharge mounds in Ajlun Mountain, Ramtha Basin and Mafraq area and partly to the northwest to the western escarpment, along Wadi el 'Arab (Figure 4.27). The Ajlun dome and the circumclinal strike of the units in the western part of northern Jordan affected the groundwater flow in the B_2/A_7 Aquifer. **Ajlun uplift** plays a role in rendering the groundwater flow in the Upper Cretaceous and underlying aquifers in radial directions; towards the Jordan Valley where it discharges along wadis such as Rajib and Kufranja, towards the Zarqa River in the south and towards north and east (Figures from 4.25 to 4.27), where as mentioned above it merges with the groundwater flow originating in Jabel Arab-Druz (JAD) area and both flow then towards northwest. While, the **Circumclinal Strike** of the units in the western part of northern Jordan, with a thick confining layer (i.e. Muwaqqar Chalk Marl, **B_3**) of around 230 m thickness confines the **B_2/A_7** aquifer. It allows the only limited discharges of the confined water of the B_2/A_7 aquifer along faults or fissures; such as Hima springs (i.e. Hammamat Mukheiba springs). But the major groundwater amount discharge further south in the area of Wadi Yabis (or as locally known as Wadi Raian). Here big springs used to discharge from the B_2/A_7 (Figure 4.35).

Accordingly, it can be stated that, the groundwater flows in the Middle and Shallow Aquifers comes mainly from Jabel Arab-Druz (JAD) into Mafraq area where the groundwater converges with the groundwater coming from the southwest from Ajlun area (Figure 4.36). From there the groundwater flows mainly, westwards to the Jordan Rift Valley and towards the Yarmouk River areas, where most of the discharge occurs (EL-NASER, 1991).

The spring's discharges from the B_2/A_7 Aquifer in the extreme northwestern part of the study area are structurally controlled by the **Dead Sea–Jordan Valley Fault**. That part characterized by circumclinal strikes of the Rijam/Shallala (**B_4-B_5**) aquifer, the Muwaqqar Chalk Marl (**B_3**) aquiclude and the underlying Amman/Wadi as Sir (**B_2/A_7**) aquifer (Figure 4.35). Therefore, this structural situation causes the groundwater of the B_2/A_7 aquifer to be confined by the B_3 formation, which consists of marly layers and form aquicludes and to flow in a southerly direction instead of continuing to the west towards the Jordan Valley and/or to the north towards the Yarmouk River (SALAMEH, 2006). The Circumclinal Strike is accompanied with circumclinal dipping with increasing angles to the N and NW towards the Yarmouk River in the north, to the W toward the Jordan River in the west and to the NE in the east (see Chapter 2 and the geological cross section GG', Plate 5 for more details).

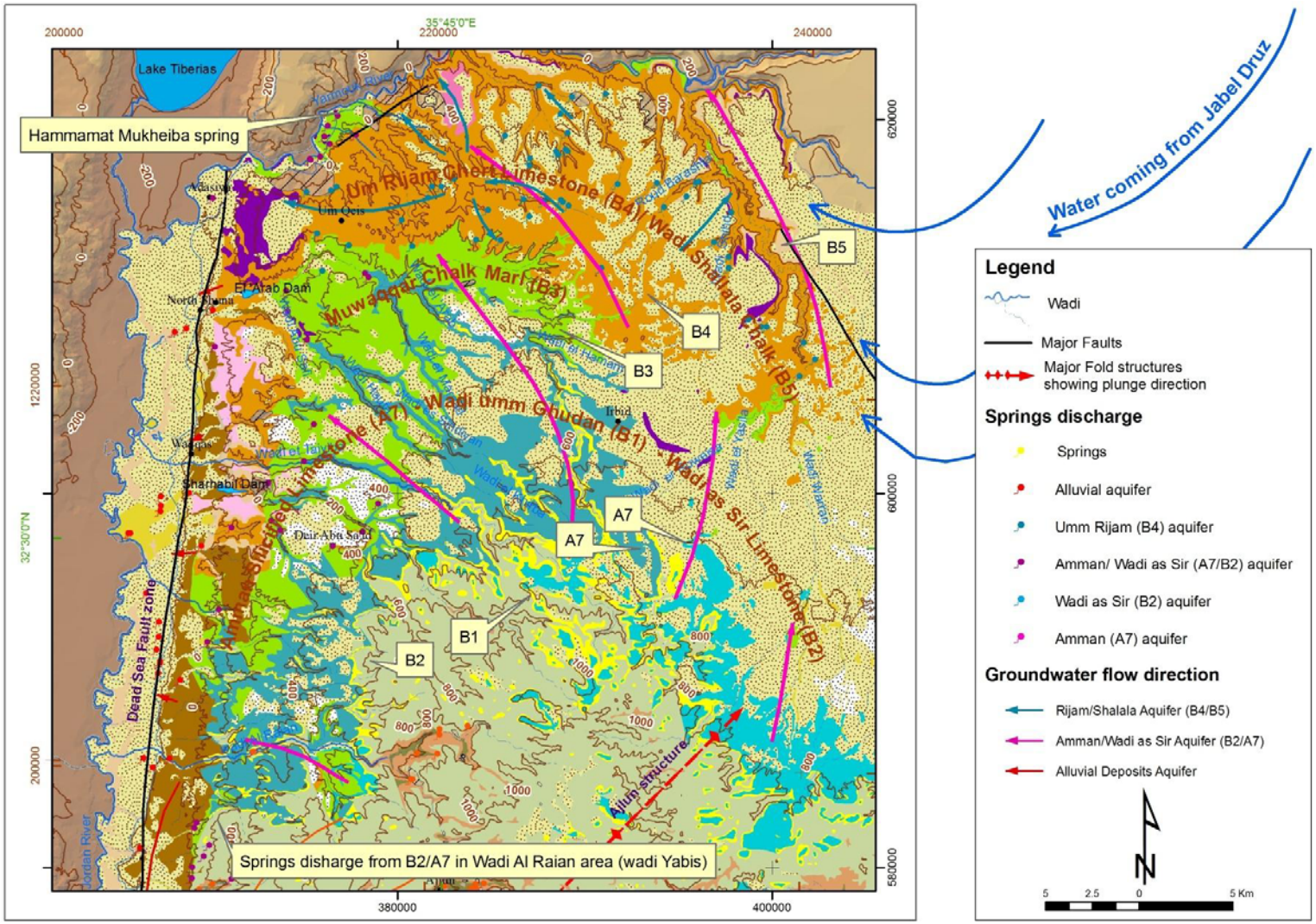

Figure 4.35: The effect of the Circumclinal Strike of the geologic units on the groundwater flow in the western part of northern Jordan (The schematic blue arrows indicate the discharge from the northeastern Basalt region and Jabel Arab-Druz toward Mafraq depression which is dewatering NW).

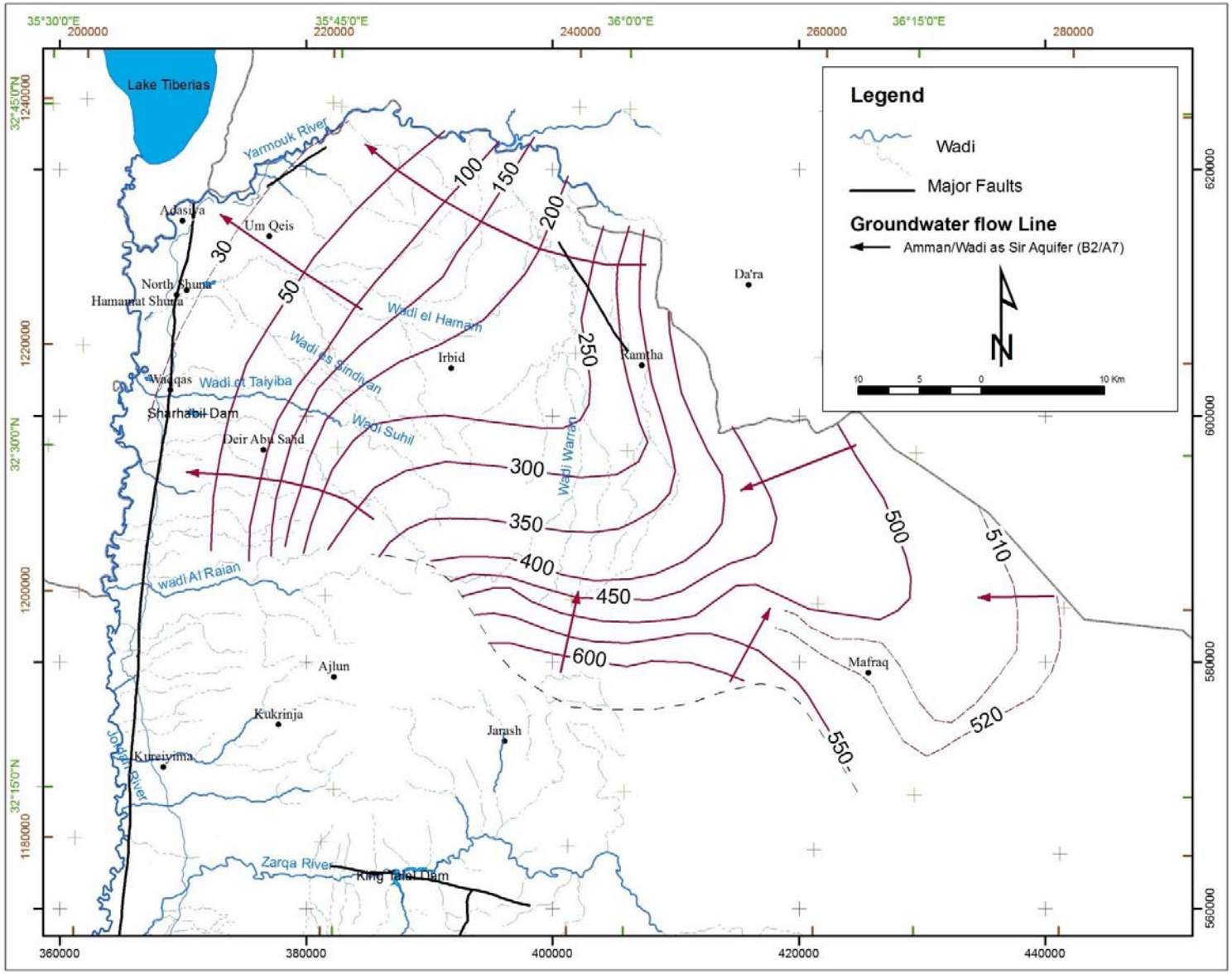

Figure 4.36: Potentiometric map of the B_2/A_7 aquifer system (modified after EL-NASER, 1991).

The groundwater in the **A_{1-2}** (Na'ur) and **A_4** (Hummar) semi aquifers behaves in the same way of the B_2/A_7 aquifer. The groundwater flow in A_{1-2} and A_4 aquifers is directed from the high mounds around Ajlun and Jabel Arab-Druz (JAD) towards the Jordan Valley without outcrops and hence no direct recharge (Figures 4.25 & 4.26). Therefore, where faults occurs the A_{1-6} (Lower Ajlun) sequence is interconnected with the overlying B_2/A_7 aquifer and the underlying Kurnub aquifer allowing here with indirect upward discharges (after EL-NASER, 1991; Figure 4.37). The geological map (Plate 4) and geological cross sections AA', BB', CC', DD' & HH' (Plate 5) supported EL-NASER (1991) conclusion.

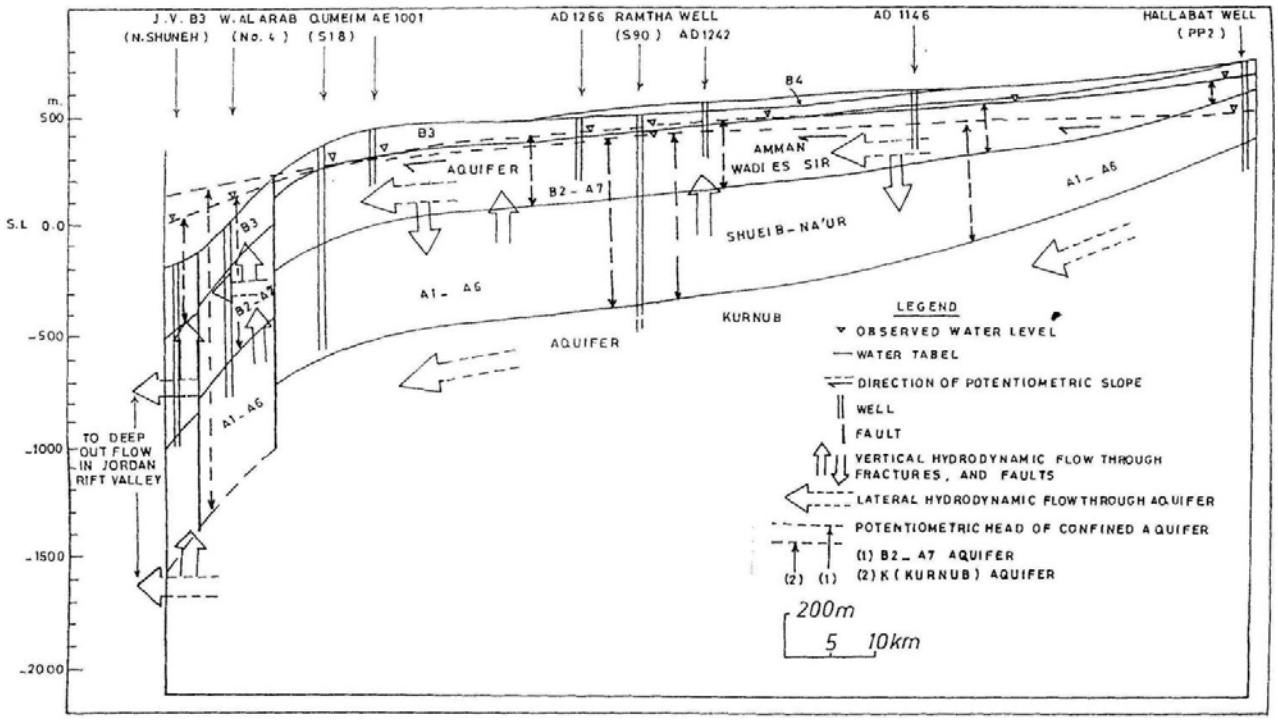

Figure 4.37: Hydrodynamic system of the northern part of Jordan (after EL-NASER, 1991).

Zarqa River structure

The outcrops and the groundwater flow pattern map (Figure 4.23) indicate that the Lower Aquifer System, the **Deep Sandstone Aquifer** is an unconfined-confined aquifer system, draining towards the Dead Sea, Jordan Valley and Yarmouk River. The effect of the Ajlun and the Zarqa River structures on this aquifer appears in the area of Zarqa River. The **Zarqa River** area represents an area of a major asymmetrical anticline striking NNE-SSW and plunging a few degrees in the SSW direction (i.e. **Suweileh or Al Baqa'a anticline structure** (Figure 2. 22 & 2.23). This anticline is the southern extension of the Ajlun Structure (as shown in Figures 2.18, 2.19 and in the geological cross sections BB′, CC′ & HH′, Plate 5). Also, geological cross sections BB′ & CC′ (Plate 5) indicate a depressional area south of Zarqa River area. Therefore,

this anticlinal structure as mentioned above diverts the groundwater towards SSW. Also, in the Zarqa River area two major dextral strike-slip faults are found; namely, **Zarqa River** and **Al Baqa'a-Er Rmamin faults** (Figure 2.20). According to the hydrogeological study along the lower reaches of Zarqa River by ODEH (2005) & ODEH et al. (2009), they concluded that these two faults cause the groundwater to diverge where the fault is perpendicular to the groundwater flow lines and to converge where the fault is parallel to the groundwater flow lines.

Waters from the Deep Aquifer System discharges along the Zarqa River due to the deep erosion of Kurnub Sandstone, forming an easier discharge pathway for the groundwater in that area (as shown in the geological cross section II', Figures 4.24). Local direct recharges to the deep Sandstone Aquifer takes place in Al Baqa'a area and along the lower reaches of Zarqa River and its tributaries (see the geological cross sections HH′, Plate 5). The replenishment of the groundwater in the Lower Aquifer System takes place mainly by percolation through the overlying Upper Cretaceous rock Unit and as sub-surface flow from the adjacent areas and aquifers (SALAMEH & UDLUFT, 1985; EL-NASER, 1991; SALAMEH & BANNAYAN, 1993) through marls of the Ajlun Group along faults and fractures and other hydraulically efficient flow paths in the alternating aquifers and aquitards LENZ (1999). According to EL-NASER (1991) the groundwater flow within the deep aquifer system is predominantly vertical in the vicinity of the Jordan Rift Valley. The aquifer gains water through the downward leakage from the B_2/A_7 aquifer and losses water through upward leakage to the B_2/A_7 due to the high confinement degree and to the fact that the potentiometric surface of the Kurnub Aquifer is higher than that of the B_2/A_7. The upwards seeps from the Kurnub Aquifer to the surface, pass through the recent sediments forming saline springs (Wadi Mallaha) (SALAMEH & BANNAYAN, 1993).

The outcrop of the Triassic and Jurassic Formations in Deir Alla area, in the southern part of the study area (**Deir Alla anticline**), create a watershed and divide the regional aquifer into two basins (Guttman et al., in Hötzl, et al., 2009): a northern basin that dips towards the Yarmouk River and the southern basin that dips towards Karama, Kafrain and the northern Dead Sea. The main aquifers within this zone are: the Lower Cretaceous, A_{1-2}, A_4 and B_2/A_7 aquifers (see geological cross section BB' & HH', Plate 5). To the southeast of Deir Alla a series of anticlines and synclines were found such as **Wadi Shueib syncline**, **Wadi Shueib anticline**, **Wadi Kafrain syncline** and the **Amman-Halabat Flexure** (Figures 2.17 & 2.20), which outlines the southeastern part of the study area (Plate 4). The uplift of Deir Alla anticline, Wadi Shueib anticline and the anticlinal structure which accompanied with Amman-Halabat flexure and strikes ENE-WSW, forces groundwater to flow westward towards the Jordan Rift Valley, while the Kafrain syncline acts as groundwater drainage system. Several springs discharges from the Ajlun aquifer in this zone to the Pleistocene layer in the Jordan Rift Valley (Figure 4.30). These springs occur mainly at the base of Ajlun Aquifer, at medium elevation (PARKER, 1970; SALAMEH, 1996).

Suweimeh-Amman-Halabat Flexure is the dominant structure in the southeastern part of the study area. It is an ENE-WSW trending structural zone of 1-5 km wide. It consists of several structural elements including faults and folds controlled by the same stress system. The fault has a downthrown block towards the northwest with vertical displacement of 400 m (SHAWABKEH, 2001). The affect of the dominant **Suweimeh-Amman-Halabat Flexure**, allows the groundwater

in the B_2/A_7 aquifer to flow partly northwest towards Zarqa River and partly northeast towards wadi el Waleh (Figures 4.27 & 4.38). Further to the south of the study area the E-W trending Siwaqa Fault acts as a barrier to the B_2/A_7 aquifer system. Also, Amman Flexure acts as a barrier and forms the south-east limit of the groundwater in the A_{1-2} and A_4 aquifers. The fault along the eastern extension of the Sweimeh-Amman-Halabat flexture forms a weakness zone with very active water pathways, where it then changes its flow direction to the east and northeast. At the longitude of the Zarqa River, in its north-south course, both the westerly (originate in the eastern part; Wadi Dhuleil, which extends to the northeast of Wadi Zarqa) and easterly (originate in the western highlands of Amman and its surroundings Seil-Zarqa) groundwater currents converge and discharge in the form of springs along Zarqa River.

The geological map of the study area (Plate 4) indicates that the fault accompanied with the Suweimeh-Amman-Halabat Structure caused the cropping out of Kurnub Sandstone Group of Lower Cretaceous age along wadi Na'ur. The fault causes the groundwater to discharge from the Deep Aquifer, partly feeding the wadi fills and partly flowing at the surface to feed the alluvial deposits in the Jordan Valley (SALAMEH, 2006).While in the area lying northeast of the Dead Sea (Plate 4) indications are there that the fault was responsible on the outcropping of the Triassic and Jurassic formations. The fault causes the groundwater to discharge from the Deep Aquifer along the side wadis and ending in the Dead Sea (SALAMEH, 2006).

The sinistral movement of the **Dead Sea-Jordan Valley Transform Fault** in the western side of the study area brings the Pleistocene and Quaternary Formations of the Alluvial Aquifer in contact with different older formations. This creates a direct hydraulic connection so that the groundwater flows in the Jordan Valley Aquifer takes place from the escarpment aquifers into the valley deposits (Figure 4.34) and discharges there under free-water table conditions (SALAMEH, 2006). The alluvial aquifer, which is limited to the Jordan Valley, is recharged in addition to the lateral flow of the adjacent aquifers from several sources such as, leakage of runoff, irrigation return flow and small amount of direct recharge. The replenishment of the Jordan Valley Aquifer was reduced due to several factors, such as heavy groundwater abstraction, diversion and storage of large quantities of flood water and surface drainage of major urban centers in Jordan such as Amman, Irbid and es Salt, flow westward through wadis towards the Jordan Valley and in dams built across the major wadis outlets (such as the Shueib, Kafrain and King Talal dams) and by diversion of most of the freshwater from Lake Tiberias.

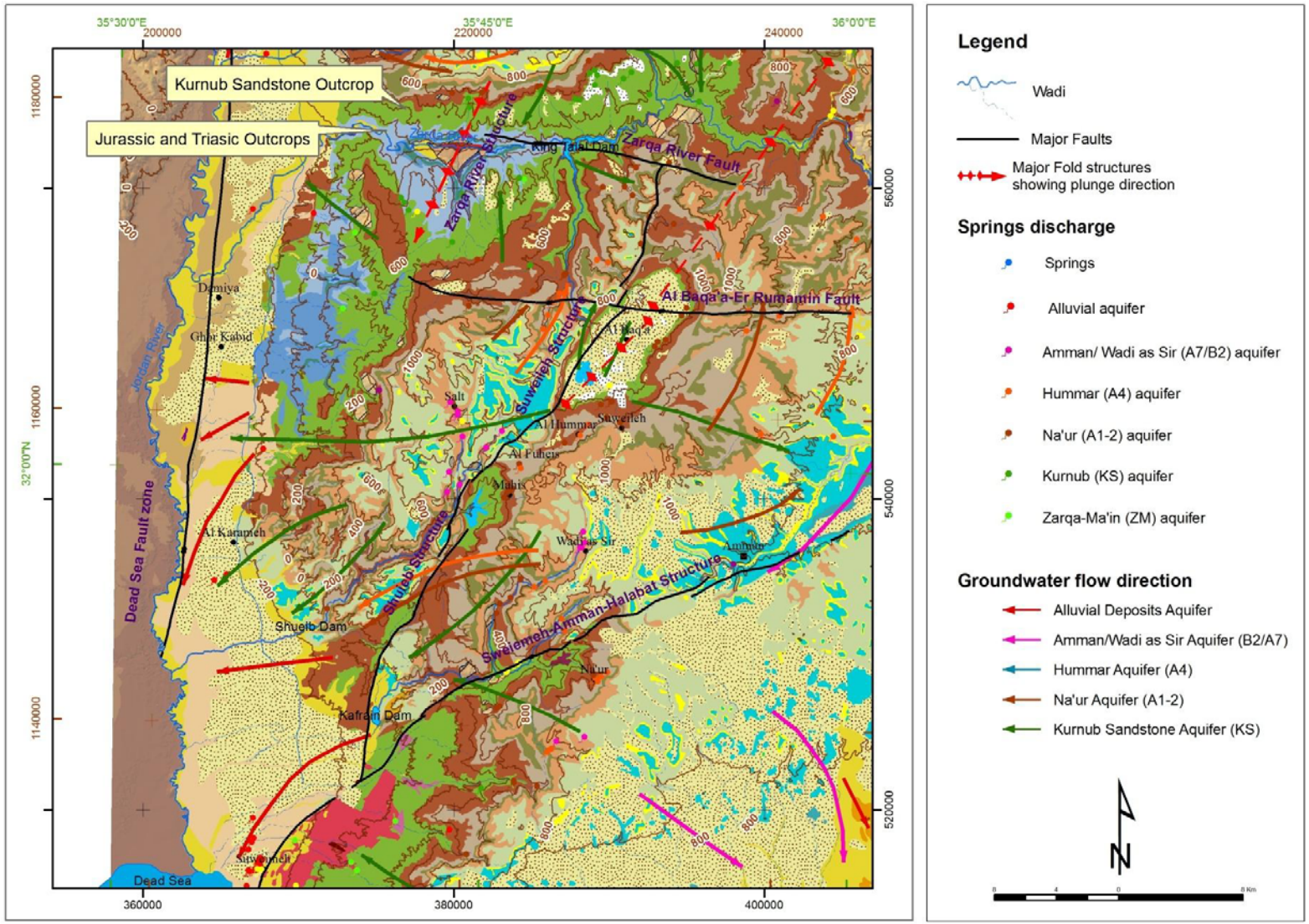

Figure 4.38: The effect of Zarqa River Structure on the groundwater flow in the central and southern part of northern Jordan.

4.4 Hydrochemistry

In the study area groundwater is the major source of water for domestic, agricultural and other water-related activities. The chemical composition of groundwater is therefore of special importance for different fields of application such as portable water, irrigation, industry etc. Its investigation is necessary to elucidate the relation between lithology and the main structural features on the chemical composition of that groundwater. Furthermore, it is also important to understand the origin of the water, the possible anthropogenic pollution as well as the assessment of the water with regard to utilization.

The chemistry of the groundwater strongly depends from the mean residence time of the water in underground. Generally, spring water is discharges few days after the precipitation events and low mineralized due to small reaction time with the rocks while on contrary discharging water with mean residence time of tens or hundreds of years or more shows high mineralization which in chemical balance with rocks of the aquifer (LINSLEY et al., 1982).

Water quality data were obtained from MWI/WAJ open files for the years 2004 and 2005. In addition, chemical analysis of the Kurnub Aquifer water was obtained from ODEH (2005) and for the Na'ur Aquifer (A_{1-2}) from JASEM (2009). The water chemical analyses of wells and springs include only the following parameters:

- Physical parameters:
  - pH and
  - Electrical Conductivity (**EC** in µS/cm)

- Chemical parameters:
  - Major cations: $\mathbf{Na^+}$, $\mathbf{Ca^{2+}}$, $\mathbf{Mg^{2+}}$ and $\mathbf{K^+}$ (in mg/l)
  - Major anions:, $\mathbf{Cl^-}$, $\mathbf{SO_4^{2-}}$, $\mathbf{HCO_3^-}$ and $\mathbf{NO_3^-}$(in mg/l)
  - Total Dissolved Solids (**TDS** in mg/l).

The **TDS** values (in mg/l) were calculated according to the following equation (FREEZE & CHERRY, 1979):

$$\mathbf{TDS}\ (\text{mg/l}) = \mathbf{Ca^{2+}} + \mathbf{Mg^{2+}} + \mathbf{Na^+} + \mathbf{K^+} + \mathbf{SO_4^{2-}} + \mathbf{Cl^-} + \mathbf{NO_3^-} + \mathbf{0.5HCO_3^-}.$$

The water quality data were categorized according to different aquifers. Then, the average value for each parameter in each water well and spring was calculated. The data on groundwater wells and springs with their chemical data were made available in MS-Excel format. Therefore, these chemical data were first recorded as locations in Jordan Traverse Mercator (JTM), then converted into the database format and finally integrated into ARC/GIS 9.3 as a shapefile format, in order to overlay other formally created layers (shapefiles), such as DEM, TIN, surface basins extends, geology, structures, groundwater flow direction, etc. (Figure 4.39).

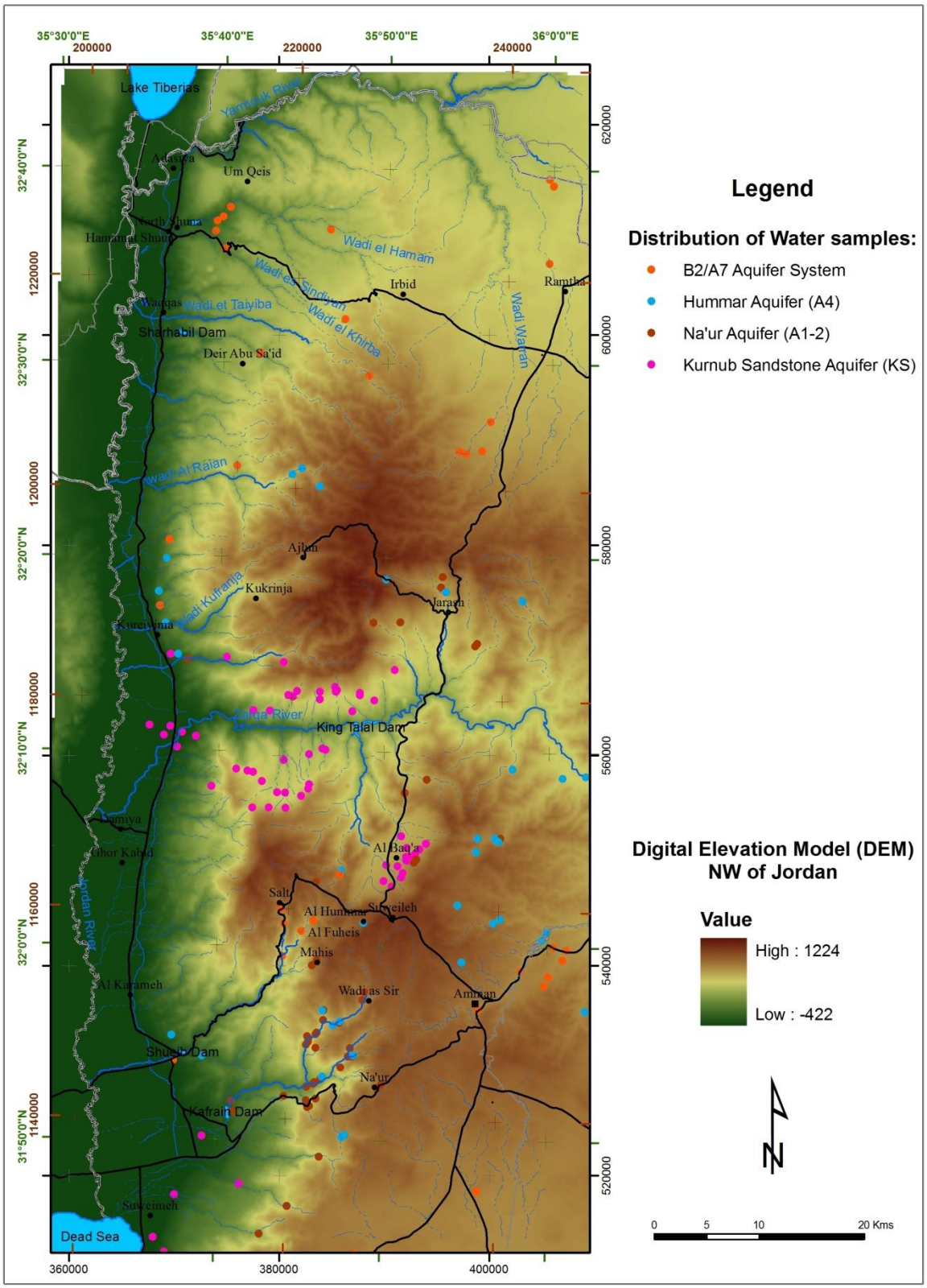

Figure 4.39: Distribution of water well and spring with water chemistry data from different aquifers within and around the study area, in the years 2004 and 2005 (WAJ open files; ODEH, 2005; JASEM, 2009).

4.4.1 Characterization of water chemistry in the different aquifers NW of Jordan

The quality of groundwater along the recharge area depends upon the chemical and physical properties of surrounding rocks, water rock intercalation and human activities affecting the groundwater. Therefore, the water quality data in the study area were used to construct for each aquifer the isosalinity map using the EC values (µS/cm) and the main cations and anions. For the classification of water in Jordan according to Table 4.12 the TDS values were used.

Table 4.12: Simple Groundwater classification based on total dissolved solids (FREEZE & CHERRY, 1979).

Category	Total dissolved solids (mg/l)
Fresh water	0–1000
Brackish water	1000–10,000
Saline water	10,000–100,000
Brine water	More than100,000

Generally, groundwater in the discharge zones tend to have higher salinity compared to that of the recharge areas due to the longer residence time and prolonged contact with the aquifer matrix (FREEZE & CHERRY, 1979). FREEZE & CHERRY (1979) categorized the groundwater salinity for the different types (Table 4.12). This categorization will be used throughout the present study. For the use as drinking water both the WHO drinking water quality standards and the JISM (Jordanian Institution for Standards and Metrology) standards are used (Table 4.13).

Table 4.13: Water Health Organization Guidelines (WHO, 1995) and Jordanian Standards for drinking water (JISM, 2001).

Parameter	WHO standards	JISM standards
Temperature (℃)	From 13 to 25	From 12 to 25
pH value	From 6.5 to 8.5	From 6.5 to 8.5
TDS (mg/l)	From 500 to 1000	From 500 to 1500
Cl^- (mg/l)	250	From 200 to 500
HCO_3^- (mg/l)	From 150 to 350	From 100 to 500
SO_4^{2-} (mg/l)	250	From 200 to 500
NO_3^- (mg/l)	50	70
Na^+(mg/l)	200	From 200 to 400
K^+ (mg/l)	12	12
Ca^{2+} (mg/l)	From 75 to 200	From 75 to 200
Mg^{2+} (mg/l)	< 125	From 50 to 150
Cu (mg/l)	0	1
Fe (mg/l)	0.3	From 0.3 to 1
Mn (mg/l)	From 0.1 to 0.5	From 0.1 to 0.2
Zn (mg/l)	3	From 3 to 5

The main factors affecting the groundwater chemistry are mainly the dissolved substances in precipitation water, geochemistry of percolated rock units, retention time of groundwater in different aquifers, weathering and erosion of rocks and soils in addition to human activities such as urbanization and industrialization (DREVER, 1988; GRAY, 1994). Therefore, the characterization of water chemistry in the two major aquifers (the Upper Aquifer System, **B_2/A_7 Aquifer** and the Lower Aquifer System, **Deep Sandstone Aquifer**) and in the minor aquifers (**Middle Aquifers**: Hummar **A_4** and Na'ur **A_{1-2}**) will be described with reference on the effect of lithology, structural features, recharge and groundwater flow direction the following sections using their EC value (Figures 4.42-I, 4.43, 4.44 & 4.45-I) and different salinity parameters in the major aquifers (Figures 4.42 from II to X & 4.45 from II to X).

In addition to that an assessment of the chemical composition of the groundwater for each aquifer was done based on the four main cations (calcium, magnesium, and sodium + potassium) and the four main anions (bicarbonate, sulfate, chloride and nitrate). PIPER (1944) proposed a trilinear diagram that permits the classification of waters, according to LANGGUTH (1966) into seven types as shown in Figure 4.40. The **GW Chart 2000 software**, version 1.23.3.0 from the US Geological survey (USGS) (WINSTON, 2000) was used for plotting this diagram.

As mentioned earlier the data obtained from MWI/WAJ open files were categorized according to different aquifers. Accordingly, these data (the average of the years 2004 and 2005) were used to draw piper diagram (PIPER, 1944) for each aquifer in order to show the water types in each aquifers and visualized how these change from one area to another. The piper diagrams for the **B_2/A_7**, the **Na'ur (A_{1-2})**, the **Hummar (A_4)** and the **Kurnub Sandstone** Aquifers are illustrated in Figure 4.46, 4.47, 4.48 & 4.49; respectively. In addition, to indicate the location of the groundwater samples each piper diagram is in correspondence with an index map showing their location according to the symbology used in the piper diagram and accompanied with table showing the composition of water in each aquifer Tables 4.15, 4.16, 4.17 & 4.18; respectively.

Water Types

Normal earth alkaline water
a: with prevailing bicarbonate
b: with prevailing bicarbonate and sulfate or chloride
c: with prevailing sulfate or chloride

Earth alkaline water with increased portion of alkalis
d: with prevailing bicarbonate
e: with prevailing sulfate and chloride

Alkaline water
f: with prevailing bicarbonate
g: with prevailing sulfate - chloride

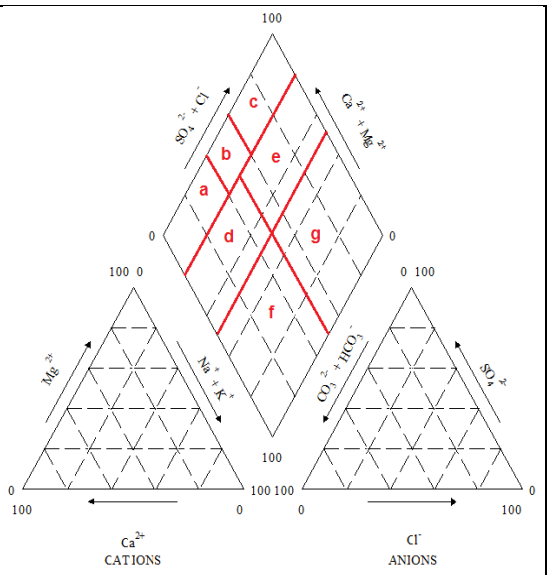

Figure 4.40: Piper trilinear diagram showing the different water types (LANGGUTH, 1966).

4.4.1.1 Characterization of water chemistry in the Upper Aquifer System (B_2/A_7 Aquifer)

The B_2/A_7 Aquifer System is the most important aquifer in Jordan. It is of Upper Cretaceous age and is composed of the Amman Silicified Limestone Formation, Al Hisa Phosphorite Formation (ASL or A_7), Wadi Umm Ghudran Formation (WG or B_1) and Wadi as Sir Limestone Formation (WSL or B_2) (as described previously in section (4.3.1.2.2). These sequences are shown in the geological cross sections (Plate 5, from AA' to HH'). The aquifer reaches the highest thickness of 400 m in the highlands of the study area (see chapter 2 & 3 for more details). In the NW of Jordan, the Upper Cretaceous rocks are karstic. The B_2/A_7 Aquifer System there consists of limestone, dolomitic limestone and dolomite with intercalated beds of sandy limestone, chalk, marl, gypsum, chert and phosphorite.

The geological map (Plate 4) shows the outcrop areas of the Amman Silicified Limestone and Al Hisa Phosphorite Formation (A_7), the Wadi Umm Ghudran Formation (B_1) and the Wadi as Sir Limestone Formation (B_2). The aquifer outcrop areas as indicated from the Digital Elevation Model (DEM) of the study area (Plate 3) are found in the highly elevated areas around Ajlun, es Salt and Amman cities. Mainly, the base of the B_2/A_7 aquifer is outcropping in the area of Ajlun Dome from there the base drops to the east towards the Azraq area, to the west towards the Jordan Valley and to the north towards the Yarmouk River area (Figure 2.7). Therefore, to the east, north and northwest of the study area, the B_2/A_7 goes over in a confined aquifer, overlain by the Muwaqqar Chalk Marl (MCM or B_3) which consists mainly of marls of Upper Cretaceous and Tertiary age (see section 4.3.1.2.2 for more details). Due to its exposure in relatively elevated areas, the B_2/A_7 aquifer receives mean annual rainfall averages ranging from 350 mm/yr to more than 500 mm/yr along most of its exposure (Figure 4.9). In addition the B_2/A_7 exposure areas have mean annual potential evaporation average range from 1900 mm/yr to more than 2000 mm/yr (Figure 4.14).

4.4.1.1.1 Electrical conductivity (EC) in the B_2/A_7 Aquifer

The spatial distribution of the EC values for the B_2/A_7 Aquifer System shows low salinity areas in the recharge areas (Figure 4.42-I). These areas are found mainly north and northeast of Ajlun and around es Salt and Amman cities. Generally, the EC values of the B_2/A_7 Aquifer are less than 1000 µS/cm.

In the northeastern part, the EC measures less than 700 µS/cm. It increases gradually to more than 800 µS/cm towards the confined part of the aquifer in the extreme north and northwest of the study area. The minimum value of EC is 505 µS/cm found in Kufr Yuba Exp. Well (AE1001) in the central northern part of the study area. The EC increased also in south direction, where it ranges from 512 µS/cm to 920 µS/cm around es Salt city.

In the western part of the study area, the EC value reaches 4270 µS/cm in Abu Falah spring (AB0568). The high EC in the spring is found because the water in this spring represents the mixture of Kurnub and B_2/A_7 Aquifers waters. The distribution pattern of the EC values for the B_2/A_7 Aquifer close to the Abu Falah spring is artificially

influenced by the interpolation method (Figure 4.42-I). The high value of EC in Abu Falah spring influencing the neighboring area by automatic interpolation scheme, gives a wrong concentration pattern in the surrounding of the spring.

An increase in the EC value towards the northeast and southeast of Amman are recognized (3871 µS/cm in AL1170 and 2640 µS/cm in CD3261, respectively). But, the increase in the EC values in both locations is attributed to over-exploitation of groundwater both for domestic and irrigation purposes. The chemical composition is changing due to the draw by of water from the deeper aquifer or partly from increasing urbanization as well as agriculture activities (irrigation return flows).

The total dissolved solids (TDS) obtained from WAJ data base for the NW of Jordan show that the TDS values range from 309.63 mg/l to 944.49 mg/l.

4.4.1.1.2 Major cations and anions in the B_2/A_7 Aquifer

The major constitute Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-} SO_4^{2-}, and NO_3^{-} are the main parameters contributing to salinity in the B_2/A_7 Aquifer System. Figures (4.42- II, III, V, VI, IX, VII, VIII & X, respectively) show the concentrations distribution of the major anions and cations in the study area. The ions concentrations distribution maps show the followings:

- The percentage of the major constitute Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-} SO_4^{2-}, and Cl^{-} (Figure 4.42, from 4.42-II to 4.42-IX, respectively) resemble those of precipitation water in Jordan (SALAMEH, 2001) in the case of short residence time in the underground which is the case of springs in high mountain areas close to the recharge areas. But all ions show an increase in their concentration towards the west due to the longer underground passage and longer migration time (i.e. towards the Jordan Valley), where also high EC values are found. A three year weighted average of the major constitute of the precipitation water samples in two rainfall stations in the study area; es salt and Deir Alla stations are shown in Table 4.14.

Table 4.14: The major constitute of the precipitation water in es salt and Deir Alla stations (3 years weighted average sample each) (SALAMEH, 2001).

	Es Salt	Deir Alla
Variable	Weighted Average	Weighted Average
Quant. (mm)	10.21	9.6
Temp.(℃)	10.81	18.5
pH	7.607	7.49
EC (µS/cm)	98.67	159.8
Na^{+} (mmol/l)	0.32	0.37
K^{+} mmol/l	0.046	0.037
Mg^{2+} (mmol/l)	0.32	0.612
Ca^{2+} (mmol/l)	0.94	1.762
Cl^{-} (mmol/l)	0.422	0.471
NO_3^{-} (mmol/l)	0.057	0.08
SO_4^{2-} (mmol/l)	0.376	0.70
HCO_3^{-} (mmol/l)	0.318	0.71
Br^{-} (mg/l)	0.066	0.318

- All salinity parameters increase as follows:

- The calcite (Ca^{2+}) concentration ranges from less than 70 mg/l to more than 95 mg/l (Figure 4.42-II). The lowest concentration of the Ca^{2+} is 58.1 mg/l found in the eastern part of the study area, in Nuaymeh Municipal 1 (PP344) well, while the highest concentration of about 125 mg/l is reached in the northwest and west of the study area; in Wadi Al Arab No.1 well (AE1007) and in Abu Falah spring (AB0568), respectively. The Ca^{2+} concentrations reach 250.9 mg/l in the area northeast of Amman, near Zarqa city, in the Refinery well (AL1180), affected by pollution due to urbanization.

- The magnesium (Mg^{2+}) concentration ranges mainly from 9.5 mg/l to 42.9 mg/l in most of the study area. The lowest concentration found in Baqouriyyeh spring (AM0530) in Wadi Shueib area, while the highest is found in Mahmoud Al Nahlawi well (AD1173) in the extreme northeast of the study area. A rapid increase of Mg^{2+} concentrations toward the west to 194.4 mg/l is found in Abu Falah spring (AB0568) and towards the northeast of Amman to 228.5 mg/l in the Refinery well (AL1180) as a result of pollution and overexploitation. It reaches more than 270 mg/l towards Madaba city in the southeast of the study area (Figure 4.42-III), as a result of water rock interaction with dolomitic rocks.

- The sodium (Na^{+}) concentration increased from the east towards the northwest part. The increase range from 6.7 mg/l in Juhfiyeh No.1/Deir Yusuf well (AB1375) to 100.5 mg/l in Wadi Al Arab No. 4 (A AE1010). A rapid increase towards the west is recognized in Abu Falah spring (AB0568) where the Na^{+} concentration reaches 561.1 mg/l (Figure 4.42-V). Different from the B_2/A_7 Abu Falah spring shows increasing content of evaporites. We have to assume that there is a leakage from the Kurnub Aquifer via a fault system which discharges directly to this spring. Therefore, the water of Abu Falah springs seems to be a mixture of Kurnub and B_2/A_7 water (Figure 4.42-V).

  Also, an increase towards the northeast and southeast of Amman is found with Na^{+} concentration reaches more than 490 mg/l (Figure 4.42-V), as a result of pollution and overexploitation.

- The potassium (K^{+}) concentration ranges from 0.8 mg/l to 22.3 mg/l, in Kufur Yuba Exp. well (AE1001) and in Jadour Tahta spring (AM0504), respectively. A rapid increase towards Abu Falah spring (A AB0568) in the west, where the K^{+} concentration reach 37.5 mg/l (Figure 4.42-VI), as a result of dissolution of residual halides still present in the Upper Cretaceous rocks and halides in the recent sediments of the Jordan Valley deposits.

- The bicarbonate (HCO_3^{-}) concentration increases from 212.9 mg/l to 616.9 mg/l in most of the study area. The lowest HCO_3^{-} concentration found in the northeast part of the study area, in Mahmoud Al Nahlawi well (AD1173) while the highest found in the northwestern part in Wadi Al

Arab No.6 well (AE3001) (Figure 4.42-VII), as a result of aquifer confinement.

- The sulfate (SO_4^{2-}) concentration increases from 0.3 mg/l in Wadi Al Arab No. 2 (AE1008) northwest of the study area towards the west to 86 mg/l in Abu Falah spring (AB0568), as a result of dissolution of residual gypsum in the rocks. The SO_4^{2-} concentration increases also to 95.1 mg/l and to 103.7 mg/l in Jadour Fouqa spring (AM0506) along Wadi Shueib and in ASWA21 jesr Al Hammam well (AL1830) south of Amman, respectively (Figure 4.42-VIII), as a result of pollution.

- The chloride (Cl^-) concentration increase from the unconfined part of the aquifer to the confined part. The Cl^- concentration in the unconfined part is 21.3 mg/l in Juhfiyeh No.1/Deir Yusuf (AD1173) and it increases to 187.4 mg/l toward the east in Mahmoud Al Nahlawi well (AD1173) and to 947.5 mg/l toward the west in Abu Falah spring (AB0568) (Figure 4.42-IX), as a result of water rock interaction and halides dissolution.

- The Nitrate (NO_3^-) concentration in the NW of Jordan ranges widely. Low concentration of 6.7 mg/l found in the unconfined part of the B_2/A_7 Aquifer, in Juhfiyeh No.1/Deir Yusuf well (AD1173). The concentration increases in the confined part of the aquifer. It reaches 100.5 mg/l in the northwest of the study area, in Wadi Al Arab No.4 well (AE1010) and about 65.3 mg/l in the eastern part in Mahmoud Al Nahlawi well as a result of pollution from cesspools and waste water inflows. The NO_3^- concentration increased rapidly to 561.1 mg/l in Abu Falah spring (AB0568) in the western part of the study area affected by irrigation return flows and waste water inflows (Figure 4.42-X).

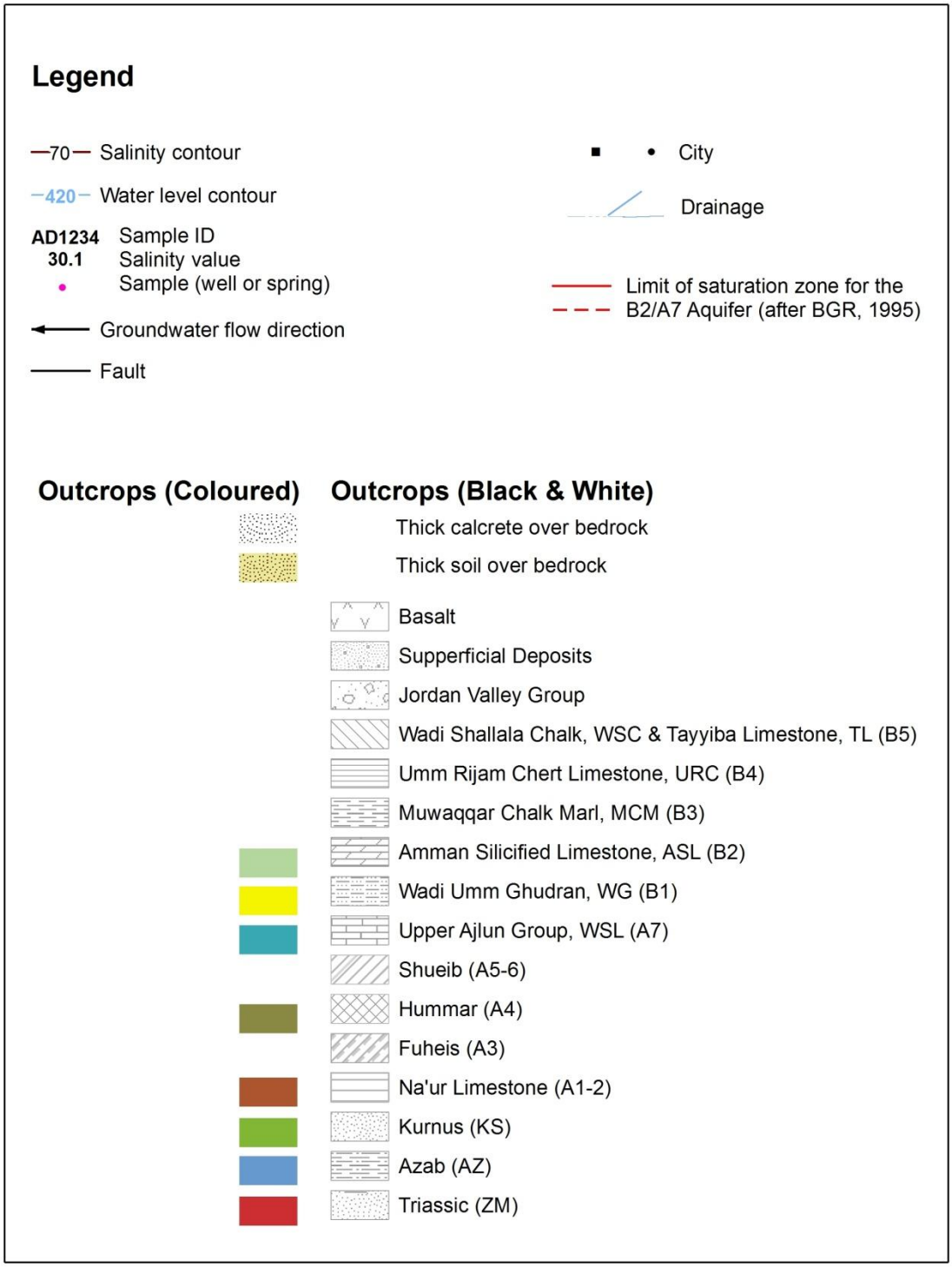

Figure 4.41: Legend for Figures 4.42, 4.43, 4.44 & 4.45.

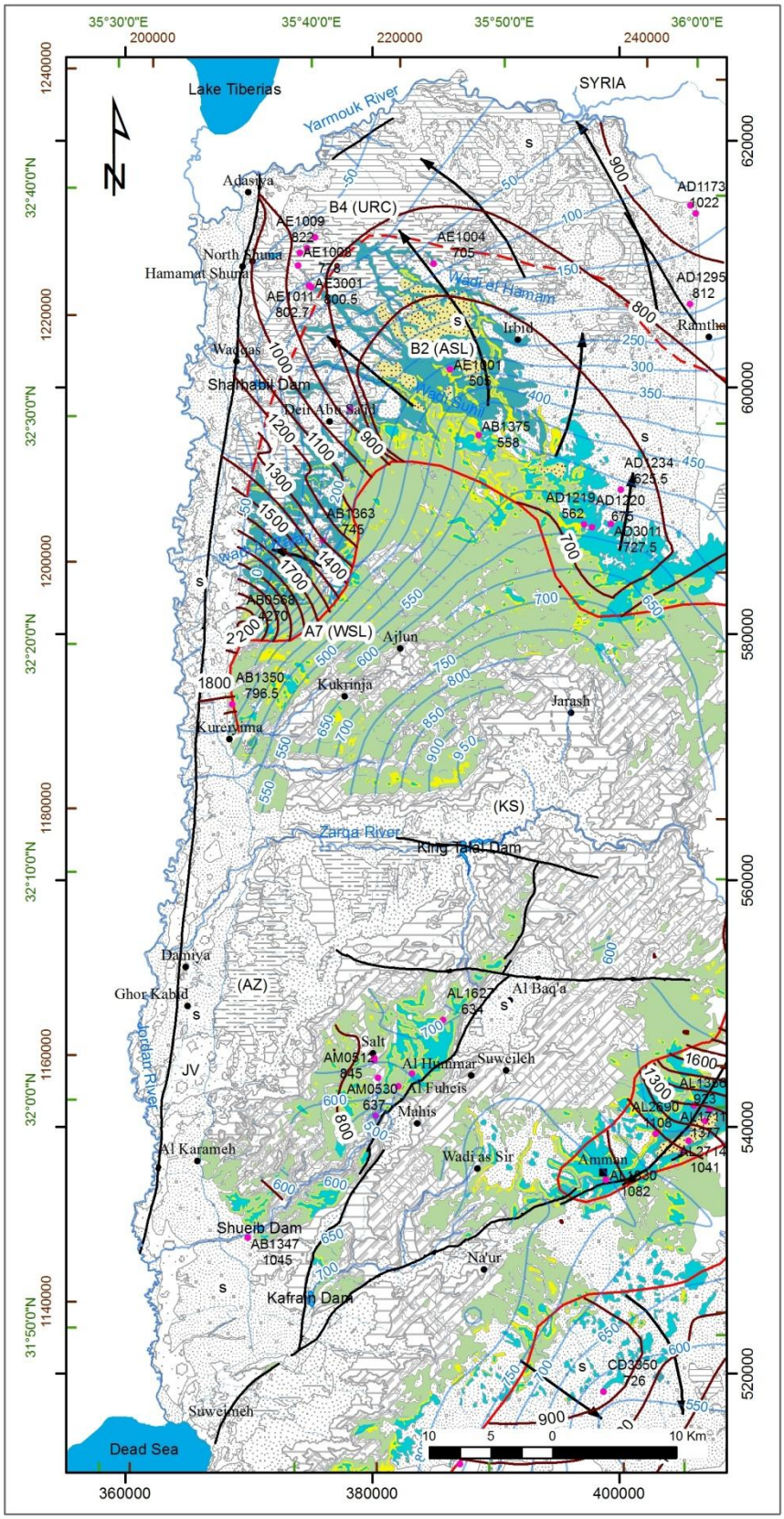

Figure 4.42-I: The spatial distribution of Electrical conductivity (EC in µS/cm) values for the B_2/A_7 Aquifer System in NW of Jordan (for legend see Figure 4.41).

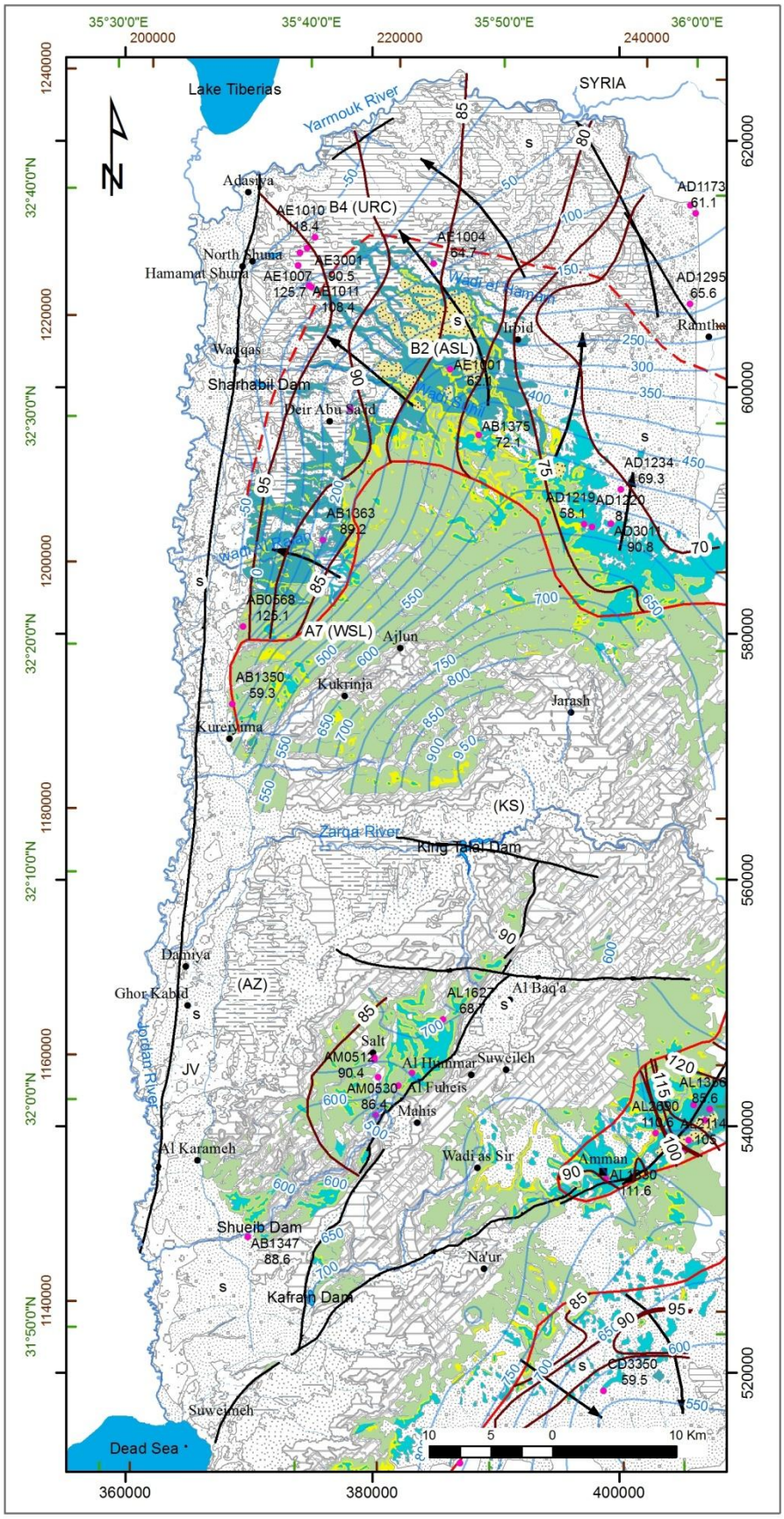

Figure 4.42-II: The spatial distribution of Calcium (Ca^{2+} in mg/l) concentrations for the B_2/A_7 Aquifer System in NW of Jordan (for legend see Figure 4.41).

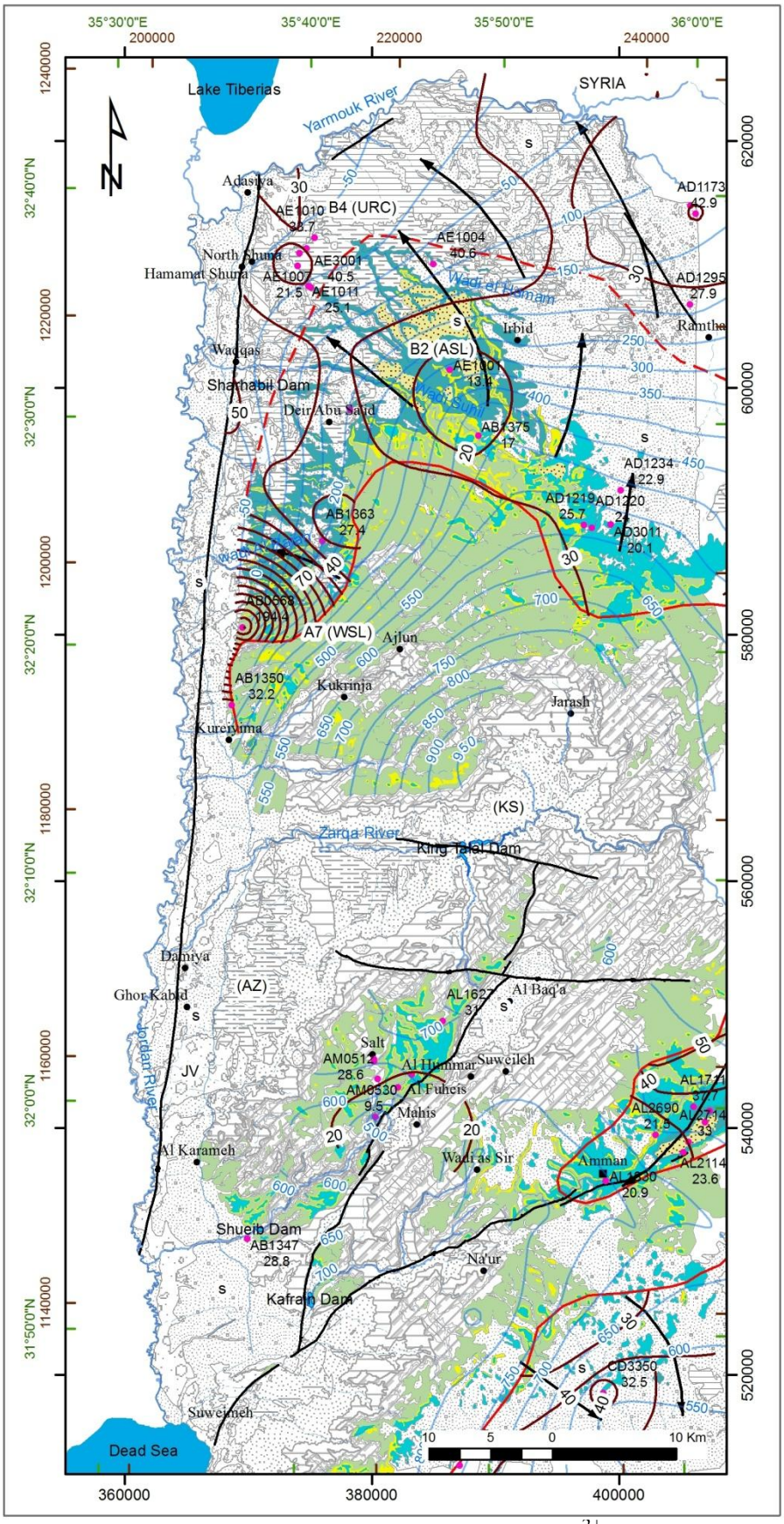

Figure 4.42-III: The spatial distribution of Magnesium (Mg^{2+} in mg/l) concentrations for the B_2/A_7 Aquifer System in NW of Jordan (for legend see Figure 4.41).

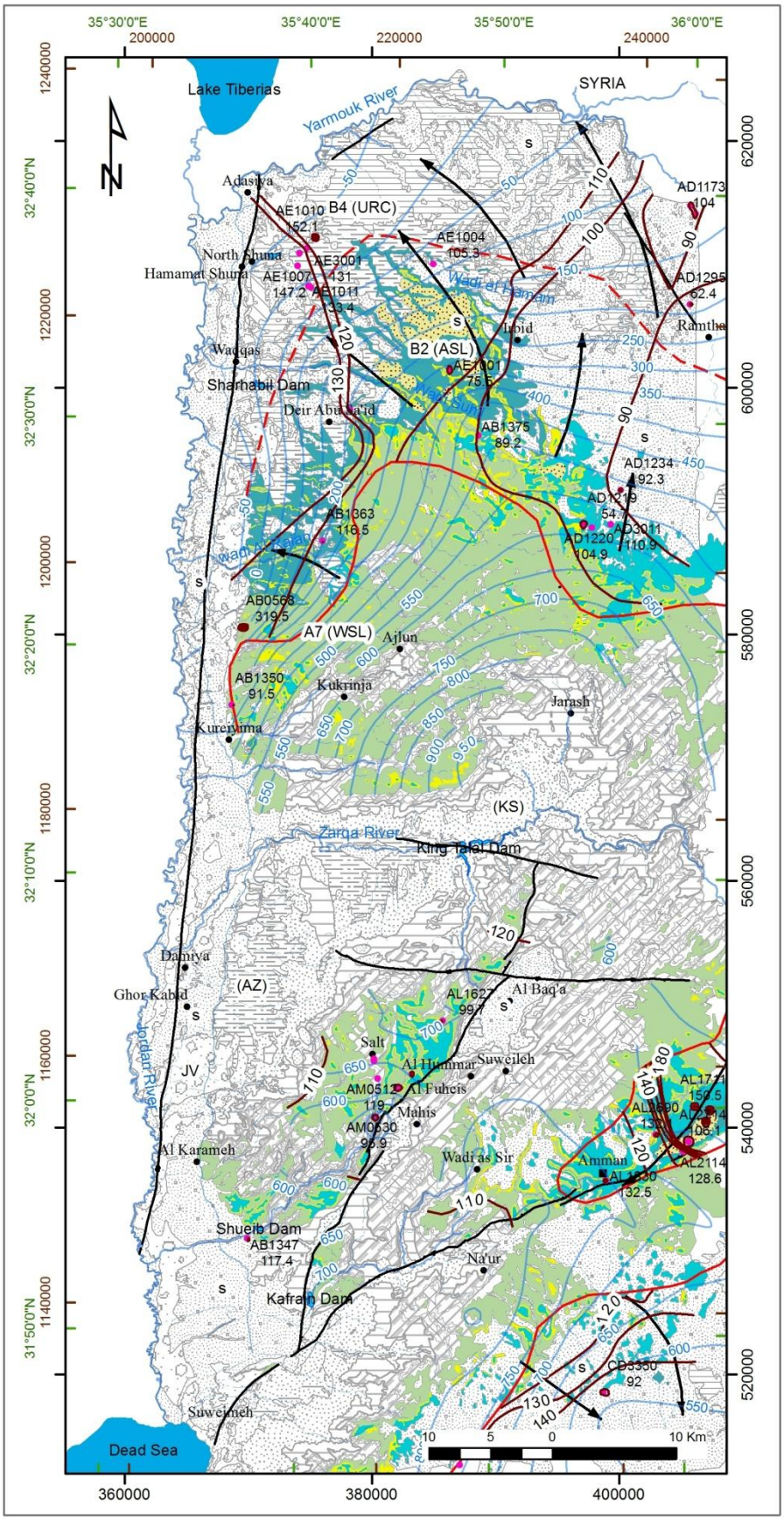

Figure 4.42-IV: The spatial distribution of the total of Calcium and Magnesium (Ca^{2+}+Mg^{2+} in mg/l) concentrations for the B_2/A_7 Aquifer System in NW of Jordan (for legend see Figure 4.41).

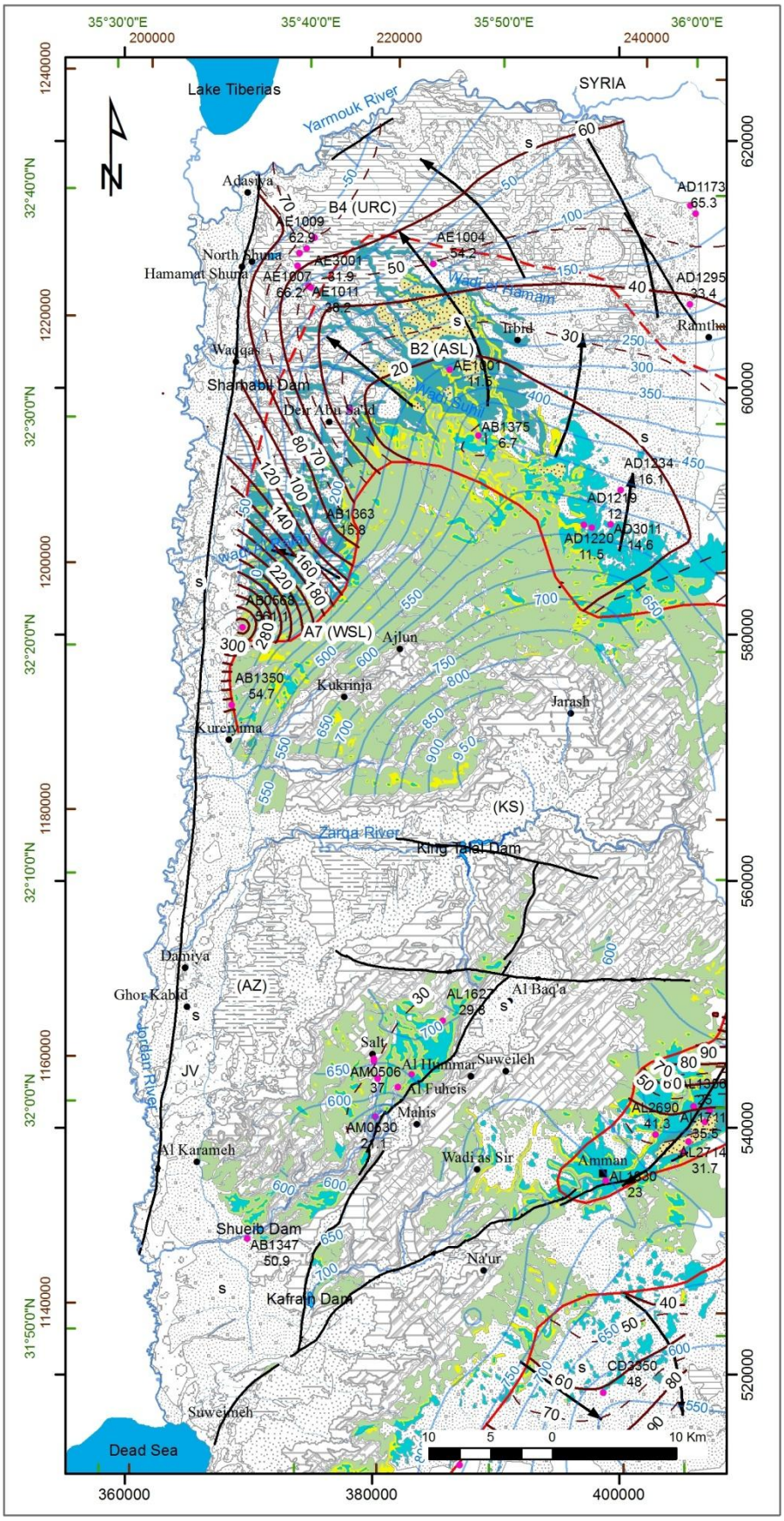

Figure 4.42-V: The spatial distribution of Sodium (Na^+ in mg/l) concentrations for the B_2/A_7 Aquifer System in NW of Jordan (for legend see Figure 4.41).

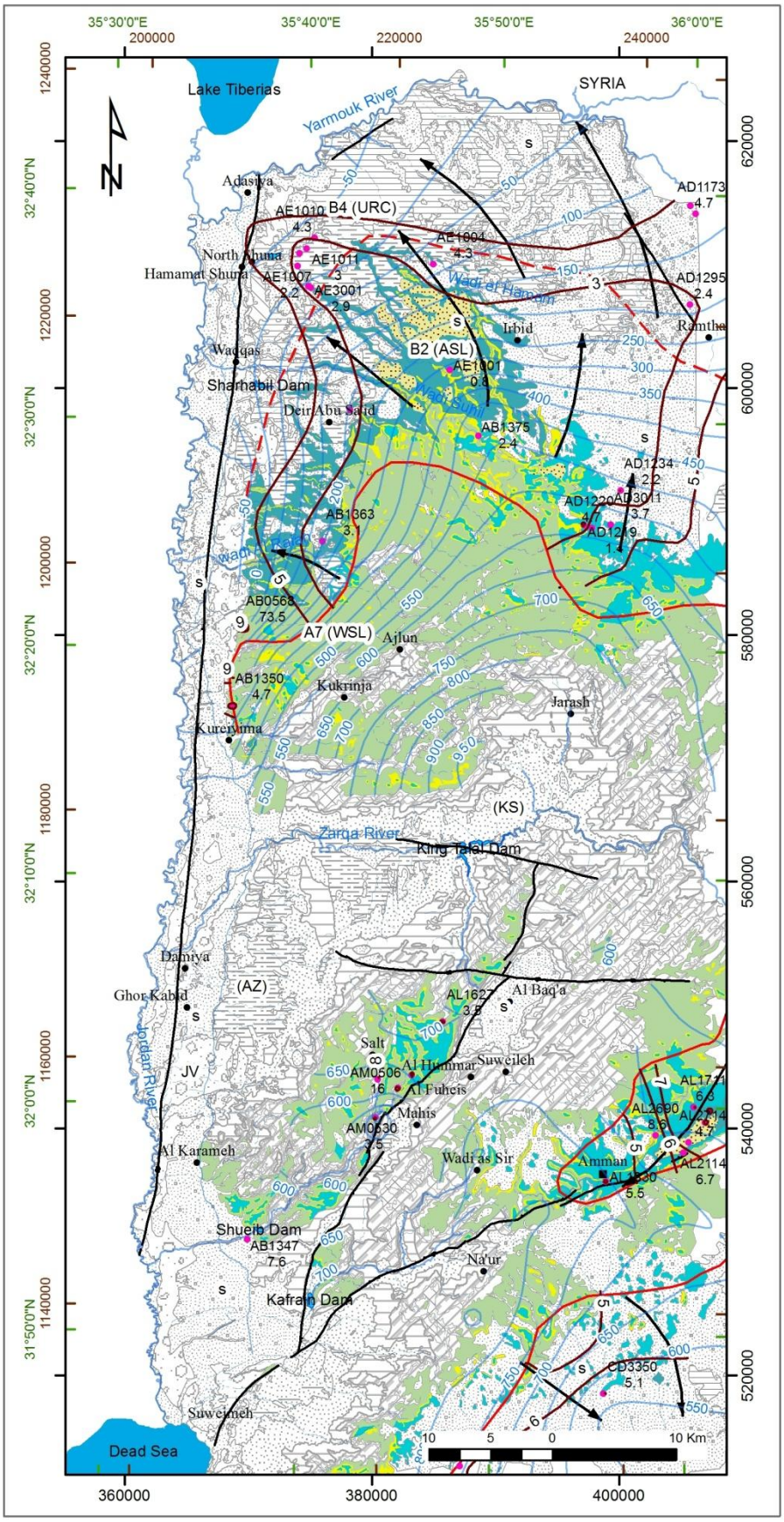

Figure 4.42-VI: The spatial distribution of Potassium (K^+ in mg/l) concentrations for the B_2/A_7 Aquifer System in NW of Jordan (for legend see Figure 4.41).

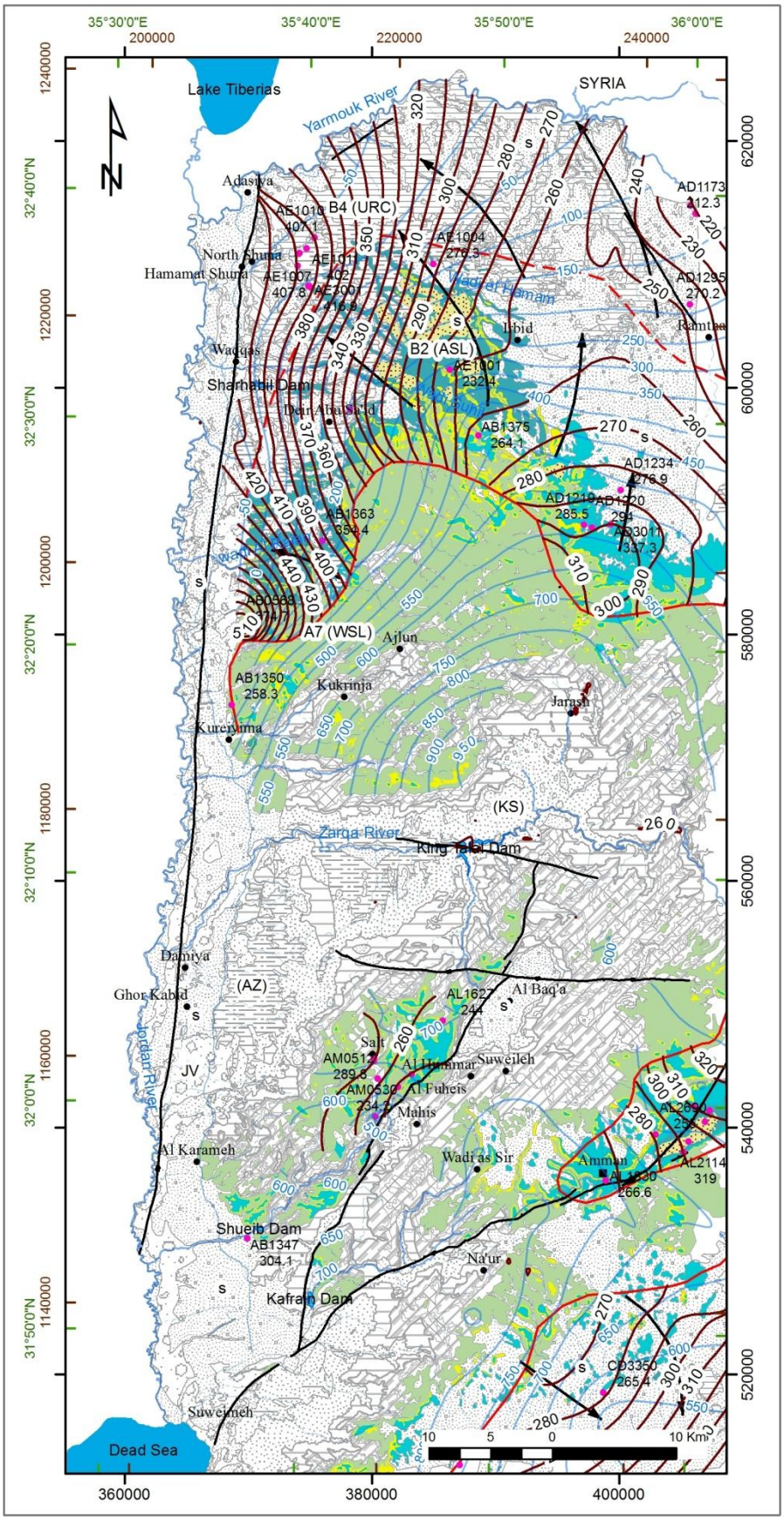

Figure 4.42-VII: The spatial distribution of Bicarbonate (HCO_3^- in mg/l) concentrations for the B_2/A_7 Aquifer System in NW of Jordan (for legend see Figure 4.41).

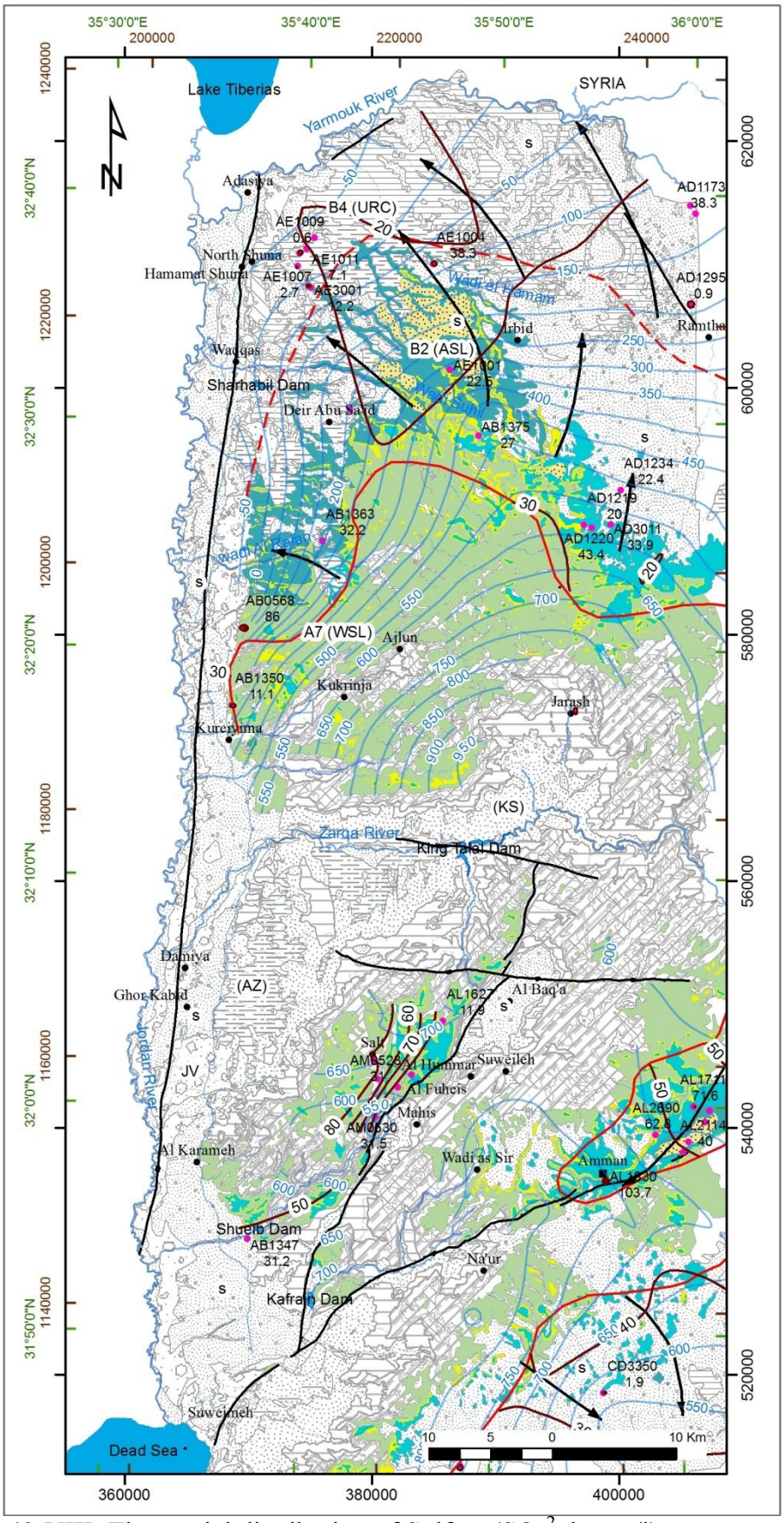

Figure 4.42-VIII: The spatial distribution of Sulfate (SO_4^{2-} in mg/l) concentrations for the B_2/A_7 Aquifer System in NW of Jordan (for legend see Figure 4.41).

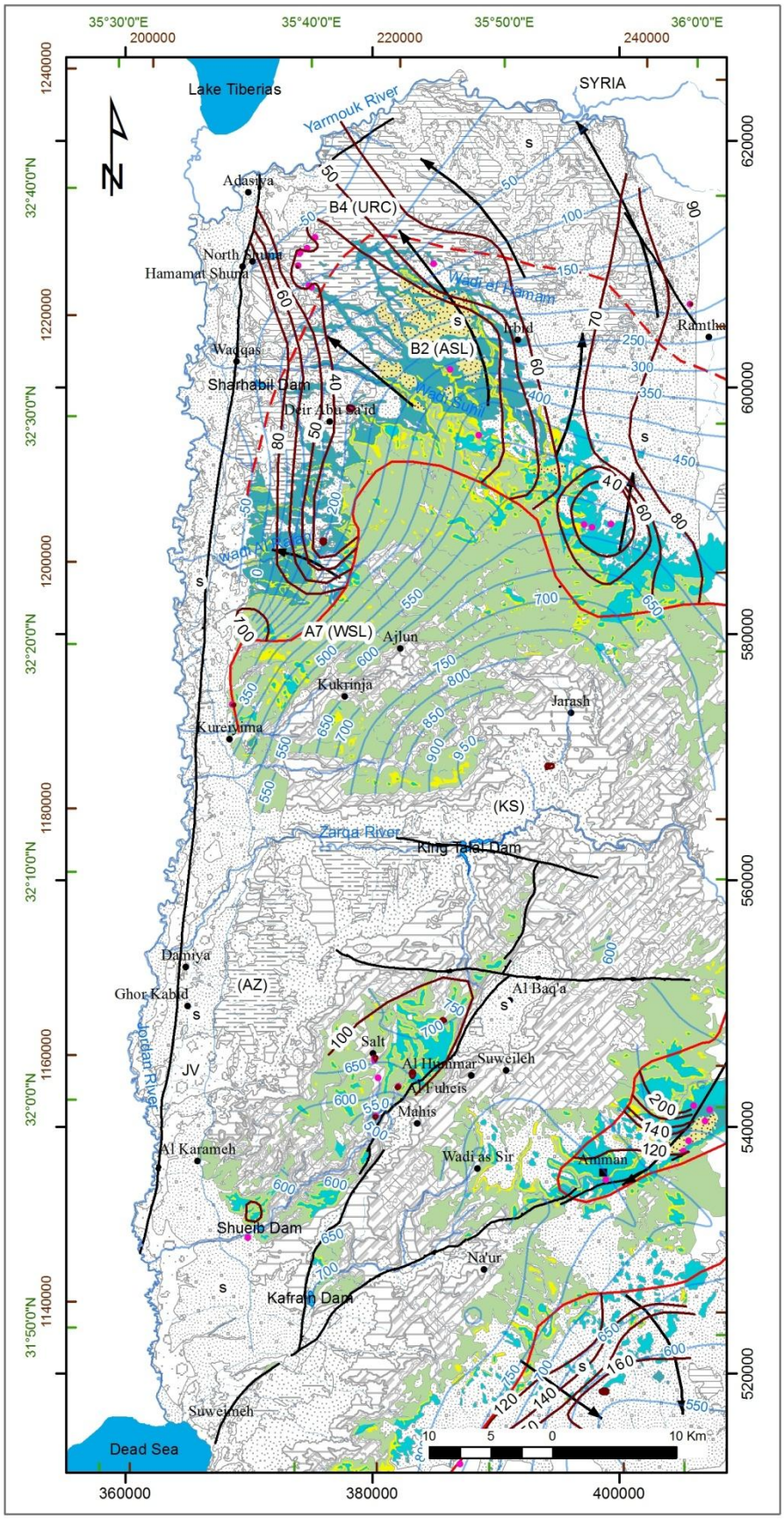

Figure 4.42-IX: The spatial distribution of Chloride (Cl^- in mg/l) concentrations for the B_2/A_7 Aquifer System in NW of Jordan (for legend see Figure 4.41).

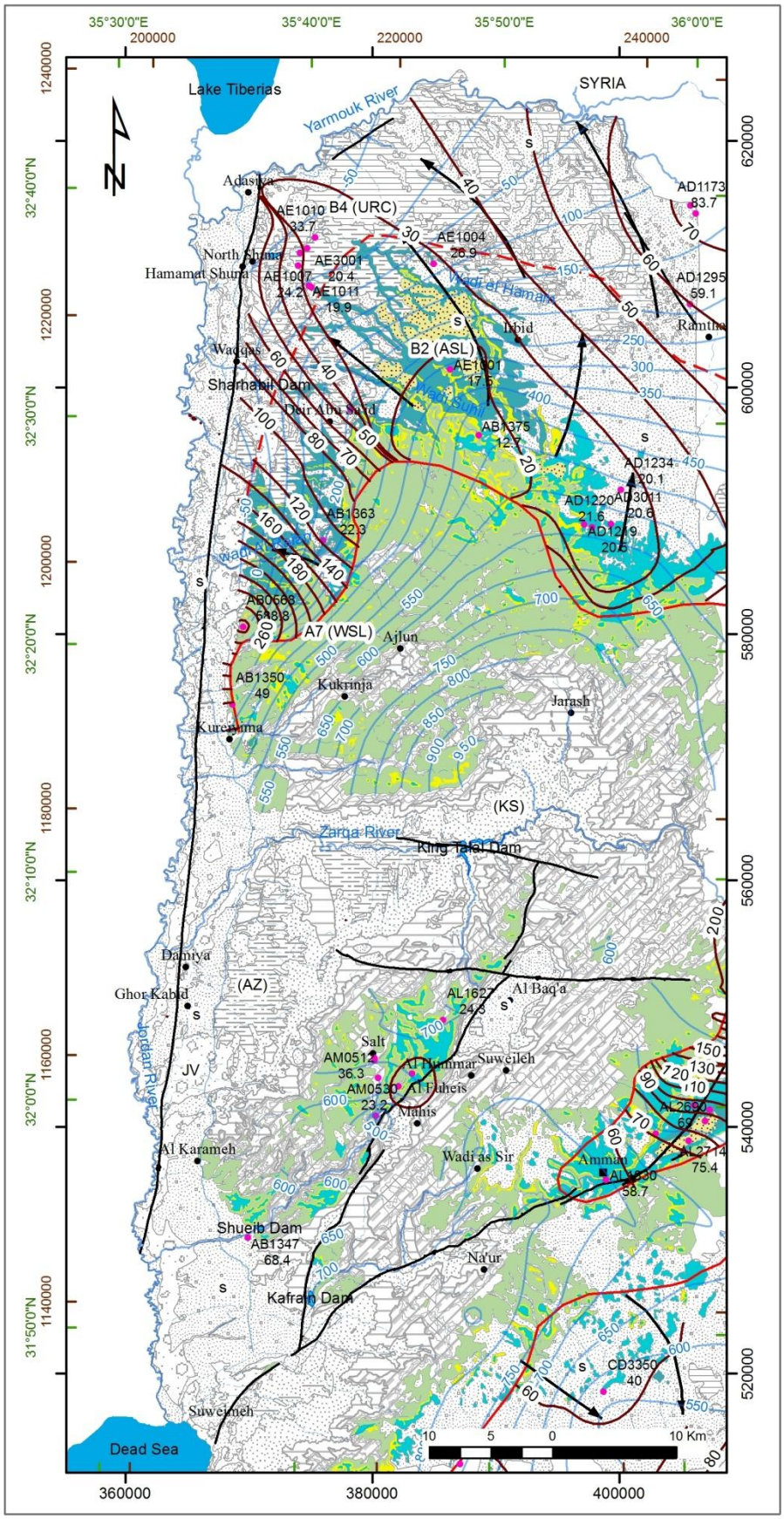

Figure 4.42-X: The spatial distribution of Nitrate (NO_3^- in mg/l) concentrations for the B_2/A_7 Aquifer System in NW of Jordan (for legend see Figure 4.41).

4.4.1.2 Characterization of water chemistry in the Middle Aquifer System, Lower Ajlun Group (A_{1-6})

In the northwest of Jordan, the **Lower Ajlun Group** represents the lower part of the Upper Cretaceous sequence. The Geological Map (Plate 4) shows the distribution and the main exposures of the Lower Ajlun Group (A_{1-6}) which reaches its widest surface distribution on the slopes of the Zarqa River valley. From there to the south, the Lower Ajlun Group outcrops are common on the slopes of the escarpment and the side wadis. The geological cross sections AA′, BB′, CC′, DD′ and HH′ (Plate 5) show that the Lower Ajlun Group has a combined outcrop thickness of 300 – 400 m (POWELL, 1989b). In the study area, the two Formations: Na'ur (NL or A_{1-2}) and Hummar (H or A_4) are the most important hydrogeological formations within this group and are considered as minor or semi aquifers while the Fuheis (F or A_3) and Shueib (Sh or A_{5-6}) are considered as aquitards.

At outcrops in the study area, the Na'ur Limestone Formation (A_{1-2}) ranges in thickness from 20 to 50 m, while the thickness of the Hummar Formation (A_4) ranges from 40 to 65 m (chapter 2 for more detailed). The Na'ur Limestone Aquifer/Aquitard (A_{1-2}) comprises a sequence of alternating limestone and marl beds overlain by yellowish – grey, soft to medium-hard marl, interbedded with thin layers of marly limestone in its middle part. The top of the Formation is marked by dolomitic limestone with chert nodules. But the Hummar Aquifer (A_4) consists of pure semi-crystalline karstic dolomite and limestone (section 4.3.1.2).

The digital elevation model DEM (Plate 3) indicates that the outcrop areas of the A_{1-2} and A_4 are relatively elevated. But due to their limited exposure they receives small amount of direct recharge in the study area. Although the thicknesses of the A_{1-2} and the overlying A_4 are comparably low, they form aquifers of local importance in areas where B_2/A_7 aquifer is missing (section 4.3.1.2).

4.4.1.2.1 Electrical conductivity (EC) in the Hummar (A_4) Aquifer and the Na'ur (A_{1-2}) Aquifer/Aquitard of the Lower Ajlun Group

The spatial distribution of the EC values for the Hummar (A_4) and the Na'ur (A_{1-2}) Aquifers are shown in Figures 4.43 & 4.44, respectively. Both figures show low EC values in areas where the Na'ur and the Hummar crop out and receives direct recharge from precipitation water. Generally, the EC values of Na'ur (A_{1-2}) and Hummar (A_4) Aquifers are less than 1000 µS/cm. According to SALAMEN & HAMMOURI (2007) the EC value of the **Lower Ajlun Group (A_{1-6})** is depending on the percolated geological units of the sequence and the pathways the water takes.

In the Hummar (A_4) Aquifer low EC values are found around the elevated outcrop areas, such as Ajlun, Amman and Suweileh. The lowest EC value is 540 µS/cm found northeast of Amman in AWSA Seil el Rusaifa No. 3 well (AL1548) and it increases towards Wadi Kafrein and Wadi Shueib in the southwest to 1000 µS/cm in al Bahaiya el Fouqa spring (AN0578) in wadi Jrea'a NO.3 well (AM1027), respectively. Also, the EC values increase towards the west to 1200 µS/cm in Kurayma No.1 well (AB1380) shown in Figure 4.43. The increase in salinity is a result of water rock

interactions, but also it is a result of pollution in this karstified aquifer exposed to inflows of water and irrigation return flows.

An increase of EC value towards the northeast of Amman is recognized in Figure 4.43. The circular distribution pattern of the EC vales towards the east of the study area (Figure 4.43) is artificially influenced by the interpolation method, where there is no EC values outside the study area was used (the data was not available from WAJ files used in this study). But generally this increase in EC values is attributed to over-exploitation of groundwater both for domestic and irrigation purposes and due to the lowering of the water table in Amman – Zarqa Basin (section 4.3.3).

In the Na'ur (A_{1-2}) Aquifer/Aquitard the lowest EC value is 576 µS/cm found in the northeast part of the study area in Ayyoub S. Haddad 1 well (AL1598). It increases towards the west to 1277 µS/cm in Wadi Rajib No.1 (AL1013). Also, the EC increased towards Wadi Kafrein in the northwestern part of the study area, where it reaches about 1302 µS/cm in Almaniyah spring Figure 4.44. The salinity increase is generally a result of water rock interaction within this poorly developed aquifer.

An Increase of EC towards the southwest to 2280 µS/cm in Mursi spring (AL 0158) is shown in Figure 4.44 where rocks of Kurnub and Jurassic crop out close to the spring location and where some major E-W trending faults (Zarqa River fault and Al Baqa' - Er Rmamin fault) extends. In addition to that the groundwater flow pattern (as shown by the arrows in Figure 4.44 or in detailed in Figure 4.25) indicated that the groundwater movement in the A_{1-2} Aquifer is directed towards the Mursi spring. In addition to the water in the Mursi spring represents mixing water of A_{1-2} Aquifer and the deeper Sandstone Aquifer via faults found where the spring located (see section 4.4.2.1.2 for more detail).

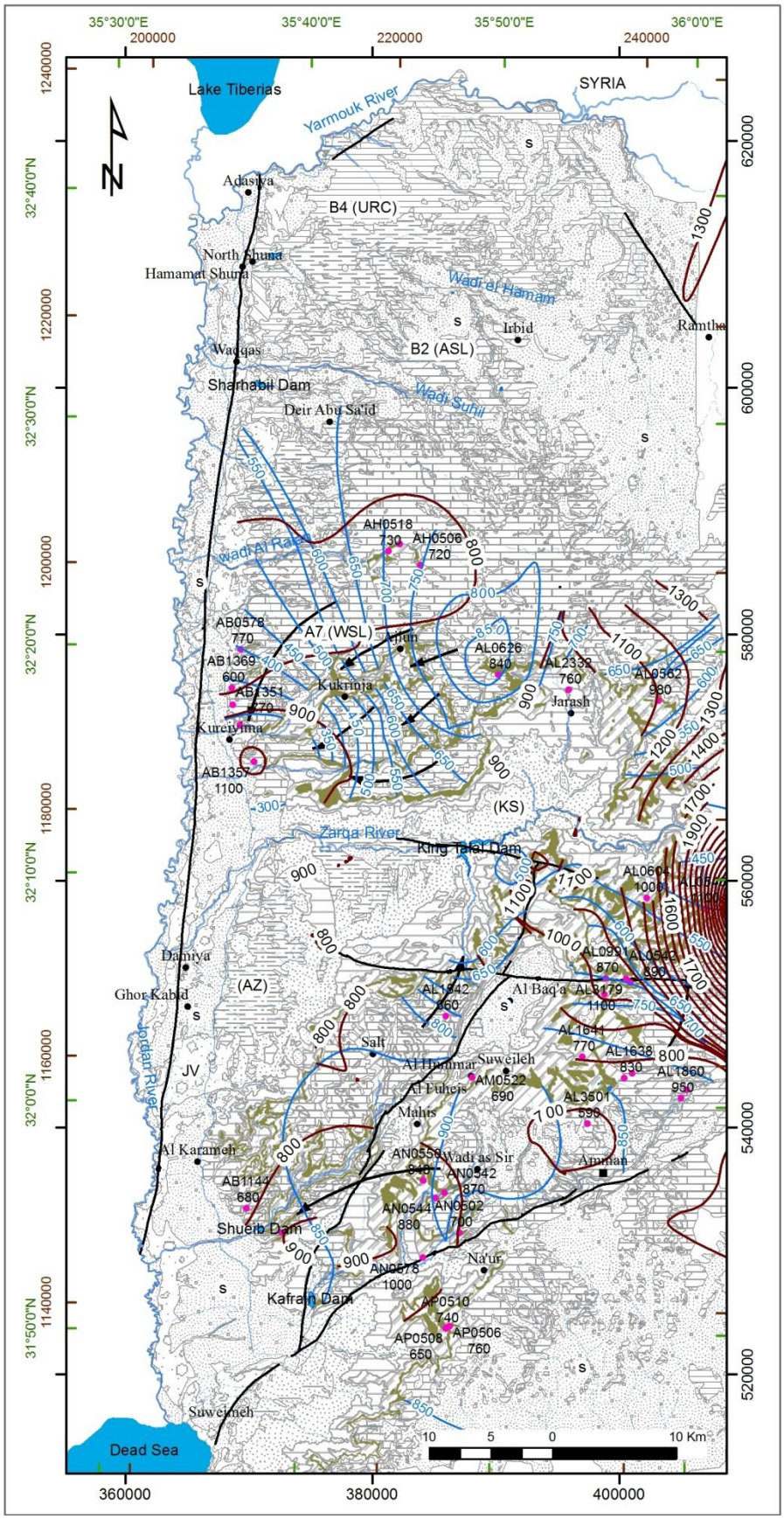

Figure 4.43: The spatial distribution of Electrical conductivity (EC in µS/cm) values for the Hummar Aquifer System (A_4) in NW of Jordan.

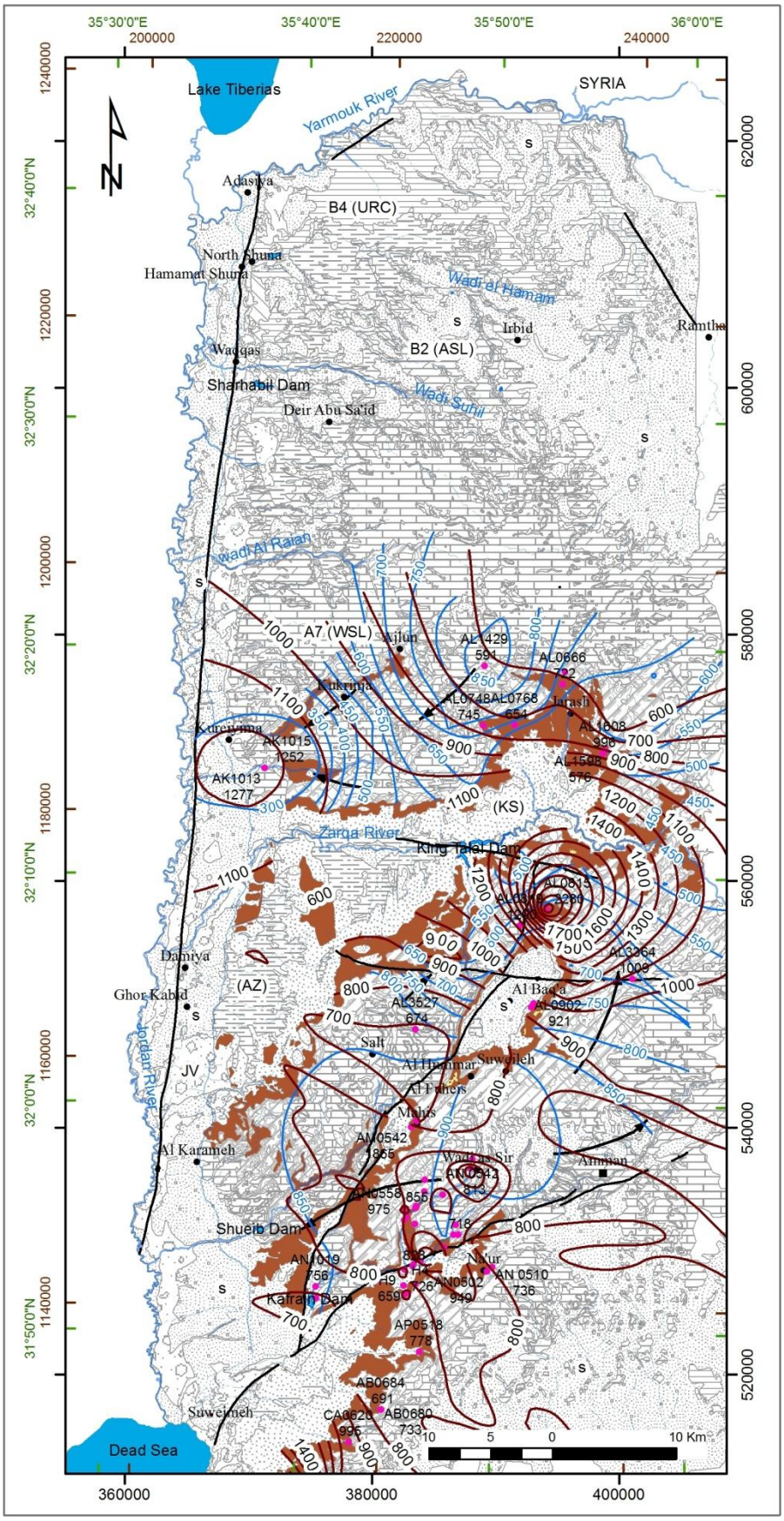

Figure 4.44: The spatial distribution of Electrical conductivity (EC in µS/cm) values for the Na'ur Aquifer System (A_{1-2}) in NW of Jordan.

4.4.1.3 Characterization of water chemistry in the Lower Aquifer System (Deep Sandstone Aquifer)

The Deep Aquifer System is a sandstone aquifer (of Nubian facies) originated as an erosional product of granitic rocks (BENDER, 1968b). It is composed in the study area of two aquifer systems: Zarqa Aquifer (Ramtha and Azab Groups of Triassic and Jurassic ages, respectively) and Kurnub Sandstone Aquifer (Kurnub Sandstone Group of Lower Cretaceous age) (as described previously in section 4.3.1.1.1). The groundwater found within this aquifer area is both confined in places and unconfined in the outcropping parts.

In the NW part of Jordan, the Lower Cretaceous rocks consists mainly of sandstones, but in small parts within the study area the sequence is made of carbonate rocks while, the intercalation of the Jurassic and Triassic rocks according to (BANDEL & KHOURY, 1981) are mainly composed of sandstones, siltstones, shales, and sandy limestone with residues of evaporites composed mainly of Gypsum. These sequences are shown in the geological cross sections (Plate 5, BB', CC' & HH'), with thicknesses of up to 1000 m in the highlands (BANDEL & KHOURY, 1981) (chapters 2 & 3).

The geological map (Plate 4) shows that the outcrop areas of the Zarqa and Kurnub Groups are limited. They are found in the surroundings of Al Baqa'a area; in the deeply eroded cores of Al Baqa'a anticline, Wadi Shueib, Wadi Na'ur, Wadi as Sir, Wadi Hisban and along the lower reaches of Zarqa River and its tributaries. The last outcrop represents the major outcrop of this aquifer. In addition to that, the Digital Elevation Model (DEM) of the study area (Plate 3) shows that the Kurnub Sandstone Group outcrop areas are located at higher altitude relative to the Jurassic and Triassic rocks outcrop areas. Therefore, the Kurnub Sandstone Group outcrop areas are characterized by high mean annual rainfall averages (around 300 mm/yr), and low mean potential evaporation average of around 1900 mm/yr, compared with the Jurassic and Triassic rocks outcrop areas which are characterized by low mean annual rainfall averages (ranges from 250 to <200 mm/yr), and high mean potential evaporation average exceeding 2000 mm/yr (Figures 4.9 & 4.14, respectively). Accordingly, direct recharge to the Deep Aquifer by infiltration of precipitation water is very limited.

4.4.1.3.1 Electrical conductivity (EC) in the Deep Sandstone Aquifer

The spatial distribution of the EC values for the Deep Sandstone Aquifer System in the study area (Figure 4.45-I) shows low salinity in the unconfined parts (i.e. outcrop areas), contrary to that in the confined parts of the aquifer. In the outcrop areas, the EC values range from 582 µS/cm (AL3662 well) along Zarqa River outcrop to 1286 µS/cm (AL1894 well) in Al Baqa'a area. In the confined parts of the aquifer, the EC values increased very fast from around 3000 µS/cm to more than 8500 µS/cm. The EC values increased westwards, to 8550 µS/cm (JICA- well) and southwestwards where the EC reaches almost 8680 µS/cm (JICA 6). In addition, an increase in EC values east wards of the study area is also shown in Figure 4.45-I, but with lower EC values compared to that in the west. Spring water discharges from this aquifer receiving direct recharge from precipitation water show also low EC values within the study area. Figure 4.45-I shows that the low EC value of 142 µS/cm can be found in

El Bald-Sahen/Sumuya spring (AL 0942) along the Zarqa River and the maximum EC value of 24400 µS/cm can be found in Al Beida spring (CA0646) in the area northeast of the Dead Sea. While other springs have high EC value, due to the fact that the groundwater within this aquifer seeps upwards through the recent sediments of the Jordan Valley to the surface, forming saline springs such as Wadi Mallaha spring (as mentioned previously in section 4.3.4) with salinity of ca. 15000 µS/cm up to 18000 µS/cm (SALAMEH, 1996).

The groundwater analyses for the Lower Sandstone Aquifer, obtained from WAJ data base, show that the total dissolved solids (TDS) in the study area range between 397.7 mg/l (AL3662 well) to 15280.1 mg/l (CA0646, Al Beida spring). The study of NASHER (2007) for a part of the Jordan Valley found that the TDS has a value of 5700 mg/l to the west of the intercatchment between Wadi Shueib and Zarqa River. According to the classification of FREEZE & CHERRY (1979) groundwater in the Deep Sandstone Aquifer falls within fresh to brackish water types (Table 4.12).

4.4.1.3.2 Major cations and anions in the Deep Sandstone Aquifer

The major constituents are the main parameters contributing to salinity in the Deep Sandstone Aquifer System. Figure 4.45 from II to X shows the concentration distribution of the major cations and anions in the study area, with the followings characteristics:

- All cations (Ca^{2+}, Mg^{2+}, Ca^{2+}+Mg^{2+}, Na^{+} and K^{+}) (Figure 4.45- II, III, IV, V and VI, respectively) show the same trend of increasing concentrations towards the west and southwest and slightly towards the east. Especially towards the SW we have to assume that high mineralized water even with higher temperature are ascending from the Deeper Sandstone Aquifers (Triassic – Paleozoic) they are mixing with water in the Kurnub Sandstone and are the sources of the high increasing mineralization of the water.

    - The Calcite (Ca^{2+}) concentrations range from 609.2 mg/l in (AL1541) Al Baqa'a 9 (W.S.C) well to 744.49 mg/l in JICA 1 well west of Zarqa River and to 931.06 mg/l in (CA0646) Wadi Al Abiad spring in the northeast corner of the Dead Sea (Figure 4.45-II).

    - The Magnesium (Mg^{2+}) concentrations range from 7.6 mg/l to 884.28 mg/l. The low values can be found along the Zarqa River (in Hammd spring) and the high value can be found in the northeast corner of the Dead Sea (in Wadi Al Abiad spring; CA0646) (Figure 4.45-III).

    - The total of Calcite and Magnesium (Ca^{2+}+Mg^{2+}) concentrations range from 77.95 mg/l in (AL3662) Al Baqa'a 9 (W.S.C) well to 870.9 mg/l in JICA 1 well west of Zarqa River and to 1815.34 mg/l in (CA0646) Wadi Al Abiad spring in the northeast corner of the Dead Sea (Figure 4.45-IV).

    - The Sodium (Na^{+}) concentrations range from 14.95 mg/l in Bassa spring in Al Baqa'a area to 1182.2 mg/l in JICA 1 well west of Zarqa River and to

1815.34 mg/l in (CA0646) Wadi Al Abiad spring in the northeast corner of the Dead Sea (Figure 4.45-V).

- The Potassium (K^+) concentrations range from 0.39 mg/l in (AL0986) Hafayer spring along Zarqa River to 164.22 mg/l in JICA 1 well west of Zarqa River and to 175.95 mg/l in JICA 6 well in the northeast corner of the Dead Sea (Figure 4.45-VI).

- A rapid increase in the concentrations of the salinity parameters of Cl^-, HCO_3^- and SO_4^{2-} toward the west, along Zarqa River and toward the southwest, northeast of the Dead Sea (Figures 4.45-VI, 4.45-VIII and 4.45-IX, respectively) is found. Their concentrations reach a maximum of 8875 mg/l for Cl^-, 1651.2 mg/l for SO_4^{2-} and 1264.33 mg/l for HCO_3^-. Whereas the NO_3^- concentrations, does not show any certain pattern of change (Figure 4.45-X).

  - The bicarbonate (HCO_3^-) concentrations range from 210.45 mg/l in (AL3662) well in Al Baqa'a area to 1264.33 mg/l in JICA 6 well in the northeast corner of the Dead Sea and to 1047.1 mg/l in JICA 1 well west of Zarqa River (Figure 4.45-VII).

  - The Sulfate (SO_4^{2-}) concentrations range from 16.56 mg/l in Burma spring along Zarqa River to 536.16 mg/l in JICA 6 well in the northeast corner of the Dead Sea and to 1651.2 mg/l in JICA 1 well west of Zarqa River (Figure 4.45-VIII).

  - The Chloride (Cl^-) concentrations range from 24.28 mg/l in Hammad spring along Zarqa River to 1772.5 mg/l in JICA 1 well west of Zarqa River and to 8875 mg/l in (CA0646) Wadi Al Abiad spring in the northeast corner of the Dead Sea and (Figure 4.45-IX).

  - The highest concentrations of Nitrate (NO_3^-) are found in the areas: northeast of the Dead Sea, Al Baqa'a area, along Zarqa River and west of the Zarqa River. The lowest concentrations is 0.16 mg/l in (AL1432) Baqa'a 5 (W.S.C) well and the highest range from 79.28 mg/l in (CA0646) Wadi Al Abiad spring in the southwest to 131.13 mg/l in (AL0982) Subeihi spring along Zarqa River and to 540.64 mg/l in JICA 1 well west of Zarqa River (Figure 4.45-X).

    The high NO_3^- content in JICA 1 well west of Zarqa River is caused by local pollution due to agricultural activity and urbanization. Therefore, the schematic interpolation gives wrong impression of the NO_3^- concentration (Figure 4.45-X).

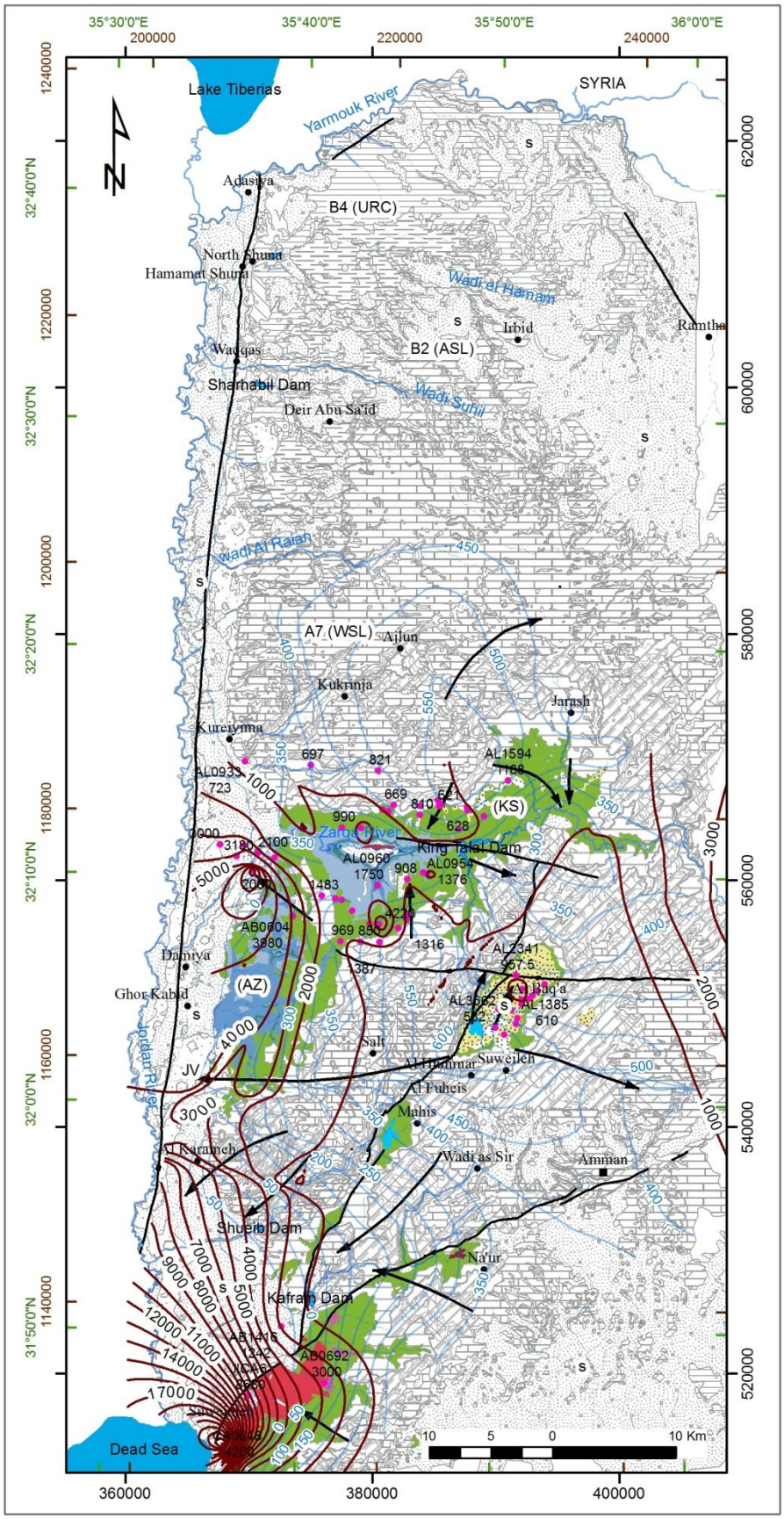

Figure 4.45-I: The spatial distribution of Electrical conductivity (EC in µS/cm) values for the Deep Sandstone Aquifer System in NW of Jordan (for legend see Figure 4.41).

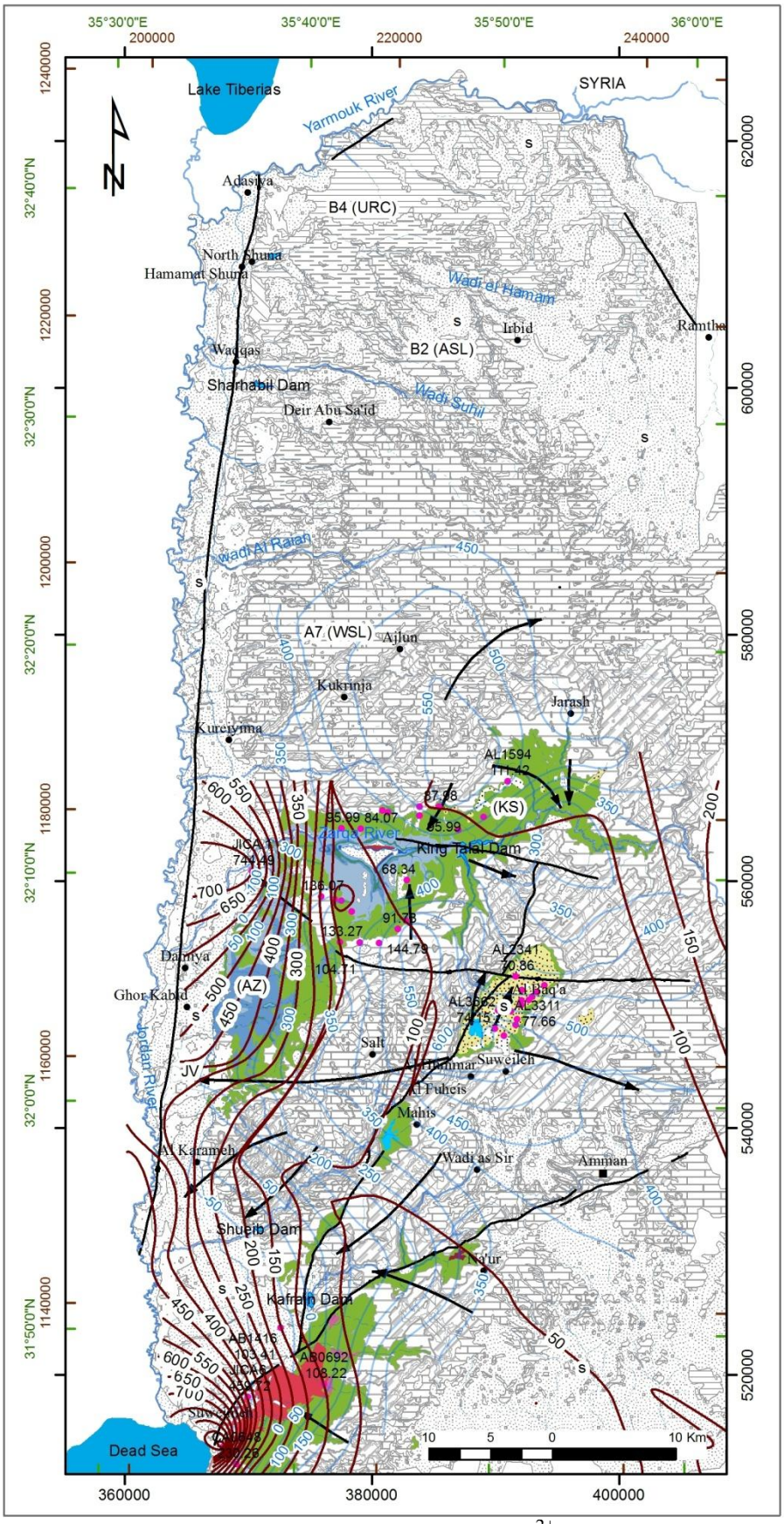

Figure 4.45-II: The spatial distribution of Calcium (Ca^{2+} in mg/l) concentrations for the Deep Sandstone Aquifer System in NW of Jordan (for legend see Figure 4.41).

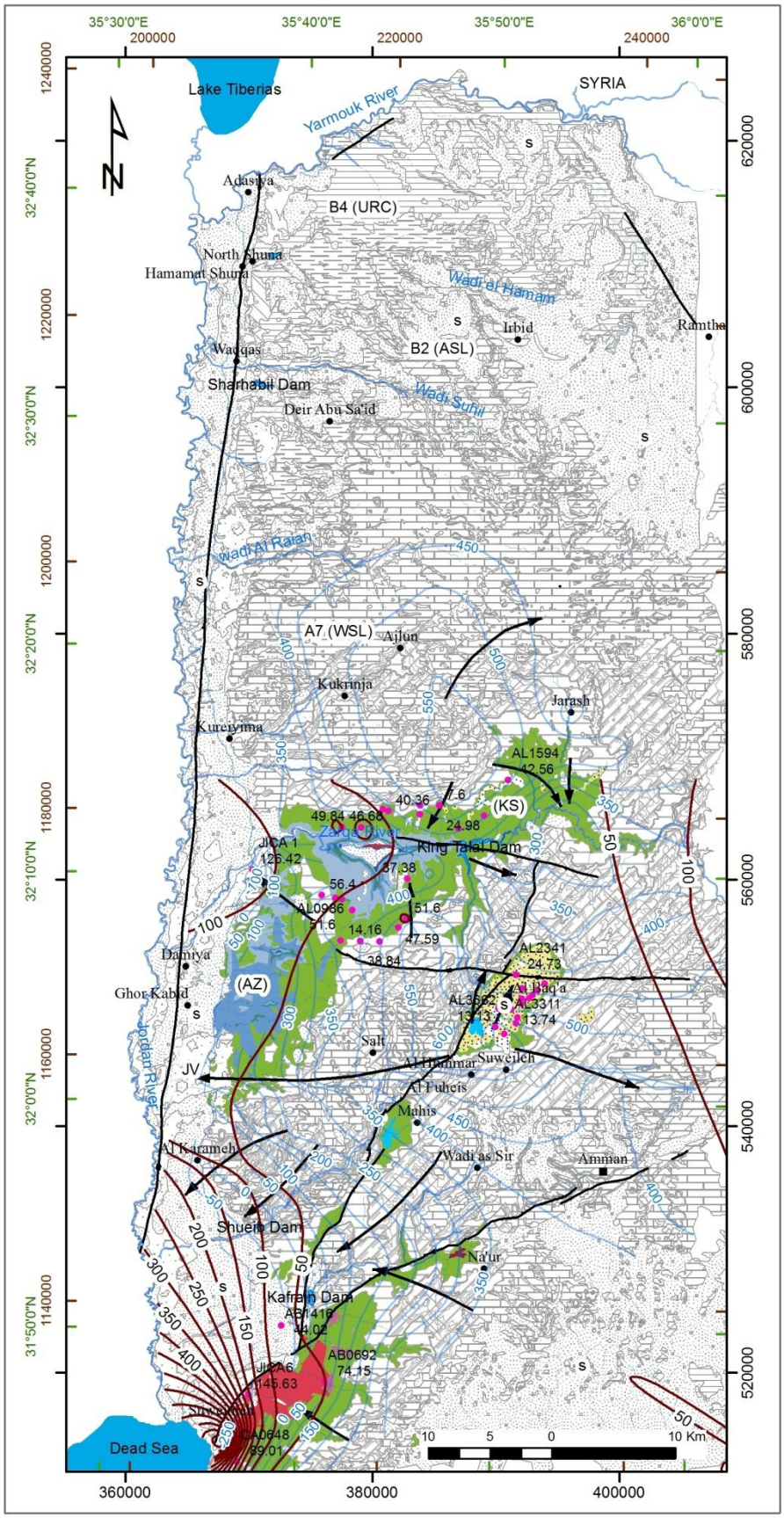

Figure 4.45-III: The spatial distribution of Magnesium (Mg^{2+} in mg/l) concentrations for the Deep Sandstone Aquifer System in NW of Jordan (for legend see Figure 4.41).

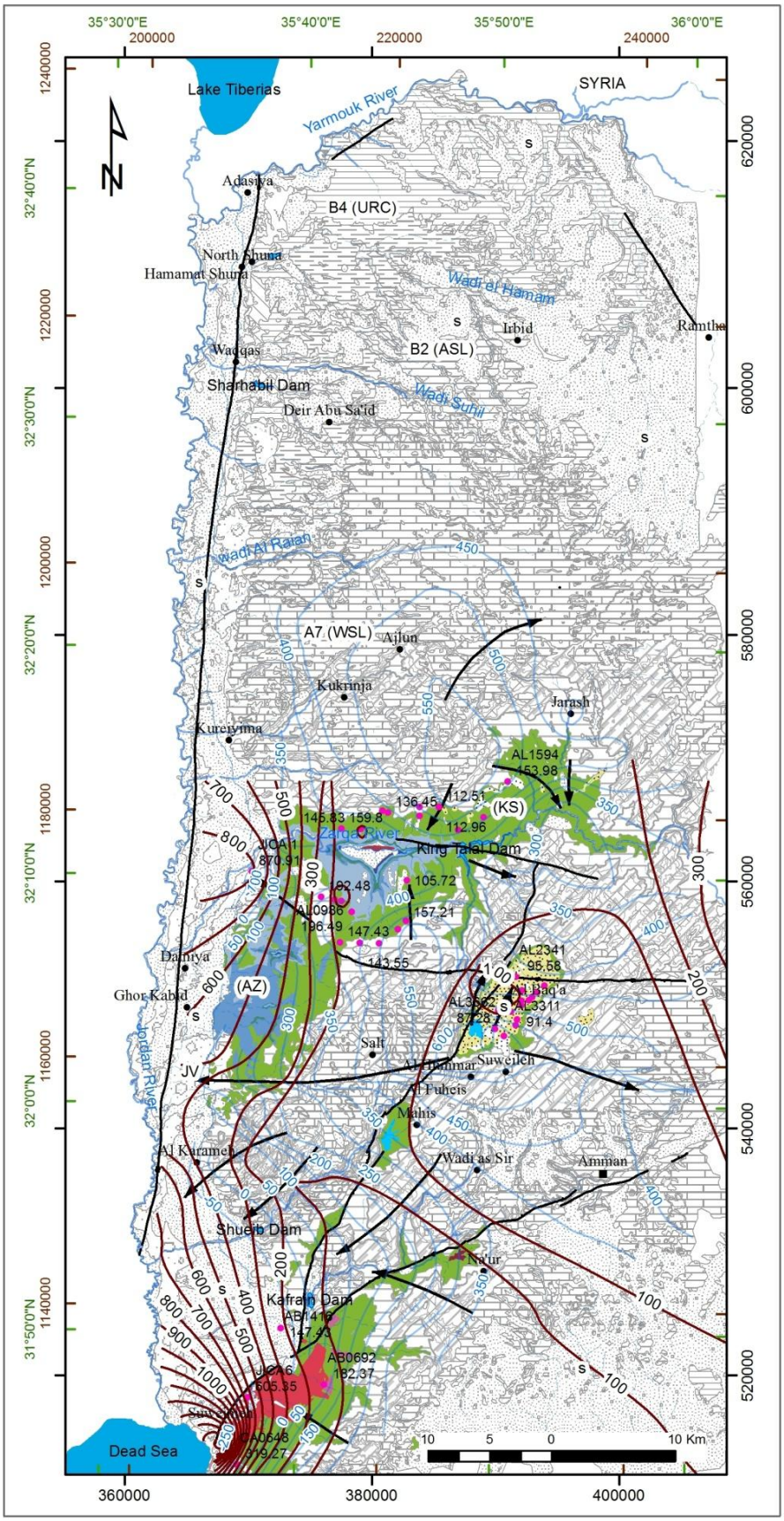

Figure 4.45-IV: The spatial distribution of the total of Calcium and Magnesium (Ca^{2+}+Mg^{2+} in mg/l) concentrations for the Deep Sandstone Aquifer System in NW of Jordan (for legend see Figure 4.41).

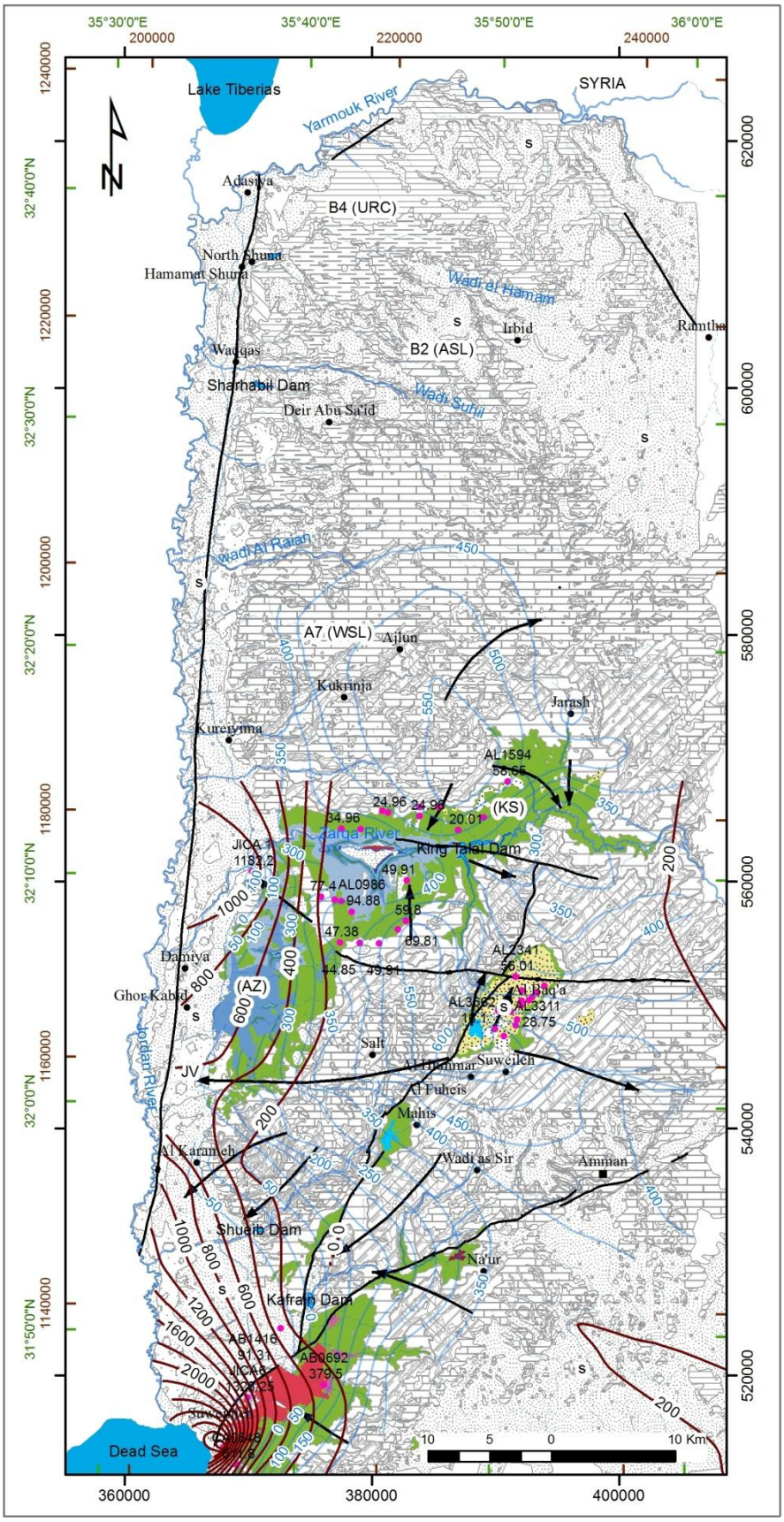

Figure 4.45-V: The spatial distribution of Sodium (Na^+ in mg/l) concentrations for the Deep Sandstone Aquifer System in NW of Jordan (for legend see Figure 4.41).

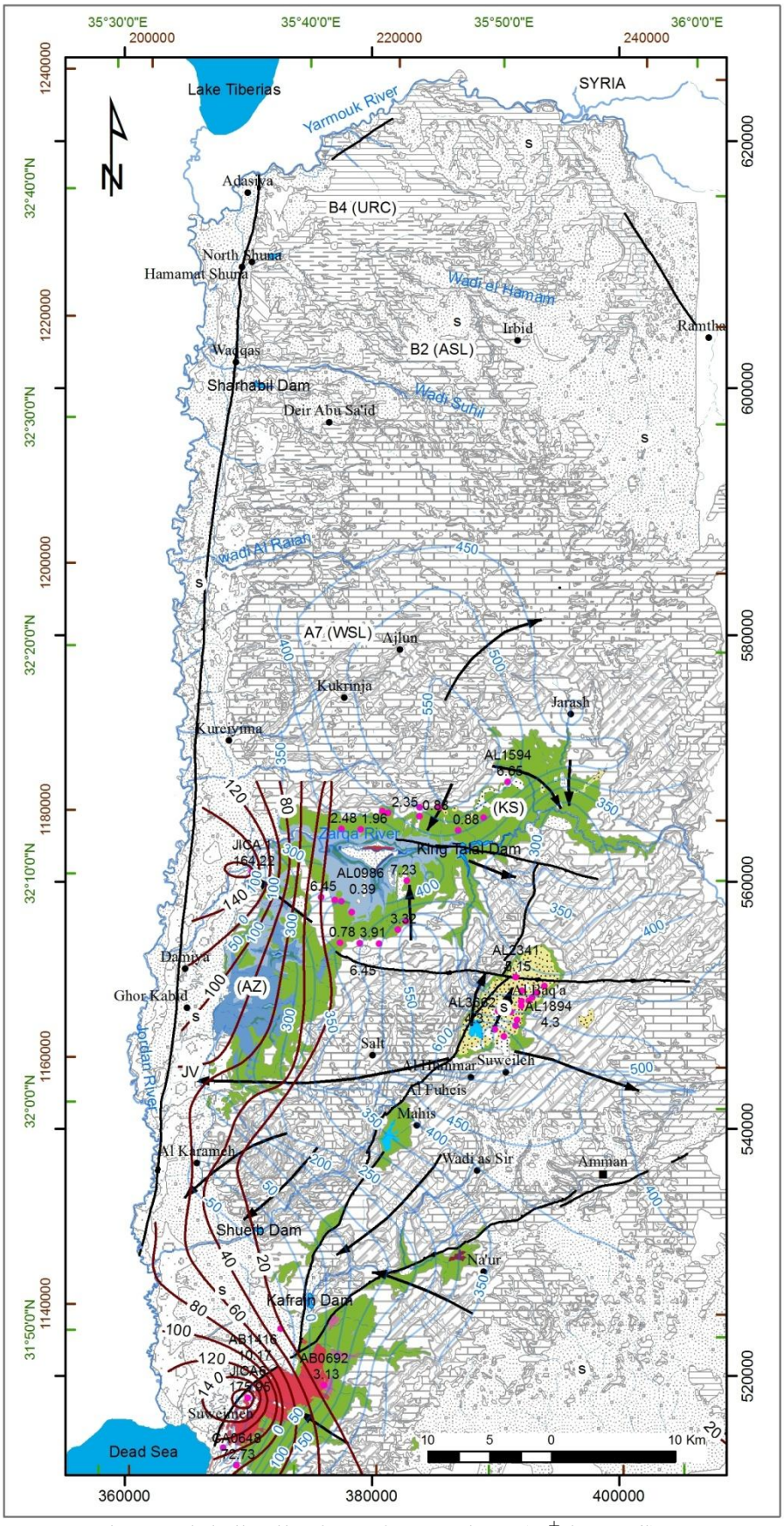

Figure 4.45-VI: The spatial distribution of Potassium (K^+ in mg/l) concentrations for the Deep Sandstone Aquifer System in NW of Jordan (for legend see Figure 4.41).

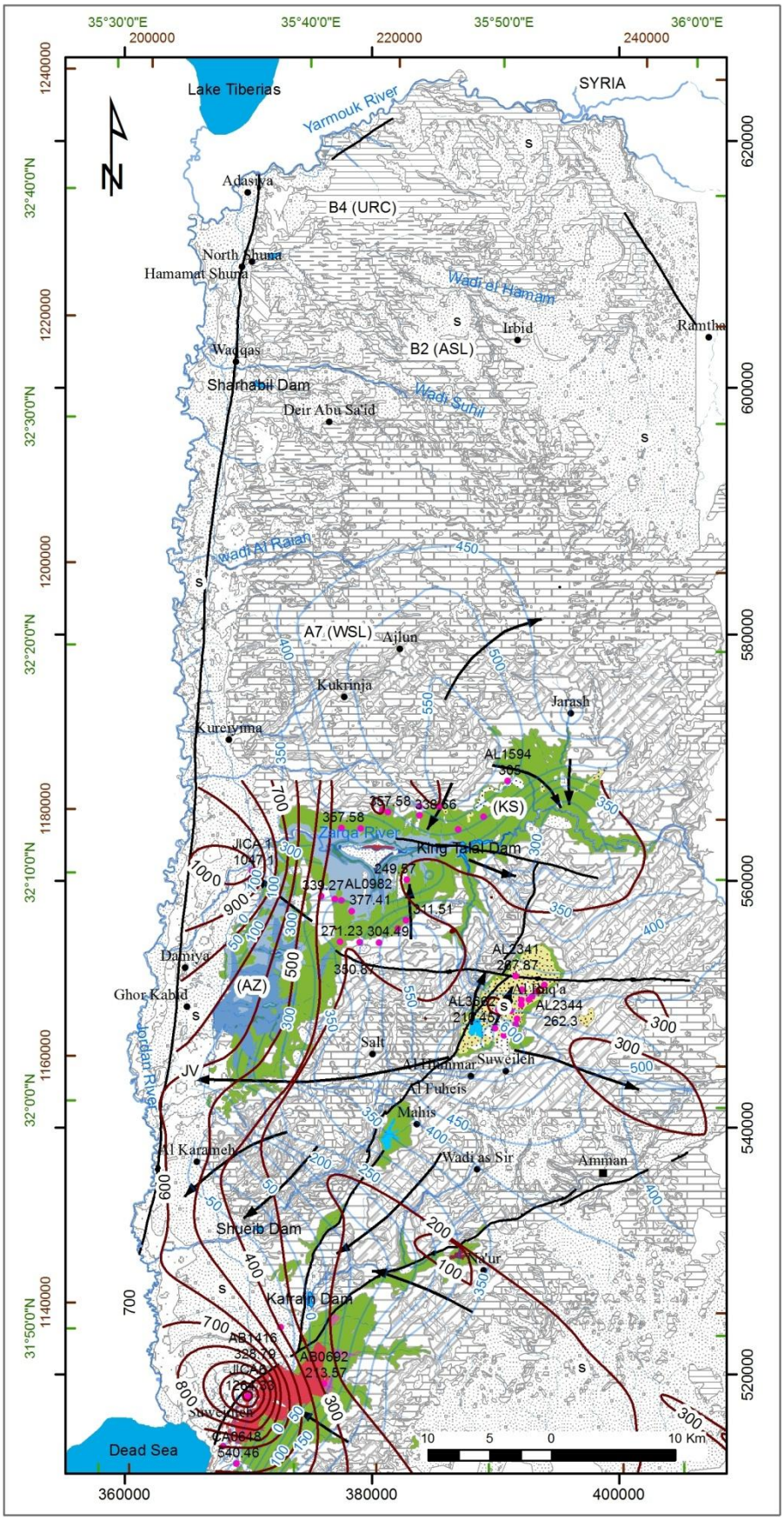

Figure 4.45-VII: The spatial distribution of Bicarbonate (HCO_3^- in mg/l) concentrations for the Deep Sandstone Aquifer System in NW of Jordan (for legend see Figure 4.41).

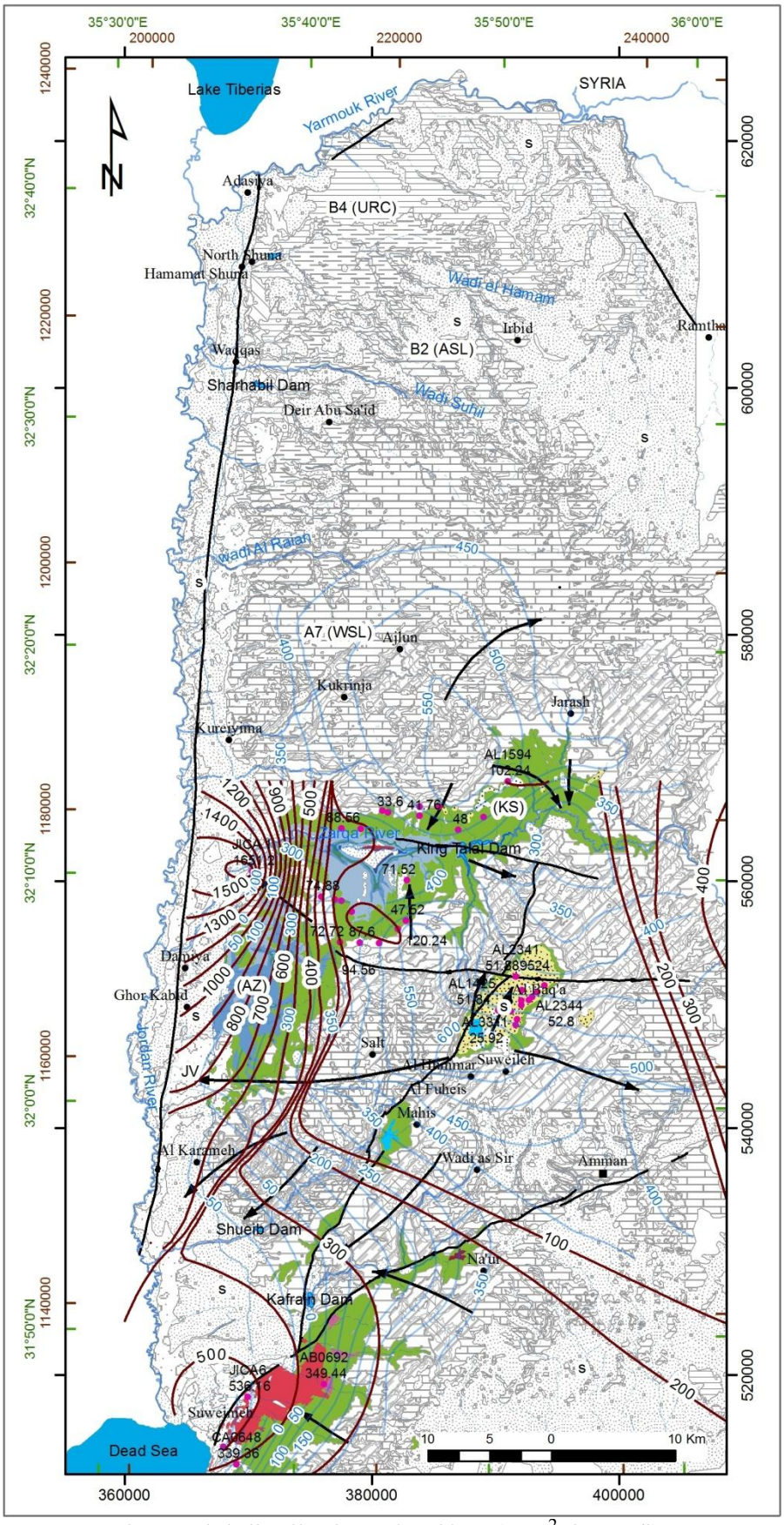

Figure 4.45-VIII: The spatial distribution of Sulfate (SO_4^{2-} in mg/l) concentrations for the Deep Sandstone Aquifer System in NW of Jordan (for legend see Figure 4.41).

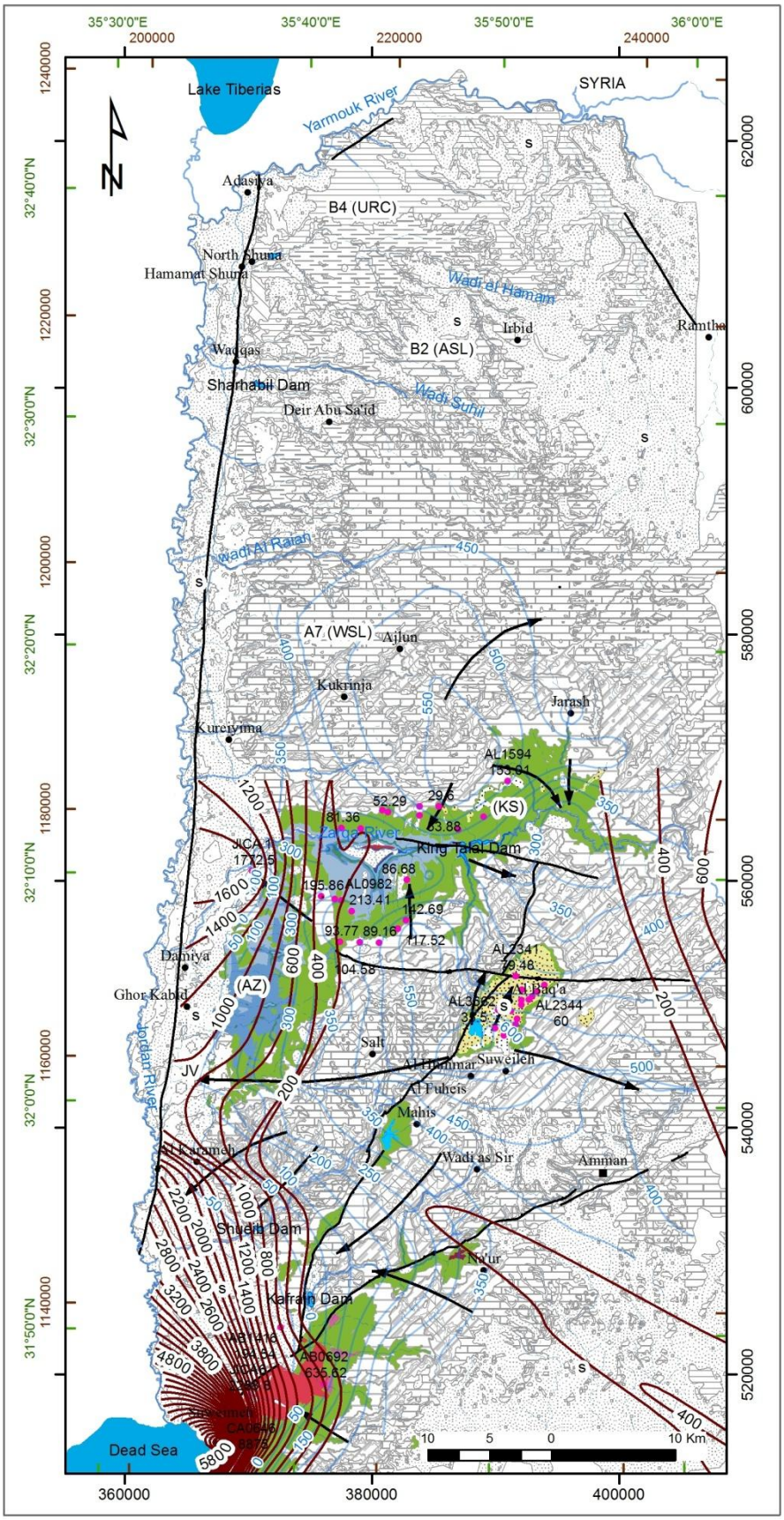

Figure 4.45-IX: The spatial distribution of Chloride (Cl^- in mg/l) concentrations for the Deep Sandstone Aquifer System in NW of Jordan (for legend see Figure 4.41).

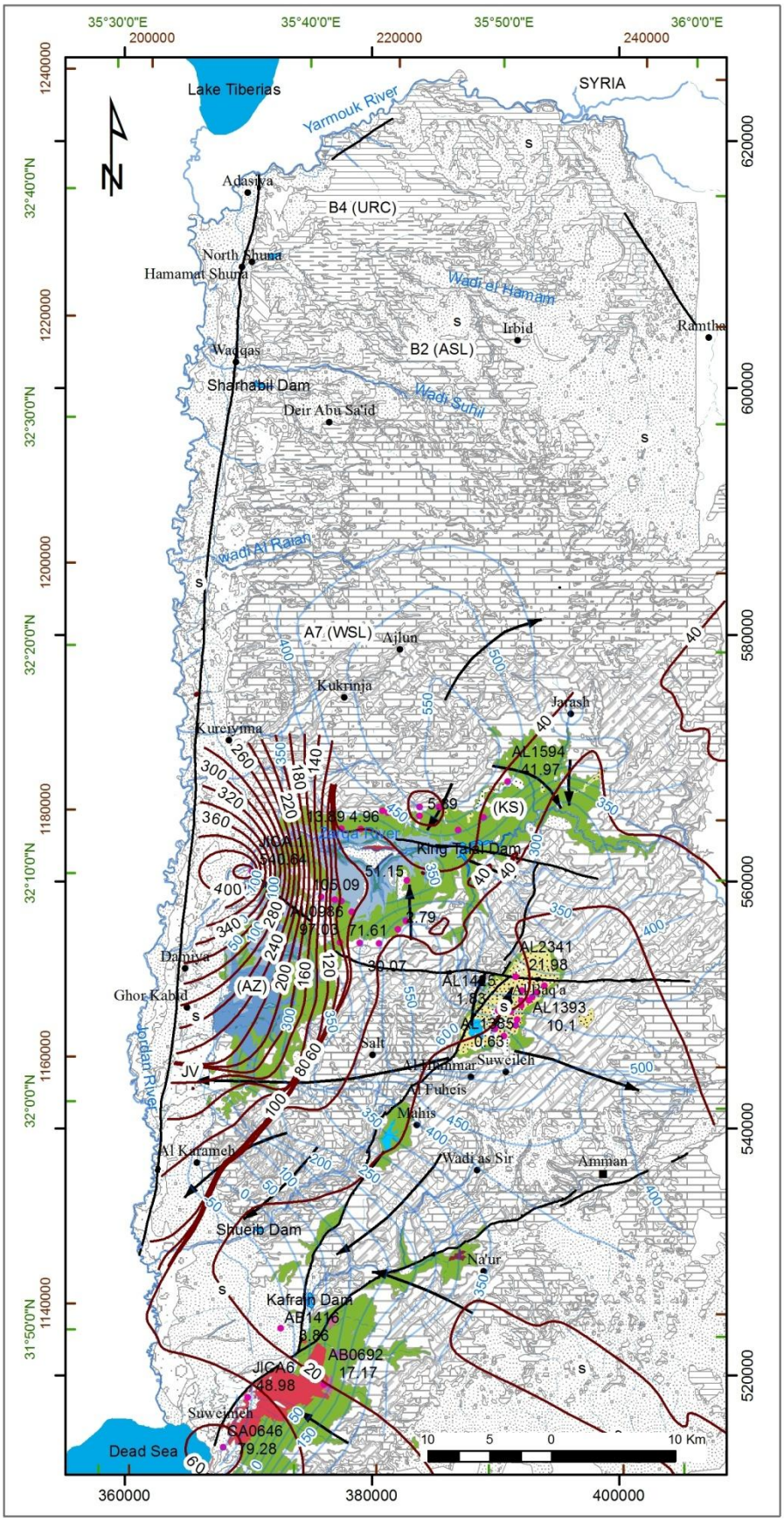

Figure 4.45-X: The spatial distribution of Nitrate (NO_3^- in mg/l) concentrations for the Deep Sandstone Aquifer System in NW of Jordan (for legend see Figure 4.41).

4.4.2 Effects of geogenic and anthropogenic factors on the groundwater chemistry

Water quality is a consequence of the natural physical and chemical state of the water as well as any alterations that may have occurred as a consequence of human activity (FETTER, 1988). The Groundwater in the study area is found in different aquifers. These aquifers have been and are affected by several structural features. Therefore, the **lithology,** the dominant **structural features** and the **recharge** and **flow of water** have major influences on the groundwater chemistry. The natural factors are known as **geogenic** parameters. In addition to that, "man-mad" effects, processes, or materials derived from human activities have major influences on the groundwater chemistry. Such parameters are known as **anthropogenic** parameters. Therefore, the water chemistry in the different aquifers are function of **geogenic and anthropogenic** parameters. These parameters can be summarized as follows:

- The interaction of precipitation water with the exposed rocks,
- Precipitation/evaporation processes,
- Dissolution of soluble salts accumulated in the surface layers,
- Dissolution of the rocks matrix and
- Ion exchange with surrounding rocks.
- Urbanization (cesspools, leaking sewer systems, waste water, traffic systems, etc).
- Agricultural activities (irrigation, fertilizations and pesticides).
- Industrial activities (emission of toxic substances, industrial waste water) and
- Touristic activities (sewage, traffic).

Due to the different parameters the groundwater shows a wide range in types, salinity and characteristics.

4.4.2.1 Geogenic effects of on groundwater salinity in the NW of Jordan

4.4.2.1.1 Upper Aquifer System (B_2/A_7 Aquifer)

The groundwater in the B_2/A_7 Aquifer System has directly evolved from precipitation water. According to SALAMEH & REMAWI (1988a) precipitation water over Jordan is normally alkaline due to the atmospheric dust, and is composed to a great extent of carbonate (SALAMEH et al., 1991). The changes in the groundwater salinity in the B_2/A_7 Aquifer in the study area and the effect of the dominant structural features can be interpreted as follows:

The alkaline precipitation over Jordan (SALAMEH & REMAWI, 1988a) affects the limestone and dolomite outcrops which form the Upper Cretaceous rocks by causing a gradual Karstification of the carbonate. Karstification phenomena in the Upper Aquifer System results in high infiltration rates well developed aquifer and high storage capacities, however low retention (SALAMEH & REMAWI, 1988a). Due to this phenomenon some major springs discharges from the B_2/A_7 Aquifer. However, the carbonate dissolution contributes in increasing the Ca^{2+} and Mg^{2+} concentrations in the groundwater in B_2/A_7 Aquifer System (Figures 4.42-II, 4.42-III; 4.42-IV & 4.45).

The precipitation water (Table 4.14) percolates through the Upper Aquifer over the highlands and reacts with rock matrix of the composed limestone and dolomite rocks (SALAMEH, 2001) (Plate 3, Plate 4 & Plate 5) where additional dissolution of minerals takes place. The MWI/WAJ groundwater data (Table 4.15) show an alkaline earth water type with prevailing bicarbonates (samples represented by red squares; Figure 4.45). This type of water represents the pure water-rock interaction of the B_2/A_7 Aquifer System without any source of pollution or additional source of mixing from adjacent aquifers (see also LANGGUTH, 1966; EL NASSER, 1991). Therefore, the water of the B_2/A_7 Aquifer is considered as fresh waters of type "normal earth alkaline with prevailing bicarbonate water" with EC values of less than 1000 µS/cm (Figure 4.42-I; Table 4.15).

The EC values and the different salinity parameters distribution maps (Figure 4.42 from I to X) indicates an increase in salinity from the unconfined to the confined parts of the aquifer. That is in addition to a rapid increase of its salinity towards the Jordan Valley. The salinity of B_2/A_7 increased also towards the areas of high population and areas of agricultural activities, northeast southwest of Amman.

The trilinear plot Figure 4.46 shows that the increases of groundwater salinity for the B_2/A_7 Aquifer are mainly in the direction of the groundwater flow from the recharge areas in the western highlands to the discharge areas (Figures 4.27 & 4.42) (e.g. the two springs towards the west of the study area: Abu Thableh (AB0534), and el Hujeijeh (AB0570) springs; Table 4.15 which represented by green triangle; Figure 4.46). The water of these springs is classified as alkaline earth water with increased portion of alkalis and prevailing bicarbonate. It shows also that the groundwater around Amman and es Salt are classified as alkaline earth water with increased portion of alkalis and prevailing bicarbonate (represented by blue stars and green crosses, respectively; Figure 4.46). In addition to that, the high salinities of the B_2/A_7 Aquifer are in agreement with the decreases of the amount of rainfall (Figure 4.9) and the increase of evaporation rates (Figure 4.14) in the study area (samples represented by pink inverted triangle towards the northeast of the study area Figure 4.46, where EC ranges from 800 to 1600 µS/cm, Cl^- >100 mg/l and Na^+ >50 mg/l; Table 4.15).

The trilinear plot Figure 4.46 shows that two springs which is completely different from the pure water of the B_2/A_7. These are: Abu Falah (AB0568) and Hammamat Mukheiba (AD0670) springs (Table 4.15) (represented in orange circle and purple open circle, respectively; Figure 4.46). The Abu Falah spring is located at the eastern side of the Jordan River and its water is classified as alkaline water with prevailing sulfate-chloride (Figure 4.46). The Hammamat Mukheiba spring is located at the lower reach of the Yarmouk River, it is emerge from the Kurnub Sandstone Aquifer and its water is thermal and classified as earth alkaline water with prevailing sulfate and chloride (Figure 4.46). Therefore, these two springs indicates a higher mixing ratio of Kurnub and B_2/A_7 Aquifers waters (see also section 4.4.1.1.1 and EL NASSER, 1991).

Several structural features in the study area play an important role in increasing the salinity in the B_2/A_7 Aquifer System. These features area mainly: the **Ajlun Dom**e, the **circumclinal strikes of the geological units** in the most northern part of Jordan, the **Dead Sea-Jordan Valley Fault** and the **highly faulted blocks** in the extreme northwest of the study area.

Table 4.15: Composition of water in the Upper Aquifer System (Amman/ Wadi as Sir, B_2/A_7) in NW of Jordan (source: MWI/WAJ data base).

	Station ID	Station Name	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	CO_3^{2-} (mg/l)	HCO_3^{-} (mg/l)	Cl^{-} (mg/l)	SO_4^{2-} (mg/l)	TDS (mg/l)	EC (µS/cm)	pH	NO_3^{-} (mg/l)
1	AB0522	ABU ZIAD spring	116.63	43.53	37.95	5.87	0.00	458.72	66.03	0.00	728.73	1036.00	7.05	0.00
2	AB0526	EL BEIDA spring	74.95	45.60	36.80	4.69	0.00	345.26	71.00	0.00	578.30	917.00	7.38	0.00
3	AB0534	ABU THABLEH spring	176.75	37.94	223.10	20.33	0.00	507.52	276.90	0.00	1242.54	2230.00	7.19	0.00
4	AB0542	TABQAT FAHIL spring	104.21	37.94	41.63	5.47	0.00	427.61	78.10	0.00	694.96	1001.00	7.22	0.00
5	AB0568	ABU FALAH spring	125.05	194.44	588.80	73.51	0.00	674.66	947.50	561.12	3251.05	4270.00	8.12	85.97
6	AB0570	EL HUJEIJEH spring	66.53	39.76	23.46	1.96	0.00	351.97	49.70	0.00	533.38	720.00	8.06	0.00
7	AB1347	SOUTH SHUNA #2 (MUNICIPALITY) well	89.31	34.57	65.17	7.04	0.00	300.93	131.83	33.92	696.89	1081.67	7.35	34.12
8	AB1350	SLEIKHAT NO 4 well	64.00	34.25	56.04	5.48	0.00	272.87	113.25	36.48	599.73	856.33	7.52	17.36
9	AB1363	JDEITA NO 1 well	89.18	27.36	22.31	3.13	0.00	354.41	37.99	15.84	582.46	745.00	7.29	32.24
10	AB1375	JUHFIYEH NO 1/DEIR YUSUF well	71.94	24.69	13.11	2.94	0.00	283.04	25.56	3.36	452.20	549.00	7.25	27.57
11	AB3005	JDEITA NO 2 well	84.17	33.93	22.77	3.91	0.00	355.02	49.70	0.00	580.57	710.00	7.51	31.07
12	AD0670	HAMMAMAT MUKHEIBA spring	122.64	45.48	116.38	16.42	0.00	352.58	227.20	0.00	880.70	1585.00	7.04	0.00
13	AD1172	ABDELRAHEEM AL U'KOUR well	66.53	34.90	83.11	5.08	0.00	239.12	169.81	37.28	675.47	998.33	7.56	39.64
14	AD1173	MAHMOUD AL NAHLAWI well	66.03	37.15	84.30	4.89	0.00	224.48	179.63	32.64	668.02	966.00	7.56	38.92
15	AD1219	NUAYMEH MUN 1 (PP 344) well	43.02	22.98	19.78	1.30	0.00	283.65	35.74	8.00	434.50	554.67	7.54	20.03
16	AD1220	NUAYMEH MUN 2 DEEP well	75.95	28.64	22.31	4.50	0.00	297.99	43.85	5.76	520.44	652.50	7.52	41.45
17	AD1234	YARMOUK UNIV. 1 DEEP (HUSUN) well	72.35	23.71	19.63	2.09	0.00	282.84	37.99	10.72	473.04	623.00	7.41	23.72
18	AD1295	MAHASI 6 (DEEP) well	64.06	29.06	59.57	2.35	0.00	268.81	107.57	22.24	554.93	783.00	7.70	1.28
19	AD3011	NUAYMEH 3 well	79.49	25.74	22.31	3.91	0.00	316.18	41.77	14.72	540.90	707.00	7.43	36.77
20	AE1001	KUFR YUBA EXP well	62.99	19.38	15.26	0.78	0.00	248.27	26.63	7.36	401.88	493.33	7.40	21.22
21	AE1004	FO'ARA EXP well	82.67	38.06	27.49	3.91	0.00	339.47	57.69	27.12	598.57	773.00	7.41	22.17
22	AE1008	WADI AL ARAB NO 2 well	118.31	20.82	21.34	2.57	0.00	389.72	36.65	51.04	641.26	796.33	7.18	0.82
23	AE1008	WADI AL ARAB NO 2 well	94.79	25.54	18.63	2.35	0.00	348.31	27.69	47.52	565.03	788.00	7.34	0.20
24	AE1009	WADI AL ARAB NO 3 well	100.47	37.25	23.00	3.00	0.00	412.36	40.59	41.92	659.07	815.33	7.32	0.48
25	AE1010	WADI AL ARAB NO 4 well	118.37	33.72	33.73	4.30	0.00	407.07	37.75	100.48	748.90	944.33	7.14	13.47
26	AE1011	WADI AL ARAB NO 5 AIN ZAHAR well	101.15	29.89	19.67	3.23	0.00	389.64	39.32	38.40	629.35	789.25	7.42	8.07
27	AE1016	DOUQARA 1 well	75.95	36.12	30.59	3.13	0.00	325.13	62.48	28.32	580.94	728.00	8.07	19.22

Page (1)

Table 4.15: Composition of water in the Upper Aquifer System (Amman/ Wadi as Sir, B_2/A_7) in NW of Jordan (source: MWI/WAJ data base).

	Station ID	Station Name	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	CO_3^{2-} (mg/l)	HCO_3^{-} (mg/l)	Cl^{-} (mg/l)	SO_4^{2-} (mg/l)	TDS (mg/l)	EC (µS/cm)	pH	NO_3^{-} (mg/l)
28	AF1001	DER ABU SA'EED NO 1 (HAMAM 1) well	95.91	33.83	21.07	3.44	0.00	398.09	43.88	21.31	635.51	775.80	7.34	17.98
29	AL1627	YAZIDIYYA NO 2 well	70.25	34.75	23.00	3.50	0.00	281.50	43.50	21.00	487.00	642.25	7.75	9.75
30	AL1830	AWSA 21 JESR ALHAMMAM well	112.00	22.67	59.67	5.67	0.00	281.67	126.33	15.00	716.67	1052.67	7.00	94.00
31	AL1831	AWSA 22/ RC 22 well	115.00	22.50	73.00	10.50	0.00	325.50	155.50	12.50	804.50	1160.00	7.00	90.50
32	AL2106	RACE CLUB NO 6 well	82.00	34.00	84.00	5.00	0.00	309.00	110.00	0.00	656.00	918.00	8.00	33.00
33	AL2114	RACE CLUB NO 14 well	105.33	26.67	62.00	6.67	0.00	325.00	146.67	12.33	724.67	1032.67	7.33	40.00
34	AL2690	AIN GHAZAL STATION 2 (NEW) well	104.00	22.67	73.67	8.33	0.00	282.67	140.33	30.00	734.67	1073.67	7.33	73.00
35	AL2714	RACE CLUB NO 18 well	79.00	29.00	71.50	5.50	0.00	269.00	153.50	16.00	668.50	1041.50	7.00	45.00
36	AM0504	JADOUR TAHTA spring	92.50	28.00	39.50	20.00	0.00	304.50	78.50	37.00	672.50	900.50	8.00	72.00
37	AM0506	JADOUR FOUQA spring	95.50	29.50	41.50	15.50	0.00	274.00	82.00	37.00	687.50	947.00	8.00	111.50
38	AM0508	FARKHA spring	50.00	16.00	35.00	7.00	0.00	150.00	42.00	34.00	415.00	860.00	8.00	82.00
39	AM0512	HAZZIR spring	95.50	24.50	34.50	9.50	0.00	295.50	66.00	32.50	611.50	853.00	8.00	53.50
40	AM0526	AL AZRAQ (FUHEIS) spring	74.00	16.50	14.50	1.00	0.00	245.50	37.00	14.00	427.00	522.50	7.50	25.00
41	AM0528	SHORE'AI spring	74.00	13.50	14.00	1.00	0.00	221.00	36.50	13.00	402.50	521.00	8.00	29.50
42	AM0530	BAQOURIYYEH spring	63.00	32.50	22.00	4.00	0.00	238.00	43.50	27.00	478.50	653.50	8.00	47.50
43	AN0530	DALIYA spring	77.00	28.00	24.00	4.00	0.00	264.00	64.00	24.00	538.00	694.00	8.00	54.00
44	AN0534	WADI ES SIR spring	97.00	25.00	25.00	2.00	0.00	289.00	71.00	27.00	576.00	744.00	8.00	39.00
45	AN0536	KHEIL (AN020A) spring	93.00	23.00	27.00	2.00	0.00	264.00	82.00	24.00	559.00	744.00	8.00	44.00
46	CD3350	AL ISRAA UNIVERSITY 2 well	60.00	32.00	40.00	5.00	0.00	265.00	71.00	48.00	523.00	726.00	8.00	2.00

Page (2)

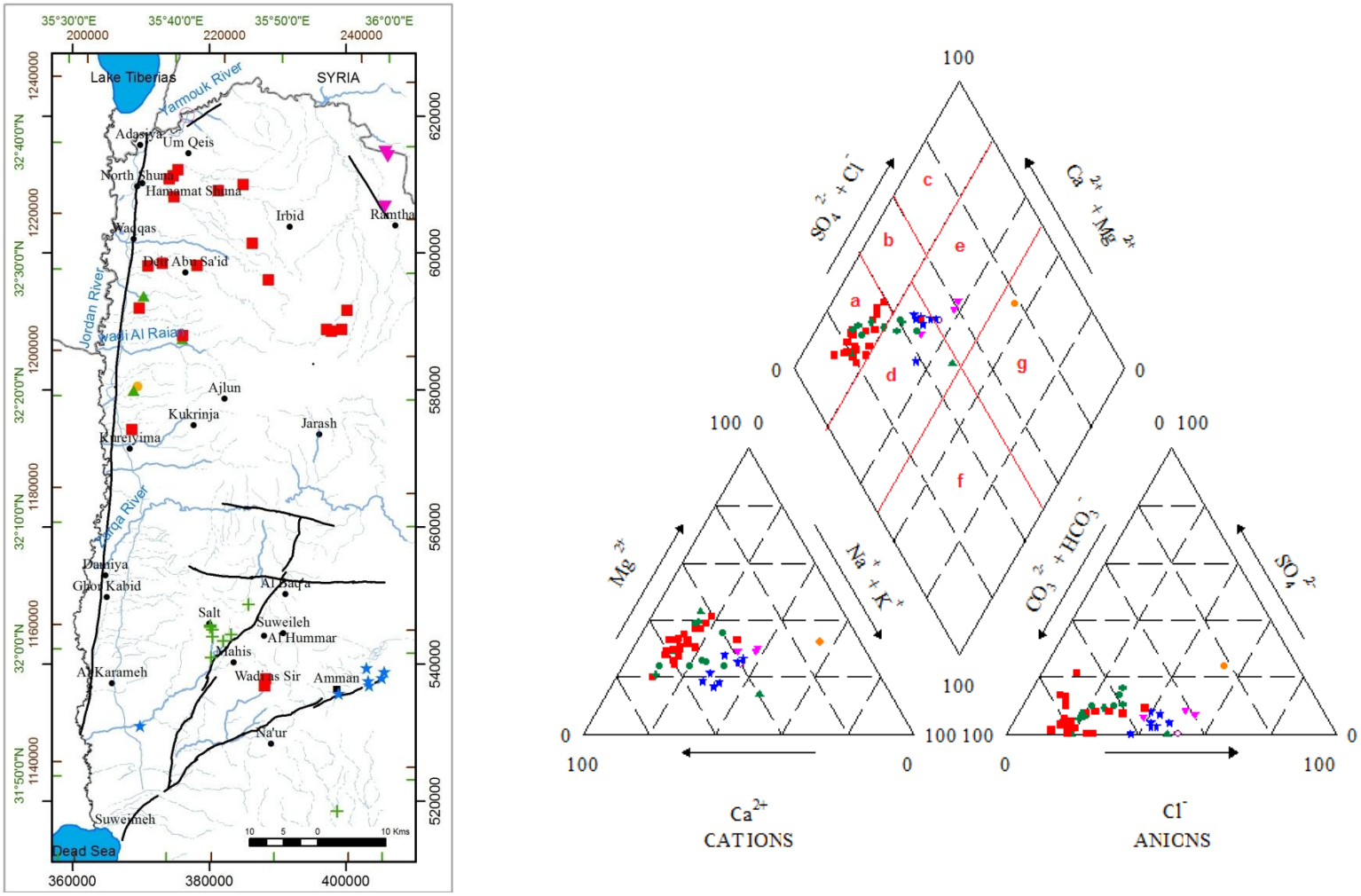

Figure 4.46: Piper diagram for the Amman/ Wadi as Sir Aquifer System B_2/A_7 in the study area with location map on the right side.

- **Ajlun Dome** is the main recharge area for the B_2/A_7 Aquifer in the study area affecting the groundwater flow in the Upper Cretaceous Aquifer and the underlying aquifers (as described previously in section 4.3.4). This dome causes the groundwater in the B_2/A_7 Aquifer to flow radially. Therefore, the salinity of B_2/A_7 groundwater around Ajlun Dome increases in the direction of groundwater flow. But due to the presence of the **circumclinal strikes** of the B_4-B_5 Aquifer (i.e. Rijam/ Shallala Formations) and the B_3 Aquiclude (i.e. Muwaqqar Chalk marl Formation) the groundwater of the B_2/A_7 Aquifer becomes confined by the B_3 which consist of marly layers. Therefore, the circumclinal strikes affected the direction of the groundwater flow which should actually discharge further north or south, to the Yarmouk Rivers or to the Jordan Valley. But the confining B_3 layer with its dip to the east, north and west causes its water to flow in a southerly direction in order to discharge to the Jordan Valley in wadi Yabis area (as described previously in section 4.3.4). Along this flow path, the EC values and all salinity parameters in B_2/A_7 Aquifer increase in a northeast, north, west and southwest directions. Due to the presence of the circumclinal strikes many springs are found in the west part of the study area. Mainly, these springs discharge from the B_2/A_7 Aquifer System as they are structurally controlled by the **Dead Sea-Jordan Valley Fault** to the west. Although the salinity increases in the flow direction the discharged water is still characterized by low salinities ranging from 500 µS/cm to 1000 µS/cm (Figure 4.42-I).

- The northwestern part of the study area is characterized by a **highly faulted zone** (Plate 4) and as well as from the western extension of the geological cross sections DD', EE' & FF' (Plate 5). In this area the water found in B_2/A_7 Aquifer, originates according to EL-NASSER (1991) partly from the Deep Kurnub water, which moves along faults and joints upwards into the overlying aquifers, especially B_2/A_7 (as explained previously in section 4.3.4 and as shown in the trilinear diagram; Figure 4.46 for the abu Falah and Hammamat Mukheiba springs). In the vicinity of the Jordan Valley, the upwards Kurnub water through faults and joints contribute to the increase in the salinity of the B_2/A_7 Aquifer water. Therefore, along the **Dead Sea-Jordan Valley Fault** all salinity parameters in the B_2/A_7 Aquifer show increases.

In accordance with this discussion, it can be stated that direct recharge to B_2/A_7 Aquifer System occurs from precipitation water which infiltrates through the soil and rock. Thus, water in this aquifer is considered as a renewable source of groundwater. But the **Ajlun Dom**e, the **circumclinal strikes of the geological units**, the **Dead Sea-Jordan Valley Fault** and the **highly faulted blocks** structural features affect the groundwater flow direction in the B_2/A_7 Aquifer, they also consequently affect the groundwater salinity by this structural features. Accordingly, the salinity of the B_2/A_7 Aquifer groundwater increases gradually from the highlands towards the Jordan Valley. The groundwater has low salinity in the highlands due to direct recharge from precipitation water. Along the flow paths this salinity increases due to the reactions of precipitation water with the rock matrix. But towards the Jordan Valley, the B_2/A_7 Aquifer waters mix with other water and shows generally increases in all salinity parameters concentrations from north to south (SALAMEH, 2001).

4.4.2.1.2 Middle Aquifer System: Hummar (A_4) and Na'ur (A_{1-2})

The water in the Hummar (A_4) (Table 4.16 & Figures 4.47) and the Na'ur (A_{1-2}) (Table 4.17 & Figures 4.48) Aquifers in the study area originates mainly from the down percolation from the B_2/A_7 Aquifer and only small amount are received from direct recharge. The groundwater in the Upper (B_2/A_7) Aquifer percolates down into the underlying semi-developed aquifers of the lower parts of the Upper Cretaceous rocks. In the Hummar (A_4) and Na'ur (A_{1-2}) Aquifers the groundwater become more saline due to the additional minerals dissolved from the intercalated evaporites such as gypsum and anhydrite. The trilinear diagrams Figures 4.47 & 4.48 indicate water of normal alkaline with prevailing bicarbonate in area where both aquifers outcropping and receive high amount of precipitation (represented by red circles and blue squares; Figure 4.47 and by green circles and blue squares; Figure 4.48). Whereas groundwater in areas where downward percolation occur water develops towards earth alkaline water with increased portion of alkalis with prevailing sulfates and chlorides (represented by green triangle; Figures 4.47 and by pink triangles; Figure 4.48). Therefore, the groundwater in the Middle Aquifer ranges from normal earth alkaline with prevailing bicarbonate to earthalkaline with increasing portions of alkalis with prevailing sulfates and chlorides (see also SALAMEH & HAMMOURI, 2007).

Nevertheless salinity and EC values in the study area for the Hummar (A_4) and the Na'ur (A_{1-2}) Aquifers (Tables 4.16 & 4.17, respectively) are generally lower than those described by SALAMEH & HAMMOURI (2007) to the south of the study area. The MWI/WAJ groundwater data shows some water samples located to the east of the Dead Sea which receives less amount of precipitation than those located in the study area. Only these water samples are similar to those presented by SALAMEH & HAMMOURI (2007) (represented by green open circles; Figure 4.47 and by blue crosses; Figure 4.47). Therefore, the water to the south of the study area is classified as earth alkaline water with prevailing sulfate and chloride or alkaline water with prevailing sulfate-chloride (Figures 4.47 & 4.48). Generally, the EC values in the Hummar (A_4) and the Na'ur (A_{1-2}) Aquifers in the study area depend on the percolated portions of the heterogeneous geologic units of the sequence and the pathways the water takes (SALAMEH & HAMMOURI, 2007). The high EC values in the area northeast of Amman shown in Tables 4.16 & 4.17 (represented by black crosses; Figure 4.47 and by blue crosses; Figure 4.48) are related to over exploitation of groundwater in Dhuleil and Zarqa Basins.

The groundwater in the Na'ur (A_{1-2}) and the Hummar (A_4) Aquifers in the northern Highlands are recharged in two main recharge mounds: around Ajlun and around Wadi as Sir city and as show in section 4.3.2.2.1 and Figures 4.25 & 4.26 the groundwater flows from both mounds radially from the high elevations towards the lower elevations. Several structural features in the area have major effects on the salinity in the Na'ur (A_{1-2}) and Hummar (A_4) Aquifer Systems. These features are mainly: the **Ajlun Dome**, **Suweileh or Al Baqa'a anticline**, **Wadi Shueib structure**, **Wadi Kafrain syncline**, **Suwayma-Amman-Hallabat structure**, the **high faulted blocks** in the extreme northwestern of the study area and the **Dead Sea-Jordan Valley Fault**. Following is a brief explanation of the effects of these structures:

Table 4.16: Composition of water in the Middle Aquifer System (Hummar, A_4), NW of Jordan (source: MWI/WAJ data base).

	Station ID	Station Name	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	CO_3^{2-} (mg/l)	HCO_3^{-} (mg/l)	Cl^{-} (mg/l)	SO_4^{2-} (mg/l)	TDS (mg/l)	EC (µS/cm)	pH	NO_3^{-} (mg/l)
1	AB0578	EL SULEIKHAT spring	65.93	37.57	29.21	6.26	0.00	301.34	53.25	0.00	493.56	770.00	8.15	0.00
2	AB1144	SAKNET EL SHUNA 2 (JRV 12B) well	85.30	36.80	70.69	4.69	0.00	276.33	158.57	39.52	689.07	677.00	7.60	17.17
3	AB1351	SLEIKHAT NO 5 well	55.21	36.36	46.81	4.89	0.00	257.73	96.56	23.04	533.45	774.00	7.42	12.86
4	AB1357	SMAHIYYAT 1/J.R.V NO 7 well	85.64	53.51	57.19	6.13	0.00	357.26	82.83	79.52	736.69	1100.67	7.44	14.61
5	AB1369	SLEIKHAT NO 3 well	43.29	30.28	35.42	3.13	0.00	192.76	68.16	65.28	440.07	600.00	7.75	1.75
6	AH0506	RASUN spring	96.59	30.04	16.79	2.74	0.00	387.35	35.50	19.20	619.27	724.00	7.22	31.06
7	AH0512	BEIDA spring	93.59	36.97	16.10	1.17	0.00	410.53	39.05	14.88	633.04	747.00	7.20	20.75
8	AH0518	URJAN TAHTA spring	89.58	38.18	16.10	1.56	0.00	398.33	35.50	15.36	615.20	731.00	7.29	20.59
9	AL0528	NIMRA spring	222.64	211.10	487.60	12.90	0.00	392.23	947.50	570.24	3081.83	4520.00	7.68	237.62
10	AL0538	UM EL URUQ spring	93.19	54.11	81.88	3.91	0.00	298.90	170.40	46.08	891.10	1286.00	7.42	142.63
11	AL0542	SABIR spring	64.73	45.96	53.59	0.39	0.00	302.56	111.12	34.08	640.05	894.00	8.13	27.62
12	AL0546	EL KHALLA spring	68.74	37.70	77.05	4.69	0.00	294.02	139.87	43.68	716.75	1079.00	7.99	51.00
13	AL0562	ES HARY (SIHRI) spring	66.53	40.25	65.32	3.91	0.00	273.89	134.19	47.52	666.35	982.00	7.55	34.74
14	AL0604	EL HAWAYAH spring	63.53	47.67	66.47	3.13	0.00	302.56	135.61	38.88	698.50	1005.00	7.99	40.65
15	AL0626	EL THAIBAH spring	64.13	31.86	63.25	3.52	0.00	183.00	124.25	66.72	569.43	835.00	6.97	32.70
16	AL0991	UMM RUMMANA AT UMM RUMMANA spring	67.94	33.68	53.82	4.69	0.00	269.01	91.95	28.32	607.38	854.00	7.67	57.97
17	AL1197	NIZAR SHUKRI SHA'SHA'A well	278.41	179.27	478.40	22.88	0.00	320.71	988.32	615.12	3115.78	4537.50	7.17	232.68
18	AL1542	YAZIDIYYA NO 3 (SALT) well	73.65	26.27	19.09	2.15	0.00	295.55	35.15	22.56	494.18	662.00	7.43	19.78
19	AL1548	AWSA SEIL EL RUSAIFEH NO 3 well	54.11	34.41	19.32	2.74	0.00	294.63	28.76	15.36	458.29	536.00	7.69	8.96
20	AL1637	YAJUZ NO 1 well	63.00	26.00	29.00	4.00	0.00	282.00	63.00	19.00	516.00	648.00	8.00	31.00
21	AL1637	YAJUZ NO 1 well	71.00	35.00	24.00	4.00	0.00	292.00	68.00	27.00	557.00	713.00	8.00	37.00
22	AL1638	YAJUZ NO 2 well	108.00	20.00	31.00	5.00	0.00	282.00	78.00	36.00	560.00	832.00	7.00	0.00
23	AL1641	YAJUZ NO 6 well	76.00	30.00	30.00	2.00	0.00	243.00	72.00	30.00	532.00	773.00	8.00	51.00
24	AL1860	RUSEIFA 17/AIN GHAZAL A1 well	90.00	23.00	73.00	7.00	0.00	266.00	120.00	36.00	661.00	948.00	7.00	47.00
25	AL2332	SA'EED YA'QUB ELMISLEH BANI M. well	80.00	28.00	30.33	3.67	0.00	280.67	65.67	41.33	564.67	762.00	7.33	34.33
26	AL3179	BEERAIN 2(SHAFA BADRAN 2) well	83.50	44.00	73.50	3.50	0.00	317.00	156.00	48.50	744.50	1107.00	8.00	19.00

Page (1)

Table 4.16: Composition of water in the Middle Aquifer System (Hummar, A_4), NW of Jordan (source: MWI/WAJ data base).

	Station ID	Station Name	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	CO_3^{2-} (mg/l)	HCO_3^{-} (mg/l)	Cl^{-} (mg/l)	SO_4^{2-} (mg/l)	TDS (mg/l)	EC (µS/cm)	pH	NO_3^{-} (mg/l)
27	AL3343	WADI EL QATTAR 1 well	63.00	41.00	51.00	4.00	0.00	249.00	114.00	31.00	590.00	816.00	8.00	39.00
28	AL3343	WADI EL QATTAR 1 well	55.00	40.00	45.00	3.00	0.00	182.00	106.00	33.00	494.00	823.00	8.00	31.00
29	AL3501	HUSSEIN SPORTS CITY No. 1 well	52.00	31.50	23.00	6.50	0.00	262.00	39.00	28.50	450.00	591.50	8.00	8.50
30	AM1027	WADI JREA'A NO 3 well	88.00	39.00	69.00	5.00	0.00	287.00	155.00	0.00	679.00	1032.00	7.00	35.00
31	AN0502	BAHHATH spring	92.00	23.00	20.00	1.00	0.00	254.00	74.00	15.00	513.00	698.00	7.00	34.00
32	AN0578	AL BUHAIRA EL FOUQA spring	92.00	45.00	40.00	3.00	0.00	331.00	97.00	78.00	715.00	1005.00	8.00	29.00
33	AP0506	FARIA (AP020A) spring	80.00	25.00	21.00	3.00	0.00	283.00	50.00	16.00	509.00	761.00	7.00	32.00
34	AP0508	AIN WADI HISBAN (AP020) spring	81.00	21.00	23.00	3.00	0.00	259.00	51.00	20.00	492.00	646.00	8.00	35.00
35	AP0510	KDEESHAH (AP020B) spring	36.00	49.00	22.00	3.00	0.00	289.00	36.00	16.00	510.00	744.00	7.00	59.00
36	CE0568	SAHOUR TAHTA spring	133.00	51.00	52.00	16.00	0.00	362.00	138.00	121.00	950.00	1184.00	8.00	77.00
37	CE0572	SAHOUR FOUQA spring	53.00	26.00	18.00	4.00	0.00	176.00	39.00	42.00	391.00	488.00	8.00	34.00
38	CE0584	ABDALLAH spring	105.00	34.00	56.00	18.00	0.00	245.00	117.00	120.00	772.00	1170.00	7.00	77.00
39	CE0618	EL-BEIDA spring	67.00	27.00	28.00	4.00	0.00	228.00	64.00	54.00	497.00	766.00	8.00	25.00

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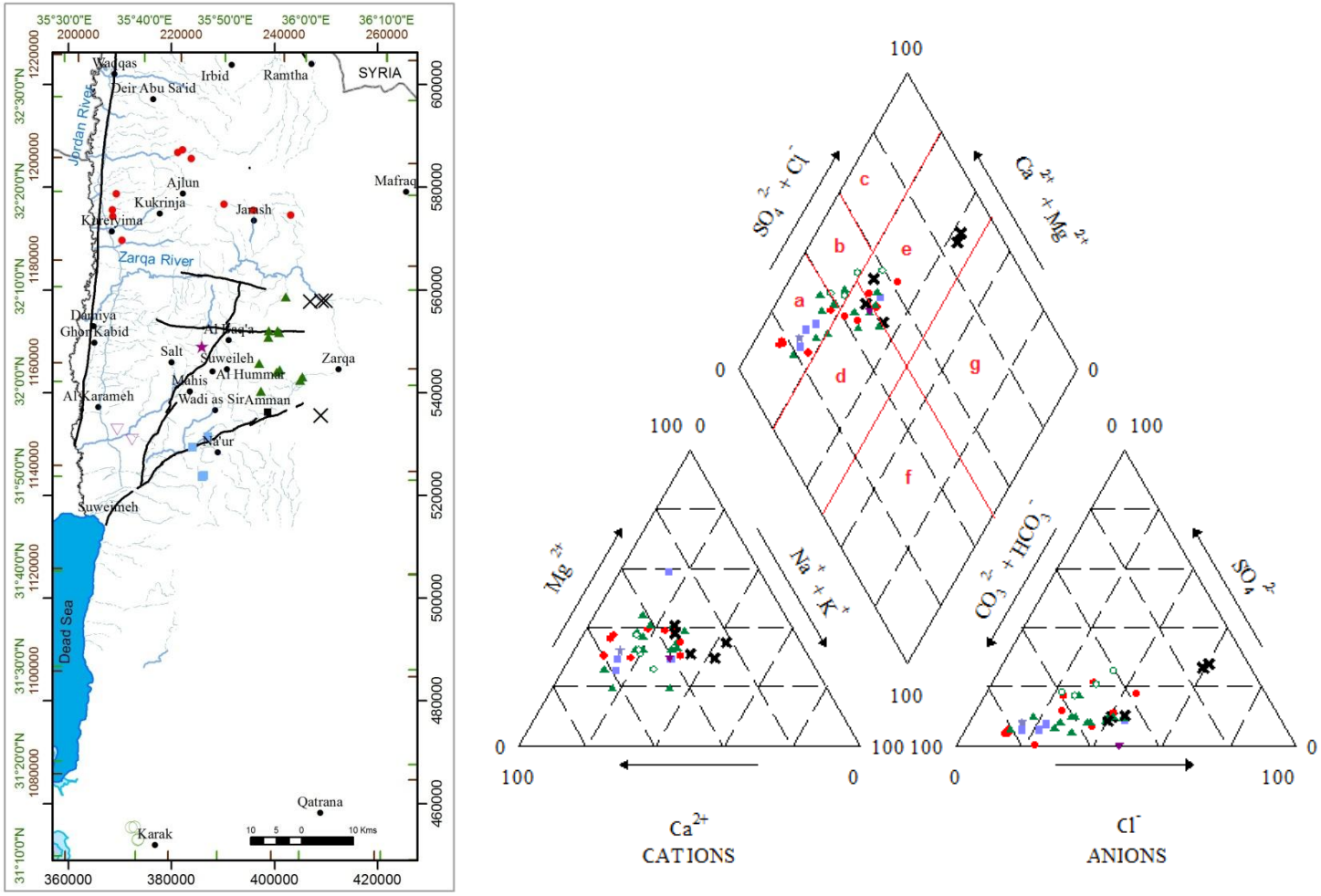

Index Map

Figure 4.47: Piper diagram for the Hummar Aquifer System (A_4) in the study area with location map on the right side.

Table 4.17: Composition of water in the Middle Aquifer System (Na'ur, A_{1-2}), NW of Jordan (source: MWI/WAJ data base).

	Station ID	Station Name	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	CO_3^{2-} (mg/l)	HCO_3^{-} (mg/l)	Cl^{-} (mg/l)	SO_4^{2-} (mg/l)	TDS (mg/l)	EC (µS/cm)	pH	NO_3^{-} (mg/l)
1	AB0680	MUSA NORTH spring	50.10	40.01	34.73	2.74	0.00	244.00	68.87	30.24	500.06	733.00	8.16	29.37
2	AB0684	MUSA SOUTH spring	65.93	29.31	31.05	1.96	0.00	234.24	67.45	28.32	489.16	691.00	7.76	30.90
3	AK1013	WADI RAJIB NO 1 well	92.99	58.37	75.56	11.93	0.00	291.58	110.41	256.08	902.63	1277.00		5.73
4	AK1015	WADI RAJIB NO 1B well	90.28	63.54	73.37	11.34	0.00	326.35	106.50	241.68	918.35	1252.00	7.26	5.30
5	AL0664	BISASS EL ROOM spring	76.95	26.27	15.41	0.78	0.00	300.12	31.60	16.80	488.14	613.00	7.52	20.21
6	AL0666	EL SHAWAHID spring	97.19	16.54	20.70	3.91	0.00	275.72	48.28	30.24	523.35	722.00	7.62	30.77
7	AL0748	ABU GHADIR spring	91.58	23.10	27.60	4.30	0.00	301.34	55.38	33.12	585.52	745.00	7.42	49.10
8	AL0768	ESH SHARQEYYAH spring	90.78	21.04	18.86	1.56	0.00	336.11	36.92	24.00	551.31	654.00	7.36	22.04
9	AL0815	MURSI (MIRSA) spring	121.44	76.12	161.00	55.13	0.00	276.33	372.75	73.92	1334.72	2280.00	7.57	198.03
10	AL0819	SHALHOUB spring	72.95	41.22	99.13	3.13	0.00	189.71	172.89	45.60	789.25	1200.00	7.71	164.62
11	AL0900	EL HARBAJ spring	67.94	35.87	71.30	4.69	0.00	224.48	156.20	45.12	653.71	1051.00	7.48	48.11
12	AL0902	ABU NUSEIR spring	65.03	40.31	50.37	1.57	0.00	242.17	122.66	65.28	607.35	921.00	7.86	19.97
13	AL1429	SOUF MUNICIPALITY NO 1 well	89.58	7.90	10.12	0.39	0.00	288.53	18.11	12.96	443.75	591.00	7.19	16.16
14	AL1598	AYYOUB S HADDAD 1 well	55.00	28.00	19.00	3.00	0.00	276.00	31.00	19.00	441.00	576.00	8.00	10.00
15	AL1608	FALEH MUSTAFA EL GHARAYBEH 1 well	83.33	37.33	53.00	4.00	0.00	296.00	112.67	33.33	675.33	981.67	7.67	55.67
16	AL3364	BEERAIN 3(SHAFA BADRAN 3) well	79.50	46.00	62.00	4.00	0.00	303.00	136.50	48.50	696.00	1052.50	8.00	17.00
17	AL3527	YAZIDIYYA NO.8 well	61.00	39.00	26.00	4.00	0.00	323.00	46.00	54.00	557.00	674.00	8.00	3.00
18	AM0534	MAHIS spring	81.00	31.00	18.00	1.00	0.00	307.00	46.00	17.00	529.00	682.00	7.00	26.00
19	AM0536	TUREIM (AM040A) spring	83.00	21.50	17.00	1.50	0.00	288.50	44.50	13.50	499.50	659.50	7.50	29.50
20	AM0542	EL JURBAN (JASUBAN) spring	47.00	12.00	41.50	7.00	0.00	266.00	89.50	31.00	546.50	872.50	8.00	52.50
21	AN0546	EL KHOUR spring	81.00	37.00	48.00	2.00	0.00	251.00	114.00	48.00	645.00	951.00	8.00	65.00
22	AN0554	TARABIL spring	100.00	35.00	35.00	3.00	0.00	307.00	92.00	39.00	664.00	922.00	8.00	53.00
23	AN0570	ADASIYEH GHARBIYA spring	73.00	34.00	26.00	2.00	0.00	300.00	57.00	24.00	544.00	684.00	8.00	28.00
24	AN0572	ADASIYA SHARQIYA (AN038A) spring	75.00	31.00	25.00	2.00	0.00	296.00	50.00	24.00	530.00	690.00	8.00	27.00
25	AN0574	UM ZWEITEENEH spring	84.00	28.00	32.00	3.00	0.00	281.00	73.00	24.00	560.00	736.00	8.00	36.00
26	AN0579	AL FUQARA AL FOUQA spring	95.00	36.00	23.00	3.00	0.00	300.00	71.00	62.00	611.00	820.00	8.00	21.00
27	AN0580	AL FUQARA AL TEHTA spring	103.00	34.00	23.00	3.00	0.00	307.00	72.00	62.00	625.00	821.00	8.00	20.00

Page (1)

Table 4.17: Composition of water in the Middle Aquifer System (Na'ur, A_{1-2}), NW of Jordan (source: MWI/WAJ data base).

	Station ID	Station Name	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	CO_3^{2-} (mg/l)	HCO_3^{-} (mg/l)	Cl^{-} (mg/l)	SO_4^{2-} (mg/l)	TDS (mg/l)	EC (µS/cm)	pH	NO_3^{-} (mg/l)
28	AP0518	MBEIRDEH spring	83.00	35.00	24.00	3.00	0.00	302.00	55.00	32.00	576.00	778.00	7.00	42.00
29	AP0520	SUMIYA spring	78.00	30.00	22.00	2.00	0.00	268.00	55.00	24.00	517.00	730.00	7.00	36.00
30	CA0520	ZARA NO 1 spring	130.00	31.00	260.00	35.00	0.00	352.00	468.00	160.00	1442.00	2130.00	8.00	7.00
31	CA0556	LEBLALEYYEH spring	133.00	66.00	51.00	8.00	0.00	287.00	142.00	251.00	1011.00	1258.00	8.00	73.00
32	CA0620	EL-KANISA spring	79.00	33.00	60.00	4.00	0.00	254.00	102.00	75.00	638.00	995.00	8.00	30.00
33	CA0626	EL DHEIB spring	52.00	33.00	64.00	4.00	0.00	214.00	104.00	53.00	553.00	830.00	8.00	29.00
34	CA0628	EL FALAH spring	101.00	81.00	161.00	7.00	0.00	290.00	355.00	178.00	1203.00	1660.00	8.00	31.00
35	CA0630	EL QATTAR spring	114.00	100.00	258.00	10.00	0.00	251.00	490.00	321.00	1572.00	2200.00	7.00	28.00
36	CA0688	ESH SHALLAL spring	142.00	38.00	485.00	59.00	0.00	289.00	806.00	222.00	2053.00	3710.00	7.00	11.00
37	CE0584	ABDALLAH spring	105.00	34.00	56.00	18.00	0.00	245.00	117.00	120.00	772.00	1170.00	7.00	77.00
38	CE0588	ABDEL-RAHIM spring	109.00	34.00	61.00	18.00	0.00	256.00	121.00	130.00	799.00	1240.00	7.00	70.00

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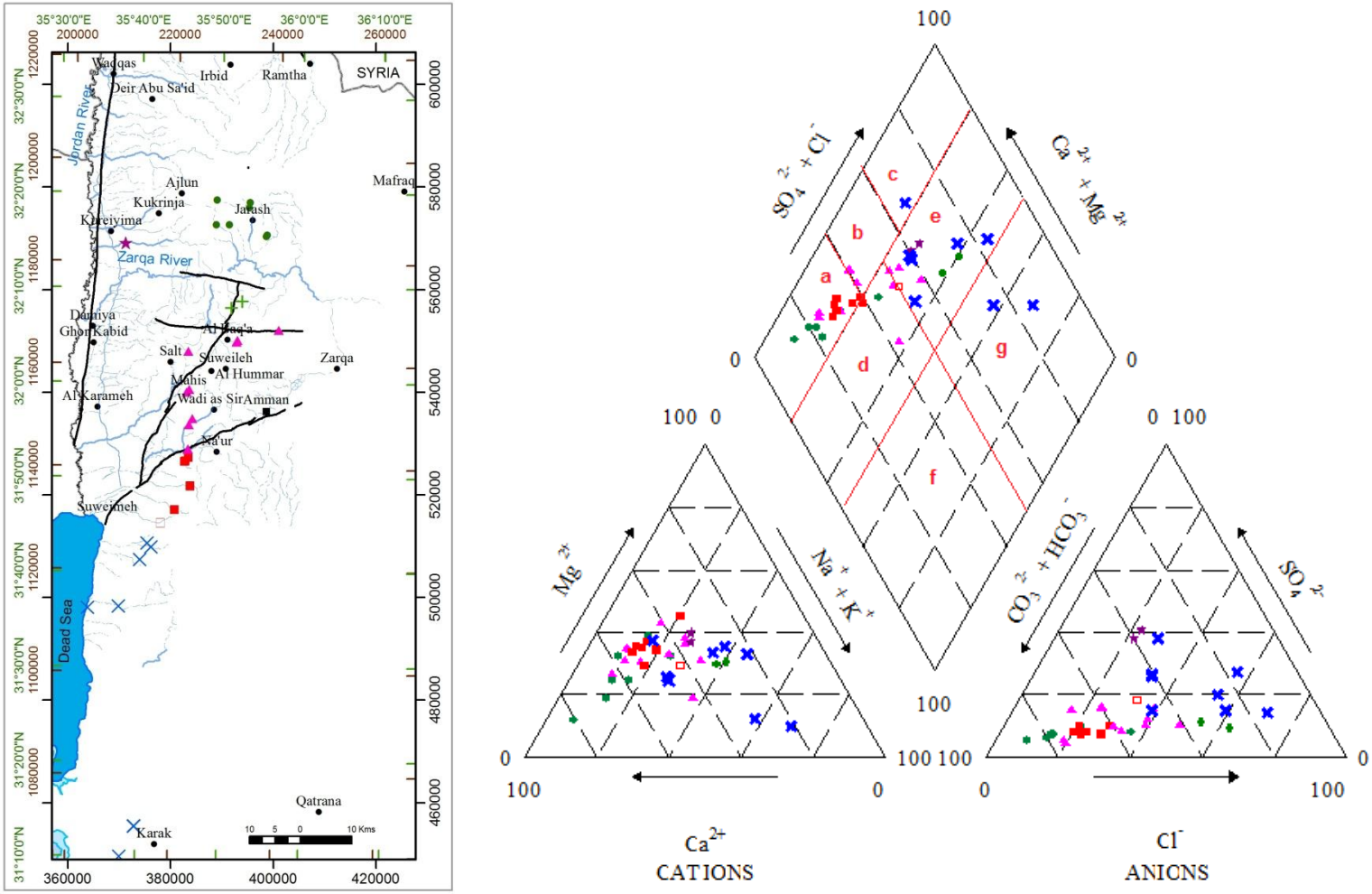

Figure 4.48: Piper diagram for Na'ur Aquifer System (A_{1-2}) in the study area with location map on the right side.

- In the northern Highlands, the **Ajlun Dome** is affecting the groundwater flow in the Middle Aquifer System in the same way it affects the upper B_2/A_7 Aquifer System. This dome causes the groundwater in Na'ur (A_{1-2}) and Hummar (A_4) Aquifers to flow towards the Jordan Valley. But, the presence of the **faults in** the extreme northwest of the study area that occur in the **Lower Ajlun Group (A_{1-6})** and presence of the **Dead Sea Transform Fault** in the western part, allow indirect upward discharge from the underlying Deep Sandstone Aquifer into the overlying B_2/A_7 Aquifer through the Middle Aquifer System (A_{1-2} and A_4). (as shown in section 4.3.4 and Figure 4.33). Therefore, due to this interconnection more saline water mixes with the waters in the Na'ur (A_{1-2}) and Hummar (A_4) Aquifers coming from Ajlun mound. Hence, both aquifers show an increase in their salinity in the same way of the B_2/A_7 Aquifer towards the west (Figures 4.43 & 4.44). The trilinear diagram shown in Figure 4.47 indicated a good example of this type of water in wadi Rajib wells No. 1 and 1B (AK1013 and AK1015, respectively; Table 4.17). The water in these wells is classified as earth alkaline water with increased portion of alkalis with prevailing sulfate and chloride (represented by pink star; Figure 4.48).

- The southern extension of the Ajlun structure**; Suweileh or Al Baqa'a anticline** diverts the groundwater to flow in a SSW direction. Meanwhile, groundwater flowing from es Salt and Wadi as Sir mounds in Na'ur (A_{1-2}) and Hummar (A_4) Aquifers are directed towards north and northeast. These waters occur in the area located between two major strike-slip faults; **Zarqa River** and **Al Baqa'a-Er Rmamin faults**. Due to the high permeability and porosity of these faults higher mineralized water ascending from the depth cause the increase in the salinity in both aquifers as shown in Figures (4.43 & 4.44). The trilinear diagram shown in Figures 4.47 & 4.48 indicated a good example of this type of water and water classified in the Hummar (A_4) Aquifer as earth alkaline water with increased portion of alkalis with prevailing sulfate and chloride (represented by black crosses; Figure 4.47) and in the Na'ur (A_{1-2}) Aquifer as earth alkaline water with increased portion of alkalis with prevailing sulfate and chloride develops to alkaline water with prevailing sulfate-chloride (represented by green crosses; Figure 4.48).

- In the southern part of the study area, the salinity of groundwater in the Na'ur (A_{1-2}) and in the Hummar (A_4) Formations increases towards west and southwest. Due to the presence of a water divide between Wadi as Sir and Suweileh, both aquifers show an increase in salinity towards east and northeast, but the salinity values are less than those in the west. This increase in salinity is related to **Wadi Shueib structure**, **Wadi Kafrain syncline** and **Suwayma-Amman-Hallabat structure.** These major structures force the groundwater to flow westward towards the Jordan Rift Valley and **Suwayma-Amman-Hallabat structure** forms the south-eastern limit of the groundwater. Along the flow path more substances are dissolved from rock matrix causing an increase of salinity in the Na'ur (A_{1-2}) and in the Hummar (A_4) Aquifers in the direction of groundwater flow, as indicated from the springs issuing there. Kurnub upward discharges along the above mentioned structures play also a role in the salinity increase of the overlying aquifers.

4.4.2.1.3 Lower Aquifer System (Deep Sandstone Aquifer)

The water salinity in the Deep Sandstone Aquifer System is mainly a result of the sodium chloride content (according to SALAMEH, 2001 and this study; Table 4.18 and Figure 4.49).

The water in this Deep Aquifer originates by downward percolation through the overlying Upper Cretaceous rock unit and as sub-surface flows from the adjacent areas and aquifers (SALAMEH & UDLUFT, 1985; EL-NASER, 1991; SALAMEH & BANNAYAN, 1993). The ultimate level is the Dead Sea, but for NW of Jordan it flows via the Jordan Valley to the Dead Sea (see Figure 4.33). It is also partly recharged by infiltration of precipitation water at its outcrop areas; mainly in Jarash, Al Baqa'a and along the lower reaches of Zarqa River and its tributaries (water in these areas is represented by blue circles and red rectangles; Figure 4.49). In the study area, the groundwater percolates from the upper to the lower aquifer where additional dissolution of minerals takes place. The groundwater which reaches the Kurnub Aquifer is over-saturated with respect to calcite and dolomite, thus both minerals start to precipitate in the rock matrix. However, the Deep Aquifer water is still under-saturated with halite and gypsum. Therefore, the type of water in the Deep Sandstone Aquifer System in the study area remains earthalkaline with prevailing bicarbonate and sulfates (Figure 4.49).

With increasing salinity the Kurnub water tends to change from a Ca^{2+}-Mg^{2+}-HCO_3^- to a Na^+-Cl^- type of water, partly with elevated sulfate contents (GTZ & MWI, 2004 and this study; Table 4.18 and Figure 4.49). Then the groundwater reaches the carbonate unit (Jurassic age) of the Deep Aquifer where dissolution of calcite and dolomite starts again after precipitation within the overlying sandstone unit. The water in this portion shows higher concentrations of gypsum and halite due to ion exchange and additional solution processes. When the groundwater reaches the foothills of the escarpment and the Jordan Valley, it mixes with a groundwater body of high chloride and sodium concentration leading to groundwater with high alkaline components.

The EC and the salinity parameters distribution maps in the study area indicate an increase of water salinity in the Deep Sandstone Aquifer mainly towards the west and southwest and partly towards the east (Figure 4.45 from I to X). The changes in EC values in outcrop areas (i.e. local recharge areas) (Figure 4.45) are attributed mainly, to the carbonate and sandstone rocks found in the eastern parts compared with clayey and salty rocks in the western parts of the study area (Plate 5) and the geological cross sections AA', BB', CC'& HH' (Plate 5). Therefore, according to SALAMEH & HAMMOURI (2007), Figure (4.45 from I to X) the water salinity in the Deep Sandstone Aquifer is related to the changes in the rock sequences along its flow path from the recharge areas in the east to the discharge areas in the west, and it is also related to the percolated portions of the heterogeneous geological units of the overlying rock sequences. An example of this type of water is the three samples in the Lisan area east of the Dead Sea (represented by blue crosses; Figure 4.49) which show a very different composition from others Kurnub water (i.e. type e; Figures 4.40 & 4.49 with high SO_4^{2-} content).

Within the study area in the Highlands, in addition to the down percolation from the overlying Upper Aquifers the direct recharge occurs through fractures and faults.

Table 4.18: Composition of water in the Lower Aquifer System (Kurnub Sandstone), NW of Jordan (source: MWI/WAJ data base).

	Station ID	Station Name	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	CO_3^{2-} (mg/l)	HCO_3^{-} (mg/l)	Cl^{-} (mg/l)	SO_4^{2-} (mg/l)	TDS (mg/l)	EC (µS/cm)	pH	NO_3^{-} (mg/l)
1	AB1416	FUAD ABU RAHMEH HERITORS well	103.41	44.02	91.31	10.17	0.00	328.79	194.54	0.00	789.41	1242.00	7.45	17.17
2	AL1385	ALLUMINUM CO. 1 well	75.85	18.12	25.88	6.65	0.00	265.66	41.36	50.88	488.25	593.50	7.33	3.86
3	AL1392	YOUSEF IBRAHEEM ALNAHAR well	65.13	25.90	69.92	2.35	0.00	306.83	77.75	85.44	633.95	816.00	7.19	0.63
4	AL1393	ABU NUSAIR well	66.87	21.08	45.23	4.56	0.00	256.81	58.81	49.28	507.50	675.67	7.18	4.86
5	AL1394	JORDAN TILES & BLOCKS COMPANY well	65.03	27.91	70.61	3.13	0.00	295.85	81.83	41.52	595.97	718.00	7.64	10.10
6	AL1395	ABDELKAREEM MIFLEH ELWRAIKAT 1 well	73.75	33.20	112.93	5.87	0.00	234.24	191.70	78.24	796.98	1175.00	7.64	67.05
7	AL1425	BAQ'A 2 (W.S.C) well	81.96	22.62	23.92	2.35	0.00	331.23	28.40	51.84	544.15	615.00	7.62	1.83
8	AL1432	BAQ'A 5 (W.S.C) well	73.35	19.09	19.78	6.65	0.00	276.33	39.05	0.00	434.41	600.00	7.32	0.16
9	AL1541	BAQ'A 9 (W.S.C) well	60.92	17.03	31.97	5.47	0.00	231.50	45.09	33.12	430.71	582.50	7.37	5.62
10	AL1575	ABDELKAREEM MIFLEH ELWRAIKAT 3 well	68.00	31.00	107.00	5.00	0.00	267.00	150.00	72.00	756.00	1118.00	7.00	56.00
11	AL1594	SALEEM A. JAWAD 6 well	111.00	43.00	59.00	7.00	0.00	305.00	153.00	102.00	822.00	1168.00	8.00	42.00
12	AL1595	YAHYA ABDELKAREEM MUHAWISH 1 well	102.00	47.00	45.00	5.00	0.00	348.00	99.00	57.00	767.00	1057.00	8.00	65.00
13	AL1894	ABDALLAH I'NEZAN & A. RASHEED well	72.00	36.00	131.00	4.00	0.00	220.00	193.00	72.00	823.00	1286.00	8.00	94.00
14	AL2341	YOUSEF & ALI ELFARE'A well	74.33	27.33	78.33	9.00	0.00	252.00	112.33	52.00	672.67	958.67	8.00	67.00
15	AL2344	ABU NUSAIR AGRICULTURAL SOCIETY well	68.00	22.00	44.00	5.00	0.00	262.00	60.00	53.00	520.00	677.00	8.00	7.00
16	AL2360	RIYASHI WELL NO 2 /JARASH well	83.33	32.33	42.67	4.67	0.00	341.33	68.00	48.00	635.00	852.33	7.00	14.67
17	AL2707	BAQ'A 15 well	79.00	19.00	25.00	7.00	0.00	290.00	34.00	40.00	496.00	600.00	7.00	2.00
18	AL3221	NATIONAL INDUSTRY 3 well	90.58	37.20	80.03	7.10	0.00	279.71	153.06	95.56	770.52	1070.50	7.46	26.58
19	AL3311	BAQ'A 19 well	77.50	14.00	29.00	11.00	0.00	259.00	42.50	26.00	479.50	626.50	7.50	20.00
20	AL3662	HAMDAN AHMAD ABDELHADI AL AWAMLEH well	74.00	13.00	16.00	4.00	0.00	210.00	36.00	0.00	398.00	582.00	7.00	44.00
21	CA0558	IDLIBAAT spring	109.00	57.00	55.00	10.00	0.00	239.00	121.00	220.00	877.00	1180.00	8.00	66.00
22	CA0648	DUREIBEH spring	230.00	89.00	612.00	73.00	0.00	540.00	1022.00	339.00	2906.00	4200.00	7.00	0.00
23	CA0686	W ZARQA' MAIN spring	105.00	51.00	444.00	52.00	0.00	188.00	852.00	222.00	1925.00	3070.00	8.00	11.00
24	CA0690	HAMMAM AMIR spring	139.00	35.00	469.00	59.00	0.00	301.00	799.00	212.00	2014.00	3670.00	7.00	0.00
25	CA0692	EL MAGHARA spring	144.00	37.00	499.00	61.00	0.00	289.00	834.00	210.00	2074.00	3740.00	7.00	0.00
26	CE0598	ABU-KARSH spring	330.00	134.00	170.00	11.00	0.00	465.00	277.00	987.00	2421.00	3240.00	8.00	46.00
27	CE0646	AIN-RASHAHA spring	263.00	152.00	495.00	39.00	0.00	338.00	785.00	930.00	3064.00	4620.00	8.00	64.00

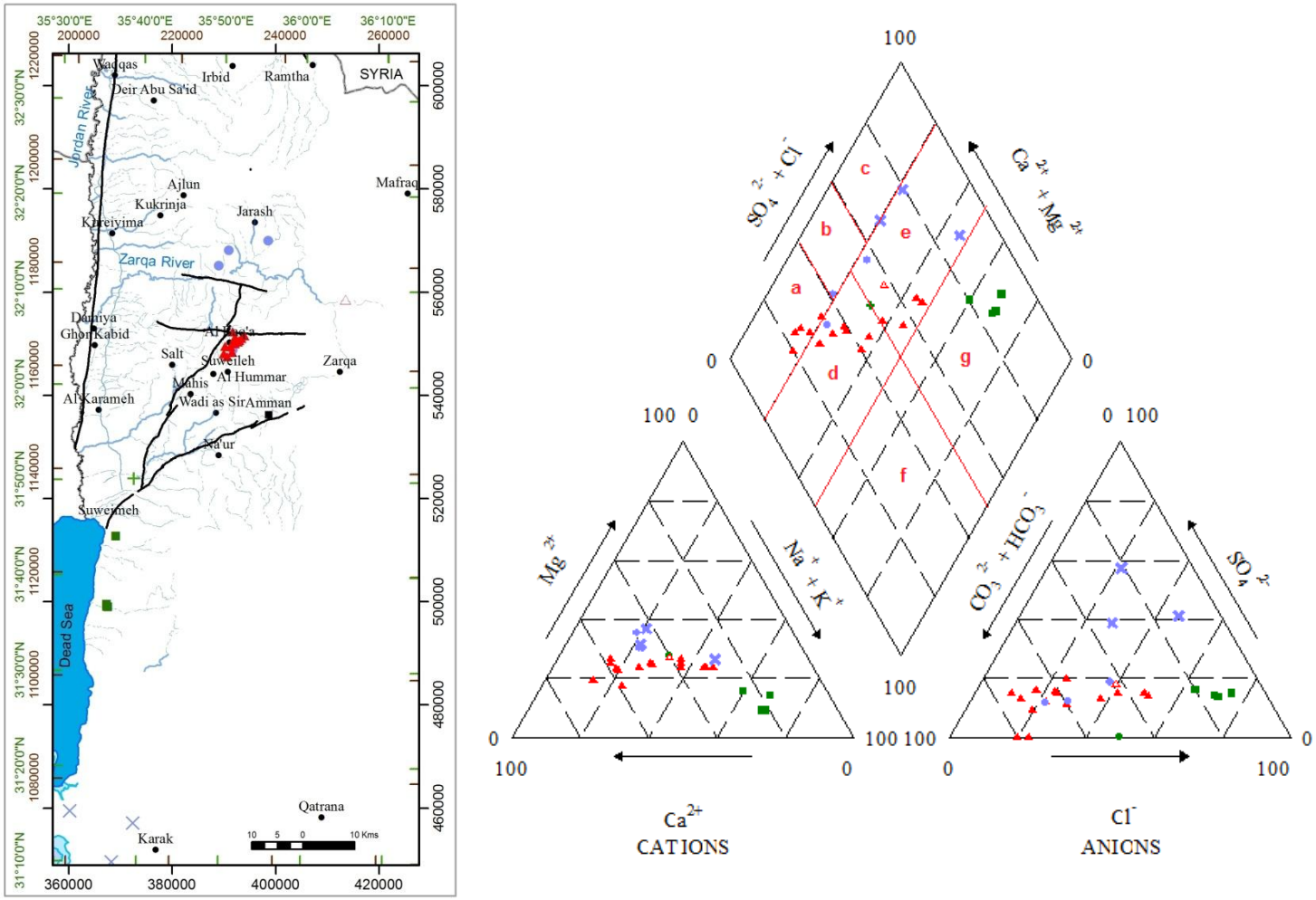

Figure 4.49: Piper diagram for the Lower Aquifer System (Kurnub Sandstone) in the study area with location map on the right side.

Along the groundwater flow in a westerly direction, the water within the Deep Sandstone Aquifer rocks borders more recent rocks of the Jordan Valley and recharges these recent rocks laterally (SALAMEH, 2001). The groundwater salinity in the Lower Aquifer System (Figure 4.45 from I to X) increases in the direction of groundwater flow within the aquifer (Figures 4.23, 4.45 & 4.49). This increase is also in agreement with the decrease of the amount of rainfall (Figure 4.9) and the increase of the evaporation rates (Figure 4.14).

The main structural features that affected the salinity in the study area are mainly the southern extension of the **Ajlun Dome**, the **east-west trending Zarqa River and Al Baqa'a-Er Rmamin faults**, the **Dead Sea Transform Fault**, **Shueib, Kafrain** and **Halabat structures**. Along these structures rocks of Jurassic, Triassic and Lower Cretaceous ages are mainly exposed.

- The effect of **Ajlun Dome** and its southern extension **Al Baqa'a anticline** and the Zarqa River and Al Baqa'a-Er Rmamin faults on the Deep Aquifer appears in the area of Zarqa River. As described previously in section (4.3.4) the Zarqa River area represent an area of asymmetrical anticline striking NNE-SSW and plunging a few degree in the SSW direction. The water originated along the highlands (i.e. around Ajlun Dome) flows towards the centre of the Zarqa River which almost coincides with the anticlinal axis (ODEH, 2009) Therefore, the anticlinal axis with its associated jointing allows the general direction of the groundwater in the Deep Aquifer to move towards SSW.

- The **east-west trending Zarqa River and Al Baqa'a-Er Rmamin faults** around the Zarqa River increase the porosity and permeability of the rocks along their trend lines. ODEH (2009) indicated that the greater amount of discharge is from springs located on the zone of converging groundwater flow lines which indicates that the strike slip faults in the Zarqa River area are high-permeability faults. The high-permeability strike slip faults act as preferential pathways for fluid migration and salute transport (LÓPEZ AND SMITH, 1995).

- The series of anticlines and synclines in **Shueib** and **Kafrain** area in addition to the anticlinal structure which accompanies the **Amman-Halabat flexure**, forces the groundwater in the Deep Aquifer to flow westward towards the Jordan Rift Valley, while the Kafrain syncline acts as groundwater drainage system (as described previously in section 4.3.4)

The groundwater of the Deep Aquifer has low salinity (EC ≈ 500 µS/cm) where direct recharge occurs over carbonate and sandstone rocks (Figure 4.45 from I to X). Away from the direct recharge areas, in the Highlands, the salinity of ground water increases to about 1000 µS/cm. The residual halite and gypsum in the Lower Ajlun Group (A_{1-6}) and the evaporites within the Jurassic, Triassic rocks along Zarqa River are the main contributors to the salizination of groundwater in the Deep Aquifer. Along the flow paths of the deep groundwater more dissolutions of soluble salts from the rock matrix, especially evaporites and easy weathering feldspars becomes the dominant hydrochemical process which causes an increase of salinity towards the SSW and W directions, where the salinity go up to a few thousands µS/cm. The evaporites within the Jurassic and Triassic rocks according to SALAMEH (2001) are the main contributors to the salizination of groundwater entering the Jordan Valley laterally, from the

eastern side, but the deposits of the ancestors of the Dead Sea; the Lisan Lake (Lisan deposits) are the main contributors of water salinity within the Jordan Valley itself.

The ground water salinity in the Deep Sandstone Aquifer System according to SALAMEH & HAMMOURI (2007) who studied of the sources of groundwater salinity along the flow path, from Disi to Dead Sea is caused by the changes of rock sequences which take place in the central and southern parts of the study area (along the Zarqa River and east and northeast of the Dead Sea, respectively) as the Permo-Triassic intercalation start to separate the Deep Sandstone Aquifer Complexes into two aquifer units (i.e. Ram and Kurnub Aquifers). The Permo-Triassic rocks contain halides, gypsum and anhydrite which are easily soluble minerals.

4.4.2.2 Anthropogenic effects on groundwater chemistry in the study area

Urbanization, agricultural and industrial activities are the main anthropogenic parameters that affect the groundwater chemistry in the study area. Due to the missing characteristics pollution parameters in the analysis the following discussion refers only to the increase of nitrate values.

The nitrate concentration is comparatively high in densely populate areas and in areas with intensive agricultural activities. The sources of nitrate close to urbanization centers can be attributed to the infiltration of municipal waste water (domestic type pollutants) or as a result of seepages from wastewater cesspools, such as es Salt and Hizzer springs (SALAMEH, 2001). And in areas of agricultural activities, the nitrate can be attributes to the use of fertilizers, use of treated waste water or blended water for irrigation, irrigation return flows into the groundwater body and over-exploitation of groundwater resources as shown clearly from the continuously dropping groundwater level (section 4.3.3).

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and conclusions

Jordan is situated in a very active tectonic region. The structural set up of Jordan is affecting the hydrology, hydrogeology and groundwater salinity in general. The northwestern part of Jordan has been selected to carry out this integrated study which aims to achieve a better understanding of how much does the structural complicity affected and complicating the recharge flow, discharge mechanism of the groundwater system and hydrochemistry in the study area. Following is the summary and the conclusions of this study.

5.1.1 Study objectives

The objective of this study was to elaborate the relationship between the structural set-up of the geologic underground and the groundwater and surface water flows in the northwestern part of Jordan. In addition interflows and leaking effects between aquifers along geologic structures and the possible impacts of structural set-up on the water salinity should be evaluated. In order to reach this goal a 3-dimensional structural model of the study area was developed based on surface and subsurface information and by using aerial photographs. In addition, 7 geologic cross sections trending E-W, and one N-S along the highlands were constructed. Also, the distribution and extents of the hydrogeological units were determined and the groundwater flow system deviated from the distribution of the constructed piezometric pressure pattern. Groundwater analyses from a dense network were used to characterize the hydrochemical composition as well as the groundwater salinities in the different aquifers and aquifer parts in the study area.

The study area is covering an area of about 5280 km^2 (Figure 1.1). The tectonic activities affecting the area are reflected in its topography, which consist of three distinctive and elongated topographic provinces that trend mainly north-south. The highlands with an E-W width of some 20 km followed by the uplifted, steep faulted margins of the Dead Sea Transform and then the Jordan Valley area further west. Therefore, four geomorphological terrains can be identified in the NW of Jordan: the Dead Sea Depression, the Jordan Valley area, the Jordan Valley escarpment and the Northern Highlands (Figure 1.5). Climate in the NW of Jordan is the result of its geographical position in the Eastern Mediterranean region, its geological structures and its relief. Generally, the study area can be classified as a semi-arid area, only in the southern Jordan Valley and the Dead Sea Depression arid condition prevailing.

5.1.2 Data base

The aims of this integrated study were reached by producing different maps and cross sections almost at a scale of 1:50,000 such as the followings:

1. The **Digital Topographic map**, the Triangular Irregular Network (**TIN**), the Digital Elevation Model (**DEM)** and the **Digital Drainage map** at a scale of 1:50,000 (Plates 1, 2, 3 & 6, respectively) show that the area under consideration is a topographically complex region due its location at the slopes to the Jordan Rift System. The study area shows considerable

topographic variations. Elevations vary from 422m bsl (the Dead Sea level 2010), to a maximum altitude of 1240 m asl, in the central eastern part of the study area. The study area consists of mountainous region on the eastern side (Jordan Highlands), trending north-south parallel to the Jordan Rift Valley. Bordering the Jordan Valley to the east is an escarpment which quickly rises to the Eastern Highlands.

The Digital topographic map (Plate 1) shows that different cities, villages and settlement have developed such as Amman, es Salt and Irbid cities along the highlands and the numerous towns along the escarpment and the Jordan Valley such as Na'ur, Wadi as Sir, Fuheis, Deir 'Alla, Ash Shuna, El Karama…..etc. The drainage system in the study area drains mainly westwards to the Jordan River, and in the northeast to the Yarmouk River where it ends ultimately in the Dead Sea (Plate 6).

2. The **Digital Geological map** shows that the sediments outcropping in the study area comprise Mesozoic and Cenozoic Formations only. Rocks of Triassic and Jurassic ages are exposed in the central and in the most southern part of the area; mainly along Zarqa River and further south along the northern shore of the Dead Sea. Cretaceous to Quaternary aged rocks covers most of the study area. No sediments older than Triassic are exposed in the study area (Plate 4). The sedimentary rocks in the study area are represented by six major geological groups, beside Pleistocene and Holocene to Recent sediments (Table 2.1). These are:

1. Ramtha Group of Triassic age
2. Azab Group of Jurassic age
3. Kurnub Sandstone Group of Lower Cretaceous age
4. Ajlun Group of Upper Cretaceous age
5. Belqa Group of Upper Cretaceous-Tertiary age
6. Pleistocene sediments of Tertiary-Quaternary age

3. The prepared Digital Topographic Map (Plate 1) and Digital Geological Map (Plate 4) at a scale of 1:50,000 for the study area were used to construct eight **Geological Cross Sections** (Figure 2.3). These geological cross sections mainly trend NW-SE and E-W, and one trends N-S along the highlands (Plate 5, from AA' to HH') and show the major structural features, the thickness and lateral extends of different geological formations in the study area.

5.1.3 Structural overview

The Geological map and the Geological Cross Sections (Plate 4 & 5, respectively) show that the tectonic features dominant in the study area comprise three major deformational phases. These phases were originally attributed according to QUENNELL (1951; 1959) and BURDON (1959b) to three phases of a clockwise rotating compressional stress systems directed successively ESE, SE and SSE, which started in the Maestrichtian (Figure 2.12) and dominating the region until Miocene (EYAL & RICHES, 1983; EYAL, 1996). The 107 km sinistral movement of the DSR was assumed to be accompanied with anticlockwise rotation of the Arabian plate (FREUND, 1965; FREUND et al., 1968).

Today the dominant structural features can be predominantly described as features partly reactivated structures of the Precambrian and traced through the Paleozoic and Mesozoic sequence as well as new deformation patterns according to the changing stress field. They are related to the:

1. Opening and closure of the Mesozoic Mediterranean basin formation trending WNW during Triassic till Cretaceous period (FLEXER et al., 1984; HOROWITZ, 2001).

2. The opening of the Red Sea due to an extensional stress pattern with low angle sinistral shear fault trending NNW-SSE (Red Sea- Suez stage) causing the separation of the African and Arabian plate in Late Eocene-Lower Miocene (VOGGENREITER & HÖTZL, 1989; BAYER et al., 1988).

3. The formation of the Dead Sea Rift as a left lateral strike slip displacement along the N-S trending transform fault (Upper Miocene-Recent) due to the deformation pattern caused by the ocean rifting in the Gulf of Aden (BAYER, 1988; GARFUNKEL & BEN-AVRAHAM, 1996).

Most of the folding system in the study area belongs to the **Syrian Folded Arc System**. Ages of folding range from Turonian to Neogene (Quaternary?) (BENTOR & VROMAN, 1951; 1954; 1960; BARTOV, 1974), whereas the deformation peaks are discerned at the late Turonian-middle Campanian (in connection with the closure and subduction of the Mesozoic Mediterranean basin), post-middle Eocene- Oligocene (Red Sea-Gulf of Suez Rifting) and late Neogene-early Quaternary (DS-transform movement) (FLEXER in HOROWITZ, 2001). This fold belt characterized by mainly, northeast trend, asymmetry due to the presence of basement controlled through deep seated reverse faults, and multiphase history of deformation (QUENNELL, 1959; BURDON, 1959b).

Example of this phase of deformation is: **Ajlun structure**. It is the major fold, which occurs in the study area, it is described as an important structure forming part of the tectonic framework of Jordan. It is the second major tectonic feature after the Dead Sea Rift (DSR) (Figure 2.15).

Fold structures are described also west of the Dead Sea by DE SITTER (1962) as a result of thrust faults in the basement and therefore, proving compressional tectonic at that time. Examples of these fold belt structures are: **Amman–Halabat Fold Structure**, **Wadi Shueib Structure** and **Suweileh (Al Baqa'a) Structure** (Figure 2.15).

According to the result from the Midyan Peninsula (BAYER et al., 1988; PURSER & HÖTZL, 1988) (in connection to the Red Sea-Suze stage) the transform movement along the Dead Sea Rift (DSR) started in the Mid-Miocene time 12-15 Million years ago and continued more or less continuously the last 12 Million years with a movement of about 9 mm/year.

As a result of the different phases of deformations, different fault and joint systems are developed in the study area. These are:

The SE-NW trending faults are less abundant than other fault trends in the study area. They may represent old extension fractures of Precambrian age, reactivated in the Turonian as a result of

the compressional stress that form the Syrian Arc Belt (QUENNELL, 1959; BURDON, 1959b). Later this fault trend was reactivated again under extensional deformation pattern, and crossed by an E-W trending faults that formed in Miocene (QUENNELL, 1959; BURDON, 1959b). Examples of such faults in the study area are: **El Kafrain Fault** and **Ramtha-Wadi Sirhan Fault** (Figure 2.15).

The E-W trending faults are the second important set of faulting in the study area because they are intimately associated with and related to the Dead Sea–Jordan Valley Fault (QUENNELL, 1959; BURDON, 1959b). These faults are oscillating around E-W, ESE-WNW or ENE-WSW (Figure 2.15). Faults with these trends are either normal, reverse or strike-slip faults. They were reactivated in Mid Miocene-Pleistocene as strike-slip faults during the formation of the Dead Sea Transform Fault System (QUENNELL, 1959). Some of the E-W trending faults may reflect deep seated reverse faults or possibly reflect ancient tectonic lines of weakness reactivated in Tertiary and Quaternary times (BURDON, 1959b). The E-W trending fault system throughout the study area is responsible for the presence and controls the major wadis with the same trend, and frequently accompanied with extensive land-sliding (Plate 4). The **Zarqa River Fault** and **Yarmouk River Fault** are good examples for that.

N-S faults were developed or reactivated since the late Miocene in connection with the Dead Sea Rift (DSR). This phase was responsible in forming the uplifted shoulders. In this phase, the change in trend of the northern Red Sea spreading centre from NW-SE to N-S deformed the east shoulder of the southern DSR, so that a limited sinistral strike slip displacement occurred.

The Dead Sea Rift (DSR) is the major tectonic feature that may be responsible for all parallel structures in the region (FREUND, 1965). Thus, all along the margins of the structure, normal faults are present with displacements of as large as a few kilometers in certain locations (ZAK & FREUND, 1981; GARFUNKEL et al., 1981). Also, it has its peculiar hydrogeological features (ROSENTHAL, et al., 2006).

Since the formation of the Dead Sea structure, it has been acting as a base level for all the surface and groundwater in the region. Plate (6) shows the drainage system in the NW of Jordan. The Yarmouk and Jordan Rivers form the natural boundary between Jordan and adjacent countries (Syria, Palestine and Israel). A number of major wadis drain the study area such as Zarqa River, Wadi el ‘Arab, Wadi Ziglab, Wadi Kufranja, Wadi Shueib, Wadi Kafrain…..etc.

The analysis of **joints data** from Black and White aerial photographs at a scale of 1:30,000 show that the densities of joints delineated in the margin of the Jordan Valley are more than that in the Mountain Range. Also, they are dense in the northeastern rim of the Dead Sea more than that in the area between the Zarqa and Yarmouk River. Joints in different directions are found in the analyzed area. They are mainly trending in a NE, NW, NS and EW directions, in descending order (Figure 2.20).

5.1.4 Subsurface Geology

Subsurface geology information was required to confirm the depth, thickness and lateral extent of aquifers and aquicludes in the study area. To achieve this, an **isopach maps** and **structural contour maps** of the different groups forming aquifers and different geological formations comprises the geological column in the study area were drawn (from Figure 3.3 to Figure 3.25) based mainly on the data from oil wells within the study and adjacent areas (Figure 3.1) and/or from water wells (for more details see chapter 3).

From the isopach and structural contour maps shown in chapter 3 for the different formations and groups new results regarding the sedimentary structure of the basin in the Cretaceous time as well as indication for an early begging of subsidence of the Sirhan rift system can be delineated for the first time. These maps show that during the sedimentation phase that the basin was subdivided during the Upper Cretaceous sedimentation in WSW-ESE oriented basin and swells. They are the source for the different sediments sequence observed in the northwestern part of Jordan. In the same way the increasing thickness of Amman Silicified Limestone (ASL), Muwaqqar Chalk Marl (MCM) and Shallala (WSC) Formations in the eastern part of Jordan indicate the beginning of subsidence of the Sirhan rift/graben system in the upper most Cretaceous (Maestrichtian age).

5.1.5 Hydrology

The average rainfall over the study area in normal, dry and wet water years (1937/38-2008/09) was calculated and represented as isohyetal maps (Figures 4.9, 4.10 & 4.11, respectively). The long term average rainfall indicated that the higher annual rainfall occurs in the mountainous region mainly in the central of the study area (with >500 mm/yr in the normal water year, <350 mm/yr in dry water year and <650 mm/yr in wet water year) from there it decreases towards the east and west. The minimum value of rainfall is found in the southwestern part of the study area, at the northeastern corner of the Dead Sea (with <250 mm/yr in the normal water year, <150 mm/yr in dry water year and <300 mm/yr in wet water year). The accumulated modeled rainfall volumes were calculated in the study area to be 1760.4 MCM/yr, 1324.6 MCM/yr and 2263.7 MCM/yr for the normal, dry and wet years, respectively (Table 4.7). In addition to that the runoff precipitation ratio (according to GTZ & NRA, 1977) was used to calculate the runoff volume in MCM/yr for the study area in normal, dry and wet years respectively (Figures 4.15, 4.16 & 4.17, respectively). The result of calculations are summarized in (Table 4.10) which shows that the total catchment area of 4445 km^2 produces a runoff of around 83.55 MCM/yr in a normal year, increasing to around 151.44 MCM/yr in a wet year representing 181.25 % of a normal year. Dry year mean sever depletion in rainfall volume reaching 43.96% of a normal average, with a calculated volume around 36.73 MCM/yr.

The local distribution of potential evaporation (in mm per year) average of calculated values period 1965 – 1972 in the study area (modified after GTZ & NRA, 1977) (Figure 4.14) shows that the mean annual potential evaporation exceeds by far the annual rainfall in the area. The mean annual potential evaporation rates of 1900 mm/yr are typical in the highlands, while the mean annual rainfall is not more than 550 mm/yr, increases in the Jordan Valley to 2600 mm/yr, while the mean annual rainfall decreases to less than 250 mm/yr (Table 4.8).

5.1.6 Hydrogeology

Hydrogeologically, the different geological groups of the Mesozoic and Tertiary sediment sequence in the study area were divided into three **major aquifer systems**. These are: the Lower Aquifer System (Kurnub Sandstone Aquifer), and the Middle Aquifer System (Hummar A_4, Na'ur A_{1-2} and Amman/ Wadi as Sir B_2/A_7 Aquifers) and the Shallow Aquifer System (B_4/B_5, Basalt and the Jordan Valley Aquifers). Each aquifer has different hydrogeological characteristics. These aquifer systems are serving as source of water for all types and uses in the study area.

The groundwater contour maps for different aquifers were constructed from the available static water level (SWL) measurements of wells and springs distributed in the area, for the year 2009 (see Figure 4.23 and Figures from 4.25 to 4.30).

The **Lower Aquifer System** (Kurnub Sandstone Aquifer) is the second most important aquifer in the study area. The aquifer receives direct and indirect recharge where it outcrops on the eastern escarpment of the Jordan Valley and the northern part of the Dead Sea. In Jarash, Al Baqa'a and along the Zarqa River and its tributaries (see Figures 2.4 & 2.5; the geological cross sections HH´, Plate 5 & Figure 4.24) direct recharge from precipitation occurs. In the Highlands recharge to the aquifer occurs by leakage from the Upper Cretaceous aquifers, percolating through fractures and faults (SALAMEH & UDLUFT, 1985; EL-NASER, 1991; SALAMEH & BANNAYAN, 1993; LENZ, 1999).

The outcrop and groundwater flow pattern map (Figure 4.23) indicate that this aquifer is an unconfined-confined aquifer system, draining towards the Dead Sea, Jordan Valley and Yarmouk River. Waters from the Lower Aquifer System discharges along the Zarqa River due to the weathering of Kurnub Sandstone in that area. The groundwater flow within this aquifer is predominantly vertical in the vicinity of the Jordan Rift Valley. The aquifer gains water through the downward leakage from the B_2/A_7 aquifer and losses water through upward leakage to the B_2/A_7 due to the high confinement degree and to the fact that the potentiometric surface of the Kurnub Aquifer is higher than that of the B_2/A_7 (EL-NASER, 1991). The upwards seeps from the Kurnub Aquifer to the surface, pass through the recent sediments forming saline springs (Wadi Mallaha) (SALAMEH & BANNAYAN, 1993).

In the study area the **Middle Aquifer Systems** (B_2/A_7, A_4 & A_{1-2} Aquifers) is directly recharged from precipitation along their outcrops in the highlands and the slops of the Jordan Valley. They are also recharged by leakage of runoff and irrigation return flow.

The **B_2/A_7 aquifer** (Amman/Wadi as Sir Formations, separated by **B_1**, Wadi Um Ghudran) is the major aquifer in the study area. It is directly recharged from precipitation along its outcrops in the highlands and the slops of the Jordan Valley. Moreover the limestones of this aquifer are highly karstified therefore, it facilitate fast infiltration of rain water to the aquifer. Figure 4.21 shows that the groundwater flow direction in the Upper Aquifer System is directed from the mounds in the area between Ajlun Mountain and Jarash, mainly to the northeast, to Ramtha Basin and Mafraq area and partly to the northwest to the western escarpment, to Wadi El-Arab and Mukheiba. Mainly, the groundwater flows in this aquifer come from the Syrian border in the

north (Jabal Arab-Druze) to the area north and northeast of Mafraq, from there the water converges with the water coming from southwest and partially with water coming from Ajlun area. From there the water flows mainly, westwards to the Jordan Rift Valley and the Yarmouk River areas, where most of the discharge occurs (EL-NASER, 1991). It partially flows towards the depressional area south of the Zarqa River after converging, due to high elevated structure of Ajlun structure. While, in the southeast of the study area i.e. the area southeast of Amman flexure, the groundwater flow within the B_2/A_7 aquifer system is directed partly northwest towards Zarqa River and partly southwest towards Wadi el Wala.

The outcrop area of the **A_{1-2} and A_4 aquifers** is limited in extent and receives small amount of direct recharge in the study area. The minor aquifer (**A_4**, Hummar & **A_{1-2}**, Na'ur)/aquitards (**A_3**, Fuheis & **A_{5-6}**, Shueib) of the study area or what is known as **A_{1-6}** (Lower Ajlun) sequence behave very complex (EL-NASER, 1991). Figures (4.19 & 4.20) indicated that groundwater flow within A_{1-2} and A_4 aquifers are localized within two areas characterized by high faulting and fracturing. These are the area NW of Zarqa River and the area between the southern eastern part of Zarqa River and Amman flexure. Generally, the faults and fractures increase the porosity and permeability of rocks in the study area as a result of extensional tectonics. Therefore, where faults occurs the A_{1-6} sequence communicate with B_2/A_7 aquifer and/or the Kurnub aquifer and that communication is better with B_2/A_7 (EL-NASER, 1991). The geological map (Plate 4) and geological cross sections AA', BB', CC', DD' and HH' (Plate 5) supported EL-NASER (1991) conclusion due to increasing intensity of faults from A_{1-6} upwards into the B_2/A_7.

The **Shallow Aquifer System** includes the B_4/B_5, Basalt and the Jordan Valley Aquifers. The **B_4 aquifer system** is of local importance in the area north of Irbid and Ramtha. This area is characterized by deeply incised wadis, which act as drainage channels. Numerous springs mark spots of emergence of groundwater. The groundwater flow in the B_4 aquifer system is mainly towards the Yarmouk River, but a small part also to wadi el 'Arab and the Jordan River Figure 4.28.

The recharge to the **Basalt aquifer system** is provided by precipitation in the elevated area of Jabel Arab - Druz (JAD). From there the groundwater moves radially in all directions (Figure 4.29). In the study area the Basalt overlies directly the B_4 aquifer and feeds it.

The Jordan Valley Alluvial Aquifer is limited to the Jordan Valley and is recharged from several sources such as lateral flow from the adjacent aquifers, leakage of runoff, irrigation return flow and small amount of direct recharge. The replenishment of the Jordan Valley Aquifer was reduced due to several factors, such as heavy groundwater abstraction, diversion and storage of large quantities of flood water and surface drainage of major urban centers in Jordan such as Amman, Irbid and es Salt, flow westward through wadis towards the Jordan Valley and in dams built across the major wadis outlets (such as the Shueib, Kafrain and King Talal dams) and by diversion of most of the freshwater from Lake Tiberias. The groundwater flow in this aquifer takes place from the escarpments into the valley deposits Figure (4.30).

The groundwater flow direction of the different aquifer and the distribution of spring's discharges from different aquifers are highly governed by the geological structures and the outcrop of the aquifer related to the morphology of the study area (Figure 4.34). Along the

highlands of the NW part of Jordan a water divide developed separating the groundwater flows to the west or to the east. The dominant structural features that have an effect on groundwater flow directions in the different aquifers are:

The **Ajlun Uplift and Dipping strata** are the major dominant structures in the northern area. These structures are represented by the **Ajlun uplift** and the **Circumclinal Strike of the geological units** in the most northern part of Jordan. In addition to the presence of the northern extension of the **Dead Sea–Jordan Valley Fault Transform** in the west. This structure has an effect on the Middle (B_2/A_7, A_4 & A_{1-2}) and the Shallow (B_4/B_5 & Basalt) Aquifer Systems (Figure 4.34). **Ajlun uplift** plays a role in rendering the groundwater flow in the Upper Cretaceous and underlying aquifers in radial directions; towards the Jordan Valley where it discharges along wadis such as Rajib and Kufranja, towards the Zarqa River in the south and towards north and east (Figures from 4.25 to 4.27).

The groundwater flows in the Shallow Aquifers (**Basalt** and **Um Rijam, B_4**) comes mainly from Jabel Arab-Druz (JAD) (Figures 4.29 & 4.28, respectively) into Mafraq area where the groundwater converges with the groundwater coming from the southwest from Ajlun area (from B_2/A_7, A_4 & A_{1-2}) (Figure 4.36). From there the groundwater flows mainly, westwards to the Jordan Rift Valley and towards the Yarmouk River areas, where most of the discharge occurs. The spring's discharges from the B_2/A_7 Aquifer in the extreme northwestern part of the study area are structurally controlled by the **Dead Sea–Jordan Valley Fault**. That part characterized by **circumclinal strikes** of the Rijam/Shallala (**B_4-B_5**) aquifer, the Muwaqqar Chalk Marl (**B_3**) aquiclude and the underlying Amman/Wadi as Sir (**B_2/A_7**) aquifer (Figure 4.35). Therefore, this structural situation causes the groundwater of the B_2/A_7 aquifer to be confined by the B_3 formation, which consists of marly layers and form aquicludes and to flow in a southerly direction instead of continuing to the west towards the Jordan Valley and/or to the north towards the Yarmouk River (SALAMEH, 2006). The Circumclinal Strike is accompanied with circumclinal dipping with increasing angles to the N and NW towards the Yarmouk River in the north, to the W toward the Jordan River in the west and to the NE in the east.

The **Zarqa River Structure** in the Zarqa River area represents an area of a major asymmetrical anticline striking SW-NE and plunging a few degrees in the SSW direction (i.e. **Suweileh or Al Baqa'a anticline structure** (Figure 2. 22 & 2.23). This anticline is the southern extension of the Ajlun Structure (as shown in Figures 2.18, 2.19 and in the geological cross sections BB′, CC′ & HH, Plate 5). Also, geological cross sections BB′ & CC′ (Plate 5) indicate a depressional area south of Zarqa River area. Therefore, this anticlinal structure as mentioned above diverts the groundwater towards SSW. Also, in the Zarqa River area two major dextral strike-slip faults are found; namely, **Zarqa River** and **Al Baqa'a-Er Rmamin faults** (Figure 2.20). Waters from the Deep Aquifer System discharges along the Zarqa River due to the deep erosion of Kurnub Sandstone, forming an easier discharge pathway for the groundwater in that area (as shown in the geological cross section II', Figures 4.24). Local direct recharges to the deep Sandstone Aquifer takes place in Al Baqa'a area and along the lower reaches of Zarqa River and its tributaries (see the geological cross sections HH′, Plate 5).

The outcrop of the Triassic and Jurassic Formations in Deir Alla area, in the southern part of the study area (**Deir Alla anticline**), create a watershed and divide the regional aquifer into two

basins (GUTTMAN et al., in HÖTZL, et al., 2009): a northern basin that dips towards the Yarmouk River and the southern basin that dips towards Karama, Kafrain and the northern Dead Sea. The main aquifers within this zone are: the Lower Cretaceous, A_{1-2}, A_4 and B_2/A_7 aquifers. To the southeast of Deir Alla a series of anticlines and synclines were found such as **Wadi Shueib syncline**, **Wadi Shueib anticline**, **Wadi Kafrain syncline** and the **Amman-Halabat Flexure** (Figures 2.17 & 2.20), which outlines the southeastern part of the study area (Plate 4). The uplift of Deir Alla anticline, Wadi Shueib anticline and the anticlinal structure which accompanied with Amman-Halabat flexure and strikes ENE-WSW, forces groundwater to flow westward towards the Jordan Rift Valley, while the Kafrain syncline acts as groundwater drainage system. Several springs discharges from the Ajlun aquifer in this zone to the Pleistocene layer in the Jordan Rift Valley (Figure 4.30). These springs occur mainly at the base of Ajlun Aquifer, at medium elevation (PARKER, 1970; SALAMEH, 1996).

The **Suweimeh-Amman-Halabat Flexure** is the dominant structure in the southeastern part of the study area. It allows the groundwater in the B_2/A_7 aquifer to flow partly northwest towards Zarqa River and partly northeast towards wadi el Waleh (Figures 4.27 & 4.38). Further to the south of the study area the E-W trending Siwaqa Fault acts as a barrier to the B_2/A_7 aquifer system. Also, Amman Flexure acts as a barrier and forms the south-east limit of the groundwater in the A_{1-2} and A_4 aquifers. The fault along the eastern extension of the Sweimeh-Amman-Halabat flexture forms a weakness zone with very active water pathways, where it then changes its flow direction to the east and northeast. At the longitude of the Zarqa River, in its north-south course, both the westerly (originate in the eastern part; Wadi Dhuleil, which extends to the northeast of Wadi Zarqa) and easterly (originate in the western highlands of Amman and its surroundings Seil-Zarqa) groundwater currents converge and discharge in the form of springs along Zarqa River.

The sinistral movement of the **Dead Sea-Jordan Valley Transform Fault** in the western side of the study area brings the Pleistocene and Quaternary Formations of the Alluvial Aquifer in contact with different older formations. This creates a direct hydraulic connection so that the groundwater flows in the Jordan Valley Aquifer takes place from the escarpment aquifers into the valley deposits (Figure 4.34) and discharges there under free-water table conditions (SALAMEH, 2006).

5.1.7 Hydrochemistry

The water chemistry in the different aquifers is function of **geogenic and anthropogenic** processes.

The groundwater in the **B_2/A_7 Aquifer System** has directly evolved from precipitation water. This type of water represents the pure water-rock interaction of the B_2/A_7 Aquifer System without any source of pollution or additional source of mixing from adjacent aquifers. Therefore, the water of the B_2/A_7 Aquifer is considered as fresh waters of type "normal earth alkaline with prevailing bicarbonate water" (Figure 4.46), with EC values of less than 1000 µS/cm.

The EC values and the different salinity parameters distribution maps of the B_2/A_7 Aquifer (Figure 4.42 from I to X) indicates an increase in salinity from the unconfined to the confined parts of the aquifer. That is in addition to a rapid increase of its salinity towards the Jordan Valley. The salinity of B_2/A_7 increased also towards the areas of high population and areas of agricultural activities, northeast southwest of Amman.

Several structural features in the study area play an important role in increasing the salinity in the B_2/A_7 Aquifer System. These features area mainly: the Ajlun Dome, the circumclinal strikes of the geological units in the most northern part of Jordan, the Dead Sea-Jordan Valley Fault and the highly faulted blocks in the extreme northwest of the study area.

The water in the **Hummar (A_4)** and **the Na'ur (A_{1-2}) Aquifers** in the study area originates mainly from the down percolation from the B_2/A_7 Aquifer and only small amount are received from direct recharge. The groundwater in the Upper (B_2/A_7) Aquifer percolates down into the underlying semi-developed aquifers of the lower parts of the Upper Cretaceous rocks. In the Hummar (A_4) and Na'ur (A_{1-2}) Aquifers the groundwater become more saline due to the additional minerals dissolved from the intercalated evaporites such as gypsum and anhydrite. The groundwater in the Middle Aquifer ranges from normal earth alkaline with prevailing bicarbonate to earthalkaline with increasing portions of alkalis with prevailing sulfates and chlorides (Figures 4.47 & 4.48). Generally, the EC values in the Hummar (A_4) and the Na'ur (A_{1-2}) Aquifers in the study area depend on the percolated portions of the heterogeneous geologic units of the sequence and the pathways the water takes (Figures 4.43 & 4.44).

Several structural features in the area have major effects on the salinity in the Na'ur (A_{1-2}) and Hummar (A_4) Aquifer Systems. These features are mainly: the Ajlun Dome, Suweileh or Al Baqa'a anticline, Wadi Shueib structure, Wadi Kafrain syncline, Suwayma-Amman-Hallabat structure, the high faulted blocks in the extreme northwestern of the study area and the Dead Sea-Jordan Valley Fault.

The water in this **Lower Aquifer (Kurnub Sandstone Aquifer)** originates by downward percolation through the overlying Upper Cretaceous rock unit and as sub-surface flows from the adjacent areas and aquifers. The water salinity in the Lower Sandstone Aquifer System is mainly a result of the sodium chloride content. The groundwater which reaches the Kurnub Aquifer is over-saturated with respect to calcite and dolomite, thus both minerals start to precipitate in the rock matrix. However, the Deep Aquifer water is under-saturated with halite and gypsum. Therefore, the type of water in the Lower Sandstone Aquifer System in the study area remains earthalkaline with prevailing bicarbonate and sulfates.

The EC and the salinity parameters distribution maps in the study area indicate an increase of water salinity in the Deep Sandstone Aquifer mainly towards the west and southwest and partly towards the east. The changes in EC values in outcrop areas (i.e. local recharge areas) are attributed mainly, to the carbonate and sandstone rocks found in the eastern parts compared with clayey and salty rocks in the western parts of the study are.

The main structural features that affected the salinity in the study area are mainly the southern extension of the **Ajlun Dome**, the **east-west trending Zarqa River and Al Baqa'a-Er Rmamin**

faults, the **Dead Sea Transform Fault**, **Shueib, Kafrain** and **Halabat structures**. Along these structures rocks of Jurassic, Triassic and Lower Cretaceous ages are mainly exposed.

5.2 Recommendations

Therefore, as a result of this study the following should be taken in consideration:

- Re-evaluation of the various structural elements in Jordan in a chronological order for better understanding of the different phases of deformations which assess having a superior 3-phase model.

- Subsurface geology and the dominant structural element should be taken in consideration to locate new water wells in the future.

- The data collected in this study (mainly wells location, formations thickness and tops and the extent of the major structural features) should be used in developing a conceptual 3D hydrogeological model for selected areas (e.g. major springs close to cities such as Hizzer spring near Es Salt city).

- The data collection with the evaluated results can be used also for groundwater measures, showing were trends to stronger pollution are developing.

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Appendix 3.1: Details of wells penetrating Lower Palaeozoic strata in Jordan (modified from NRA Files).

Well ID	Well name	Driller Year	Palestine Grid		Geographic Coords		Jordan Traverse Mercator		KB elevation	Ground elevation	Total depth	Formation at	Shows Remarks
			East	North	Lat(N)	Long(E)	East	North	(m)	(m)	(m)	total depth	
DH-1	Dahikiyeh 1	NRA 1983	359347	111900	31 35 01	37 12 14	519417.351	495163.716	529.4	524.3	4433	Amud Fm	Dry
JF-1	AL jafr 1	JHO 1989	280235	946567	30 06 10	36 21 11	437791.783	331354.474	870.8	862.9	4047.8	Granite	Dry
JF-2	AL jafr 2	NRA1990	292588	968766	30 18 07	36 29 02	450385.661	353182.106	850.3	848	1303	Umm Tarifa Fm	Dry
HZ-4	Hamzeh 4	NRA 1985	358037	121750	31 40 21	37 11 32	518268.864	505028.150	555.4	550.3	3984	Umm Tarifa Fm	Oil in WS2
HZ-13	Hamzeh 13	NRA 1985	355001	122305	31 40 41	37 09 37	515243.072	505632.546	565.2	560.1	3551	Umm Tarifa Fm	Dry
NH-1	Northern High Lands 1	NRA 1986	266560	179720	32 12 24	36 14 01	427780.012	564478.041	609.8	603	4017	Saramuj Fm	Dry
NH-2	Northern High Lands 2	NRA 1987	245929	224830	32 36 54	36 01 06	407908.660	609920.195	514.4	507.3	3722.5	Amud Fm	
RH-1	Risha 1	NRA 1983	449660	232320	32 38 59	38 11 22	611768.076	613968.995	672	666.9	3177	Umm Tarifa Fm	Dry
RH-2	Risha 2	NRA 1984	412350	250180	32 49 10	37 47 49	574701.333	632447.369	653.4	648.3	3314	Amud Fm	Dry hole
RH-3	Risha 3	NRA 1986	530061	228688	32 35 38	39 02 36	691933.000	609146.743	852.9	845.9	4200	Amud Fm	Gas Well
RH-4	Risha 4	NRA 1987	528005	227374	32 34 58	39 01 16	689858.899	607867.592	863.6	858.5	3515	Umm Tarifa Fm	Gas shows
RH-5	Risha 5	NRA 1987	530853	228012	32 35 15	39 03 06	692713.029	608454.706	854.9	846.9	3252	Umm Tarifa Fm	Gas shows
RH-6	Risha 6	NRA 1987	530698	229288	32 35 57	39 03 01	692580.064	609733.027	846.2	840.8	3010	Umm Tarifa Fm	Gas Well
RH-7	Risha 7	NRA 1987	529188	229205	32 35 56	39 02 04	690976.946	609527.255	850.1	842.1	2682	Umm Tarifa Fm	Gas Well
RH-8	Risha 8	NRA 1988	519525	226493	32 34 39	38 55 50	681375.700	607124.358	849.9	844.6	3097	Umm Tarifa Fm	Gas Well
RH-9	Risha 9	NRA 1988	530339	230462	32 36 35	39 02 49	692240.336	610885.210	849.6	841.5	2720	Umm Tarifa Fm	Gas shows
RH-10	Risha 10	NRA 1988	522239	229325	32 36 08	38 57 38	684214.412	609989.118	843.1	837.8	2779.5	Umm Tarifa Fm	Gas shows
RH-11	Risha 11	NRA 1988	460758	253341	32 50 10	38 18 51	623067.939	634788.150	725.9	717.8	3208	Umm Tarifa Fm	Dry
RH-12	Risha 12	NRA 1988	520036	227497	32 35 11	38 56 11	681901.729	608118.512	857.9	852.5	2733	Umm Tarifa Fm	Gas shows
RH-13	Risha 13	NRA 1988	519478	225254	32 33 59	38 55 47	681306.451	605893.788	855.6	847.6	2732.5	Umm Tarifa Fm	Dry
RH-14	Risha 14	NRA 1988	499461	230333	32 37 05	38 43 07	661406.753	611302.817	834.4	829.1	3323	Umm Tarifa Fm	Dry
RH-15	Risha 15	NRA 1989	526180	240555	32 42 07	39 00 24	688256.428	621057.471	813.5	804.4	2703	Umm Tarifa Fm	Gas shows
RH-16	Risha 16	NRA 1989	529303	227633	32 35 05	39 02 06	691152.474	608104.956	859.3	850.2	2714	Umm Tarifa Fm	Gas Well
RH-17	Risha 17	NRA 1989	494713	243590	32 44 20	38 40 22	656894.658	624627.548	790	781	1749	Batra FM	Dry
RH-18	Risha18	NRA 1990	528666	226755	32 34 37	39 01 40	690505.666	607234.319	874.3	865.2	2750	Umm Tarifa Fm	Gas Well
RH-19	Risha19	NRA 1990	449650	141200	31 49 45	38 09 46	610173.753	522955.493	694.4	687.5	3570	Amud Fm	Dry
SA-1 (PP3)	Safra 1	PLY 1957	279999	137389	31 49 25	36 22 16	440505.728	521940.084	748.3	748.3	2582	Granite	Dry
SW-1 (PP6)	Suweileh 1	PLY 1959	229812	165407	32 04 48	35 50 34	390803.866	550778.813	634.3	634.3	2329	Salib FM	Oil & Gas Shows
WG-1	Wadi Ghadaf 1	INA 1969	325020	111380	31 35 02	36 50 33	485094.026	495205.124	577.7	577.7	3081	Ordov . Sdst	Dry
WG-2	Wadi Ghadaf 2	NRA 1983	319000	114000	31 36 30	36 46 46	479119.018	497922.069	568.1	563	3740	Salib FM	Oil shows in Cenomian
WH-1	Wadi Hazim 1	INA 1971	361831	123101	31 41 03	37 13 56	522083.640	506316.024	530.6	530.6	1861	Palaeozoic	Dry
WR-2	Wadi Rijal 2	NRA 1981	341590	128925	31 44 23	37 01 12	501945.387	512468.054	550.2	545	3510	?Umm Tarifa	Oil shows
WR-4	Wadi Rijal 4	NRA 1982	334300	130200	31 45 09	36 56 36	494678.916	513862.011	530.1	525	3103	?Umm Tarifa	Oil shows
WS-1	Wadi Sirhan 1	INA 1971	381000	43650	30 57 53	37 25 03	539917.650	426616.266	565	559.7	1800	Umm Tarifa Fm	Dry
WS-2	Wadi Sirhan 2	NRA 1984	366318	60496	31 07 09	37 16 02	525519.280	443666.997	609	603.9	3331	Amud Fm	Dry
WS-3	Wadi Sirhan 3	NRA 1986	360355	988596	30 28 19	37 11 29	518412.666	371932.173	882.6	877.5	4580	Unass Volc	Dry
WS-4	Wadi Sirhan 4	NRA 1988	396240	9446	37 39 13	37 34 10	554597.006	392197.071	827.7	625.4	1788	Umm Tarifa Fm	Light Oil in Ordovician
WS-5	Wadi Sirhan 5	NRA 1988	396996	11259	30 40 11	37 34 40	555381.353	393997.147	634.2	628.8	1542	Umm Tarifa Fm	Oil shows
WS-6	Wadi Sirhan6	NRA 1989	396549	8299	30 38 36	37 34 21	554885.002	391046.604	633.8	631.5	1530	Umm Tarifa Fm	Oil shows
WS-7	Wadi Sirhan 7	NRA 1989	391872	17874	30 43 49	37 31 33	550366.907	400688.016	626.9	621.6	1525.5	Umm Tarifa Fm	Oil shows
WS-8	Wadi Sirhan 8	NRA 1989	398293	6720	30 37 43	37 35 25	556604.548	389440.554	640.3	638	1582	Umm Tarifa Fm	Oil shows
WS-9	Wadi Sirhan 9	NRA 1989	398269	996494	30 32 11	37 35 16	556520.222	379389.057	682.2	679.9	1696.5	Umm Tarifa Fm	Oil and Gas shows
WS-10	Wadi Sirhan 10	NRA 1989	411885	17613	30 43 27	37 44 04	570356.858	400108.196	595.5	588.4	4293	Salib FM	Dry
WS-11	Wadi Sirhan11	NRA 1989	391098	18904	30 44 23	37 31 04	549609.826	401729.238	631.8	626.4	1660	Umm Tarifa Fm	Dry
WS-12	Wadi Sirhan 12	NRA 1989	394509	14365	30 41 54	37 33 09	552946.195	397139.743	631.3	625.9	1700	Umm Tarifa Fm	Dry
WS-13	Wadi Sirhan 13	NRA 1989	395952	14254	30 41 49	37 34 03	554385.828	397005.927	622.3	620	1651.5	Umm Tarifa Fm	Dry
WS-14	Wadi Sirhan 14	NRA 1989	427250	994300	30 30 39	37 53 20	585335.265	376573.114	595.3	590.2	2181	Umm Tarifa Fm	Dry

Key to drilling company abbreviations:

FIN= Fina Exploration Jordan B.v.;
INA = Indusrija Nafta Zagreb Yogoslavia;
JHO = Jordan Hunt Oil Company Co.;
NRA = Jordan Natural Resources Authority;
PLY = Zpauley Oil Exploration with Phillips Petrolum Co.

Appendix 3.2: Details of wells penetrating Permian, Triassic and Jurassic strata in Jordan (modified from NRA Files).

Well ID	Well name	Driller Year	Palestine Grid		Geographic Coords		Jordan Traverse Mercator		KB elevation	Ground elevation	Total depth	Formation at	Shows Remarks
			East	North	Lat(N)	Long(E)	East	North	(m)	(m)	(m)	total depth	
AJ-1	Ajlun 1	NRA 1991	222690	188581	32 17 22	35 46 08	384068.944	574067.487	1147.1	1140	3796.5	Basement	Dry
DH-1	Dahikiyeh 1	NRA 1983	359347	111900	31 35 01	37 12 14	519417.351	495163.716	529.4	524.3	4433	Amud Fm	Dry
ER- 1A	Er Ramtha 1A	TOT 1978	246533	208828	32 28 14	36 01 25	408244.657	593911.937	603.9	603.9	2754	Kurnub Group	Dry
F-1	Fuluk 1	NRA 1991	344678	138753	31 49 41	37 03 16	505192.749	522237.984	580.7	571.6	2667	Salib Fm	Dry
GTZ-2D	Geothermal GTZ-2D	NRA 1987	208000	111900	31 35 55	35 36 35	368213.636	497786.795	210	210	1313.3	Salib Fm	
GTZ-3D	Geothermal GTZ-3D	NRA 1987	204500	112100	31 36 01	35 34 23	364717.396	498044.060	-270	-270	1100	Salib Fm	
HZ-1	Hamza 1	NRA 1983	355097	122536	31 40 48	37 09 41	515342.845	505861.842	564.5	559.4	3216.5	Ramtha Group	Oil Well (in Hummar Formati
HZ-4	Hamza 4	NRA 1985	358037	121750	31 40 21	37 11 32	518268.864	505028.150	555.4	550.3	3984	Umm Tarifa Fm	Oil in WS2
HZ-8	Hamza 8	NRA 1985	352984	125590	31 42 29	37 08 22	513280.643	508948.345	561.6	556.6	3595	Ramtha Group	Oil in wadi Essir Formation
HZ-11	Hamza 11	NRA 1985	356390	119815	31 39 19	37 10 28	516590.749	503121.525	575	569	3500	Ramtha Group	Oil Well (in Hummar Formati
HZ-13	Hamza 13	NRA 1985	355001	122305	31 40 41	37 09 37	515243.072	505632.546	565.2	560.1	3551	Umm Tarifa Fm	Dry
HZ-14	Hamza 14	NRA 1986	354000	123000	31 41 04	37 08 59	514253.762	506343.416	558	553	3301	Ramtha Group	oil well & Oil shows in Kur
JV-1	Jordan Valley 1	PLY 1959	207038	137081	31 49 32	35 36 02	367568.118	522833.369	-283	-283	1098	Azab Gruob	
KH-1	Khalidiya 1	NRA 1970	272000	174800	32 09 42	36 17 26	433136.601	559469.303	607.2	605	1333.3	Suwayma Fm	Dry
NH-1	Northern High Lands 1	NRA 1986	266560	179720	32 12 24	36 14 01	427780.012	564478.041	609.8	603	4017	Saramuj Fm	Dry
NH-2	Northern High Lands 2	NRA 1987	245929	224830	32 36 54	36 01 06	407908.660	609920.195	514.4	507.3	3722.5	Amud Fm	
QA-1	Qitar el Abd 1	FEJ 1990	380635	210733	32 28 14	37 26 59	542134.486	594129.676	943	934	2560	Suwayma Fm	Dry
RH-1	Risha 1	NRA 1983	449660	232320	32 38 59	38 11 22	611768.076	613968.995	672	666.9	3177	Umm Tarifa Fm	Dry
RH-2	Risha 2	NRA 1984	412350	250180	32 49 10	37 47 49	574701.333	632447.369	653.4	648.3	3314	Amud Fm	Dry hole
RH-3	Risha 3	NRA 1986	530061	228688	32 35 38	39 02 36	691933.000	609146.743	852.9	845.9	4200	Amud Fm	Gas Well
RH-4	Risha 4	NRA 1987	528005	227374	32 34 58	39 01 16	689858.899	607867.592	863.6	858.5	3515	Umm Tarifa Fm	Gas shows
RH-5	Risha 5	NRA 1987	530853	228012	32 35 15	39 03 06	692713.029	608454.706	854.9	846.9	3252	Umm Tarifa Fm	Gas shows
RH-6	Risha 6	NRA 1987	530698	229288	32 35 57	39 03 01	692580.064	609733.027	846.2	840.8	3010	Umm Tarifa Fm	Gas Well
RH-7	Risha 7	NRA 1987	529188	229205	32 35 56	39 02 04	690976.946	609527.255	850.1	842.1	2682	Umm Tarifa Fm	Gas Well
RH-8	Risha 8	NRA 1988	519525	226493	32 34 39	38 55 50	681375.700	607124.358	849.9	844.6	3097	Umm Tarifa Fm	Gas Well
RH-9	Risha 9	NRA 1988	530339	230462	32 36 35	39 02 49	692240.336	610885.210	849.6	841.5	2720	Umm Tarifa Fm	Gas shows
RH-10	Risha 10	NRA 1988	522239	229325	32 36 08	38 57 38	684214.412	609989.118	843.1	837.8	2779.5	Umm Tarifa Fm	Gas shows
RH-11	Risha 11	NRA 1988	460758	253341	32 50 10	38 18 51	623067.939	634788.150	725.9	717.8	3208	Umm Tarifa Fm	Dry
RH-12	Risha 12	NRA 1988	520036	227497	32 35 11	38 56 11	681901.729	608118.512	857.9	852.5	2733	Umm Tarifa Fm	Gas shows
RH-13	Risha 13	NRA 1988	519478	225254	32 33 59	38 55 47	681306.451	605893.788	855.6	847.6	2732.5	Umm Tarifa Fm	Dry
RH-14	Risha 14	NRA 1988	499461	230333	32 37 05	38 43 07	661406.753	611302.817	834.4	829.1	3323	Umm Tarifa Fm	Dry
RH-15	Risha 15	NRA 1989	526180	240555	32 42 07	39 00 24	688256.428	621057.471	813.5	804.4	2703	Umm Tarifa Fm	Gas shows
RH-16	Risha 16	NRA 1989	529303	227633	32 35 05	39 02 06	691152.474	608104.956	859.3	850.2	2714	Umm Tarifa Fm	Gas Well
RH-17	Risha 17	NRA 1989	494713	243590	32 44 20	38 40 22	656894.658	624627.548	790	781	1749	Batra FM	Dry
RH-18	Risha18	NRA 1990	528666	226755	32 34 37	39 01 40	690505.666	607234.319	874.3	865.2	2750	Umm Tarifa Fm	Gas Well
RH-19	Risha19	NRA 1990	449650	141200	31 49 45	38 09 46	610173.753	522955.493	694.4	687.5	3570	Amud Fm	Dry
RH-23	Risha 23	NRA 1991	526601	180617	32 09 45	38 59 19	687665.021	561180.812	912.5	903.4	3339	Umm Tarifa Fm	Gas Well
S90	Irbid -Ramtha Xroads E	NRA 1969	248700	211470	32 29 39	36 02 48	410455.091	596516.816	578.8	#N/A	2194	?Salit	Dry
SH-5	Strat Well On Tapline	NRA 1971	350000	165000	32 03 49	32 06 55	510957.170	548992.202	620	680	1407	Ramtha Group	Dry
SQ -1	Siwaqa 1	NRA 1991	356762	79822	31 17 41	37 10 15	516311.308	463150.498	580.1	574.6	1850	Umm Tarifa Fm	
SW-1 (PP6)	Suweileh 1 (pp6)	PLY 1959	229812	165407	32 04 48	35 50 34	390803.866	550778.813	634.3	634.3	2329	Salib Fm	Oil & Gas Shows
WH-1	Wadi Hazim 1	INA 1971	361831	123101	31 41 03	37 13 56	522083.640	506316.024	530.6	530.6	1861	Palaeozoic	Dry
WR-2	Wadi Rajil 2	NRA 1981	341590	128925	31 44 23	37 01 12	501945.387	512468.054	550.2	545	3510	?Umm Tarifa	Oil shows
WR-4	Wadi Rajil 4	NRA 1982	334300	130200	31 45 09	36 56 36	494678.916	513862.011	530.1	525	3103	?Umm Tarifa	Oil shows

Key to drilling company abbreviations:

FEJ = Fina Exploration Jordan B.v.;
INA = Indusrija Nafta Zagreb Yogoslavia;
NRA = Jordan Natural Resources Authority;
PLY = Zpauley Oil Exploration with Phillips Petrolum Co.;
TOT = Total Exploration (Jordan Branch)

Appendix 3.3: Details of wells penetrating Cretaceous and Paleogene strata in Jordan (modified from NRA Files).

Well ID	Well name	Driller Year	Palestine Grid		Geographic Coords		Jordan Traverse Mercator		KB elevation	Ground elevation	Total depth	Formation at	Shows Remarks
			East	North	Lat(N)	Long(E)	East	North	(m)	(m)	(m)	total depth	
AD-1	Adla 1	AMO 1988	329898	97023	31 27 19	36 53 33	489838.698	480934.140	607.8	600.2	1782.8	Kurnub Group	Dry
AJ-1	Ajlun 1	NRA 1991	222690	188581	32 17 22	35 46 08	384068.944	574067.487	1147.1	1140	3796.5	Basement	Dry
AZ-1 (PP1)	Azraq 1 (pp1)	UN 1962	321200	142160	31 51 43	36 48 25	481679.250	525972.192	516.2	515	1299	Kurnub Group	Dry
DH-1	Dahikiyeh 1	NRA 1983	359347	111900	31 35 01	37 12 14	519417.351	495163.716	529.4	524.3	4433	Amud Fm	Dry
ER- 1A	Er Ramtha 1A	TOT 1978	246533	208828	32 28 14	36 01 25	408244.657	593911.937	603.9	603.9	2754	Kurnub Group	Dry
F-1	Fuluk 1	NRA 1991	344678	138753	31 49 41	37 03 16	505192.749	522237.984	580.7	571.6	2667	Salib Fm	Dry
GTZ-2D	Geothermal GTZ-2D	NRA 1987	208000	111900	31 35 55	35 36 35	368213.636	497786.795	210	210	1313.3	Salib Fm	
GTZ-3D	Geothermal GTZ-3D	NRA 1987	204500	112100	31 36 01	35 34 23	364717.396	498044.060	-270	-270	1100	Salib Fm	
HO-1	Heavy Oil 1 (W Rajil)	NRA 1986	342260	127657	31 43 42	37 01 37	502593.353	511188.971	542.3	540	1568.5	Hamza Fm	Heavy Oil
HO-2	Heavy Oil 2 (W Rajil)	NRA 1986	343340	134450	31 47 22	37 02 22	503785.525	517960.750	547.1	540	3364	Kurnub Group	Oil in wadi Essir, WS2
HZ-1	Hamza 1	NRA 1983	355097	122536	31 40 48	37 09 41	515342.845	505861.842	564.5	559.4	3216.5	Ramtha Group	Oil Well (in Hummar Formati
HZ-2	Hamza 2	NRA 1984	356800	122850	31 40 58	37 10 45	517050.328	506147.649	571	565	3257	Kurnub Group	Oil in Shueib Formation
HZ-3	Hamza 3	NRA 1985	353222	126150	31 42 47	37 08 32	513527.750	509504.078	562.1	556.9	3262	Lower Ajlun G	Oil in wadi Essir Formation
HZ-4	Hamza 4	NRA 1985	358037	121750	31 40 21	37 11 32	518268.864	505028.150	555.4	550.3	3984	Umm Tarifa Fm	Oil in WS2
HZ-5	Hamza 5	NRA 1985	354400	123600	31 41 23	37 09 15	514663.490	506936.537	550.9	550.9	3310	Kurnub Group	Oil shows in Shueib Formati
HZ-6	Hamza 6	NRA 1985	353425	122750	31 40 56	37 08 37	513674.867	506103.066	549.6	543.6	3165	Kurnub Group	Oil shows in Shueib Formati
HZ-7	Hamza 7	NRA 1985	350158	122777	31 40 59	37 06 33	510409.510	506183.637	548.5	542.5	2900	Kurnub Group	Oil in wadi Essir Formation
HZ-8	Hamza 8	NRA 1985	352984	125590	31 42 29	37 08 22	513280.643	508948.345	561.6	556.6	3595	Ramtha Group	Oil in wadi Essir Formation
HZ-9	Hamza 9	NRA 1985	351390	127520	31 43 32	37 07 23	511718.838	510903.154	565	559	3580	Kurnub Group	Dry
HZ-10	Hamza 10	NRA 1985	355894	122760	31 40 55	37 10 11	516143.214	506072.584	567.2	561.4	3199	Kurnub Group	Oil Well (in Hummar Formati
HZ-11	Hamza 11	NRA 1985	356390	119815	31 39 19	37 10 28	516590.749	503121.525	575	569	3500	Ramtha Group	Oil Well (in Hummar Formati
HZ-12	Hamza 12	NRA 1986	354583	122823	31 40 58	37 09 21	514833.716	506156.987	557.7	552.7	3084	Kurnub Group	Oil Well
HZ-13	Hamza 13	NRA 1985	355001	122305	31 40 41	37 09 37	515243.072	505632.546	565.2	560.1	3551	Umm Tarifa Fm	Dry
HZ-14	Hamza 14	NRA 1986	354000	123000	31 41 04	37 08 59	514253.762	506343.416	558	553	3301	Ramtha Group	oil well & Oil shows in Kur
HZ-15	Hamza 15	NRA 1986	353534	123351	31 41 16	37 08 42	513793.707	506701.870	561	556	3214	Kurnub Group	Dry
HZ-16	Hamza 16	NRA 1987	352852	121761	31 40 25	37 08 15	513085.880	505124.185	544.2	539.1	3161	Kurnub Group	Dry
JF-1	AL jafr 1	JHO 1989	280235	946567	30 06 10	36 21 11	437791.783	331354.474	870.8	862.9	4047.8	Granite	Dry
JF-2	AL jafr 2	NRA1990	292588	968766	30 18 07	36 29 02	450385.661	353182.106	850.3	848	1303	Umm Tarifa Fm	Dry
JV-1	Jordan Valley 1	PLY 1959	207038	137081	31 49 32	35 36 02	367568.118	522833.369	-283	-283	1098	Azab Gruob	
KH-1	Khalidiya 1	NRA 1970	272000	174800	32 09 42	36 17 26	433136.601	559469.303	607.2	605	1333.3	Suwayma Fm	Dry
L-1	El Lisan 1	PLY 1960	194334	74338	31 15 36	35 27 54	353839.227	460300.140	-324	-324.3	3672	Salt	Oil shows
NH-1	Northern High Lands 1	NRA 1986	266560	179720	32 12 24	36 14 01	427780.012	564478.041	609.8	603	4017	Saramuj Fm	Dry
NH-2	Northern High Lands 2	NRA 1987	245929	224830	32 36 54	36 01 06	407908.660	609920.195	514.4	507.3	3722.5	Amud Fm	
NRA-1	El Lisan NRA 1	NRA 1967	197550	70900	31 13 44	35 29 55	357066.718	456845.309	-362		1346	Salt	
QA-1	Qitar el Abd 1	FEJ 1990	380635	210733	32 28 14	37 26 59	542134.486	594129.676	943	934	2560	Suwayma Fm	Dry
QUR	Qurayyat (saudi)	PAR 1967	372481	84472	31 20 08	37 20 16	532164.194	467693.557	534	534	2000	Maastrichtian	
RH-1	Risha 1	NRA 1983	449660	232320	32 38 59	38 11 22	611768.076	613968.995	672	666.9	3177	Umm Tarifa Fm	Dry
RH-2	Risha 2	NRA 1984	412350	250180	32 49 10	37 47 49	574701.333	632447.369	653.4	648.3	3314	Amud Fm	Dry hole
RH-3	Risha 3	NRA 1986	530061	228688	32 35 38	39 02 36	691933.000	609146.743	852.9	845.9	4200	Amud Fm	Gas Well
RH-4	Risha 4	NRA 1987	528005	227374	32 34 58	39 01 16	689858.899	607867.592	863.6	858.5	3515	Umm Tarifa Fm	Gas shows
RH-5	Risha 5	NRA 1987	530853	228012	32 35 15	39 03 06	692713.029	608454.706	854.9	846.9	3252	Umm Tarifa Fm	Gas shows
RH-6	Risha 6	NRA 1987	530698	229288	32 35 57	39 03 01	692580.064	609733.027	846.2	840.8	3010	Umm Tarifa Fm	Gas Well
RH-7	Risha 7	NRA 1987	529188	229205	32 35 56	39 02 04	690976.946	609527.255	850.1	842.1	2682	Umm Tarifa Fm	Gas Well
RH-8	Risha 8	NRA 1988	519525	226493	32 34 39	38 55 50	681375.700	607124.358	849.9	844.6	3097	Umm Tarifa Fm	Gas Well
RH-9	Risha 9	NRA 1988	530339	230462	32 36 35	39 02 49	692240.336	610885.210	849.6	841.5	2720	Umm Tarifa Fm	Gas shows
RH-10	Risha 10	NRA 1988	522239	229325	32 36 08	38 57 38	684214.412	609989.118	843.1	837.8	2779.5	Umm Tarifa Fm	Gas shows
RH-11	Risha 11	NRA 1988	460758	253341	32 50 10	38 18 51	623067.939	634788.150	725.9	717.8	3208	Umm Tarifa Fm	Dry
RH-12	Risha 12	NRA 1988	520036	227497	32 35 11	38 56 11	681901.729	608118.512	857.9	852.5	2733	Umm Tarifa Fm	Gas shows
RH-13	Risha 13	NRA 1988	519478	225254	32 33 59	38 55 47	681306.451	605893.788	855.6	847.6	2732.5	Umm Tarifa Fm	Dry
RH-14	Risha 14	NRA 1988	499461	230333	32 37 05	38 43 07	661406.753	611302.817	834.4	829.1	3323	Umm Tarifa Fm	Dry
RH-15	Risha 15	NRA 1989	526180	240555	32 42 07	39 00 24	688256.428	621057.471	813.5	804.4	2703	Umm Tarifa Fm	Gas shows
RH-16	Risha 16	NRA 1989	529303	227633	32 35 05	39 02 06	691152.474	608104.956	859.3	850.2	2714	Umm Tarifa Fm	Gas Well
RH-17	Risha 17	NRA 1989	494713	243590	32 44 20	38 40 22	656894.658	624627.548	790	781	1749	Batra FM	Dry
RH-18	Risha 18	NRA 1990	528666	226755	32 34 37	39 01 40	690505.666	607234.319	874.3	865.2	2750	Umm Tarifa Fm	Gas Well

Part (1)

Appendix 3.3: Details of wells penetrating Cretaceous and Paleogene strata in Jordan (modified from NRA Files).

Well ID	Well name	Driller Year	Palestine Grid		Geographic Coords		Jordan Traverse Mercator		KB elevation	Ground elevation	Total depth	Formation at	Shows Remarks
			East	North	Lat(N)	Long(E)	East	North	(m)	(m)	(m)	total depth	
RH-19	Risha 19	NRA 1990	449650	41200	31 49 45	38 09 46	610173.753	522955.493	694.4	687.5	3570	Amud Fm	Dry
RH-20	Risha 20	NRA 1990	529946	229551	32 02 37	39 02 37	691832.153	610010.301	848.6	839.5	2728	Umm Tarifa Fm	Gas Well
RH-21	Risha 21	NRA 1991	527466	229114	32 35 55	39 00 58	689256.299	609464.852	823.3	847.8	2804.5	Umm Tarifa Fm	Dry
RH-22	Risha 22	NRA 1990	527233	223461	32 35 55	39 00 58	688958.467	603785.185	881.3	872.2	2765	Umm Tarifa Fm	Gas shows
RH-23	Risha 23	NRA 1991	526601	180617	32 09 45	38 59 19	687665.021	561180.812	912.5	903.4	3339	Umm Tarifa Fm	Gas Well
RH-24	Risha 24	NRA 1992	528031	225918	32 34 15	39 01 19	689868.778	606399.200	874.4	868.9	2748.5	Umm Tarifa Fm	Gas Well
RH-25	Risha 25	NRA 1992	529784	226530	32 34 33	39 02 27	691631.537	606987.590	861.4	856.9	2752	Umm Tarifa Fm	Gas Well
RH-26	Risha 26	NRA 1992	538534	184460	32 11039	39 07 03	699667.857	564810.333	929.3	920.2	2803	Umm Tarifa Fm	Gas Well
RH-27	Risha 27	NRA 1993	525269	227047	32 34 46	38 59 37	687191.057	607320.306			2750		Dry
RH-28	Risha 28	NRA 1994	524093	203462	32 22 13	38 58 17	685544.599	584060.310	890.54	881.4	2742	Dubaydib Fm	Gas shows
RH-29	Risha 29	NRA 1994	536019	185987	32 12 28	39 05 24	697062.542	566263.290	921.45	912.4	2851	Dubaydib Fm	Dry
RH-30	Risha 30	NRA 1994	549880	195449	32 17 17	39 14 36	711316.065	575469.501	944.84	933.7	3043	Dubaydib Fm	Dry
RH-31	Risha 31	NRA 1995	540291	181439	32 10 00	39 08 05	701364.875	561792.002	936.36	927.3	2849	Dubaydib Fm	Dry
RH-32	Risha 32	NRA 1995	529660	233741	32 36 49	39 02 27	691565.849	611197.086	841.87	836.4	2700	Dubaydib Fm	Gas shows
RH-33	Risha 33	NRA 1995	530700	225824	32 34 09	39 02 59	692477.918	606276.719	860.5	855	2755	Dubaydib Fm	Dry
RH-34	Risha 34	NRA 1995	528751	184183	32 11 42	39 00 49	689882.236	564707.488	919.5	910.4	2748	Dubaydib Fm	Gas shows
RH-35	Risha 35	NRA 1994	537665	184805	32 11 52	39 06 30	698790.836	565197.153	925.7	916.6	2811	Dubaydib Fm	Gas
RH-36	Risha 36	NRA 2001	529518	221644	32 11 52	39 06 30	691350.182	601853.068			3320		Dry
RH-37	Risha 37	NRA 2003	527553	185532	32 12 19	39 00 08	688781.195	565826.023			3352		Dry
RH-38	Risha 38	NRA 2002	527595	221627	32 31 48	39 00 08	689426.441	601868.940			3300		Gas Well
SA-1 (PP3)	Safra 1	PLY 1957	279999	137389	31 49 25	36 22 16	440505.728	521940.084	748.3	748.3	2582	Granite	Dry
SW-1 (PP6)	Suweileh 1	PLY 1959	229812	165407	32 04 48	35 50 34	390803.866	550778.813	634.3	634.3	2329	Salib FM	Oil & Gas Shows
SH -5	Streat Well On Tapline	NRA 1971	350000	165000	32 03 49	32 06 55	510957.170	548992.202	620	680	1407	Ramtha Group	Dry
SM -1	Smeica 1	WAJ 1989	370500	188000	32 16 03	37 20 14	531886.629	571168.121	755	755	890	Usayhim Fm	
SQ -1	Siwaqa 1	NRA 1991	356762	79822	31 17 41	37 10 15	516311.308	463150.498	580.1	574.6	1850	Umm Tarifa Fm	
WG-1	Wadi Ghadaf 1	INA 1969	325020	111380	31 35 02	36 50 33	485094.026	495205.124	577.7	577.7	3081	Ordov . Sdst	Dry
WG-2	Wadi Ghadaf 2	NRA 1983	319000	114000	31 36 30	36 46 46	479119.018	497922.069	568.1	563	3740	Salib FM	Oil shows in Cenomian
WH-1	Wadi Hazim 1	INA 1971	361831	123101	31 41 03	37 13 56	522083.640	506316.024	530.6	530.6	1861	Palaeozoic	Dry
WR-1	Wadi Rajil 1	INA 1970	341855	128767	31 44 18	37 01 22	502207.664	512305.806	545.1	545.1	3076	Kurnub Group	Oil shows
WR-2	Wadi Rajil 2	NRA 1981	341590	128925	31 44 23	37 01 12	501945.387	512468.054	550.2	545	3510	?Umm Tarifa	Oil shows
WR-3	Wadi Rajil 3	NRA 1982	342368	126487	31 43 04	37 01 40	502683.101	510018.858	545.6	540.5	2810	Kurnub Group	Oil shows
WR-4	Wadi Rajil 4	NRA 1982	334300	130200	31 45 09	36 56 36	494678.916	513862.011	530.1	525	3103	?Umm Tarifa	Oil shows
WS-1	Wadi Sirhan 1	INA 1971	381000	43650	30 57 53	37 25 03	539917.650	426616.266	565	559.7	1800	Umm Tarifa Fm	Dry
WS-2	Wadi Sirhan 2	NRA 1984	366318	60496	31 07 09	37 16 02	525519.280	443666.997	609	603.9	3331	Amud Fm	Dry
WS-3	Wadi Sirhan 3	NRA 1986	360355	988596	30 28 19	37 11 29	518412.666	371932.173	882.6	877.5	4580	Unass Volc	Dry
WS-4	Wadi Sirhan 4	NRA 1988	396240	9446	37 39 13	37 34 10	554597.006	392197.071	827.7	625.4	1788	Umm Tarifa Fm	Light Oil in Ordovician
WS-5	Wadi Sirhan 5	NRA 1988	396996	11259	30 40 11	37 34 40	555381.353	393997.147	634.2	628.8	1542	Umm Tarifa Fm	Oil shows
WS-6	Wadi Sirhan6	NRA 1989	396549	8299	30 38 36	37 34 21	554885.002	391046.604	633.8	631.5	1530	Umm Tarifa Fm	Oil shows
WS-7	Wadi Sirhan 7	NRA 1989	391872	17874	30 43 49	37 31 33	550366.907	400688.016	626.9	621.6	1525.5	Umm Tarifa Fm	Oil shows
WS-8	Wadi Sirhan 8	NRA 1989	398293	6720	30 37 43	37 35 25	556604.548	389440.554	640.3	638	1582	Umm Tarifa Fm	Oil shows
WS-9	Wadi Sirhan 9	NRA 1989	398269	996494	30 32 11	37 35 16	556520.222	379389.057	682.2	679.9	1696.5	Umm Tarifa Fm	Oil and Gas shows
WS-10	Wadi Sirhan 10	NRA 1989	411885	17613	30 43 27	37 44 04	570356.858	400108.196	595.5	588.4	4293	Salib FM	Dry
WS-11	Wadi Sirhan11	NRA 1989	391098	18904	30 44 23	37 31 04	549609.826	401729.238	631.8	626.4	1660	Umm Tarifa Fm	Dry
WS-12	Wadi Sirhan 12	NRA 1989	394509	14365	30 41 54	37 33 09	552946.195	397139.743	631.3	625.9	1700	Umm Tarifa Fm	Dry
WS-13	Wadi Sirhan 13	NRA 1989	395952	14254	30 41 49	37 34 03	554385.828	397005.927	622.3	620	1651.5	Umm Tarifa Fm	Dry
WS-14	Wadi Sirhan 14	NRA 1989	427250	994300	30 30 39	37 53 20	585335.265	376573.114	595.3	590.2	2181	Umm Tarifa Fm	Dry

Key to drilling company abbreviations:

Part (2)

FEJ = Fina Exploration Jordan B.v.;
INA = Indusrija Nafta Zagreb Yogoslavia;
JHO = Jordan Hunt Oil Company Co.;
NRA = Jordan Natural Resources Authority;
PAR = Parsons Basil;
PLY = Zpauley Oil Exploration with Phillips Petrolum Co.;
TOT = Total Exploration (Jordan Branch)
UN = United Nations Development Programme;
WAJ = Water Authority of Jordan

Appendix 4.1: Long term rainfall averages for stations in the study area (normal year, wet year and dry year averages for the water years from 1937/38 to 2008/09) (from MWI Files).

Station ID	Station Name	Jtm (E)	Jtm (N)	Altitude	Normal Year Average	Wet Year Average	Dry Year Average
A0001	SHUNA (WADI ARAB)	370041.759	609755.438	-197.0	353.1	426.5	261.3
AB0001	AL-TAIYIBA	379414.177	602097.056	365.0	487.7	607.4	377.8
AB0002	DEIR ABI SAID	376330.831	597148.271	330.0	454.0	569.7	338.3
AB0003	EL-QARN	366061.255	581118.017	-178.0	314.7	436.5	192.9
AB0004	KH.EL-WAHADNEH	372318.634	578513.195	590.0	391.9	498.8	260.3
AB0008	KUFR AWAN	376500.134	589344.582	470.0	478.1	630.6	384.5
AD0001	MUKHEIBA	376209.191	619652.820	-75.0	384.3	467.1	291.1
AD0002	HARTHA	391694.233	618691.689	450.0	412.1	535.5	304.8
AD0003	KUFR SAUM	387378.356	617764.380	455.0	478.7	624.8	340.8
AD0004	SAMAR	386165.135	616984.771	425.0	488.7	594.1	376.2
AD0005	UM QEIS	376124.949	614653.677	360.0	453.1	572.9	351.8
AD0006	ADASIYA SCHOOL	369147.940	616071.362	-180.0	385.3	461.7	270.7
AD0007	BAQURA AGR. STATION	370075.404	611755.147	-200.0	372.1	447.9	270.0
AD0008	KHARJA	395629.243	614825.232	455.0	430.0	562.0	325.2
AD0009	HAWWARA	397393.410	600795.187	560.0	352.7	455.4	274.9
AD0010	HUSN	394810.196	595838.375	680.0	374.9	495.2	277.5
AD0011	EN NUEIYIME	397680.513	588090.096	785.0	293.3	390.5	226.5
AD0012	RAMTHA BOYS SCHOOL	406446.308	603943.198	520.0	267.0	347.2	195.2
AD0013	KHANASIRA	410135.150	585381.794	860.0	194.7	270.0	139.9
AD0016	MAFRAQ POLICE POST	425541.313	579824.706	695.0	149.6	208.4	102.2
AD0017	RIHAB	414508.466	577809.043	900.0	238.8	339.6	165.2
AD0018	IBBIN	388377.417	581945.380	1105.0	545.6	697.1	380.7
AD0019	MAFRAQ AIR PORT	428098.611	577282.271	686.0	163.7	223.3	121.7
AD0021	TURRA	405377.767	611761.074	450.0	272.6	351.6	210.9
AD0022	HOSHA	411740.066	591654.723	600.0	147.3	189.7	116.1
AD0036	MAQARIN GAUGING STATION	392256.502	622382.381	?	506.7	639.2	440.4
AE0001	IRBID SCHOOL	391945.129	603886.769	585.0	402.0	543.6	288.7
AE0002	IRBID AGR. STATION	392219.874	602382.087	555.0	442.7	551.6	321.1
AE0003	KAFR YUBA	387215.972	602166.086	560.0	494.5	634.1	373.4
AE0004	KAFR ASAD	379023.465	608604.263	350.0	473.1	613.7	371.9
AG0001	WADI JURUM	368536.523	591578.161	-180.0	299.8	366.8	232.9
AH0001	ISHTAFEINA	381978.742	582052.275	920.0	549.5	707.0	422.6
AH0002	WADI EL-YABIS	368631.097	585275.688	-200.0	303.4	417.4	220.1

1

Appendix 4.1: Long term rainfall averages for stations in the study area (normal year, wet year and dry year averages for the water years from 1937/38 to 2008/09) (from MWI Files).

Station ID	Station Name	Jtm (E)	Jtm (N)	Altitude	Normal Year Average	Wet Year Average	Dry Year Average
AH0003	RAS MUNEIF EVAP. STATION	388415.843	584244.873	1150.0	529.6	668.0	397.8
AJ0001	AJLUN POLICE POST	382528.535	579042.841	760.0	631.5	780.6	478.2
AJ0002	KUFRINJA	377860.995	575020.341	640.0	605.8	756.1	455.5
AJ0003	WADI KUFRINJA	368239.154	573780.606	-200.0	270.0	333.1	201.6
AL0002	MIDWAR	405439.548	573660.451	760.0	225.6	330.4	169.0
AL0004	JARASH	395925.457	572819.042	585.0	358.6	468.8	274.4
AL0005	KITTA	390918.329	572402.478	665.0	555.5	704.2	402.3
AL0006	DIBBIN NATIONAL PARK	390381.796	570211.311	780.0	554.6	719.1	390.2
AL0007	JARASH BR. (OLD ROAD)	389565.484	563224.540	145.0	218.2	330.6	68.3
AL0008	ALUK	398413.473	560077.373	630.0	355.8	469.3	242.2
AL0009	DEIR ALLA (NRA)	370780.605	564236.994	-180.0	272.7	348.3	203.0
AL0010	DEIR ALLA AGR. STATION	369772.435	563753.695	-224.0	276.7	375.3	212.8
AL0011	RUMMAN	389707.280	559722.002	650.0	281.7	380.2	197.3
AL0017	SWEILIH	390453.414	544408.880	1000.0	512.7	706.3	393.5
AL0018	JUBEIHA	392956.143	544567.468	980.0	475.0	618.0	361.3
AL0019	AMMAN AIRPORT	404363.854	538978.730	790.0	268.5	359.9	195.8
AL0020	AMMAN AIN GHAZAL	401651.390	538223.561	720.0	242.1	341.7	182.3
AL0021	AMMAN JABEL TAJ	400826.833	536737.181	800.0	321.9	360.0	
AL0022	AMMAN HUSSEIN COLLEGE	399035.569	537266.774	834.0	377.4	489.5	282.7
AL0024	AMMAN LANDS DEPT.	398814.980	536020.405	821.0	421.1	530.6	275.1
AL0025	AMMAN JABEL LUWEIBDA NRA	398514.233	535975.371	840.0	404.9	523.4	322.0
AL0026	BURMA	385319.630	566495.365	600.0	436.8	590.4	339.0
AL0027	SUBEIHI	377688.085	558621.554	500.0	415.4	579.4	306.2
AL0028	RUMEIMIN	386611.667	553973.060	675.0	369.7	513.4	285.5
AL0029	TAB QIRA'	395010.284	547833.564	975.0	260.6	403.6	141.4
AL0030	RUJM ESH-SHOUK (BADRAN)	399550.546	550258.383	950.0	416.6	557.5	316.0
AL0031	AIN ZARBI	403958.243	544685.379	800.0	146.3	233.8	58.8
AL0032	YAJUZ	397968.141	545284.531	850.0	313.5	487.8	188.9
AL0033	AMMAN RADIO STATION	399236.471	531263.400	925	339.9	418.2	261.6
AL0035	K.H.NURSERY EVAP. STATION (BAQ'A)	391059.278	550799.138	700.0	344.4	472.4	263.8
AL0036	PRINCE FEISAL NURSERY	395808.912	565820.797	300.0	341.2	481.7	250.9
AL0037	AMMAN CIGARETTE COMPANY	400723.557	536538.887	780.0	352.2	469.8	258.2
AL0038	AMMAN AL WIHDAT	399285.962	534262.610	825.0	367.7	484.8	192.2
AL0039	ABU HAMID	394551.820	550341.233	700.0	205.4	256.6	137.1

2

Appendix 4.1: Long term rainfall averages for stations in the study area (normal year, wet year and dry year averages for the water years from 1937/38 to 2008/09) (from MWI Files).

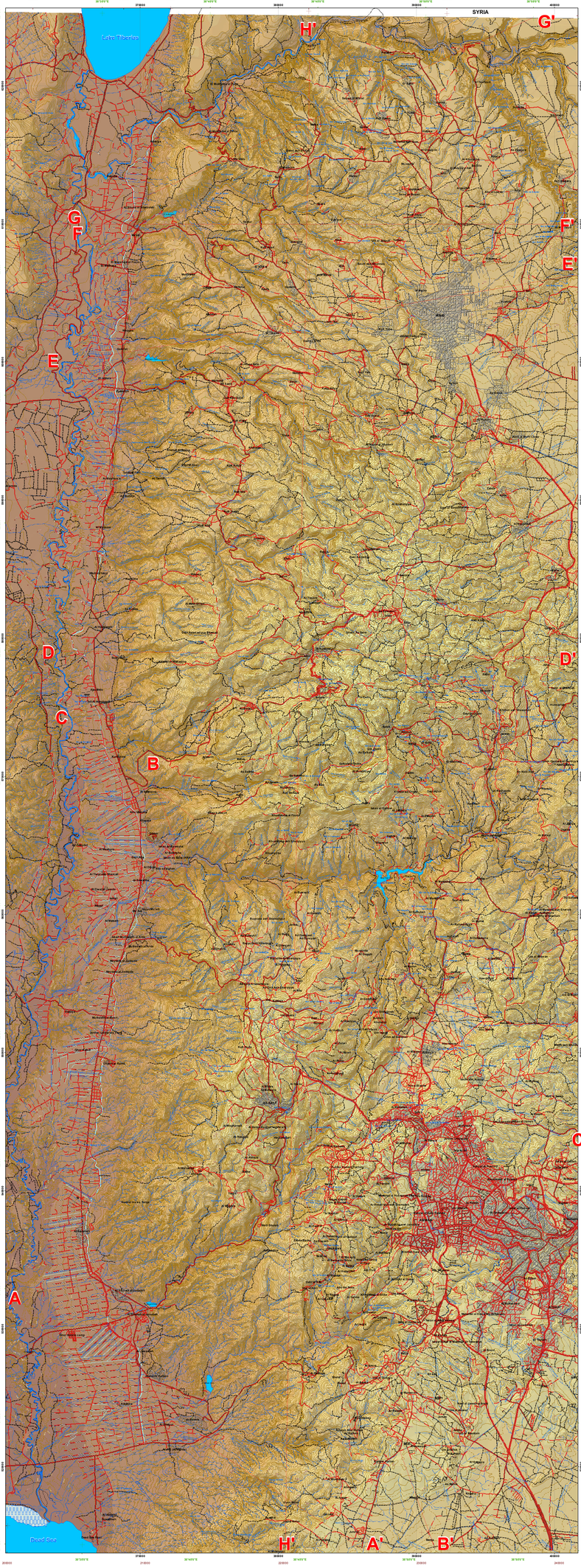
Station ID	Station Name	Jtm (E)	Jtm (N)	Altitude	Normal Year Average	Wet Year Average	Dry Year Average
AL0040	WADI UM AL-DANANIR	388368.171	551343.775	565.0	316.0	471.8	207.0
AL0041	AIN AL-BASHA	389816.477	548219.609	680.0	586.8	592.2	581.3
AL0042	AMMAN JABEL AMMAN (NRA)	396324.702	536611.543	840.0	480.6	645.0	377.8
AL0043	ABU ALANDA	402027.474	530717.363	990.0	285.8	450.7	212.6
AL0044	MAJDAL	390630.123	567107.025	500.0	429.7	653.4	324.5
AL0045	UM JAUZA	381087.892	552564.567	860.0	487.9	648.8	356.2
AL0046	EL-'AL	389179.096	521728.808	800.0	321.3	409.2	233.3
AL0047	SIHAN	382767.218	557337.101	495.0	377.7	496.0	289.0
AL0050	QAFQAFA	400354.438	580545.288	930.0	310.8	403.9	230.3
AL0051	WADI ZARQA GAUGING STATION	393607.789	565757.418	230.0	316.5	432.0	267.0
AL0057	WADI ES-SIR (NRA)YARD	391030.929	536998.996	900.0	482.6	629.4	335.8
AM0001	SALT	379980.394	546082.343	796.0	600.3	768.8	436.4
AM0002	WADI SHU'EIB AGR.STATION	378853.236	538400.273	300.0	362.0	466.9	264.6
AM0003	WADI SHU'EIB KM 47	377831.938	537117.021	220.0	264.5	359.4	217.0
AM0004	SHUNET NIMRIN EVAP. STATION	370242.346	531741.679	-185.0	143.3	210.2	94.7
AM0005	HUMMAR	387950.659	544250.288	925.0	507.2	647.6	372.1
AM0006	IRA	373923.506	542682.219	650.0	273.0	382.0	202.2
AM0007	SOUTH SHUNA	371242.201	531725.185	-160.0	177.9	254.5	125.7
AN0002	WADI ES-SIR	388321.624	536443.717	720.0	517.6	689.9	401.3
AN0003	NA'UR	389181.197	527929.086	800.0	442.1	617.7	308.1
AN0004	ADASIYA JANOUBIYA	383351.107	526125.030	750.0	238.4	316.6	172.6
AN0005	KAFREIN DAM	374431.282	524971.825	-153.0	70.5	155.5	13.9
AP0001	ER-RAMA	375393.261	522655.735	-185.0	161.2	224.9	108.1
CC0002	MA'IN	380226.346	506374.782	810.0	320.0	531.1	218.3
CC0004	MUSHAQQAR EVAP. STATION	386723.702	518369.007	800.0	327.6	418.3	243.8
CD0001	SAHAB	405676.984	527657.227	830.0	260.6	387.3	195.3
CD0002	YADUDA FAHID ABU JABER	397129.886	524798.034	850.0	331.0	472.8	203.3
CD0004	BEIR EL-TUNEIB	400043.552	519550.027	795.0	243.5	330.7	156.4
CD0024	YADUDA FAHID ABU JABER	397129.886	524798.034	850.0	312.2	405.6	242.3
CD0025	UM EL-AMAD	395506.899	517324.584	800.0	305.4	415.3	211.1
CD0026	EZ-ZEITUNA EVAP. STATION	396168.942	515013.655	765.0	203.7	308.3	146.6

3

LIST OF PLATES (Digital Maps)

Plate 1	Topographic map of the study area at a scale of 1:50,000.
Plate 2	Triangular Irregular Network (TIN) of the study area at a scale of 1:50,000.
Plate 3	Digital elevation model (DEM) of the study area at a scale of 1:50,000.
Plate 4	Geological map of the study area at a scale of 1:50,000.
Plate 5	Geological Cross sections of the study area at a scale of 1:50,000. (AA´, BB´, CC´, DD´, EE´, FF´, GG´, HH´).
Plate 6	Drainage map of the study area showing the surface water basins at a scale of 1:50,000.

NW of JORDAN Topographic Map



Scale 1:50,000

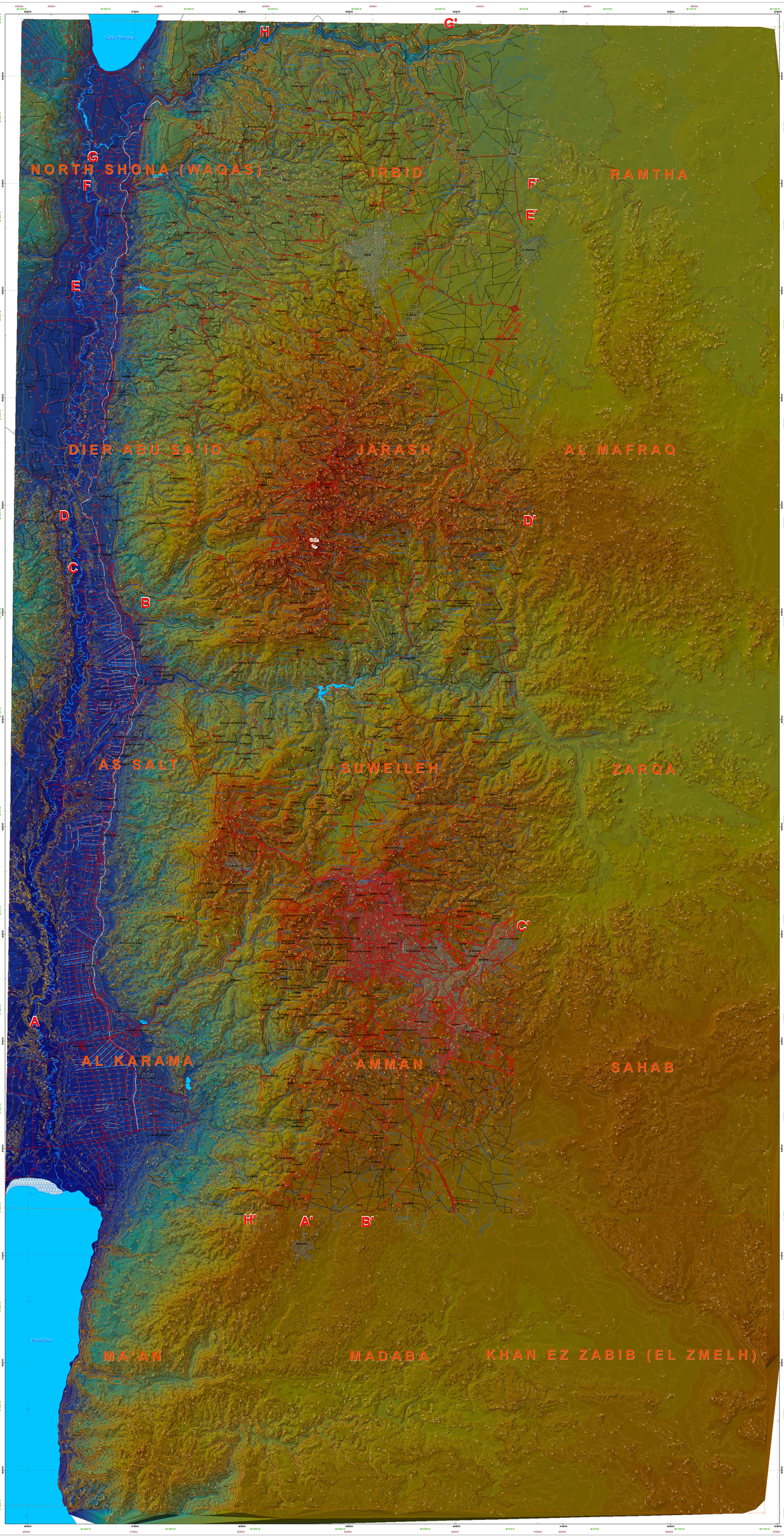
0 75000 150000 300000 450000 Meters

Digitized topographic maps in scale of 1:50000 prepared by the Royal Jordanian Geographic Centre (RJGC) in Amman, and the United Nations Agency for International Development in Jordan (UNAID) in Amman, Jordan, in cooperation with the United States Agency for International Development (USAID) in Amman, Jordan.

CONTOUR INTERVALS ARE 20 METRES
MAPS ARE PRODUCED IN THE UNIVERSAL TRANSVERSE MERCATOR (UTM) PROJECTION
ZONE 36 SPHEROID: INTERNATIONAL 1924 DATUM: ADOS 1950

THE ACCURACY OF THE HORIZONTAL DATA IS 15 METRES
THE ACCURACY OF THE VERTICAL DATA IS 20 METRES

NW of JORDAN Triangular Irregular Network (TIN)



Scale 1:50,000

0 75000 150000 300000 450000 Meters

Geographic coordinates, datum is Lat/Lon (1-WGS84 projection) for Europe, Africa, Middle East Region, Projection Mercator/Transverse Mercator, Ellipsoid for all projections is WGS 1984 and all Geographic Grid, Grid and Map Numbers for Topo Maps Based on Lat/Lon Grid

LOWER DIGITAL CONTOURS
NEW IN GENERATED DIGITAL TOPOGRAPHIC MAPS
United States Geological Survey
Reston, Virginia 22092 USA
Technical Information Center
Mail Stop 516, National Center
MINERAL RESOURCES DIVISION
FIRST EDITION JUNE 1990

BLACK TRIANGULAR CROSS-HATCHED TIMES AND MAPS AREAS IN MOUNTAINOUS ZONE ARE

LINES FORMED BY THE INTERSECTION OF THE SURFACE WITH A SERIES OF HORIZONTAL PARALLEL PLANES, EQUALLY SPACED VERTICALLY

PRODUCTS OF THE MINERAL RESOURCES DIVISION ARE PRODUCED BY THE USGS WITH THE COOPERATION OF THE MINISTRY OF PUBLIC WORKS, HASHEMITE KINGDOM OF JORDAN

Legend

- Spring
- Spot elevations in metres
- Dams
- River
- International Border

Contours

- Index contour
- Intermediate contour
- Supplementary contour

Cities and Villages

- Major City
- City
- Village
- Village in Settlement

Wadies

- General Mark Ashutuh (East Ghor Canal)
- Wadies
- Top Line

Roads

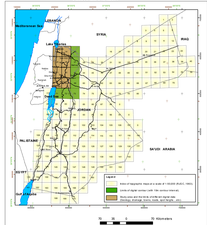
- All weather, two lanes wide
- All weather, two lane narrow wide
- All weather, 5-7m wide
- All weather, less than 5m wide
- All weather, hard surface, one lane wide
- Fair or dry weather, loose surface
- Track
- Trail
- All weather, loose or light surface, 5m wide
- Pipe Track
- Track
- Railroad
- Abandoned Railroad

- Sheets Limit
- Geological cross section

NW of Jordan Triangular Irregular Network (TIN)

Elevation

- 1150 - +1200
- 1100 - 1150
- 1050 - 1100
- 1000 - 1050
- 950 - 1000
- 900 - 950
- 850 - 900
- 800 - 850
- 750 - 750
- 650 - 700
- 600 - 650
- 550 - 600
- 500 - 550
- 450 - 500
- 400 - 450
- 350 - 400
- 300 - 350
- 250 - 300
- 200 - 250
- 150 - 200
- 100 - 150
- 50 - 100
- 0 - 50
- -50 - 0
- -100 - -50
- -150 - -100
- -200 - -150
- -250 - -200
- -300 - -250
- -350 - -300
- -400 - -350
- -422 - -400



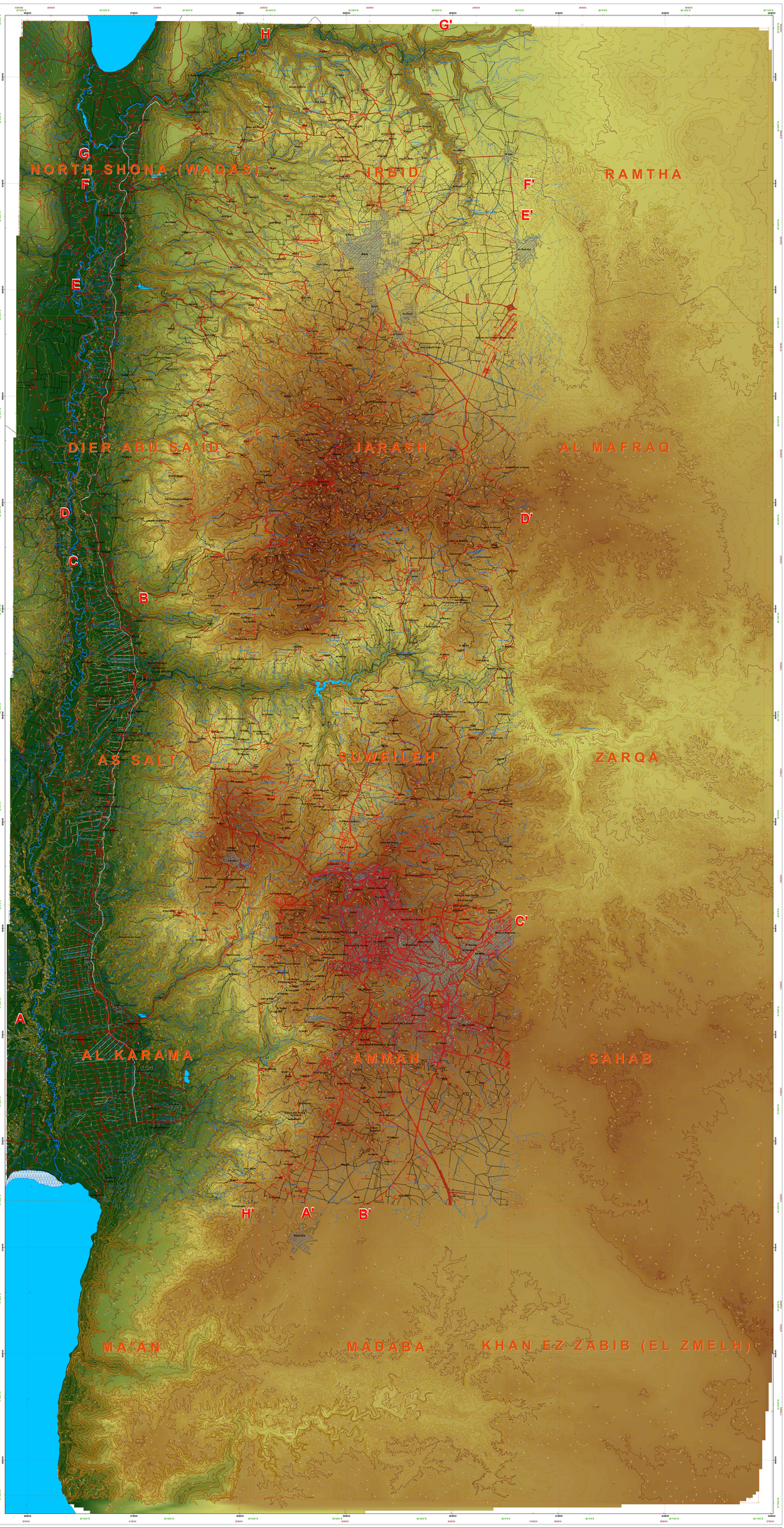
Appendix (1.2) Triangular Irregular Network (TIN) of the study area at a scale of 1:50,000.

Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley

Prepared By Geol.
Jafra Salem Salameeh

Karlsruhe, Germany/ 2011

NW of JORDAN Digital Elevation Model (DEM)



Scale 1:50,000

0 75000 150000 300000 450000 Meters

Digital Elevation model (DEM) at a scale of 1:50,000 prepared for the Kingdom of Jordan under United States Agency for International Development's (USAID) Project "Development of Water Resources in the Jordan Valley" (Contract No. 278-0248) implemented by the Water Resources Consultant Company (WRC).

COORDINATE SYSTEM, DATUM, METERS

Transverse Mercator projection, TM36W

Datum Ancient Jerusalem Datum Adjusted to Ancient Jerusalem Datum

MAGNETIC DECLINATION 3°15'0.0"
ANNUAL CHANGE 0°0'0.0"

MEAN, AUTHORIZED CLIMATOLOGICAL TIME LINE FOR WATER AGENCY, 35 EASTERN MERIDIAN LINE

CONTOUR INTERVAL 100 METERS

CONTOUR ELEVATIONS ON MEAN SEA LEVEL BASED ON ARBITRARY HYDROGRAPHIC TRANSFERRED TIDE FOR LAKE LOTS, TO CONVERT TO ELEVATIONS ABOVE

MEAN TIDE ELEVATIONS ARE 0.0 METERS FOR LAKE LOTS AND 0.0 METERS FOR THE DEAD SEA

Legend

- Spring
- Spot elevation in meters
- Cave
- Cliff
- International Border

Contours

- 100m contour
- Intermediate contour
- Supplementary contour

Cities and Villages

- Major City
- City
- Village or Settlement

Waters

- General Water Abstraction (Canal Other Canal)
- Waters
- Tide Line

Roads

- 4A weather, two lanes wide
- 4A weather, more than 7m wide
- 4A weather, 5m wide
- 4A weather, less than 5m wide
- 4A weather hard surface, one lane wide
- Fair or dry weather, loose surface
- Track
- Trail
- 4A weather, loose or light surface, 5m wide
- Plane Track
- Railway
- Railroad
- Abandoned Railroad

Sheets Limit

Geological cross section

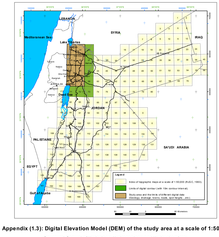
NW of Jordan Digital Elevation Model (DEM)

Value

High : 1224

Low : -422

INDEX TO ADJOINING SHEETS



Appendix (1.3): Digital Elevation Model (DEM) of the study area at a scale of 1:50,000.

Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley

Prepared By Geol.
Jude Salem Salameh

Karlsruhe, Germany/ 2011

NW of Jordan Geological Map

Scale 1:50,000

0 2500 5000 10000 15000 20000 Meters

Digitized from geological maps at a scale of 1:50,000 produced by the Natural Resources Authority, National Mapping Project (NR-A, 1993 - 2006).

COORDINATE SYSTEM IS ARBITRARY
WITH SUPPLEMENTARY GRID LINES IN METRES
Natural Grid Coordinates are in metres
IN ADDITION, WHEN CONDITION PERMITS
Universal Transverse Mercator Grid
PROJECTION:TRANSVERSE MERCATOR
SPHEROID:INTERNATIONAL

BLACK NUMBERED GRID INDICATE THE 1000 METER JORDAN TRANSVERSE MERCATOR GRID

GREEN NUMBERED GRID INDICATE THE 100 METER SECTIONS WITHIN THE 1000 METER UNIVERSAL TRANSVERSE MERCATOR GRID (UTM) ZONE 36 SHADED ALTERNATELY

DATUM: INTERNATIONAL 1909 - NO DATUM SHIFT BETWEEN ARMY AND CIVILIAN DATUM
RELIEF IS RELATIVE TO MEAN SEA LEVEL - ONE SPHEROID

Topographic Symbols

- Spring
- Spot elevations in metears
- Dams
- River
- International Border

Contours

- Index contour
- Intermediate contour
- Supplementary contour

Cities and Villages

- Major City
- City
- Village or Settlement

Wadies

- Qanat el Malk Abdullah (Eastr Ghor Canal)
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- All weather, two lanes wide
- All weathe, more than 7m wide
- All weather, 5-7m wide
- All weather, less than 5m wide
- All weather, hard surface, one lane wide
- Fair or dry weather, loose surface
- Track
- Trail
- All weather, loose or light surface, 5m wide
- Pierre Track
- Track
- Railroad
- Abandoned Railroad

Geological Symbols

- Section Lines Location
- Strike and Dip

Structural features

- Fault, certain
- Fault, approximate
- Fault, tick shows downthrow side
- Fault approximate, tick shows downthrow side
- Dextral strike slip fault
- Sinstral strike slip fault
- Fault inferred beneath superficial deposits
- Lineament
- Anticlinal axis
- Synclinal axis
- Anticlinal axis, plunging
- Synclinal axis, plunging
- Synclinal axis, inferred
- Anticlinal axis, overturned
- Monoclinal flexture
- Anticlinal axis, inferred & plunging
- direction of movement

Lithological Boundaries

- Geological boundary, bedrock
- Geological boundary, bedrock inferred
- Geological boundary, superficial deposits

Lithological Symbols

CZ	Landslide
Q	Basalt
Qfs	Thick soil over bedrock
S	Thick soil
Qfs	Thick soil
Qfs	Thick colluvia over bedrock
Qfs	Alluvium of Fans
Qfd	Alluvium Delta
Qg	Alluvium Gravel
Qc	Alluvium & Wadi Sediments
Qt	Floodplit Gravels
Qzs	Zarqa Siltstone / Lisan Marl Gravel
Ql Qz	Lisan Marl, Lacustrine gravels facies
Qbv	Shuwayr Volcanic
Qbg	Baghur Conglomerate
Qa	Amram
Qs	Sahem
Qrg	Rwagan Conglomerate
Tq	Tayyibe Limestone
Wdc	Wadi Shallale Chalk
Ulm	Umm Rijam Chert Limestone
Wsq	Wuwaqqar Chalk Marl
Ajm	Al Hisa Phosphorite
Ahm	Amman Silicified Limestone
Rj	Rj. Hisa Phosphorite/ Amman Silicified
Wdl	Wadi Umm Ghudran
Wsd	Wadi as Sir Limestone
Fdh	Fuhis/Hummar/Ghudrb
Hum	Hummar
Ghudrb	Ghudrb
Fuhis	Fuhis
Na'ur	Na'ur Limestone
Kurnub	Kurnub
Ajlun	Ajlun
Muqheiqiq	Muqheiqiq Limestone
Hayala	Hayala Volcaniclastic
Rum	Rum Sandstone
Rama	Rama / Hamam / Mughannyya
Dishah	Dishah Limestone
Sir	Sir Sandstone
Umq	Umq Cayalana / Nimr Limestone
Abu	Abu Ruweiqa Gypsum
Ln	Lisan Marl / Umm Tina
Mukeiyla	Mukeiyla Sandstone-Shale
Hudian	Hudian Limestone
Suwaqha	Suwaqha Sandstone Limestone-Shale

Landslide
Basalt (Pliocene - Recent)

Superficial Deposits (Quaternary)

Jordan Valley Group (Upper Tertiary - Quaternary)

Belqa Group (Upper Tertiary - Quaternary)

Ajlun Group (Upper Tertiary - Quaternary)

Kurnub Sandstone Group (Lower Cretaceous)

(Jurassic)

Zarqa - Malih Group (Jurassic - Triassic - Permian)

(Triassic)

(Permian)

INDEX TO ADJOINING SHEETS

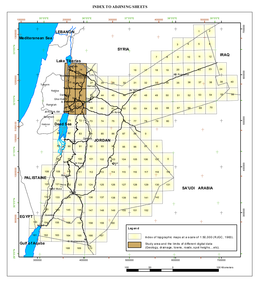

Plate 2: Digital geological map of the study area at a scale of 1:50,000

(digitized from 9 paper geological maps at a scale of 1:50,000 produced by NRA, 1993 - 2006)

Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley

Prepared By Geol.
Julia Salem Sahawneh

Karlsruhe, Germany/2011

Plate 5
(Geological Cross Section AA´)

Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley

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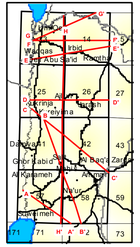


Legend

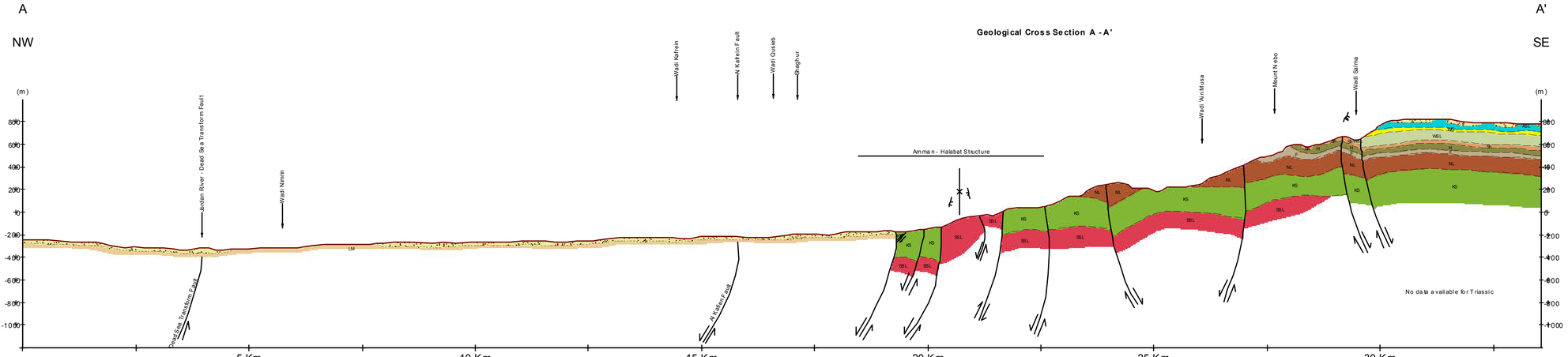
- Area Name
- Topography
- Fault with relative movement

Lithological Boundary

- Geological boundary, bedrock inferred
- Geological boundary, superficial deposits

Lithological Symbols

	Soil
LM LMg	Lisan Marl; Lacustrine gravels facies
ASL	Amman Silicified Limestone
WG	Wadi Umm Ghudran
WSL	Wadi as Sir Limestone
Sh	Shueib
H	Hummar
F	Fuheis
NL	Na'ur Limestone
KS	Kumub
SSL	Suwayma Sandstone Limestone-Shale



Horizontal Scale = 1:50,000
Vertical Scale = 2.5 x Horizontal Scale

Plate 5 (A A´): Geological Cross Section A - A' of the study area at a scale of 1:50,000.

Plate 5
(Geological Cross Section BB´)

Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley

Prepared By Geol.
Julia Salem Sahawneh

Karlsruhe, Germany/ 2010

Legend

- Area Name
- Topography
- Fault with relative movement

Lithological Boundary

- Geological boundary, bedrock inferred
- Geological boundary, superficial deposits

Lithological Symbols

S	Soil
Ag	Alluvium Gravel
	Landslide
ASL	Amman Silicified Limestone
WG	Wadi Umm Ghudran
WSL	Wadi as Sir Limestone
Sh	Shueib
H	Hummar
F	Fuheis
NL	Na'ur Limestone
KS	Kurnub
AZ	Azab
ZM	Zarqa Ma'in

Geological Cross Section B - B'

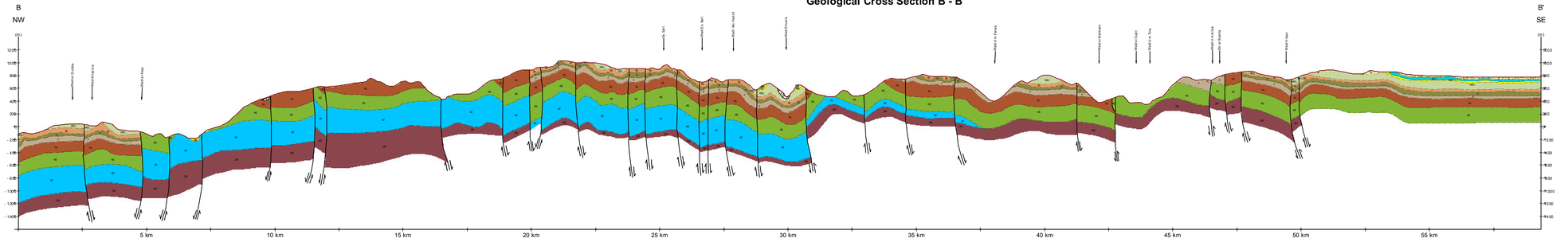


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Plate 5 (B B´): Geological Cross Section B - B' of the study area at a scale of 1:50,000.

Plate 5
(Geological Cross Section CC´)

Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley

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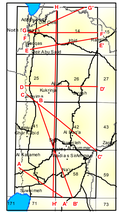
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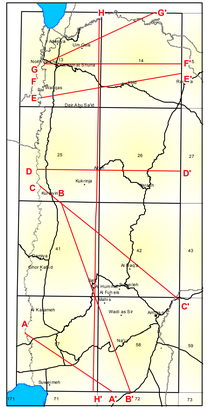
Plate 5
(Geological Cross Section DD´)

Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley

Prepared By Geol.
Julia Salem Sahawneh

Karlsruhe, Germany/ 2010



Legend

- Area Name
- Topography
- Fault with relative movement

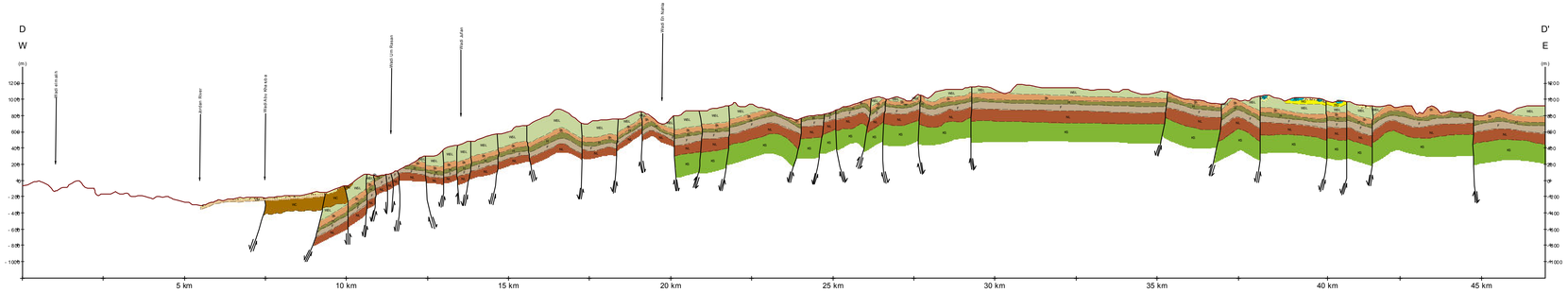
Lithological Boundary

- Geological boundary, bedrock inferred
- Geological boundary, superficial deposits

Lithological Symbols

s	Soil
LM	Lisan Marl
WC	Waqqas Conglomerate
ASL	Amman Silicified Limestone
WG	Wadi Umm Ghudran
WSL	Wadi as Sir Limestone
Sh	Shueib
H	Hummar
F	Fuheis
NL	Na'ur Limestone
KS	Kurnub

Geological Cross Section D - D'



Horizontal Scale = 1:50,000
Vertical Scale = 2.5 x Horizontal Scale

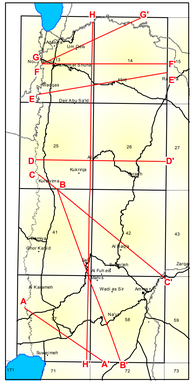
Plate 5 (DD´): Geological Cross Section D - D' of the study area at a scale of 1:50,000.

Plate 5
(Geological Cross Section EE´)

Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley

Prepared By Geol.
Julia Salem Sahawneh

Karlsruhe, Germany/ 2010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Irbid
Al Mafraq
Ajloun
Jerash
Wadi Abu Rabi'
Kufranja
Al Ashrafiyah
Ar Rusayfah
Az Zarqa
Al Azraq
Al Karak
Wadi as Sir
Al Ma'an
Ash Shawbak
Ma'an
Al Jufrah
Al Hallabat
Al Qatrana
Al Ghuwayr
Al Qaysiyah
Al Hasa
Al Ghadir
Al Ghamr
Al Ajfar
Al Qurayqirah
Al Qadisiyah
Al Ghawr
Al Ghanimah
Al Ghuwayrah
Al Ghadaf

Plate 5
(Geological Cross Section FF´)

Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley

Prepared By Geol.
Julia Salem Sahawneh

Karlsruhe, Germany/ 2010

H
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A
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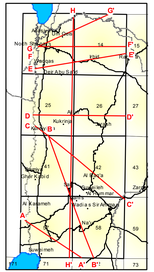
H'
Irbid
Ajloun
Jerash
Mafraq
Al Zarqa
Al Karak
Madaba
Amman
Al Balqa
Ma'an
Al Aqabah
Wadi as Sir
Tafilah
Quweirah
Aqaba
Wadi Rum
Ad Dawhah
Al Azraq
Al Ruwaysah
Al Jafr
Al Qatranah
Al Ghawr
Al Mudawwarah
Ash Shawbak
Al Ma'an
Al Hasa
Al Qadisiyah
Al Ghadir
Al Ghuwayr
Al Ghuwayr
Al Ghuwayr

Plate 5
(Geological Cross Section GG´)

Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley

Prepared By Geol.
Julia Salem Sahawneh

Karlsruhe, Germany/ 2010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Irbid
Mafraq
North Shuna
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Jerash
Amman
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West Abu Rabia
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26
27
Kuraymah
D
D'
C
Madaba
B'
Al Qatrana
Ma'an
Al Karak
Tafilah
Al Jafr
Aqaba
A
C'
Al Ghuwayr
Wadi Ar Rum
Wadi Ar Sirhan
Ar Ruwayshed
Al Mafraq
Al Ma'an
Al Hasa
Al Azraq
Al Jawf
Al Qurayyat
Rafha
Turaif
Al Ula
Tabuk
Al Wajh
Al Bad'
Al Ghadir
Al Ghawr
Al Ghawr
Al Ghawr

Plate 5
(Geological Cross Section HH´)

Structural Control of Hydrology, Hydrogeology and Hydrochemistry along the Eastern Escarpment of the Jordan Rift Valley

Prepared By Geol.
Julia Salem Sahawneh

Karlsruhe, Germany/ 2010

Legend

Area Name
Topography
Fault with relative movement

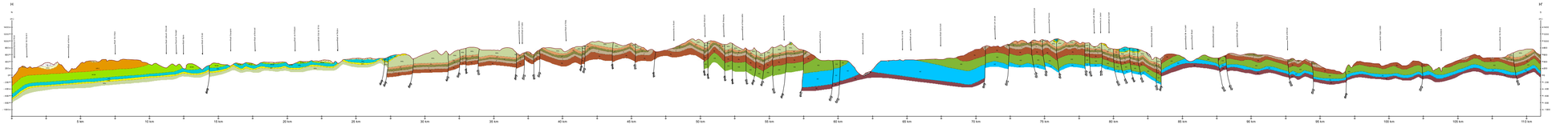
Lithological Boundary

Geological boundary, bedrock inferred
Geological boundary, superficial deposits

Lithological Symbols

Cl	Calcrete
s	Soil
LS	Landslide
WSC	Wadi Shallala Chalk
URC	Umm Rijam Chert Limestone
MCM	Muwaqqar Chalk Marl
ASL	Amman Silicified Limestone
WG	Wadi Umm Ghudran
WSL	Wadi as Sir Limestone
Sh	Shueib
H	Hummar
F	Fuheis
NL	Na'ur Limestone
KS	Kurnub
AZ	Azab
ZM	Zarqa Ma'in

Geological Cross Section H - H'



Horizontal Scale = 1:50,000
Vertical Scale = 2.5 x Horizontal Scale

Plate 5 (HH´): Geological Cross Section H - H' of the study area at a scale of 1:50,000.